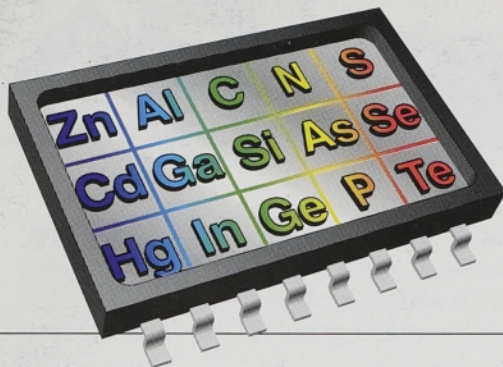




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June 2001

Volume 7 Number 5

VCSELS

Lighting up the
metro market

TriQuint buys
Sawtek

TRW creates
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Gallium found
in Nevada

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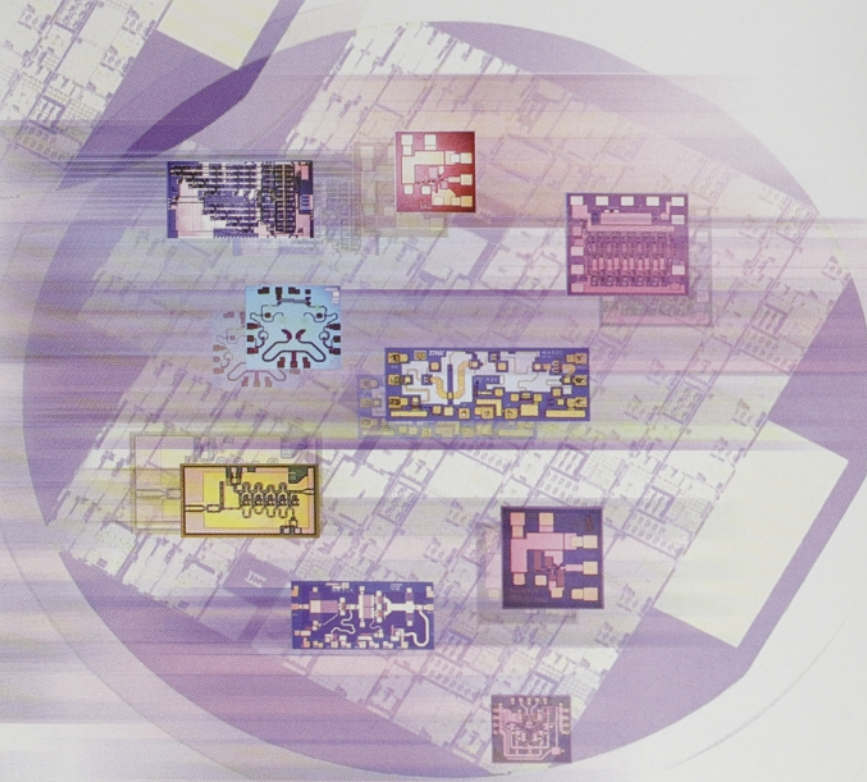
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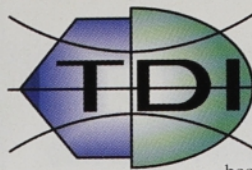
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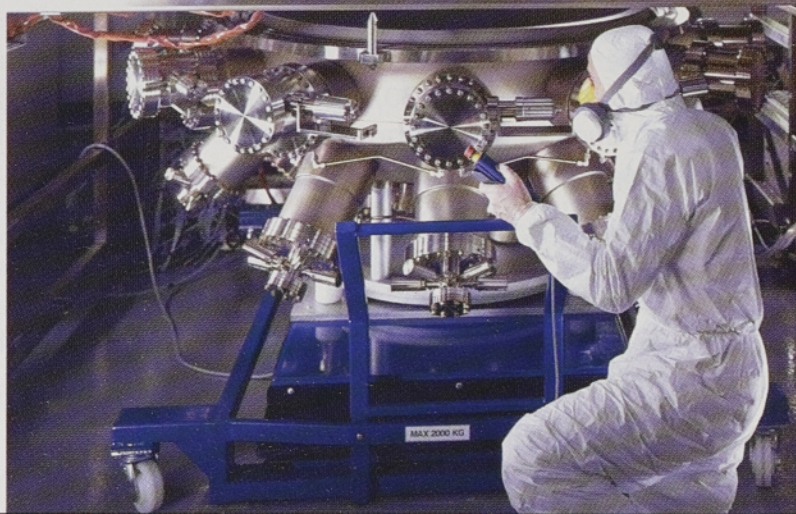
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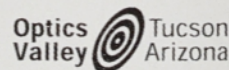
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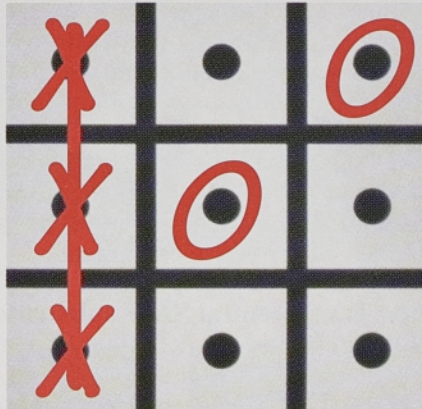
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Compound Semiconductor welcomes new editorial staff member

Compound Semiconductor magazine is pleased to announce the appointment of Jon Newey as assistant editor. Jon joins the magazine after spending several years at the Defence Evaluation and Research Agency (DERA) in Malvern, UK, where he was involved with characterization

of electronic materials using techniques such as SIMS, as well as managing several projects involving silicon germanium epitaxy and related fields. He will be based in the UK editorial offices of *Compound Semiconductor*, which are located in Bristol.

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AUGUST
TECHNOLOGY

TriQuint–Sawtek merger targets modules

TriQuint Semiconductor is to merge with Sawtek, a manufacturer of passive RF filtering technology, in a stock deal currently worth almost \$1.3 billion. The combination of TriQuint's GaAs manufacturing expertise and Sawtek's surface acoustic wave (SAW) filter technology will create "a powerhouse in the RF and GaAs component sector", according to Dale Pfau of CIBC World Markets.

The merged company will focus on developing and manufacturing integrated modules with a high level of functionality and fewer discrete components. This type of product is increasingly on the radar screen of major handset manufacturers, who are asking for "plug and play" modules that let them concentrate on adding value to other portions of wireless phones such as software and data services.

"Sawtek's filter technology plus our strength in active devices will enable us to sell complete RF front-end modules to new and existing customers," said Steven Sharp, chairman, president and CEO of

the combined companies.

Sawtek's products include SAW filters for mobile handsets and infrastructure, band-pass filters, resonators, oscillators and SAW-based subsystems for microwave and RF applications. TriQuint makes GaAs-based ICs including PAs, LNAs and up-/downconverters for wireless and fiber-optic communications, and satellite and aerospace equipment.

GaAs is a potential SAW substrate

SAW filters convert RF signals to the acoustic range. Unwanted signals can be removed at very low frequencies, and the filtering device can also be miniaturized. The acoustic wave must travel in the surface of a piezoelectric material. GaAs is a suitable candidate, and the material offers the potential for integrating SAW devices with electronics.

While higher levels of integration have been achieved in the digital portion of the phone, the RF section is still dominated by large numbers of partially integrated

components. A number of GaAs manufacturers are now looking at ways to reduce this component-count.

"The front-end module of a handset has been the most challenging part of the design for cell-phone manufacturers," said Kimon Anemogiannis, the former CEO of Sawtek and head of the new subsidiary. "While the RF portion now typically contains PA modules, a front-end design will still contain up to 200 components. Integrating PAs and SAW filters reduces component inventories and the time needed to design new phones, and as the module can be pre-tested, increases the mobile-phone yield. We are targeting products for both existing phones and upcoming 3G networks."

Sawtek will operate as a wholly owned subsidiary of TriQuint, making products at its facility in Orlando, Florida and selling them under its own brand name. TriQuint and Sawtek shareholders will own 64% and 36% of the new company, respectively.

Gallium prospectors strike it rich

A gold prospecting company has identified land in Nevada that could become the only mine in the world producing gallium as its primary product. At present, the world's supply of newly mined gallium is a by-product of very large mining operations for other commodities, namely aluminum and (to a lesser extent) zinc.

The mining company, Gold Canyon Resources, is currently evaluating samples from the Cordero property in Humboldt County, Nevada. The average gallium concentration is 82.5 g per metric ton of material (1 t = 1000 kg), with a core area which may exceed 200 g/t, according to Robert Carrington, geological consultant for Gold Canyon. "It's extremely rare to find gallium concentrated to any appreciable degree," he said. "There are only two or three other such deposits in the world."

The ore lies beneath 1–5 m of alluvial deposits, and Carrington estimates that it can be mined at a cost of \$5–10/t. "Even

at the modest trading price of \$500/kg of gallium, the property appears to have significant potential," he added. As recently as October 2000, the spot price of gallium was \$550/kg; by March 2001 this had risen to \$2000/kg, and exceeded \$4000/kg in May.

Gold Canyon has not yet determined whether it will refine the gallium after it is extracted from the ore, although Carrington speculates that it may be possible to obtain gallium with 5 or 6N purity using a standard SX–EW (solvent extraction – electro-winning) process.

Demand drives production increase

Gold Canyon estimates that the total worldwide gallium consumption in 2000 was nearly 200 t, of which 130 t was newly mined. The remainder came from government stockpiles or from the recycling of manufacturing scrap. GEO Gallium, the world's largest extractor of virgin gallium metal, recently announced plans for a fourfold increase in production which will involve rebuilding an existing extraction facility in Australia (see *Compound Semiconductor* April 2001,

p4). Gallium feedstocks for GEO's facility, which will have an ultimate annual capacity of 100 t, are supplied from an aluminum extraction plant in the same location. GEO also extracts about 33 t per year at its site in Germany, and refines the material in France and Germany. Extraction facilities in China and Ukraine are also planning to increase their production.

Meanwhile, Dowa Mining is to invest about ¥5 billion (\$40 million) to increase its annual production volume of refined Ga to 160–170 t, around two-and-a-half times higher than the 65 t produced in fiscal 2000. Dowa Mining is the only company to refine gallium from by-products of zinc processing, and also relies heavily on recycling.

Carrington estimates that the Cordero property could eventually produce as much gallium as GEO's facility in Australia. "If the overall economics are feasible, and Gold Canyon decides to proceed with the mine, then gallium extracted from this site could reach the market in as little as 18–24 months," said Carrington, while noting that this represents the fastest possible scenario.

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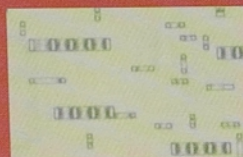
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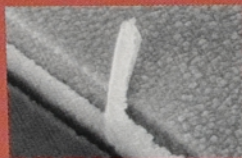
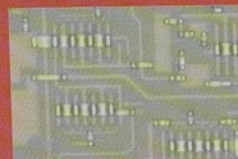
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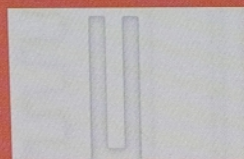
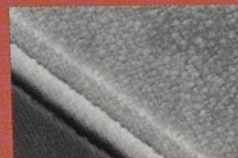


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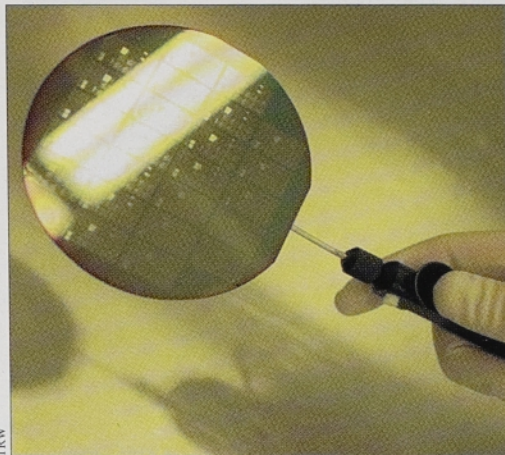
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TRW forms Velocium to sell InP and GaAs

TRW, which has spent over a decade developing high-speed InP-based devices, has created a new company to manufacture these products for fiber-optic and wireless communication systems. The product lines of the spin-off, named Velocium, will also include TRW's current commercial GaAs components. Based in Manhattan Beach, California, Velocium will be headed by Dwight Streit, who has played an important role in TRW's advanced semiconductor development program over the last six years. This program recently culminated in the world's first 4 inch InP production facility (see *Compound Semiconductor* Sept/Oct 2000, p6).

Velocium will use TRW's facility exclusively for the development of new products. TRW says this InP line represents the first high-volume source for InP devices, which will include integrated photoreceivers, modulator drivers and amplifiers for 40 Gbit/s fiber-optic networks, in addition to power amplifiers for 2.5G and 3G wireless handsets. The company's product development activities will take advantage of TRW's exten-



One of the first 4 inch wafers from TRW's recently opened indium phosphide production line.

sive design capabilities, in addition to those of selected industry partners.

"TRW has invested more than \$300 million to bring its advanced semiconductor capabilities to commercial markets, and we've committed an additional \$70 million this year for InP manufacturing capacity expansion and product development," said Tim Hannemann, president and CEO

of TRW Space & Electronics. "Establishing Velocium as a separate business leverages this investment by focusing on these rapidly growing markets."

Velocium's first InP device will be an OC-768 (40 Gbit/s) integrated photoreceiver, which will be available in volume quantities from May. Additional 10 and 40 Gbit/s optical network products will be in volume production by the summer, and wireless power amplifiers will be available by 2002.

"TRW started to make GaAs HBTs eight years ago, and was very successful at building these devices for companies such as Nokia and RFMD, a company that now holds 35% of the HBT market," says Velocium's new president Dwight Streit. "We see a similar opportunity opening up for InP power amplifiers, which will be used in applications operating from cellular up to millimeter bands, and which leverage the high power-added efficiency, linearity and low noise advantages of these devices. For fiber-optic transceivers, InP devices offer a speed advantage and an ability to be integrated with other devices such as photoreceivers."

Raytheon supplies GaAs HBTs to Hyundai

Raytheon's RF Components Division (Andover, MA) is supplying production volumes of its GaAs HBT power amplifier for Hyundai's TX-20B PCS handset platform. One of the largest wireless handset manufacturers in Korea, Hyundai has earmarked the dual-band, tri-mode TX-20B for the US CDMA market. Raytheon's RMPA 1951 GaAs HBT is part of a small outline PA module designed for PCS and wireless local loop applications.

The agreement marks the first in a

series of anticipated production orders between Raytheon and Hyundai, and is expected to boost Hyundai's share of the growing wide-band CDMA market. "This agreement further confirms our long and successful relationship with Hyundai," said Russ Wagner, vice-president of strategic development for the RF Components Division. "We feel that this agreement will help us to further expand our presence in Asia while helping Hyundai broaden its product base and market share."

Celeritek loses GaAs orders for satellites

Celeritek has lost approximately \$18.5 million in orders for GaAs-based devices used in satellites. The company, which makes MMIC power amplifiers for PCS handsets, wireless local loop subscriber units and

base stations, also reported that a number of its customers in the radio market have recently rescheduled or delayed orders. In light of the current slowdown in the wireless communications market, and after adjusting for order delays and uncertainties, the company now believes its order backlog stands at around \$60 million, compared to \$91 million at the end of last year.

Siemens orders HBT PAs from RFMD

RF Micro Devices has received production orders for both GSM and DCS/PCS power amplifiers from Siemens. Shipments are expected to begin in July and increase to the multi-million-dollar level during this calendar year, says the company.

RFMD will supply Siemens with GaAs HBT-based PAs for its S40 and S42 wireless phones, both of which are recently introduced triple-band handsets (GSM 900/GSM 1800/GSM 1900) with WAP (wireless application protocol) functionality. Analysis by Gartner Dataquest places Siemens as the world's fourth largest manufacturer of handsets, with a 6.9% market share. "We anticipate additional orders for future platforms, which could quickly establish Siemens as one of our top-ten accounts," said president and CEO David Norbury.

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CDMA PA modules order for Anadigics

Anadigics has recently announced production orders and pre-production shipments for two of the company's CDMA power amplifier modules from a leading CDMA handset manufacturer. The orders are for Anadigics' new series AWT6105 and AWT6106 InGaP HBT modules that are designed to provide both low- and high-band operation for CDMA handsets. Anadigics expects this order to ramp up in the second half of the year, and estimates around \$20-25 million in revenue for 2002.

"CDMA represents the fastest growing segment of the wireless handset market," said Bami Bastani, president and CEO. "The positive response from the leading CDMA OEM handset manufacturer to our products underlines the success of our InGaP HBT efforts in the wireless marketplace. This production win is an important step in achieving our goal of gaining over 50% of our wireless revenue from non-MESFET products by the end of 2001."

Alpha buys Kopin's HBT epiwafers

Kopin has signed a multi-year contract to provide InGaP HBT transistor wafers to Alpha Industries. Kopin's epiwafer products are used in the manufacture of PA circuits for digital cellular and PCS handsets, ICs for next generation 3G wireless devices, and 2.5 and 10 Gbit/s optical network ICs. In addition, Kopin recently announced a collaboration with Rockwell to develop InP HBTs to support next generation wireless and optical networking systems (see *Compound Semiconductor* April 2001, p15).

"We are very excited to announce our supply partnership with Alpha Industries," said John Fan, Kopin's president and CEO. "We have worked closely with Alpha's technical and product teams and are looking forward to supporting their expansion of HBT programs. This validates our strategic plan to deliver precisely what communications circuit manufacturers are looking for - high-performance HBT wafer production that is reliable, consistent and highly scalable."

Cree doubles blue LED performance again

Cree recently unveiled a new version of its high-brightness InGaN-on-SiC blue LED that doubles the output of its UltraBright device introduced last October. Called MegaBright, the company's new LED operates at a dominant wavelength of 470 nm and exhibits a typical brightness of 10 mW (at 30 mA). This output matches the highest brightness of sapphire-based devices, says the company. The MegaBright device is based on the same shaped-chip geometry as the UltraBright device, having a top area of $300 \mu\text{m}^2$

and a p-n junction area of $240 \mu\text{m}^2$ (see *Compound Semiconductor* November 2000, p11).

Cree says the emitter is designed for full-color outdoor video displays, automotive lighting and PDA backlighting. Other applications for the device include architectural illumination and contour lighting, and patio and special effects lighting.

Over the last three years Cree says it has increased the brightness of its LED products by a factor of ten. "We have

made tremendous progress increasing the brightness of our silicon carbide-based LEDs," said Neal Hunter, chairman and CEO. "Our LEDs now exceed sapphire-based devices at a price/performance point unequaled in the nitride industry. The brightness we've achieved places the company squarely in the forefront of volume production devices at the 10 mW level."

Evaluation and qualification samples are now on offer, with volume production expected this month.

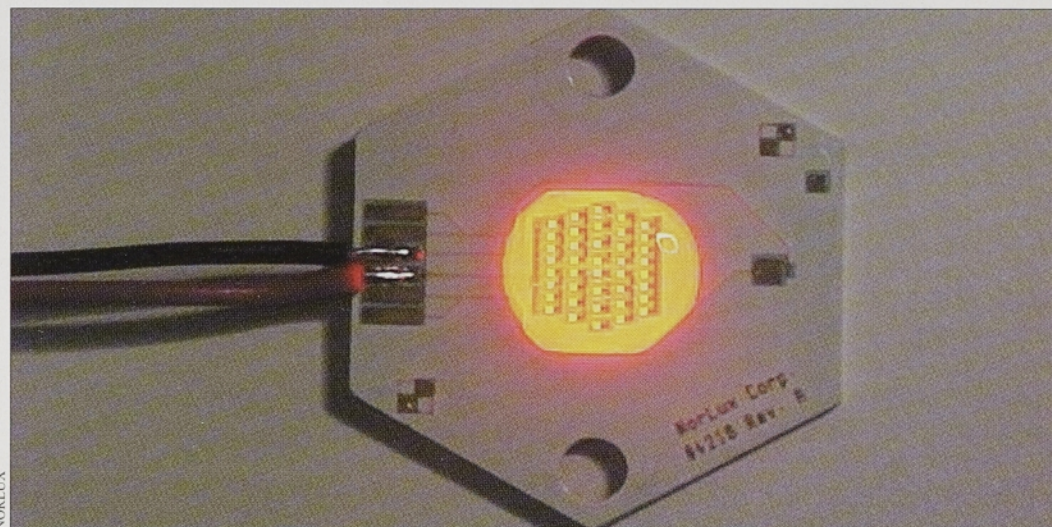
Uniroyal subsidiary NorLux samples first LED lighting products

NorLux has developed its first product – a new high-power LED package containing multiple LEDs. NorLux was recently formed by Uniroyal Technology to specialize in the design of custom lighting solutions based on high-brightness LEDs (*Compound Semiconductor* May 2001, p7).

The new LED package is known as the "Hex" due to the hexagonal shape of its aluminum substrate board (see photo). The hexagonal configuration allows efficient and flexible packing with other Hex substrates. Each hexagon contains a central emitter region about 0.375 inches in diameter containing as many as 40 LEDs. The aluminum is used for thermal dissipation but not electrical conductivity, and the chips are wire bonded and connected to two top contacts on the substrate to facilitate the anode and cathode.

Differing numbers of Uniroyal's InGaN or AlInGaP high-brightness chips can be arranged on the substrate depending on the type of light output required. The light output can be monochrome, full-color (using RGB), or white (using RGB or binary complementary blue and yellow LEDs). The chips and bonds are encapsulated in a high optical index material for light extraction and protection of the die and wire bonds.

NorLux's Hex substrate packages have a final diameter of 1.25 inches, and can be packed densely to achieve high levels of brightness. The substrate affords a thermal resistance of less than 10°C/W compared to around 350°C/W for a standard



NorLux's "Hex" chip connects as many as 40 LEDs in a small 0.375 inch diameter area. The devices are attached to a 1.25 inch diameter hexagonal aluminum substrate which acts as a heat sink.

5 mm LED lamp. This allows the LEDs to be driven at higher power levels.

Preliminary data sheets for a Hex substrate board containing 40 red AlInGaP/GaAs devices testify to a luminous efficiency of 20 lm/W for a forward current of 0.45 A. A 470 nm blue Hex offers 4 lm/W, while the company's 525 nm green offers 9.5 lm/W.

"The hexagons are packed very densely," says NorLux's general manager Andy Lipman. "The die are also concentrated in a very small area, which makes them an ideal source for optical coupling. The package is designed to have primary optics attached to increase the light output."

NorLux is currently sampling the Hex

and says the new devices target industrial applications such as machine vision, in addition to signage, architectural illumination, and decorative and retail lighting solutions.

Uniroyal gets more light

In more news, Uniroyal Optoelectronics (UOE) has achieved new levels of brightness from its high-brightness red LEDs manufactured at its facility in Tampa, Florida. UOE is producing 618 nm and red (626 nm) absorbing substrate AlInGaP/GaAs LEDs that contain an integrated Bragg reflector and exhibit a brightness output ranging from 140 to 200 mcd in die form.

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Courts rule in patent cases

Recent months have seen further developments in the various patent lawsuits relating to nitride-based LEDs. A number of cases are being fought in the US and Japan, with Nichia, Toyoda Gosei and Cree the chief protagonists.

Nichia's Cree case thrown out

The Tokyo District Court has dismissed the lawsuit filed in December 1999 by Nichia against Sumitomo Corporation, one of Cree's distributors in Japan (see *Compound Semiconductor* Jan/Feb 2000, p10). Nichia alleged that certain Cree blue LED products infringed Japanese patent number 2918139.

Nichia had sought an injunction against the sale in Japan of Cree's standard brightness blue LED products, claiming that the LED device structure infringed the patent in question. In a decision handed down on May 15 in Tokyo, a three-member panel of judges found that the Cree products did not infringe the patent. Cree argued that its products employ a structure fundamentally different from the structure disclosed in the patent.

"The Tokyo District Court's decision represents a significant victory for Cree," said Cree's chairman and CEO Neal Hunter. "We succeeded in defending our products in the case, and that success lends further support to our long-standing belief that Cree's SiC-based LEDs differ in significant ways from LEDs produced by our competitors."

Nichia claims victory over Rohm

Nichia is claiming to have won a victory over Rohm in the on-going war over InGaN LED patents. The battle (or perhaps skirmish) in question was an unusual complaint that Rohm had lodged with the United States International Trade Commission (ITC), alleging that Nichia was

infringing on two of Rohm's US patents (see *Compound Semiconductor* February 2001, p8). The ITC has the power to block imports that might harm domestic US industries; this case was very unusual because neither of the parties to the complaint is an American company.

In a strongly worded statement issued on May 15, Nichia claimed that Rohm had been forced to withdraw the complaint to stave off potentially embarrassing disclosures following the ITC's grant of a discovery motion to Nichia. "It is unheard of that an ITC investigation is abandoned midway through the process like this," said Mark Grant, Nichia's lead counsel. "Nichia believes they would have proven that Rohm fabricated a domestic industry to obtain ITC jurisdiction, and knowingly asserted invalid and unenforceable patents."

Commenting on the outcome, Noboru Tazaki, managing director and general manager of Nichia's Optoelectronics Products Division, said "We believe the motion to withdraw removes any doubt that the ITC complaint was frivolous and that manufacturers in the US will have ongoing access to Nichia's LEDs. This turn of events also eliminates concern over the availability of violet and blue laser diodes in the US, as Nichia is the world's only commercial supplier of these parts."

Toyoda Gosei decision reversed

The Tokyo High Court has reversed a previous decision that rendered one of Toyoda Gosei's patents invalid. Patent number 2737053 concerns the buffer layer structure of double heterostructure nitride-based LEDs with an undoped light-emitting layer. The patent, which could prove to be important in Toyoda Gosei's patent "war" against Nichia, was deemed invalid in October 1999.

Taiwanese InGaN LED makers ramp up

Several companies in Taiwan are expanding their capacity to produce InGaN-based blue and green LEDs. According to local sources, Epistar, a leading supplier of AlInGaP chips and epiwafers, initiated production of InGaN epiwafers last year. The company now has a capacity of 5 million chips per month, and its

new factory will accommodate a monthly capacity of 15 million chips.

Huga Optotech, a nitride LED specialist, achieved volume production of epiwafers in the fourth quarter of last year. Its current capacity is also 5 million chips per month, with plans to increase this to 10 million by the end of this year.

Sony and UDC to develop OLED displays

Universal Display Corporation (UDC) and Sony will jointly develop high-efficiency active matrix organic LED (OLED) displays for use in large-area monitors. UDC, a manufacturer of organic LEDs based in Ewing, New Jersey, will combine its high-efficiency electro-phosphorescent materials with Sony's low-temperature polysilicon active matrix OLED technology. Using this combination, Sony recently produced a 13 inch diagonal display consisting of 800×600 pixels. The company says the display is slightly thicker than a credit card and has the potential to replace bulky cathode ray tubes.

Organic LED sources offer several advantages over liquid crystal displays (LCDs): OLEDs are self-luminous, which



Sony's 13 inch OLED screen features a silicon TFT active matrix to drive the pixels, which are made from UDC's electro-phosphorescent organic light emitters.

allows a wide viewing angle and high contrast ratio, in addition to precise color reproduction. "We believe that Sony's vision of a thin, lightweight OLED television monitor is a dramatic confirmation of the essential attributes of OLED technology," said UDC's president and COO, Steven Abramson.

"UDC and their research partners have been developing innovative OLED technologies for more than seven years," added Tetsuo Urabe, Sony's general manager of OLED development. "The combination of Sony's advanced active matrix-OLED technology and UDC's expertise in OLED R&D will accelerate the realization of this revolutionary flat panel display technology for large area applications."

UDC announces blue organic emitters

UDC and its research partners at Princeton University and the University of Southern California (USC) have developed the world's first efficient blue phosphorescent-based OLED. When combined with red and green phosphorescent OLEDs, the blue emitter establishes the primary color palette and promises to open markets to full-color, active matrix OLED displays.

In traditional OLEDs, the light emission is obtained by fluorescence, which results from a transition from a singlet

excited state of a material. An OLED doped with fluorescent material has an upper efficiency limit of 25%. Using electro-phosphorescent materials as the color dopant, both singlet and triplet excited states are exploited, extending the efficiency limit to almost 100%.

According to principal investigator Mark Thompson of USC, phosphorescent materials offer considerable power efficiency advantages compared to fluorescent OLEDs, which are being developed by companies such as Eastman Kodak and Cambridge Display Technologies. "Efficiency is critical for long battery life in portable display appli-

cations, and longer lifetimes for video monitor applications," he says.

The new device consists of a fluorinated iridium organometallic complex with a luminous efficiency of around 12 cd/A. The initial lifetime is several hundred hours, which exceeds that of UDC's phosphorescent green OLED when it was first developed last year. UDC's green device is now capable of a lifetime of 10 000 hours, making it equivalent to inorganic LEDs. UDC is developing strategic collaborations with a view to eventual commercialization, including one with MOCVD system manufacturer Aixtron to produce OLED thin film production equipment.

NITRIDE NEWS

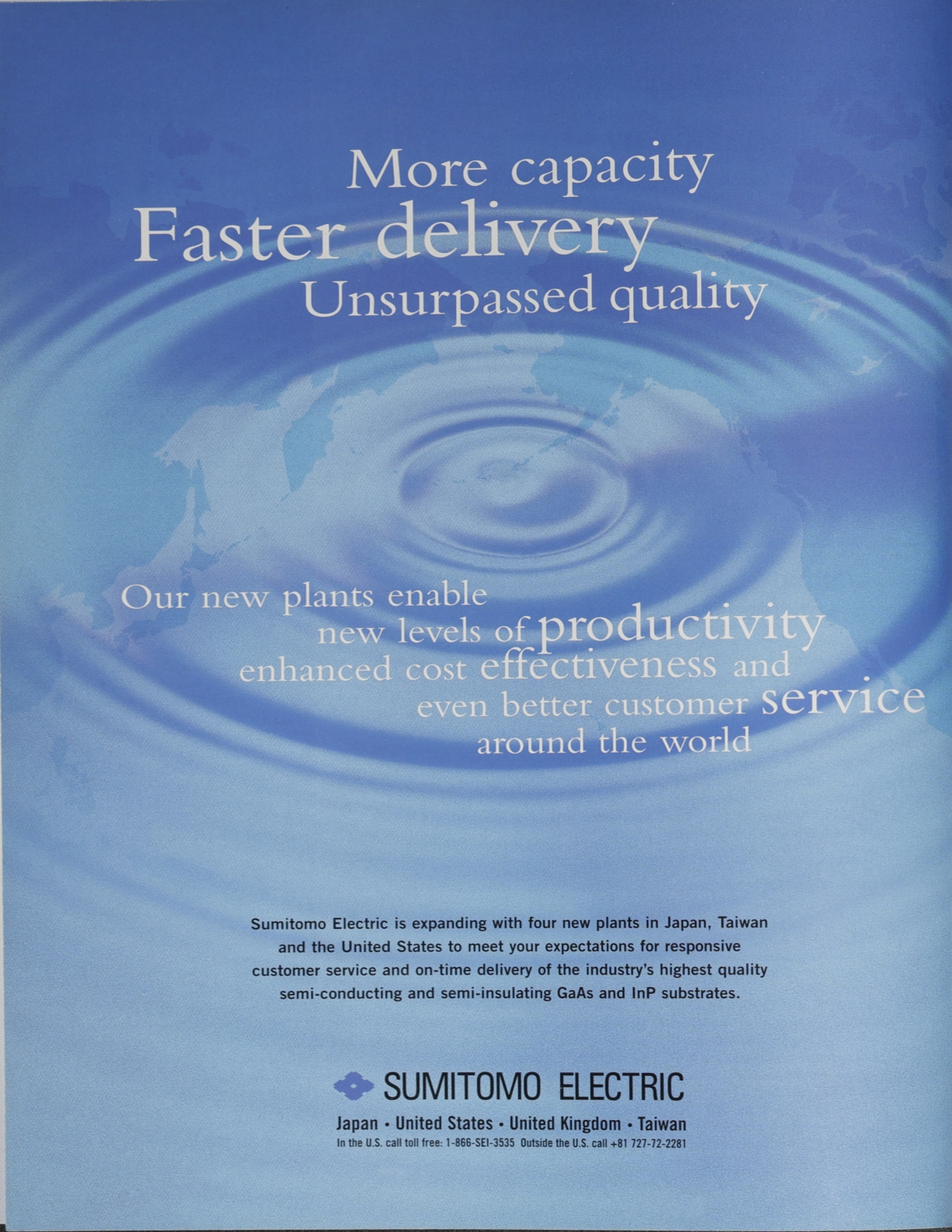
Air Force funds Sterling's SiC research

Sterling Semiconductor has been awarded \$1 million by the US Air Force to continue its research into semi-insulating SiC substrates. The 28 month contract is a Phase II continuation of a SBIR contract, and reflects Sterling's initial success with substrates prepared in the R&D stages during Phase I. The Air Force provides a 3:1 match of the company's internal R&D funding. Semi-insulating substrates are highly resistive, a property that is essen-

tial to devices used in wireless applications. SiC also offers superior properties to those of GaAs semi-insulating substrates, which are the current platform for a variety of wireless devices found in cell phones and other high-volume applications. The material provides excellent heat dissipation during device operation, and offers a high electric breakdown field (5–6 times higher than GaAs or Si) – a distinct advantage for high voltage

RF power devices.

"Semi-insulating SiC substrates are needed for a wide range of commercial and military communication devices to provide superior performance compared to conventional silicon and GaAs substrates," said Robert Soran, president and COO of parent company Uniroyal Technology. "SiC substrates can be used as a platform for both SiC and GaN epitaxial growth, depending on device requirements."



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Rapid VCSEL developments continue

Recent months have seen a host of new VCSELs emerge from a number of manufacturers including AXT and Emcore. This trend is continuing with new products emerging based on the oxide confinement structure and aimed at growth areas such as the Gigabit Ethernet and Fibre Channel standards.

Emcore show off 10 Gbit/s VCSELs

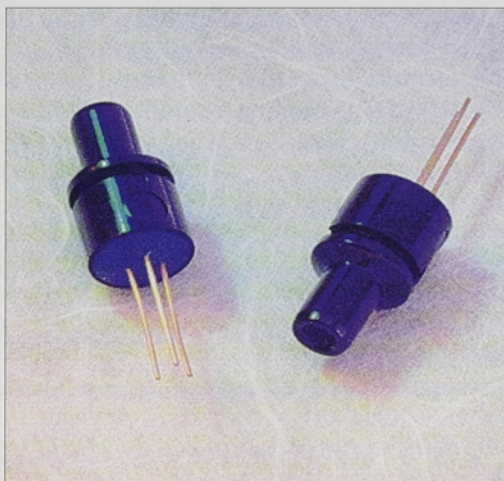
At the Optical Fiber Communication conference (OFC) in Anaheim, CA, Emcore debuted its 850 nm 10 Gbit/s oxide VCSEL, the first such product on the market. These new VCSELs are available as bare die or can be built into optical subassemblies. The device is designed for optical interconnect applications under 300 meters, including local area networks (LANs) such as Gigabit Ethernet and Fibre Channel.

The 10 Gbit/s VCSEL has two topside co-planar contacts to facilitate high-speed packaging. The typical optical output power range is 1 mW, with a numerical aperture of the emitted beam less than 0.25. The device has a current threshold less than 1 mA, with nominal slope efficiency of 0.4 W/A.

"Our oxide VCSELs have higher speeds, lower current thresholds and greater uniformity than conventional ion-implanted VCSELs" says Hong Hou, vice-president of Emcore's Optical Device Division, "and they are the ideal source for short reach and very short reach datacom applications."

Blaze and Cognet choose Emcore

Emcore has announced the availability of a family of course wavelength division multiplexing (CWDM) VCSELs for high-speed data communications. The devices, which consist of four oxide VCSELs with wavelengths of 778 nm, 800 nm, 825 nm, and 850 nm, have been selected by Blaze Network Products and Cognet Microsystems for use in their CWDM modules. Each VCSEL operates at 3.125 Gbit/s for an aggregate bandwidth in excess of 10 Gbit/s. With thresholds averaging 2 mA per VCSEL and typical slope efficiencies of 0.5 mW/mA, light output of 2 mW or more can be obtained with minimum power usage.



Emcore has launched SC and LC transmitter optical subassemblies (TOSAs) for 850 nm applications.

Blaze is the first commercial venture to exploit WDM for short wavelength and data communications applications. Its 10 Gbit/s module designed for optical connect applications under 300 meters – including LANs such as Gigabit Ethernet and Fibre Channel – is the first of its kind in the marketplace (see page 44).

Cognet Microsystems is a manufacturer of amplifiers and laser drivers for SONET, OC-48, OC-192 and 10 Gigabit Ethernet markets and recently became a division of Intel.

Emcore has demonstrated speeds of up to 12.5 Gbit/s, and was the first vendor to produce oxide VCSELs in commercial quantities. The oxide VCSEL product line has been expanded to accommodate several datacom applications, including Gigabit Ethernet, Fibre Channel, OC-192 and OC-768.

Optical sub-assemblies released

Emcore has also announced the availability of its first SC and LC transmitter optical subassemblies (TOSAs), designed for 850 nm applications. The TOSA packages (see figure 1) perform at data rates of 1, 1.25, 2.1 or 2.5 Gbit/s, which are suitable for Gigabit Ethernet, Fibre Channel and OC-48 applications. The availability of a single product for all applications will enable customers to reduce the number of inventory items they must carry.

SC transceivers have the largest in-

stalled base in Gigabit Ethernet and 1.25 Gbit/s Fibre Channel applications, while LC transceivers are the most popular module for 2.125 Gbit/s Fibre Channel and OC-48 short reach applications. Samples of the new products, which incorporate Emcore's 2.5 Gbit/s oxide VCSELs, are available now, with production volumes available by the end of the second fiscal quarter.

"Our customer base has been requesting a cost effective, reliable, turn-key product for easy integration into their transceiver modules," said Hong Hou. "Emcore can now provide its customers with bare die, arrays, packaged components and optically aligned packages to meet their specific product needs."

AXT launch oxide VCSELs

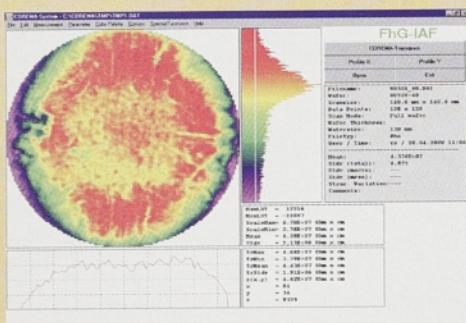
AXT has commenced volume production of oxide-confined VCSELs designed for data modulation rates up to 3.125 Gbit/s. Typical output powers are 1.0 mW, with peak power output exceeding 5.5 mW. The oxide VCSELs are highly efficient, and have output slope efficiencies of 0.45–0.50 W/A. Applications for this product include VSR Ethernet, Fibre Channel for storage area networks, optical interconnections and other optical transceiver applications.

New product line from Honeywell

Meanwhile, the VCSEL Products Division of Honeywell has announced the full production release of its oxide-isolated VCSEL product line, which will include a set of high-performance 850 nm VCSELs packaged for high-speed data communications (> 2 GHz).

"Extensive work in understanding the oxide VCSEL process interactions and effects on long-term reliability has resulted in a product approaching the reliability of our successful ion implant VCSELs," says Paul Chapman, vice-president and general manager of the VCSEL Products Division. While the oxide VCSEL line has just been formally released for general sale, the release represents the culmination of extensive design work at Honeywell, which is supported by a wealth of reliability data and months of trials by a limited customer list.

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Multiplex receives \$105 million funding boost

facilities for material growth, processing and packaging, and will also contain assembly lines. The company will continue to maintain two other facilities in New Jersey as well as its high-speed design center in California.

Multiplex is a developer of active photonic components and subsystems for telecom applications. Product offerings include 10 Gbit/s 1550 nm and 1310 nm EMLs, high-sensitivity 10 Gbit/s photoreceivers, high-power 980 nm pump lasers, 10 Gbit/s tunable EML transmitters (see *Compound Semiconductor* May 2001, p57), and 10 Gbit/s transponders.

AXT announces 1310 nm edge-emitters

packaged die and packaged TO-56 forms.

"The market for telecommunications wavelength lasers continues to show strong demand as metropolitan area networks are expanded," said Morris Young, president and CEO.

This is AXT's second Fabry-Perot EE laser and joins the 980 nm pump laser launched in February (see *Compound Semiconductor* April 2001, p24). AXT is an established supplier of substrates, and has vertically integrated to include LEDs, EE lasers and VCSELs in its product range in recent years.

Qusion collaborates with university

development efforts in the integrated components field.

Qusion Technologies aims to create integrated optical devices for 40 Gbit/s systems and beyond. This news comes at a time of major expansion for the company which recently announced the opening of a state-of-the-art manufacturing facility in North Brunswick, New Jersey, as well as the closing of its first round of financing of \$9.5 million dollars.

Blue Sky Research ramps up production

subsidiary Blue Sky Systems. Blue Sky Research is scheduled to deliver production quantities of the EDFA pump modules and optical cross-connect switches in late 2001. Programmable lasers are expected in the spring/summer of 2002.


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Suppliers work on pluggable transceivers

A group of sixteen companies have announced a new initiative for next-generation 10 Gigabit pluggable (XGP) fiber-optic transceivers. Members of the XGP group will independently develop 10 Gigabit transceivers based on this multiple source agreement (MSA). The XGP group will leverage the work that was done by last year's small form factor pluggable MSA to ensure quick development of a market-ready design. This

MSA is intended to establish a common design amongst several manufacturers, giving designers a choice of sources for 10 Gigabit transceivers.

The XGP covers five 10 Gigabit transceiver types, including 850 nm serial, 850 nm CWDM, 1310 nm serial, 1310 nm CWDM and 1550 nm serial. The companies intend to work on a common design interface for multiple protocols in 10 Gigabit networking and storage applications.

UEC Group reveals optoelectronic plans

United Epitaxy Company (UEC) has undergone a reorganization with a view to increasing its optoelectronic product portfolio. UEC Group has set up a number of subsidiaries, concentrating on areas including epitaxy, device processing and device packaging. Using MOVPE as its core technology, UEC Group has to date focussed on LED and laser diode production since its founding in 1993.

The UEC Group subsidiary Elite Advanced Laser will concentrate on chip packaging and has begun to provide lasers for CD-RW systems. Lasers for DVD systems are being assessed by cus-

tomers, with volume production expected to start later this year.

A further subsidiary, LinkComm Wireless, is still raising capital. UEC Group's plan is for LinkComm to focus on development and production of GaAs epitaxial products and will include a four and six inch InGaP/GaAs HBT process.

UEC Group has begun to ship 850 nm VCSELs targeted at the Gigabit Ethernet market in sample quantities. Besides the VCSELs, UEC Group has also developed 1310 nm and 1550 nm laser products for the long distance communications market.

Gigacomm goes for VCSELs

Gigacomm, a Taiwan-based manufacturer of fiber-optic components, is preparing to start volume production of a range of VCSELs, starting with a 2.5 Gbit/s, 850 nm VCSEL in August, with a 10 Gbit/s version available in 2002. Also planned for 2002 are VCSELs at 1310 and 1550 nm, a 1310 nm edge-emitting laser, and a tunable laser. In ad-

dition, Gigacomm is to introduce InP- and GaAs-based photodetectors.

Gigacomm is 25% owned by Epistar, an established manufacturer of LED epiwafers and chips. Another shareholder with a 25% stake in the company is the US-based E20 Communications, a producer of VCSEL-based fiber-optic transceivers.

This issue's cover theme: Vertical Cavity Surface Emitting Lasers

- Emcore describes oxide-confined VCSELs (page 33)
- Picolight uses VCSELs to deliver more bandwidth (page 37)
- Commercializing long wavelength VCSELs (page 43)
- VCSELs power 10 Gbit/s transponders (page 44)
- The Peregrine approach to integrating VCSELs with Si CMOS (page 47)
- Bandwidth9 aims for DWDM market with tunable VCSELs (page 49)

We know
you want it.



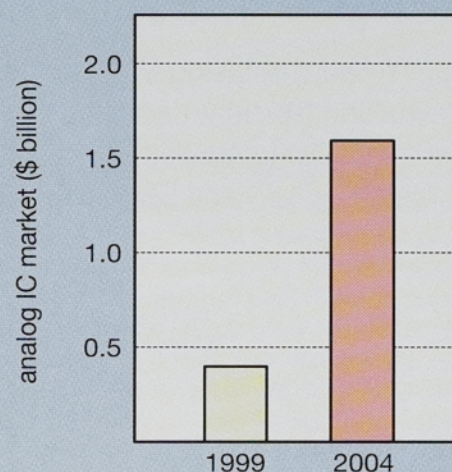
Advanced epitaxial technology with high performance and easy implementation. At EpiWorks we have what you want, and we know what you need. We realize that material specs don't tell the whole story; what really matters is device performance. How do we know? Because we're experts in device design and development as well as epi wafer production. We work with you to develop optimized layer structures for your application and then make sure it drops easily into your fabrication line. And, with each generation of technology, we're confident we can keep you on the competitive edge. Now, isn't that what you're really looking for?



Fiber-optic analog IC market growing

According to a report by Strategy Analytics, the fiber-optic analog IC market is expected to grow from \$350 million in 1999 to \$1.6 billion in 2004, with GaAs technology being predominant. The GaAs analog IC devices prevalent in fiber-optic systems include laser drivers, transimpedance amplifiers (TIAs), and devices to multiplex and demultiplex signals. The explosion in demand for increased bandwidth is shifting the focus of the technology to the 10 Gbit/s market. While the current economic slowdown has resulted in GaAs companies reducing their earnings forecasts, the fiber-optics market for analog ICs will provide a growth area for the GaAs industry. However, with the performance of SiGe encroaching into the

Analog IC market growth



areas traditionally the domain of GaAs, the GaAs companies will need to significantly reduce their average selling prices if they are to remain competitive.

The report also predicts that the move towards 10 Gbit/s and beyond will result in a shift away from bare die to modules. There will be increased integration of TIAs with photodetector diodes within modules for use in Gigabit Ethernet and Fibre Channel datacom markets. The 40 Gbit/s market is expected to become the second largest market for fiber-optic systems by 2004 and will be dominated by InP.

"Fibre-Optic Analog ICs Market" is available from Strategy Analytics – see "www.strategyanalytics.com".

Optical interconnects increase their grip

According to a new ElectroniCast global market forecast, subsystems for internal optical interconnects consumed \$81.7 million of the fiber-optics components market in 2000. This global value will increase to \$896 million in 2005 and \$6.91 billion in 2010.

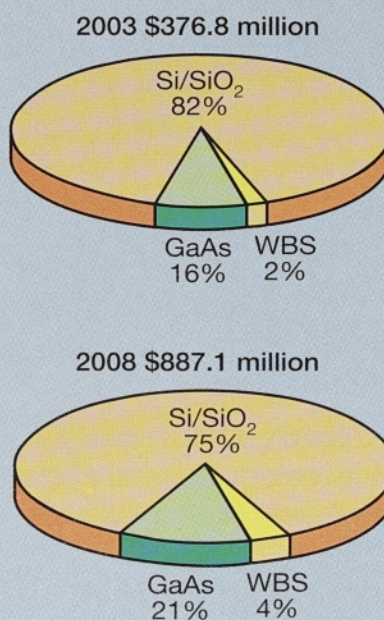
Optical signal interconnection has been used in steadily expanding volumes over the past decade in short reach applications such as communication between modules within equipment units and also unit-to-unit interconnects. Optical interconnects are also now finding practical use in multichip modules (hybrid optoelectronic ICs) and other packages. The factors driving this accelerating demand include:

- The trend to higher data rates per microprocessor, and the rapidly increasing number of microprocessors per machine.
- The rapidly decreasing cost of internal optical interconnect links, supported by lower cost emitter and detector chips.
- Expanding DWDM, giving many more wavelengths/channel, thus more optical interconnect links.

"The Internal Optical Interconnect Components & Subsystems Market & Technology Forecast" is available from ElectroniCast – see "www.electroni-cast.com" for details.

Wide bandgap semiconductors warm up

HTE market forecast



The world market for high temperature electronics (HTE) has been forecast to reach \$376.8 million by 2003 and is expected to grow to \$887.1 million by 2008. However, a report from the High Temperature Electronics Network (HITEN) warns that a large increase in the current level of investment is needed if cost-effective high temperature devices

are to become commercially available.

Initial applications will be those that are the least price sensitive, where the benefits of using HTE components justify their high cost. The leading application is currently in the equipment used for oil and gas well data logging. This market is expected to reach \$170.2 million by 2008. The largest potential market is the automotive industry where a 200–250°C technology is required for engine control systems, electronic braking and exhaust sensors. This is the type of high volume market needed to bring on this technology. This sector is predicted to be worth \$561 million by 2008.

Wide bandgap semiconductors, such as SiC, will be critical in enabling applications above 300°C. Few components specified for operation in ambients above 125°C are currently available, though several silicon and SOI high temperature ICs and sensors are on the market. Active SiC devices are also now becoming commercially available. The forecast also predicts that with the slow uptake of the wide bandgap devices, GaAs HTE devices will benefit from an increase in market share, rising from 16% in 2003 to 21% of HTE devices in 2008.

"The World Market for High Temperature Electronics" is available through HITEN – see "www.hiten.com".

GaAs—SILICON STYLE

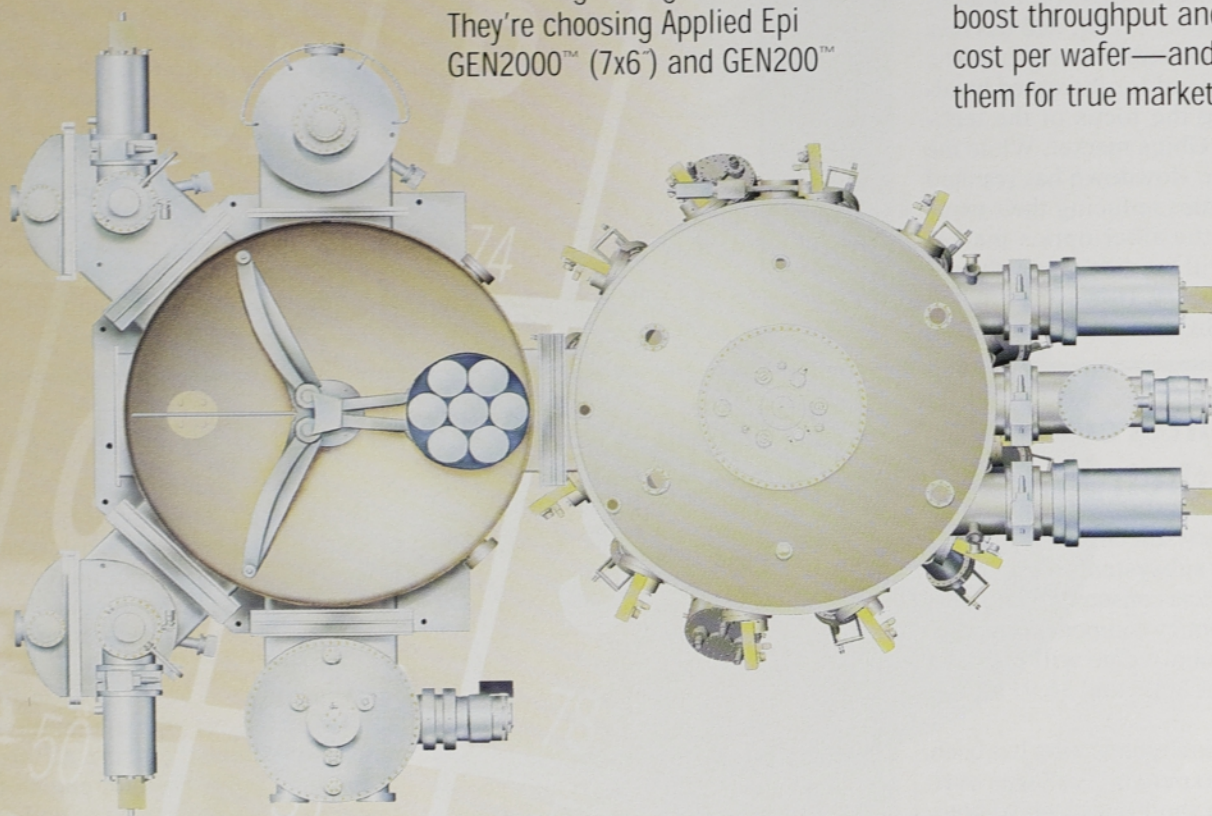
WHICH WILL HAPPEN FIRST?

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Fixed wireless broadband market set to grow

Subscriber growth to 2006

Year	Global subscribers (millions)
2000	0.1
2001	0.4
2002	2.4
2003	4.3
2004	6.7
2005	9.7
2006	13.6

Reports from Strategis Group and Allied Business Intelligence (ABI) have both forecast significant growth for the fixed wireless broadband market. Services such as LMDS, MMDS and other broadband wireless access (BWA) services are emerging as strong alternatives to wired connections through cable modems and

DSL. The ABI study predicts that global subscribers to MMDS, BWA and the unlicensed spectrum will grow from 0.4 million in 2001 to 13.6 million in 2006. This is significant for the GaAs MMIC manufacturers, as broadband wireless networks will become an increasingly important market for their devices.

The Strategis Group report focuses on the US market and also forecasts subscriber growth. The figures show a growth from 0.4 million in 2001 to 5.4 million in 2005, despite some recent high profile bankruptcies amongst service providers.

"MMDS & Broadband Wireless Access: Market & Opportunities for Data Subscribers" is available from ABI – see "www.alliedworld.com". "US Fixed Wireless Markets" is available from Strategis Group – see "www.strategisgroup.com".

WDM components increase share in FTTO

Growth forecast for WDM components

Component type	1999 (\$ millions)	2004 (\$ millions)
Dense WDM components	46 (5%)	562 (18%)
Coarse WDM components	58 (6%)	400 (13%)
Total FTTO component value	900	3050

There will be a major increase in the communication bandwidth requirements to homes and small businesses based in primarily residential areas, plus fiber connections to "downtown" business subscribers, according to a new forecast from ElectroniCast Corporation.

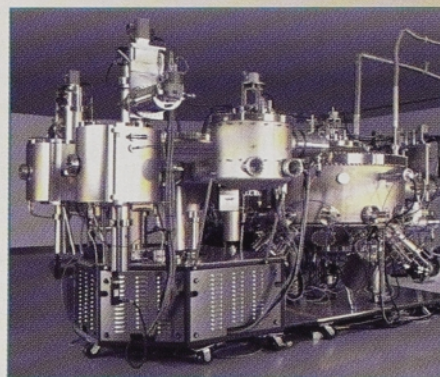
Business/government demand for communication bandwidth over the next decade is expected to generate a volume of communication equipment production sufficient to drive down the cost of network fiber-optic equipment and components for metro/access broadband and residential broadband communication.

The advancements in business broad-

band communications will have an impact at all levels in the communication food chain, including optoelectronic, optical and other components that are required in network equipment. The US consumption of components for fiber-to-the-office (FTTO) was estimated at \$900 million for 1999 and is forecast to grow to \$3.05 billion by 2004. The components for DWDM and CWDM accounted for 11% of the 1999 figure and show impressive growth to a 31% share of the total FTTO component value in 2004.

"Metro/Access Fiber Optic Network Services, Equipment and Components Forecast" is available from ElectroniCast – see "www.electronicast.com".

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The best way to get your news into *Compound Semiconductor* magazine and our Web site, www.compoundsemiconductor.net, is to e-mail the editor, Tim Whitaker, on tim.whitaker@compsem.com.

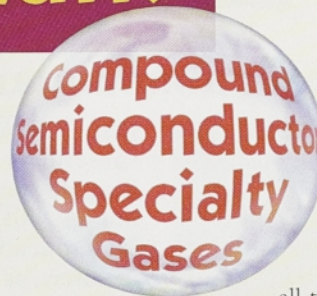


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Accent buys I-V measurement technology

Accent Optical Technologies (Bend, OR) has acquired the intellectual property relating to GaAsCode Ltd's pulsed current-voltage (I-V) measurement instrument. GaAsCode's system measures conditions that exist in practical RF, microwave and millimeter wave circuits. The system is designed for FETs, HEMTs, HBTs and BJTs as well as lasers and photodetectors.

Accent will incorporate this technology into its product line and officially launch new products early in the third quarter of this year. Finalized in April for an undisclosed sum, the GaAsCode acquisition extends Accent's products from materials process control to device and IC process control.

Accent passes mapper milestone

In more news, Accent has sold its 100th RPM 4000 rapid photoluminescence mapper system (see photo) to laser and LED



Accent's RPM 4000 rapid photoluminescence mapper system

manufacturer Nova Crystals. Accent's system generates photoluminescence wafer maps to provide information on

epitaxial wafers and devices structures, including alloy composition and film uniformity, material quality and the presence of defects. The first RPM system was launched just over two years ago and was followed last year by the RPM 4000 model, which is a fully-automated room temperature PL mapping system complete with wafer handler.

"The demand for the rapid photoluminescence mapper has paralleled the growth of both our customers and the market segments including LED, telecom and datacom lasers, VCSELs and detectors," said Raj Mundhe, vice-president of sales, marketing and business development in Accent's Optoelectronics Division. "Our RPM4000 customers are finding that they no longer have to use a random sample measurement approach, but can afford to test every wafer. In an average manufacturing environment, this costs only 16 cents per wafer."

Companies scoop top UK business awards

Two British companies, Thermo VG Semicon and Oxford Instruments Plasma Technology, have been awarded "The Queen's Award for Enterprise". The awards are given on the basis of performance in the categories of international trade, innovation and sustainable development, and represent the highest recognition a UK company can receive for business achievement.

MBE system wins for innovation

Thermo VG Semicon, a business unit of

Thermo Electron (Waltham, MA), received the award in the innovation category for its V100 production MBE reactor. The award recognizes "outstanding and continuous innovation" resulting in a substantial improvement in business performance and commercial success. According to the company, the V100 is the most widely used MBE system worldwide for the production of GaAs-based electronic devices.

"Until Thermo VG Semicon introduced the V100 in 1991, MBE was a research-oriented technique capable of manufacturing device wafers in relatively limited quantities," said Richard Syron, chairman and CEO of Thermo Electron.

"As a result of the V100, major suppliers in the wireless sector are able to manufacture tens of thousands of device wafers per year."

Oxford awarded for overseas trade

Oxford Instruments Plasma Technology (OIPT) won in the international trade category, which recognizes achievement in overseas earnings by business units in the UK. OIPT, based in Yatton near Bristol, supplies plasma and ion-beam processing equipment. The company's overseas revenue, including sales to 22 countries in Europe, Asia and the US, now accounts for 85% of its turnover. In total, OIPT's sales reached \$50.4 million last year.

Nitrogen suitable for MOCVD growth

The University of California in Santa Barbara (UCSB) and Aeronex (San Diego, CA) have completed a study on the effects of Aeronex's gas purifiers on the quality of MOCVD film growth.

Conducted by professors Steven Denbaars and Jim Speck, the year-long

project found that in a nitrogen atmosphere, Aeronex's N₂ purifier was as effective at removing oxygen- and carbon-bearing species as palladium cells used in a hydrogen ambient.

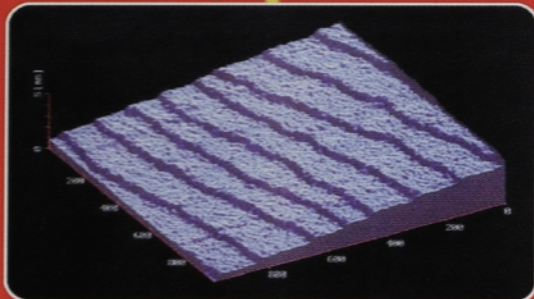
The UCSB study concluded that nitrogen gas has the potential to replace hydrogen in MOCVD growth systems with no loss in purity of the epitaxial film. This could lead to lower material costs and improved safety of the growth

process for devices such as InGaN LEDs and GaAs-based FETs and HBTs, says the company.

"Challenges in purity and doping control demand cleaner precursor gases," said UCSB's Jim Speck. "We found that Aeronex's purifiers provide a final measure to ensure gas quality and to protect against contamination that may be introduced by the gas delivery system or other process components."

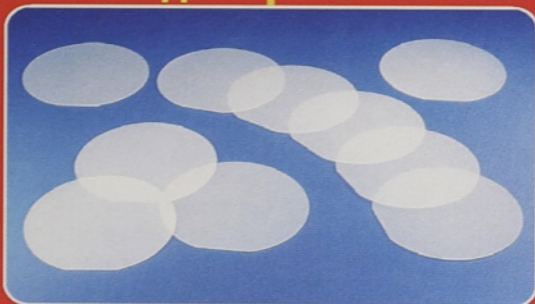
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Molecular Layer STEP Substrate



(Orientation) (0001)
(Roughness on terrace surface) $R_a \leq 0.05\text{nm}$
(Step height) 0.21nm

Sapphire Substrates



Surface roughness:
(Guaranteed value) $R_a \leq 1.0\text{nm}$, $R_{\text{max}} \leq 5.0\text{nm}$
(Typical value) $R_a \leq 0.2\text{nm}$, $R_{\text{max}} \leq 1.0\text{nm}$

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MATERIALS & EQUIPMENT

Epitaxy equipment sales

● The **National Research Council** (Ottawa, ON, Canada) has ordered a **Thermo VG Semicon V90 MBE** system. Scientists at the Canadian establishment's Institute for Microstructural Sciences will use the reactor to develop compound semiconductor devices targeting optoelectronic and high-speed electronic applications.

● **Mitsubishi Electric** has placed a repeat order for a 2400G3 MOCVD system from **Aixtron** for its Itami plant in Japan. Fitted with an *in situ* characterization module, the new system will be used by the R&D group in the development of new laser structures.

● **NGK Insulators** has ordered an **Aixtron AIX 200/4** reactor for its R&D corporate technical center in Nagoya, Japan. The company's Thin Film Application project group will use the AIX 200/4 RF-S reactor for R&D in the field of nitride-based optoelectronic devices.

● **Marconi Optical Components** has placed orders for three **Aixtron** production MOCVD reactors to be used in its optical component manufacturing operations in Northamptonshire, UK.

Marconi is currently expanding its production capacity and the company will install another AIX 2600G3 (5×6-inch) system for the growth of GaAs devices, and two more AIX 2400 (8×3-inch) reactors for the production of InP-based lasers. All three MOCVD systems are scheduled for delivery in the fall of 2001.

● **Multiplex** (South Plainfield, NJ), a manufacturer of pump lasers, tunable lasers, electroabsorption modulators and receivers, is to buy two AIX 2400G3 reactors (35×2-inch or 5×6-inch wafer capacity) from **Aixtron**. Multiplex will use the new reactors for the growth of InP/GaInAsP devices used in optical components supporting telecommunication applications.

PEOPLE NEWS

CyOptics, a supplier of optoelectronic components that include 40 Gbit/s electroabsorption modulators and 10 Gbit/s pulse generating lasers, has appointed former Lucent veteran **John V Pilitsis** as CEO. Pilitsis will be responsible for leading the company's strategic business focus and operations, while CyOptics' Eran Yarkoni continues in his role as president. CyOptics is headquartered in Waltham, Massachusetts with fully integrated production facilities in Israel. Pilitsis worked at AT&T/Lucent Technologies for 18 years and served as president of Lucent Optoelectronics from 1993 to 1998. His latest position was as CEO of FiTel Technologies, the US subsidiary of Furukawa.

Matheson Tri-Gas (San Jose, California) has announced that **William J Kroll** will head up its Compound Semiconductor Group, an internal initiative set up to develop manufacturing expertise for AsH₃ and PH₃. Operating from the company's Semi-Gas division, the group intends to increase hydride manufactur-

ing four-fold over its current level. Matheson's new appointee has considerable semiconductor experience gained from postings at Bell Laboratories, BOC and seven years as a senior marketing manager at Matheson Tri-GaAs. His most recent position was with Emcore as executive vice-president of business development.

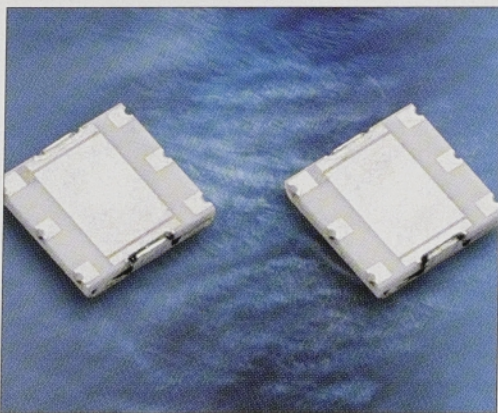
J Douglas Sinclair has joined **Nova Crystals** in the role of vice-president of engineering. Sinclair has over 28 years of experience with Bell Laboratories, and for the past 15 years served as director of Lucent's Materials Reliability and Component Processing Research Department. His responsibilities will include overseeing device fabrication, process metrology, burn-in, and reliability and testing procedures. In addition, he will play a key role in transitioning the company's recently announced 10 Gbit/s 1310 nm surface emitting laser (see *Compound Semiconductor* April 2001, p19) to high-volume production at its expanded facility in San Jose, California.

WIRELESS PRODUCTS

Mitsubishi shrinks MMIC PA packages

Sunnyvale, CA. Mitsubishi Electric has rolled out two new MMIC PAs based on its GaAs HBT process. The company's new BA01202 chipset boasts increased performance, a 25% reduction in idle current and 35% reduction in overall size, and is designed for the 1.9 GHz CDMA band.

This device is complemented by the BA01203, engineered for the 800 MHz CDMA band. The two amplifiers feature



a single positive 3.2 V supply, 25 dB of gain and 50 ohm matching from a 6 × 6 mm module package. Sampling now as a combined 800/1900 MHz chipset, the company's BA01202 and BA01203 devices are currently in volume production for \$6 per 10 000 units.

www.mitsubishichips.com

RF Nitro offers InGaP/GaAs PAs

Charlotte, NC. RF Nitro Communications has released a new series of broadband InGaP/GaAs RF and microwave MMIC amplifiers optimized for high frequency applications. These 50 ohm cascaded gain blocks are suited to driver and distributed amplification requirements of VSAT, point-to-point, point-to-multipoint, LMDS and optical networks requiring high frequency operation, high gain and good IP3 performance.

These new devices are offered in chip,



4 lead ceramic micro-X and a new 5 lead micro-X ceramic package with automatic gain control. The NBB series (4 lead and chip) and NDA series (5 lead and chip) operate up to 17 GHz.

www.rfnitro.com

MwT introduces GaAs amplifiers

Fremont, CA. A new range of ultra-linear driver amplifiers covering the 800–960, 1800–2000 and 2100–2500 MHz ranges has become available from Microwave Technologies (MwT). These devices feature output powers (P1) of +24 dBm with IP3 values of +42 dBm and 18 dB return loss for simple circuit integration. In addition, the company has introduced two fully-matched 4 W amplifiers for broadband wireless access applications using MMDS and ISM bands. Delivering 36 dBm of power at the 1 dB compression point and 13 dB of gain, these transistor PAs are manufactured using the company's GaAs MESFET technology.

The MPS-242520-83 operates in the 2.4–2.5 GHz range and the MPS-252720-83 from 2.5 to 2.7 GHz. Both parts are fully matched to 50 ohms and use flange packages for thermal performance and reliability.

The company also manufactures AlGaAs/InGaAs PHEMTs for power and gain applications at millimeter-wave frequencies. The H15 is a PHEMT with a 0.3 μm gate length and 630 μm gate width. The device demonstrates a P1dB of 0.5 W with gain greater than 7.5 dB across the 18–26 GHz band in a balanced amplifier module.

www.mwtinc.com

NEC's SPDT switches hit the mark

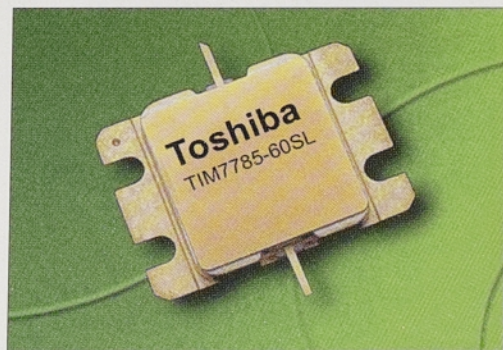
Santa Clara, CA. NEC's new UPG137GV and UPG138GV are L-Band single pole double throw (SPDT) GaAs-based MMIC switches developed for digital cellular, PCS and WLAN applications. These devices feature a wide bandwidth, low insertion loss and high P1dB. The UPG137GV operates on a +3 to +5 V control voltage, while the UPG138GV operates from –3 to –5 V. Both devices are housed in an 8 pin SSOP package and are available on tape-and-reel.

For the L- and S-band, the company has also introduced a low insertion loss GaAs SPDT switch. Based on a GaAs FET process and designed for PCS, WLAN, WLL and Bluetooth applications, the UPG158TB operates from 300 MHz to 2.5 GHz and is housed in a 6 pin (2.0 × 1.25 × 0.9 mm) super mini-mold package. High linearity switching is offered, and a P_{in} (at 1 dB) of +26.5 dBm and P_{in} (0.1 dB) of +23.0 dBm, for a control voltage of 3 V.

www.cel.com

Toshiba launches 60 W GaAs FET

San Jose, CA. Toshiba has introduced a 60 W C-Band internally-matched GaAs HFET power amplifier for the 7.7–8.5 GHz range. The TIM7785-60SL targets gateway or earth station satellite



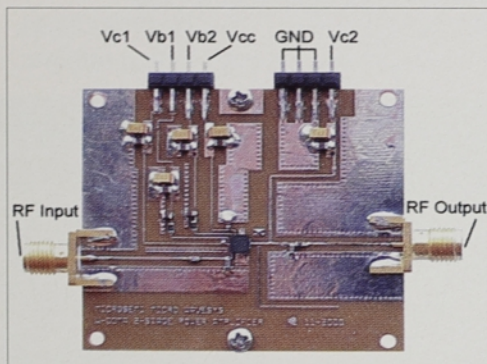
communications systems (SATCOM), and long-haul point-to-point terrestrial communications. At 48 dBm, Toshiba's device is one of the highest output power devices available at this frequency range.

Featuring a gain of 6 dB, the device is designed for the high linearity required for the modulation at communications data rates. In addition, the TIM7785-60SL features the same 2-16G1B hermetically sealed packaging used in the company's range of C-Band devices operating above 12 W. Toshiba says the HFET process is well suited to high-power microwave devices because its inherently higher carrier concentration enhances output power and gain. The HFET also benefits from a Schottky barrier that is higher than comparable GaAs MESFETs, achieving improved gate breakdown voltage for a reduced gate leakage current – a critical parameter for higher power operation. Samples will be available in July, with production in October.

www.chips.toshiba.com

Microsemi unveils WCDMA PA

Santa Ana, CA. Microsemi has unveiled a high efficiency linear PA targeting 3 V mobile hand-held devices. Manufactured using the company's new InGaP/GaAs HBT RFIC process, the MWS11-PH43-CS is designed for use as a final RF amplifier in WCDMA and CDMA2000 applications, spread spectrum systems and other linear applications in the 1800–2000 MHz band. Two 16 pin package versions exist for these PAs: a $3 \times 3 \text{ mm}^2$ chip scale package (CSP) with external input/output match, and an

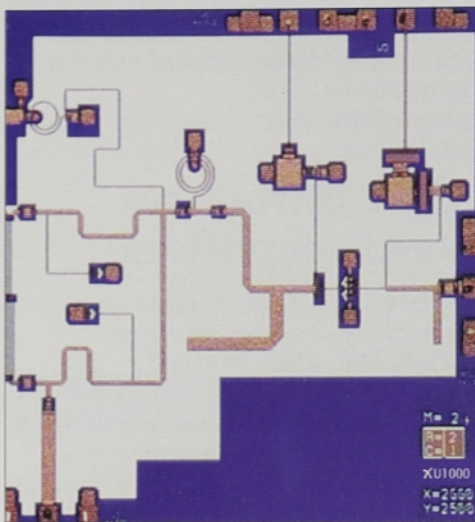


internally I/O matched module. Operating from a single 3 V supply, typical features of these devices include 27 dBm of linear output power, 28 dB of linear gain, 40% linear efficiency and an idle current of 70 mA.

www.microsemi.com

Mimix single chip MMIC up-converter

Houston, TX. Mimix Broadband has introduced a fully-integrated GaAs MMIC up-converter consisting of a single fundamental mixer followed by a single-stage amplifier. Using a $0.15 \mu\text{m}$ gate length GaAs PHEMT technology (obtained from external sources), the XU1000 up-converter covers the 17–27 GHz frequency band, and demonstrates a small signal gain of 0 dB with third order intercept point of +12 dBm across the designated band. The single chip design lowers



power consumption and operates at +3.0 V DC supply.

Used in conjunction with the company's XP1000 PA and XB1000 gain block amplifier, the XU1000 forms a complete millimeter-wave transmitter. It also has smaller size and lower cost designs and is suitable for millimeter-wave point-to-point radio, local multipoint distribution services (LMDS), SATCOM and VSAT applications.

"The integration of a gain stage with the mixer reduces the subsequent gain needed to realize the transmit power level required in a radio, reducing overall chip count in many cases," said CTO Jim Harvey. "In conjunction with the other integrated devices available for the 17 to 27 GHz bands, this device allows users to manufacture radio terminals with lower overall active device count, compared to other designs."

www.mimixbroadband.com

FIBER-OPTIC PRODUCTS

Corning offer 980 nm submarine pump laser

Corning, NY. Corning has introduced a 980 nm pump laser designed for submarine use in long-haul optical networks. Manufactured at Corning OTI (formerly Pirelli Componenti Ottici) in Italy, the new 980 nm pump laser provides 120 mW of output power and a reliability of <100 FIT to meet the stringent requirements of submarine EDFA manufacturers. "The capabilities of Corning OTI's business in 980 nm pump lasers for submarine complement and supplement Corning Lasertron's terrestrial 980 pump capabilities," said Adriano Zuccala, general manager of Corning OTI. "This product supports Corning's efforts to supply all the components and devices required to build fiber-optic networks."

www.corning.com

Multilink RZ/NRZ SiGe chipset

Somerset, NJ. Multilink continues to target metro, long-haul and ultra long-haul transmission networks with its latest chipset, a SiGe-based multiplexer (MTC1233) with integrated clock multiplier unit and demultiplexer with integrated clock and data recovery (MTC1234). This chipset offers a significantly increased level of integration by directly supporting the generation and recovery of return-to-zero (RZ) format data signals. The device also supports NRZ format signals, while operating at networking data rates of 10.0, 10.7 or 12.3 Gbit/s. Ultra long haul transmission systems are now using RZ format and enhanced forward error correction SFEC to increase performance. The MTC1233 and MTC1234 are designed to service this application, and include an on-chip phase-frequency detector and VCO to ease RZ system implementation and exceed SONET jitter requirements. Multilink is also addressing metro needs with adapted versions (the MTC1233M and MTC1234M) optimized for NRZ-only applications.

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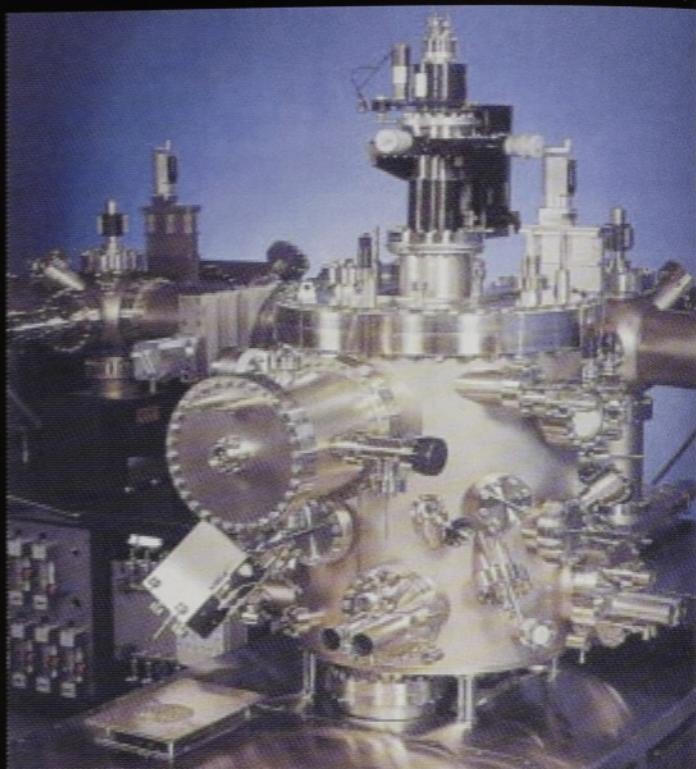
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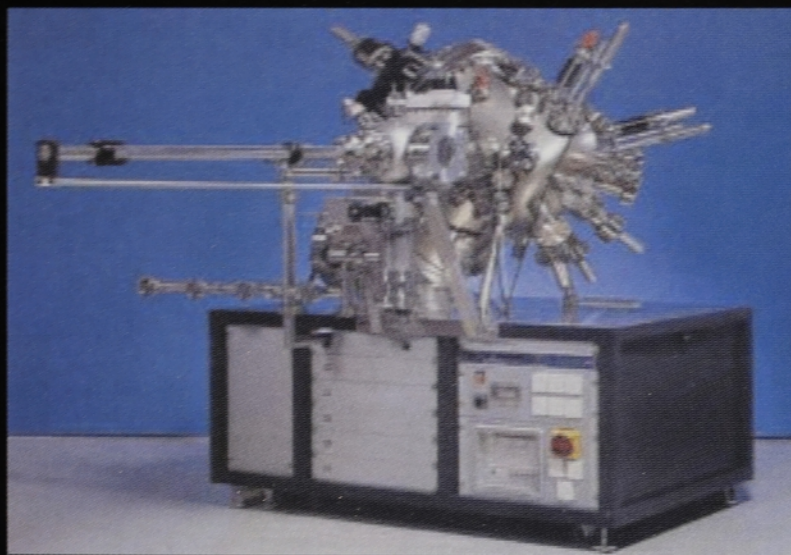
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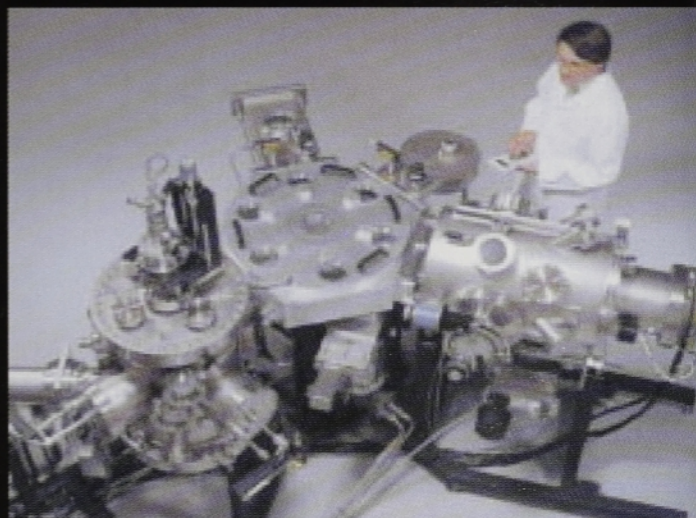
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Uncooled lasers and 40 Gbit/s modulators

Considerable research effort is being expended on high-speed components to meet the requirements of next-generation networking applications for greater bandwidth and wider temperature range. With this aim, Mitsubishi Electric is developing 40 Gbit/s electroabsorption modulators, in addition to 1300 nm Fabry–Perot lasers operating at 10 Gbit/s.

40 Gbit/s modulator

At the recent Optical Fiber Communication conference (19–24 March, Anaheim, CA), K Takagi and colleagues from Mitsubishi described a 40 Gbit/s electroabsorption modulator. The device contains an InGaAsP MQW structure as the absorption layer. Transparent InGaAsP waveguides are integrated either side of this layer to shorten the modulator length to 75 μm and provide a total device dimension of 300 μm . The modulator was grown on a semi-insulating InP:Fe substrate, which reduced the parasitic capacitance to 0.07 pF and afforded higher

bandwidth performance.

The device featured a 15 dB extinction ratio at an operating wavelength of 1553 nm. Accelerated aging tests were used to confirm a reliability of more than 17 million hours at 25 °C.

10 Gbit/s Fabry–Perot laser

Mitsubishi's T Kadowaki and colleagues provided details of the company's 10 Gbit/s Fabry–Perot laser at the same meeting. Based on a ridge waveguide structure, the company's device operates uncooled at 1300 nm and provides 5 mW of output power.

To increase the operating frequency, Mitsubishi has increased the laser's front and rear facet reflectivity and decreased the cavity length to 200 μm . The active regions are a modification of the usual InGaAsP QWs, employing five AlGaInAs wells to improve the laser's temperature dependence on threshold current and slope efficiency.

A low power consumption of 1.4 dB

(at 1E10 BER) was achieved, with a dispersion characteristic for singlemode transmission of +10.3 ps/nm. The results hold promise for an FP laser suitable for uncooled operation at OC-192 data rates for applications such as 10 Gigabit Ethernet over 3 km distances.

Reliability testing was also used to determine the effect of aluminum in the QW structure on the catastrophic optical damage (COD) limit. A device with a 200 μm cavity length and front and rear facet reflectivities of 65 and 90% was tested at 10 mW output power and a temperature of 85 °C. Stable operation was obtained for more than 6500 hours, leading to an estimated lifetime of 200 000 h. Mitsubishi says this result equals the performance of conventional Fabry–Perot lasers employing InGaAsP active regions.

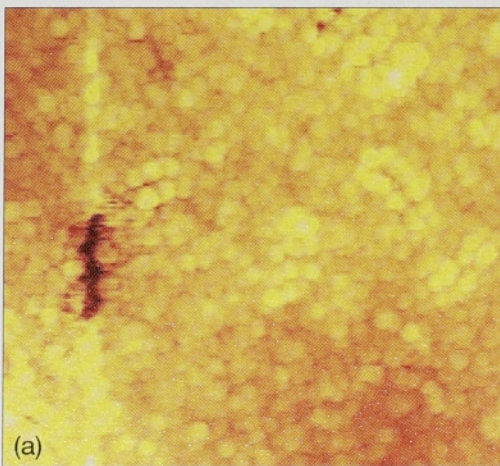
No deterioration in COD limit was noted during the test, and a pulsed output power of more than 200 mW could be sustained without fluctuation for up to 1300 h.

BEEM reveals electrical properties of dislocations and nanopipes

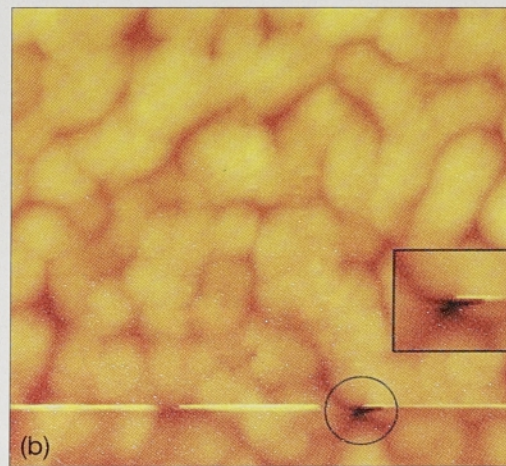
It has been shown that SiC power devices fabricated on micropipe-free SiC wafers exhibit a dramatic improvement in electrical properties compared with devices fabricated on wafers containing micropipe defects; see P G Neudeck and J A Powell in *Electron Device Letters* 1994, **15**, p63. Micropipe-related defects cause pre-avalanche breakdown in SiC power devices by facilitating electrical discharge through the hollow core of nanopipes under high electric field operation. This mechanism contributes to large leakage currents.

A team led by C V Reddy and V Narayanamurti at Harvard University have employed ballistic electron-emission microscopy (BEEM) to image dislocations and nanopipes in SiC that have so far proved difficult to detect with either SEM and AFM techniques (*Journal of Applied Physics* 2001, **89**, p5797).

Topographic AFM images taken from 300 $\times$ 300 nm areas on two different SiC samples reveal different kinds of defects (see figure). Image (a) shows a



BEEM imaging of SiC used for power devices reveals a) commonly observed defect with deep trench; b) nanopipe defect responsible for large leakage currents.



defect with an associated deep trench that is commonly observed all over the SiC matrix. A nanopipe-related defect is shown in the image labeled (b), and the area is enlarged in the inset.

BEEM spectroscopy performed on the defect and the adjacent area revealed that large electric currents are concen-

trated around the nanopipe/dislocation sites. The authors note that the nanopipe may not actually have a hollow core to facilitate the electrical discharge. However, they conclude that since the defect is highly conducting, it is responsible for the large leakage currents observed in SiC power devices.



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AMCC eyes SiGe for 40 Gbit/s parts

While some manufacturers have identified indium phosphide as the material of choice for future OC-768 parts, AMCC has already demonstrated silicon germanium products for this market. Bob Metzger and Tim Whitaker report.

Although the optical networking industry is currently migrating from 2.5 to 10 Gbit/s, device manufacturers are already beginning to develop the components that will be needed for the OC-768 (40 Gbit/s) systems that are expected to be deployed in the next 2–3 years. While many have conceded that Si-bipolar and CMOS can handle 2.5 Gbit/s applications, there is no clear technology winner for 10 Gbit/s devices. Early 10 Gbit/s parts were implemented using GaAs, while SiGe HBT and even CMOS parts are now available at this data rate.

When it comes to 40 Gbit/s devices, many assume that the technologies of choice will be HEMTs or HBTs based on either GaAs or InP. Several manufacturers have already announced plans to implement 40 Gbit/s components in InP. These include such compound semiconductor heavyweights as Vitesse, RF Micro Devices and the newly formed TRW spin-off Velocium (see page 7). The indication is that the intrinsic high speed of InP devices, coupled with the ability to integrate ICs with optical devices (e.g. telecom lasers and detectors) on the same wafer, make this material the best choice for 40 Gbit/s components. Additionally, many people within the compound semiconductor community believe that silicon simply will not be able to perform at 40 Gbit/s.

Applied Micro Circuits Corporation (AMCC) does not share this belief, and is backing SiGe for 40 Gbit/s applications in the most emphatic way possible – by introducing commercial 40 Gbit/s parts. “Our philosophy is that if you can do it in silicon, you should,” says Ken Prentiss, AMCC’s director of marketing for telecom products, who cites the benefits associated with high-volume manufacturing in the silicon industry and many years of investment. Prentiss also mentions AMCC’s experience with SiGe as an

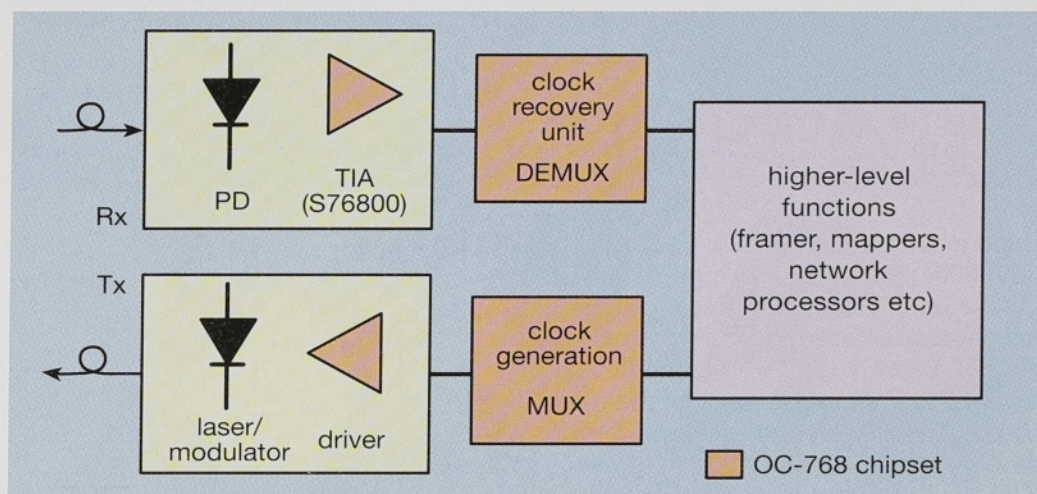


Fig. 1. Block diagram showing AMCC's planned chipset for OC-768 applications. The company has introduced a SiGe TIA with 45 GHz bandwidth, and also recently demonstrated an open eye diagram at 40 Gbit/s from a multiplexer IC.

important factor in choosing this technology for next generation parts. “We have eight 10 Gbit/s parts in SiGe that have been shipping for a year or more,” he says. “Although we don’t ignore other technologies [such as GaAs or InP], we haven’t found a reason to use processes other than those based on silicon in the markets we address. Our customers care more about whether you meet their price, performance and delivery targets than what technology is used, and we believe that SiGe is the optimum technology to meet these needs.”

Why not use indium phosphide?

Like many other manufacturers considering the 40 Gbit/s market, AMCC evaluated the possibility of using InP. “One major reason that we rejected InP was the need to introduce a high level of integration in our serdes (multiplexer and demultiplexer) ICs – we need many thousands of gates,” says Prentiss. As manufacturers such as Velocium and Vitesse begin to commercialize InP-based electronics and move up the manufacturing

curve, the ability to increase transistor counts and enhance yields will undoubtedly improve. Today, however, the ability to achieve significant yield at the 10 000 transistor level does not exist for InP-based devices.

While AMCC also appears to be skeptical about issues such as the manufacturability of InP devices, and the availability of InP wafers, other companies are equally concerned as to whether SiGe HBTs have the performance capability to be used in the implementation of 40 Gbit/s circuits.

Proof of 40 Gbit/s performance

Rather than claiming what should be possible, AMCC has answered the question of SiGe’s capabilities by using the technology to produce 40 Gbit/s circuits. Figure 1 shows a schematic of an OC-768 (40 Gbit/s) electronics portion of an optical network that AMCC hopes to implement using a more advanced version of IBM’s commercially-available SiGe process (see sidebar). The first part of this system to be implemented in SiGe is the

IBM's commercially-available SiGe process

IBM's BiCMOS 6HP technology combines an 8 inch CMOS production line running a 2.5 V, 0.25 μm gate length process with a SiGe HBT process in which the Ge content across the base ranges from 2 to 12%. The HBT portion of the process offers two versions of HBTs: a standard high-speed device with f_t and f_{max} values of 47 and 65 GHz, respectively, and a

modified collector HBT that enables high-voltage operation with f_t and f_{max} values of 27 and 55 GHz, respectively. The standard version exhibits a BV_{CEO} of 3.35 V, while the higher voltage version exhibits a value of 5.4 V. Both these devices are available in emitter widths of 0.3, 0.42 and 0.78 μm , with variable lengths. The narrow emitter width improves the noise figure, while the

wider emitters are better suited to higher power applications and make matching easier. The process features 4–7 layers of metal with tungsten-stud contacts and vias, in which the thick final metal layer coupled with a thick dielectric are used to fabricate inductors. In addition the technology features deep trenches to enhance isolation and improve RF performance.

the need for any special impedance optimizing circuitry. In addition, InP-based HBTs operate at a significantly lower turn-on voltage (0.7 V as compared to 1.2–1.4 V) and at lower current densities, therefore consuming less power than SiGe parts.

While AMCC considers the use of SiGe to be a critical element in their deployment of OC-768 circuitry, it is not sufficient in and of itself to meet the performance criteria. There are several additional factors that allow them to reach the 40 Gbit/s milestone. For example, the availability of low resistance interconnects is extremely important. The AMCC SiGe chips contain up to seven layers of metallization, five of which are made from copper. This results in lower sheet resistance, and also reduces on-chip voltage drops and raises parasitic pole frequencies. In addition, due to the use of a dielectric trench for isolation and multiple layers of dielectrics to isolate the various metal layers, the available dielectric thickness is several times greater than in most VLSI processes. This can be utilized to greatly reduce parasitic capacitances, which in turn improves speed performance. The performance of inductors is also improved by increasing Q. In addition, because IBM uses a BiCMOS process, the multiple device types on a single substrate allow greater flexibility in design. It is these elements – when added together with custom design approaches – in which the designers know how to optimize the circuitry to enhance SiGe transistor performance, that has allowed AMCC to enter into the 40 Gbit/s marketplace using SiGe.

No one disputes the fact that InP-based devices have the fundamental characteristics to be used in the fabrication of 40 Gbit/s devices. With the circuits developed by AMCC, it is now clear that no one can dispute that SiGe is also capable of producing 40 Gbit/s devices. So what will be the material/device of choice? It is difficult to tell at this point, but it might be best to remember that a wide range of materials and device structures are currently being used to manufacture 10 Gbit/s components. With some manufacturers backing InP, while others such as AMCC are committed to SiGe, it seems likely that, at least at the outset, a diverse range of technologies will be used to manufacture 40 Gbit/s circuitry.

transimpedance amplifier (TIA – part #S76800) which provides high-speed amplification of current received by an external photodetector in the receiver frontend. The TIA can successfully handle data rates up to 48 Gbit/s and accept return-to-zero (RZ) and non-return-to-zero (NRZ) data streams for enhanced performance. The 45 GHz bandwidth of the TIA allows the implementation of OC-768 operation without having to resort to using a PIN-diode to optically amplify the incoming data signal. The TIA features a transimpedance gain of 220 ohms, and with a low input noise of 4 μA , this allows signals as low as 50 μA to be detected with a BER of only $1\text{E}-10$. Using a –5.2 V power supply, the TIA dissipates 0.6 W.

In addition, AMCC has also just announced a 40 Gbit/s MUX, another key element in the implementation of the system detailed in figure 1. The 40 Gbit/s eye-diagram is shown in figure 2. It is anticipated that remaining 40 Gbit/s building blocks will be available by the end of the year.

Performance trade-offs

In light of the parts produced by AMCC, it is clearly false to claim that SiGe cannot be used to make 40 Gbit/s circuits. However, there are certain inherent limitations to a silicon-based bipolar process which make this a significant challenge.

When considering a high-speed bipolar process, the issue of breakdown is of primary concern. Speed in these devices is improved by decreasing the electron transit time, which is accomplished primarily by thinning the base and increas-

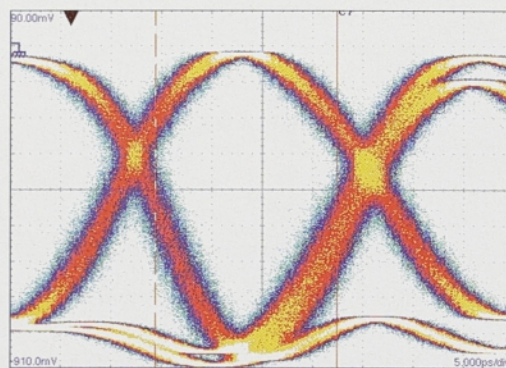


Fig. 2. The 40 Gbit/s eye diagram for a SiGe multiplexer IC, recently demonstrated by AMCC.

ing the doping levels at the collector–base junction. As a consequence, there is an accompanying reduction in breakdown voltage. While the supply range for the 40 Gbit/s TIA is 8.5 V ($V_{\text{CC}} = 3.3$ V and $V_{\text{EE}} = -5.2$ V), AMCC is able to utilize IBM's advanced SiGe process even though its BV_{CEO} is less than the 8.5 V supply range.

The reason that the low breakdown SiGe process can be used for this application is that BV_{CEO} is a measure of the collector-to-emitter breakdown when the base electrode is open-circuited. However, the collector breakdown can be increased when the base looks into any finite impedance. By realizing this limitation, AMCC circuit designers optimize the impedance that the base sees in order to enhance the device breakdown. In an InP-based process (for a double heterostructure device in which InP is used in both the emitter and collector) a BV_{CEO} of 8–12 V is possible, therefore eliminating

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Oxide VCSELS rise to the challenge

With the latest developments in oxide confinement further boosting performance, VCSELS are looking in good shape to keep pace with the rapid advances in high-speed fiber-optics, writes Ian Aeby of Emcore's Optical Device Division.

In only a decade or so, vertical-cavity surface-emitting lasers (VCSELS) have moved from a technological curiosity to a critical component in powering high-performance, low-cost optical fiber data communications equipment. One key reason is that the highly competitive nature of the global communications market has led to continual technological advances in the fiber-optics arena.

One such advance is the switch from VCSELS fabricated using ion implantation to so-called oxide-confined VCSELS. These devices are fabricated with a high aluminum content buried layer, which is subsequently oxidized under conditions of high temperature and high humidity to form the device aperture. Oxide VCSEL devices, which are now commercially available, operate at higher speeds and have lower threshold currents than ion-implanted VCSELS.

Another factor driving technological advances in this field is a simultaneous trend towards higher data communications speeds, which has increased the demand for low-cost, high-speed optical interconnects. Examples include the new 2X Gigabit Ethernet and 2X Fibre Channel standards; the new OC-192 very-short-reach (VSR) interconnect designed for low-cost intra-office applications; and the InfiniBand architecture, which has the potential to substantially improve overall data throughput in servers.

A radical step

VCSELS are revolutionary compound semiconductor microlaser diodes. The device emits light vertically from the surface of a fabricated wafer in a direction perpendicular to the p-n junction. The first VCSELS were made by combining bulk active regions with metal mirrors. Subsequently, other approaches were tried including dielectric mirrors, semiconductor distributed Bragg reflector

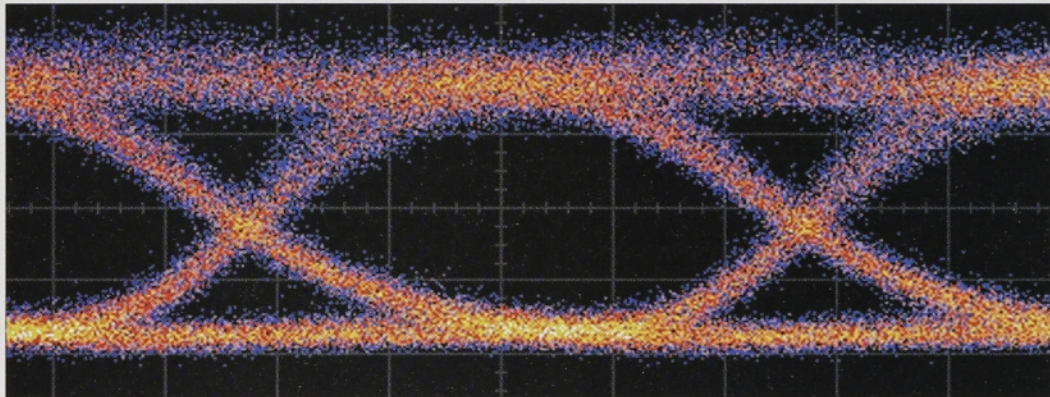


Fig. 1. An open 100 ps eye diagram from an oxide VCSEL, indicating that such devices can be utilized for high-speed transmission at data rates up to 10 Gbit/s.

(DBR) mirrors and air-semiconductor DBR mirrors. Approaches to current confinement include ion-implanted gain-guided lasers, etched air-post lasers, selective etched air-confined lasers, native-oxide-confined lasers and regrown buried heterostructure lasers.

VCSEL emission wavelengths can be tailored from visible to near-infrared by a simple materials modification in the laser cavity of the basic structure. The ability to manufacture these lasers using standard microelectronics fabrication methods allows chip-on-board integration of VCSELS with other components without requiring pre-packaging.

Advantages of VCSELS

VCSELS have a number of important advantages that have catapulted them to the distinctive position of being the technology of choice for a wide range of data communications products. With a low threshold of between 1 and 6 mA, VCSELS offer very efficient power conversion. They can deliver transmission speeds of between 1 and 10 Gbit/s (see figure 1), yet have a modulation swing of only 5–10 mA, which keeps power consumption low. The latest generation of VCSELS do not require hermetic packag-

ing, yet typical mean lifetimes for well manufactured devices range from 10 to 100 years. At the same time, the circular, low-divergence output beams provided by VCSELS eliminate the need for corrective optics in most applications.

A key advantage of VCSELS relative to edge-emitting lasers is that each device can be probe-tested on the wafer before fabricating and packaging. This enables manufacturers to identify defective chips before subassemblies are produced. This allows VCSELS to generally offer much higher yields than edge-emitting lasers.

A VCSEL normally has both the cavity mirrors and the gain region grown by a single epitaxial step on a 50 or 75 mm diameter substrate. DBR mirrors are created by growing quarter-wavelength thick layers of semiconductors with alternating refractive indices. After growth, the next step is to fabricate the laser using processing steps that are analogous to integrated circuit manufacturing. The first volume applications of VCSELS almost universally used proton implantation to selectively destroy the epitaxial crystalline structure as part of the laser fabrication process. The damage that was incurred in this process made these devices more difficult to control than is

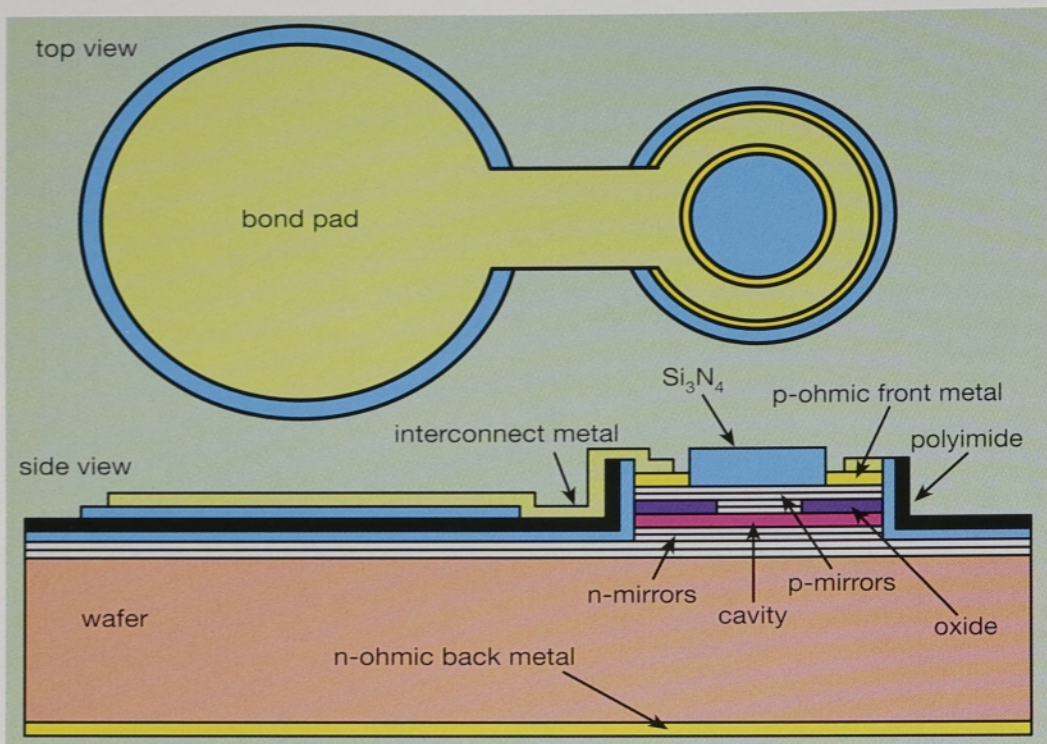


Fig. 2. A cross-section of an oxide-confined VCSEL with a plan view of the metal contact arrangement.

desirable in a high-volume manufacturing process, and resulted in poor device-to-device uniformity. The process also led to high series resistance in the mirror layers, causing less efficient laser current injection into the active region.

Move to oxide confinement

The latest advancement is the development of oxide-confined VCSELs that offer significant performance improvements. Instead of using protons to define the active region, this approach uses a selective oxide layer (see figure 2). A layer of aluminum gallium arsenide with high aluminum content is laid down and a mesa is etched to expose high oxide layers. The wafer is heated, typically to 400–450 °C, and steam is introduced to initiate the oxidation process. Oxidation moves from the edges towards the center while the temperature and duration of the process control the width of the oxidized layer. The oxide layer provides both electrical insulation and a light-guiding effect, because the refractive index of aluminum oxide is lower than that of gallium arsenide. The lateral oxidation rate can be as high as micrometers per minute using GaAlAs layers as thin as tens of nanometers. Figure 3 shows a plan-view optical micrograph of the complete VCSEL, while figure 4 is an SEM shot of the cen-

tral light-emitting region, surrounded by the ring contact.

The oxide-confined approach simultaneously increases the current injection efficiency and reduces series resistance. The result is a significant improvement in power conversion efficiency. The bottom line is high-speed performance – data rates of 2.5–10 Gbit/s can be achieved without compromising other properties. Threshold current, slope efficiency and output power all vary less than 5% from device to device. This allows the fabrication of highly uniform arrays, enabling multichannel, parallel optics applications.

Oxide VCSELs also exhibit improved temperature performance. The high slope efficiency of VCSELs produced by these methods provides a very low thermal budget, which aids module design. The advantages offered by oxide VCSELs enable low-cost, higher-speed LAN transceivers. VCSELs produced by oxide-confined methods were first introduced in November 1999, so this approach is now an established and mature technology that has demonstrated high manufacturability and reliability.

Use in 10 Gbit/s applications

Along with technological improvements, the applications supported by these optical devices have also seen some major

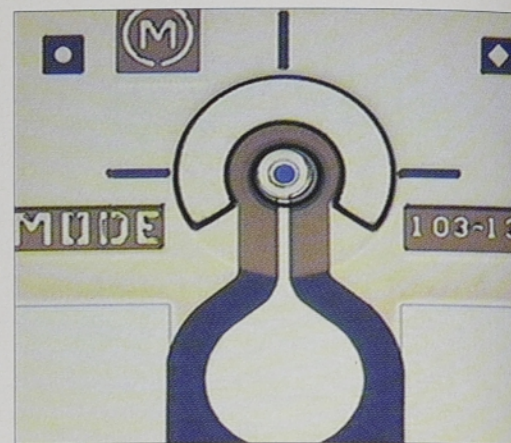


Fig. 3. A plan-view optical micrograph of the entire VCSEL showing the ring configuration of the p-contact surrounding the light-emitting region.

developments. VCSELs have achieved a dominant position in the Gigabit Ethernet and Fibre Channel transceiver market, primarily because LEDs encountered obstacles caused by their very wide beam emission and broad spectral emissions. As 10 Gbit/s standards emerge in both the Ethernet and Fibre Channel spaces, nearly all industry observers agree that VCSELs will continue to play a dominant role.

The real question is, which type of VCSEL implementation will the market turn to for 10 Gbit/s standards? Three competing implementations each stand a good chance and the odds are that all will co-exist at various stages of the product cycle. Parallel fiber approach has already been used in the first practical low-cost 10 Gbit/s solution to reach the market. On the other hand, wavelength-division multiplexing (WDM) may be another contender in the emerging high-speed data communications markets. However, most industry observers believe that it will be some time before WDM technology migrates from public network applications, where high costs have historically been acceptable, to much more price-sensitive end-user applications. A serial 10 Gbit/s solution doesn't exist in commercial implementations yet. However, many industry experts expect it to emerge as the eventual winner because of its simplicity – a single laser transmitting down a single strand of fiber, combined with the use of time-division multiplexing (TDM).

Use in Ethernet and Fibre Channel

While these issues shake out, 2X and 4X Ethernet and Fibre Channel implementations are expected to make a significant

impact. The key advantage is that there is typically enough margin built into backplanes and edge cards that the speed of existing switches and routers can be doubled simply by switching out the transceivers. Meanwhile, a new generation of parallel optical modules based on VCSEL technology is enabling dramatic improvements in central office (CO) and point of presence (POP) backplane interconnect solutions. Copper interconnects are unable to route data at the speeds required by the latest generation of edge switches used in public networks and customer premise equipment, while current high-speed optical links are too expensive and bulky. With 12 channels each operating at 2.5 Gbit/s over a dedicated fiber strand, the new parallel modules deliver 30 Gbit/s of capacity while using as little as 1.5 inches of board space.

Another important advantage of the new modules, which are just beginning to reach the market, is that they cost well under \$1000, compared with \$5000–\$10 000 for the 10 Gbit/s modules that they are expected to replace.

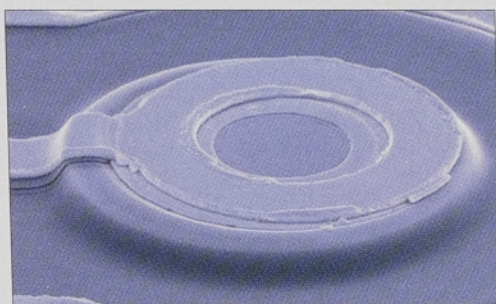


Fig. 4. Plan-view SEM image of the VCSEL, showing the inner ring electrode structure.

New applications

Finally, we are just now seeing the emergence of a new class of high-speed VCSEL-based solutions: I/O products that are designed to make connections at distances of just a few meters, from microprocessor to disk drives and other peripherals, within switches and routers, etc. An interesting approach is the InfiniBand architecture, which is already supported by 215 members of the InfiniBand trade association. InfiniBand architecture's point-to-point linking tech-

nology will be used as the basis for an I/O fabric that will increase the aggregate data rate between servers and storage devices. More important, the I/O fabric of InfiniBand architecture will take on a role similar to that of traditional mainframe channel architecture that used point-to-point cabling technology to maximize overall I/O throughput by handling multiple I/O streams simultaneously. An innovative product in this space is Infineon Technologies' 12-channel parallel optical link (PAROLI), which is designed to connect telecommunications and data communications components and equipment for board-to-board or rack-to-rack applications.

VCSELs provide a sensible, cost-effective solution for speeding up the transmission of data in the near term while delivering the reliability that both customer premise equipment and public network applications require.

Ian Aeby is at Emcore's Optical Device Division (formerly MODE), Albuquerque, New Mexico.

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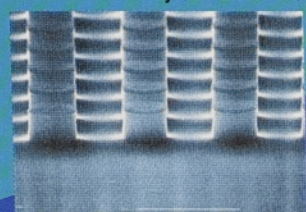
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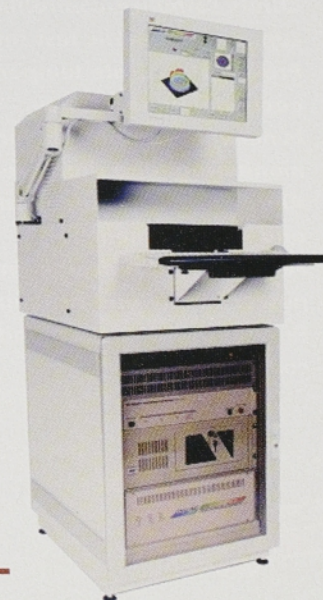
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VCSELs poised to deliver more bandwidth

VCSEL-based optical interconnects are already established in short-reach networks. Chris Simoneaux of Picolight looks at their prospects in other areas of the network.

Optical interconnect technology is rapidly permeating all levels of the modern network. This includes optical switch interconnects for very-short-reach (VSR), rack-to-rack or switch-to-aggregation-device interconnects, short-reach storage-area network (SAN) and local-area network (LAN) links for enterprise networks, as well as longer-reach links for optical metro/access interconnects.

The dominant laser communications for these optical interconnections are transceivers based on vertical-cavity surface-emitting lasers (VCSELs). They are solidly entrenched in the network for SAN and LAN backbones. With the appearance of 10 Gbit/s VCSEL-based transceivers, VCSEL array transceivers, and 1310 nm operation, the technology is rapidly migrating “upward” into ultrahigh-bandwidth enterprise switching and SAN applications, “inward” into backplanes of large optical switches, and “outward” into optical metro and access applications (see figure 1).

The current position

Optical interconnection technology has evolved from primitive forms of Fiber Distributed Data Interface (FDDI) to the 10 Gigabit Fibre Channel standard currently being developed. Today, Fibre Channel supports speeds of up to 2.125 Gbit/s and is moving forward to meet requirements for 4 Gbit/s and 10 Gbit/s data rates. Other standards organizations, such as IEEE 802.3ae for 10 Gigabit Ethernet, Optical Internetworking Forum (OIF) and InfiniBand are developing their respective optical link technologies, utilizing VCSEL-based optics and further illustrating the need for mass deployment of high-speed networking components. Many networking OEM suppliers are initiating physical-layer designs even before standards have been adopted, hoping for future harmonization.

Meanwhile, VCSEL technology has

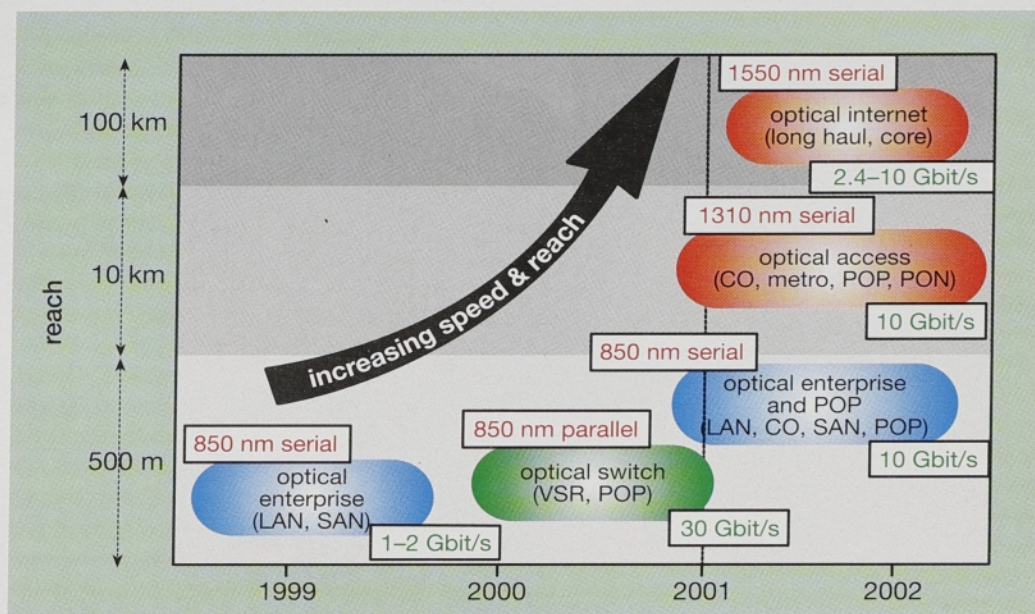


Fig. 1. The development of VCSEL arrays, 1310 nm devices and 10 Gbit/s transceivers is causing VCSELs to expand “upward” into ultrahigh bandwidth enterprise switching, “inward” into backplanes of large optical switches, and “outward” into metro/access applications.

spread into the VSR optical switch interconnect space via parallel optics, and is poised to infiltrate the metro/access space via longwave (1310 nm) VCSELs (see figure 2). Here, VCSEL technology will help resolve the problem of insufficient bandwidth in some of the optical switch and metro/access segments that have limited access to the high-end metro core and long-haul segments of the network. Until now, the only option for this segment was high-end, very expensive transport-style optics, making it difficult to justify these ports on cost grounds.

Early implementations

VCSELs were first implemented in the Gigabit Interface Converter (GBIC), 1 × 9, and Gigabit Link Module (GLM) form factors. This was followed by Small Form Factor (SFF) solder-in design, backed by a multi-source agreement (MSA) and later by the Small Form Factor Pluggable (SFP)

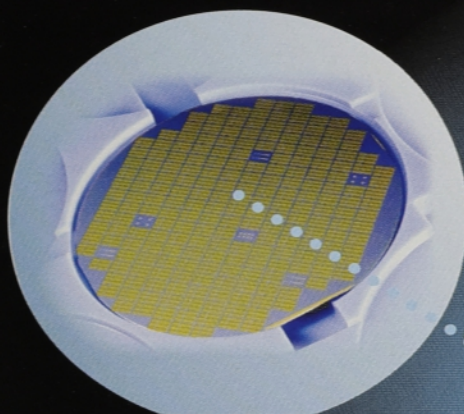
MSA module. There is a trend toward lower power, more compact, higher-density modules with system-management functions that will also be essential to the evolutionary process.

VCSELs and the new standards

The demand for high bandwidth and density, combined with low power consumption requirements, is leading to the deployment of parallel optical modules using arrayed VCSELs and PIN diodes. Current efforts are focused on modules using four- and 12-channel VCSEL array technology with passive coupling optics (for “piping” the light to the outside world), and multichannel alignment processes. Parallel optics are ideal for the VSR links that are required in backplanes for rack-to-rack, switch-to-switch, and switch-to-aggregation device interconnects. These interconnects are earmarked for use in OC-192 VSRC, multichannel

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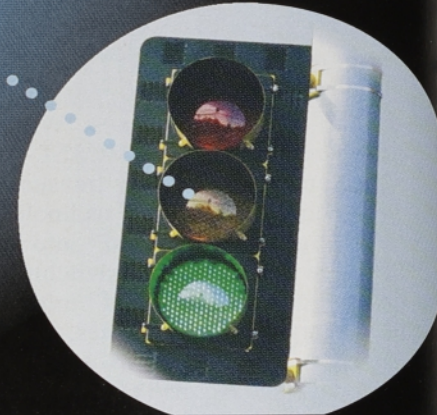
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Gigabit Ethernet, proprietary 1.6 and 2.5 Gbit/channel links, multichannel XAUI extension, and T11.1 HIPPI (see box). They are expected to migrate into short-reach enterprises as four- and 12-channel InfiniBand modules in the next few years. Today's parallel solutions at 1–3.125 Gbit/s/channel will move to 5 and 10 Gbit/s/channel solutions with an effective aggregate bandwidth of up to 120 Gbit/s.

At this time 1 Gbit/s solder-in and plug-gable modules are the transceivers of choice, in the form of a GLM, GBIC, 1 × 9, SFF or SFP solution. The NCITS X3T11 is developing a 4 Gbit/s Fibre Channel specification, which may result in a 4 Gbit/s optical transceiver implementation, although there is not yet a working group to define physical implementations. If 4 Gbit/s optical modules are implemented, they will probably take on the same form factor as the current SFP products.

Speeding ahead

Some believe that a jump to 10 Gbit/s for transceivers is more appropriate. The NCITS, IEEE, and OIF are converging on data rates around 10 Gbit/s. The NCITS X3 body has approved a T11.2 optical working group to develop 10 Gigabit Fibre Channel physical implementation standards. IEEE has a task group called 802.3ae to develop standards for 10 Gigabit Ethernet. The 10 Gbit/s Fibre Channel transceivers will most probably leverage the design of 10 Gbit/s Ethernet as both share plans for a four-lane electrical interface and similar data rates.

Another emerging standard is InfiniBand which, if successful, would be integrated into the Fibre Channel link structure during 2002 or 2003. This switch/bus architecture reduces the types of buses in the system to just CPU and InfiniBand. The attached InfiniBand network interface cards will provide the appropriate translation protocol and the electro-optic functions. InfiniBand's native data rate is 2.5 Gbit/s, with plans for serial, and four- and 12-channel parallel versions, resulting in 2.5, 10, and 30 Gbit/s aggregate bandwidth implementations, respectively.

Most physical-layer developments will focus on faster data rates and improved system/link management capabilities. An initiative essential for future optical modules is on-board management services. Management implementations are cur-

Standards explained

InfiniBand An architecture and specifications for data flow between processors and I/O devices that promise greater bandwidth and almost unlimited expandability in tomorrow's computer systems. In the next few years, InfiniBand is expected to gradually replace the existing Peripheral Component Interconnect (PCI) shared-bus approach used in most of today's personal computers and servers.

FDDI – Fiber Distributed Data Interface A very-high-speed local-area networking (LAN) architecture with optical fiber as the transmission medium.

Fibre Channel An industry standard specification for computer channel communications over optical fiber. It offers data transmission speeds of 132–1062 Mbit/s and transmission distances of 1–10 km.

10 Gigabit Ethernet Being standardized in IEEE 802.3a, this is a developing telecommunication technology that offers data speeds up to 10 Gbit/s. Built on the

Ethernet technology used in most of today's LANs, 10 Gigabit Ethernet is described as a “disruptive” technology that offers a more efficient and less expensive approach to moving data on backbone connections between networks, while also providing a consistent technology end-to-end.

NCITS X3T11 This is a standards organization that is responsible for developing the Fibre Channel standards (among others). X3T11 is a working group within the NCITS that is specifically responsible for Fibre Channel.

GBIC – Gigabit Interface Converter The GBIC is a 1 Gbit/s transceiver module that is used in the enterprise/storage-area network (SAN) market area. From the GBIC, the Small Form Factor (SFF) and Small Form Factor Pluggable (SFP) transceivers then evolved (meaning half the size of a GBIC in SFF, then half the size of a GBIC plus pluggable in an SFP).

OC-192 – Optical Carrier OC-192 denotes a transmission standard for fiber-optic data transmission in SONET

frames at data rates of 9.95 Gbit/s.

VSRC – Very-Short-Reach Converter An OIF-defined spec for converting a serial OC-192 stream of data into a 12 × 1.25 parallel format. The data are encoded and sent across parallel ribbon fiber up to 500 m.

XAUI – 10 Gbit/s Attachment Unit Interface X stands for 10 Gbit/s. Attachment unit interface is the term used in the 10 Gigabit Ethernet standard to describe the electrical interface between the MAC layer and the physical layer. The XAUI interface consists of four 3.125 Gbit/s serial links for transmission and four for receive plus control. Additional encoding steps are also defined.

HIPPI – High-Performance Parallel Interface A standard point-to-point protocol for transmitting large amounts of data at up to billions of bits per second over relatively short distances, mainly on LANs.

EFM – Ethernet in the First Mile A standardization effort to use Ethernet technology as the access protocol as opposed to ATM.

rently being developed with both OEM and optical module vendors, and the end goal is a common electrical interface and data structure to spur widespread adoption by the industry.

Equipping for the last mile

As mentioned earlier, there is a critical bandwidth deficiency in the metro/access

portion of the network comprising the final few kilometers leading to businesses and residences. One solution is the extension of optical fiber through the access network across the last mile. This not only requires a critical mass of deployed fiber, but also the readiness of service providers, and the availability of affordable, easily managed, multiplexing equip-

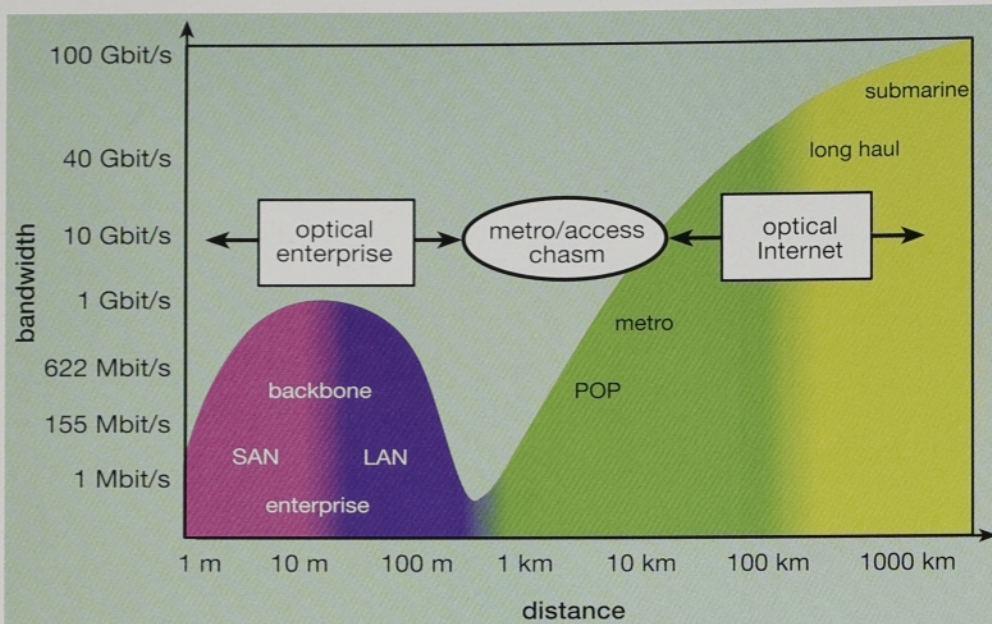


Fig. 2. The accessible bandwidth problem. There is a bandwidth mismatch between the enterprise and long-haul networks, and a growing bandwidth chasm in the metro/access and switch interconnect segments. In an ideal, "bandwidth-unchallenged" world, this graph would be a horizontal line across the network.

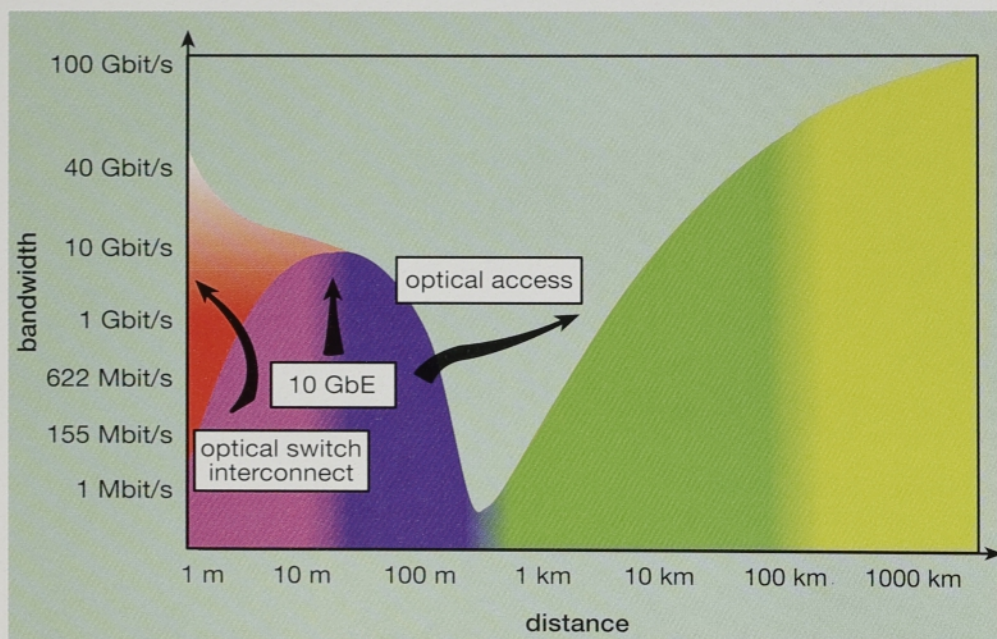


Fig. 3. Short-reach optical interconnects are bridging the gap in the optical metro/access space, using long-wavelength VCSEL technology to span the extra distance.

ment. It is this last point where economical, efficient and high-performance VCSEL-based interconnects are being prominently featured.

VCSEL transceiver technology is uniquely qualified to play at all the key aggregation points in the access network. New gigabit data rate VCSEL-based transceivers consume less than 500 mW and require just a fraction of the typically

required board space. They offer improved cost-effectiveness and flexibility, while handling not only single-wavelength point-to-point transmission, but also multiple protocols, shared passive-optical network interfaces, and in the near future, coarse WDM or multiple protocols on separate wavelengths.

If there are alternatives to the access network, they probably will not be de-

rived from today's generation of DWDM technology. This International Telecommunications Union (ITU) grid technology is two orders of magnitude more costly than VCSEL optics, and optimized for distances over 100 km rather than the 10 km range of metro/access networks.

1310 nm VCSELs

The "sweet spot" of the metro/access market will be served by 1310 nm VCSEL transceivers at the 10 Gbit/s data rate, achieving the necessary reach up to 10 km (see figure 3). Picolight has successfully developed 1310 nm VCSEL-based metro/access-specific transceivers, and plans to sample these interconnect solutions later this year. Picolight's approach – and the approach most leading technologists support – is to "stand on the shoulders of proven 850 nm VCSEL technology". 1310 nm VCSEL technology is poised to replicate the successful 850 nm oxide VCSEL transceiver model. Materials, packaging and fabrication approaches that have been proven in the high-volume short-reach VCSEL transceivers are key to developing the volume metro/access market, which dwarfs the network core in terms of unit shipments.

In the past few years systems architects and technology planners have begun writing 1310 nm VCSEL-compatible interface specifications into standards such as 10 Gigabit Ethernet, and are debating codification of this technology into Ethernet in the First Mile (EFM). The IEEE 802 LAN/MAN Standards Committee (LMSC) last year formed a new study group to develop a project proposal for this standard, which will apply the proven and widely used Ethernet networking protocol to the customer initial access market. Picolight is working closely with this group to help shape standards and promote the use of future-proofed VCSEL solutions that will provide the critical interconnect technology.

The new generation of 1310 nm VCSEL transceivers also promises to be capable of supporting multiple wavelengths, far enough apart (four, 10 or 16 wavelengths, fairly widely spread) to maintain direct modulation, and therefore cost-effectiveness. This future-proof feature can allow an order of magnitude increase in optical bandwidth across the access or metro fiber, without the severe cost penalty which is imposed by DWDM architectures.

Packaging advances

Optical component packaging becomes critical as high-speed and high-volume requirements converge. Today's current high-speed, high-volume, cost-effective "Ethernet" or "enterprise" VCSEL transceiver packaging model is expected to extend further into the link layers to include the serializer/deserializer (or SERDES), Transmission Protocol, and eventually, the system protocol function. As InfiniBand is implemented, we may see the same trend, as the integration will expand up to the switch/bus interface.

OEMs want pluggability, simple board implementation, and more EMI-friendly and robust integrated packaging. Design trends include EMI-enhanced all-metal housings, panel/bezel mounting and hot-pluggability.

Long-wavelength 1310 nm transceivers are expected to use much the same packaging technology as 850 nm solutions. The most important access transceiver packaging approach will be hot-pluggable, compact transceiver configurations

such as those used in the enterprise and SAN space to enable optical service provisioning on demand.

Pluggable transceivers allow customers and service providers to purchase a 32- or 64-socket concentrator or switch and then populate ports as needed without bringing down the network. This concept has revolutionized the way enterprise LAN and SAN networks are designed and deployed, and will have a similar impact on access equipment design as this market evolves.

Manufacturing advances

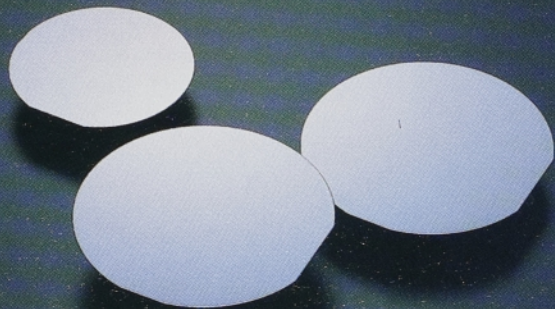
In collaboration with industry leaders, such as Newport, Picolight has worked to establish a high-volume automated test and assembly capability for 850 nm solutions that will map well to the coming generation of 1310 nm products. With process advances and new alignment algorithms, significant improvements in alignment capabilities have been achieved over the past several years. Precision computer-controlled motion stages and sophisticated

alignment algorithms ensure maximum coupling efficiency. These algorithms are also now being built into the firmware on the manufacturing equipment controller board to reduce intra-instrument communication latency and drive down the cycle time for the alignment process.

VCSEL transceiver technology is already firmly entrenched in the optical enterprise for SAN and LAN backbones, and is rapidly penetrating the market for high-speed optical switching equipment. Soon, as many as 250 million desktops and homes worldwide will become targets for the gigabit bandwidth necessary to deliver high-speed Internet access for a host of new broadband entertainment and information applications. The foundation has been established for VCSEL-based interconnects to help deliver on that promise.

Chris Simoneaux is a director of product line management at Picolight, US. Tel. +1 303 530 3189; e-mail "csimoneaux@picolight.com".

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Commercializing long-wavelength VCSELS

*In this two-part feature, **Richard Dixon** describes how a number of obstacles have been overcome to make long-wavelength VCSELS a commercial reality. Starting overleaf, **Tim Whitaker** discusses the use of 850 nm VCSELS in 10 Gbit/s transponders.*

VCSELS operating at the telecom wavelengths of 1310 and 1550 nm have the potential to become low-cost alternatives to edge-emitting lasers. However, despite strong demand for VCSELS at long wavelengths, the ability to grow an optimal combination of a good quality active region and high-reflectivity mirrors is technologically challenging.

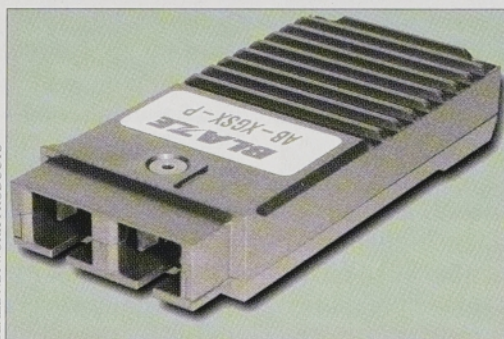
A number of different approaches have been tried. Gore Photonics has used wafer fusion to combine a 1300 nm active region with GaAs-based DBR mirrors and an integrated optical pump (see *Compound Semiconductor* July 2000, p54). As described below, several companies – Cielo, Infineon and E2O – have used InGaAsN active regions lattice-matched to GaAs-based DBRs, while Nova Crystals and Bandwidth9 have developed monolithic InP-based VCSELS. Also, CoreTek is having success with its MEMS-based tunable VCSEL structure.

Nova reaches 10 Gbit/s at 1310 nm

Last year Nova Crystals introduced a 2.5 Gbit/s 1310 nm surface emitter providing CW operation up to 1 mW in a single spatial mode. At this year's Optical Fiber Communication conference (OFC) in March, the company demonstrated an updated 10 Gbit/s version of this electrically injected device with an output of 7 mW, achieved by integrating an optical amplifier into the device.

The VCSEL is a monolithic InP-based device grown by a single MOVPE sequence. A number of other components have also been monolithically integrated on-chip, including a power monitor diode and an electroabsorption modulator. All functions were integrated into a chip size of just 600 × 300 µm.

The company aims to extend the range of its VCSELS into the metro domain and later to longer reaches for telecom applications. According to CEO Felix



The Afterburner-XGSX from Blaze is a coarse WDM transceiver containing four short-wavelength VCSELS. Vertical emitters at telecom wavelengths are expected to become cost-effective alternatives to edge-emitting lasers.

Ejeckam, this will mean addressing limitations in spatial mode operation and reducing polarization in the device. "The polarization state is particularly significant for these applications, as increased polarization leads to dispersion which affects long distance operation," says Ejeckam.

Nova says both single spatial mode and single polarization state operation have been achieved over the entire current and temperature range (from –40 to 85°C). The company is presently ramping up production of its 2.5 Gbit/s VCSELS, and plans to have its 10 Gbit/s devices ready for sampling as early as July/August, with volume production around the end of the year.

Bandwidth9 demos 1550 nm VCSEL

As well as manufacturing a MEMS-based 2.5 Gbit/s tunable VCSEL (see p49), Bandwidth9 has also developed a single wavelength monolithic InP-based 1550 nm VCSEL. Single mode fiber operation at 2.5 Gbit/s has been achieved over 150 km up to 75°C. The output power is 0.5 mW and the single mode side suppression ratio is >35 dB.

Active regions prove popular

Unlike Nova Crystals, Cielo Communications has developed a monolithic VCSEL lattice-matched to GaAs, which is grown by MBE. The active region consists of three 6 nm thick InGaAsN/GaAs QWs and 30 undoped pairs of AlAs/GaAs for the bottom DBR stack. A 24-pair C-doped AlGaAs/GaAs stack forms the top DBR.

In May, the company reported at CLEO error-free 10 Gbit/s operation over 10 km of single mode fiber with an emission peak centered on 1289 nm. Lasing was sustained up to 125°C with a spectral line width of 0.05 nm. The maximum output power was 1 mW at room temperature, with 2.5 mW available in multi-mode operation.

"We investigated both antimonide- and nitride-based GaAs active regions, and feel that the nitrides have provided better photoluminescence intensity and make better lasers," says marketing manager Jess Bisberg. "The wafer bonding approach complicates manufacture, and makes it more difficult to design array structures." Cielo plans to incorporate its new 10 Gbit/s VCSELS into a series of integrated optical subsystems to be announced later this year.

Infineon backs quaternary QWs

Infineon's new 1300 nm VCSEL employs two 6.5 nm $\text{In}_{0.35}\text{Ga}_{0.65}\text{As}_{0.982}\text{N}_{0.018}$ QWs in the active region, which are lattice matched at this composition to GaAs/AlGaAs top and bottom DBR mirrors. Infineon uses RF-coupled plasma source MBE to grow the nitride layers.

Operating at OC-192 data rates, the maximum wavelength is 1308 nm (at 8 mA), with a CW output power of 1 mW at 25°C, although lasing can be sustained up to 80°C. The threshold current is 2.0–2.2 mA and typical side mode suppression is 40 dB.

Henning Riechert of Infineon's corporate research group says the company decided that the wafer fusion was not ideally suited to volume production. "We chose the InGaAsN route for the active region because of the fast progress we have already made with this materials system." (See *Compound Semiconductor* July 2000, p71.)

E2O evaluates different approaches

E2O Communications also recently announced a long-wavelength VCSEL which operates at 1320 nm with a single-mode CW output power of more than 2 mW at room temperature. According to Wenbin Jiang, vice-president of advanced technology, E2O is working on a number of approaches, although its current device is based on standard long-wavelength materials.

"We are currently studying InGaAsN for the active region, but there are still concerns about reliability because nitro-

gen is difficult to incorporate and tends to degrade," says Jiang.

CoreTek leads the way in high power

CoreTek, which is now part of Nortel Networks, is poised to introduce a new 40 Gbit/s tunable laser capable of high-power operation in the 1514–1564 nm wavelength range. Known as MEM-LASE, the device employs a MEMS-based curved top mirror and a deposited dielectric bottom mirror around the InGaAsP QW active region (see *Compound Semiconductor* July/August 1999, p32). The device is tuned by applying a voltage to the top MEMS mirror, which changes its curvature and hence alters the cavity length.

The device is optically pumped by a 1300 nm laser diode which allows a very high peak power of 30 mW, and up to 20 mW across the entire 50 nm tuning band.

According to CoreTek's president

Parvis Tayebati, this is the first such device to offer the requisite output power for telecom applications at 10 and 40 Gbit/s data rates in a tunable format. "The key to the power lies in the optical pumping technique employed," says Tayebati. "The high power leads to the high quality spatial line width of around 2–4 MHz, which is maintained in single mode operation by our curved MEMS mirror. In system trials this had produced a modulated signal that only needs amplification every 80 km and regeneration every 600 km."

At present, the device is externally modulated, although there are plans to integrate a GaAs-based Mach-Zehnder modulator into a smaller package in future. The tuned signal can be locked using an integrated front-end locking system. Tayebati says that beta testing is currently underway, and product introduction is expected by the last quarter of the year.

VCSELS power 10 Gbit/s transponders

There are three general ways to achieve aggregate bandwidths of 10 Gbit/s. One is to combine multiple channels in parallel. Another is to combine four or more wavelengths along a single fiber using coarse wavelength division multiplexing (CWDM). Also, it is possible to have a serial solution using a single channel at 10 Gbit/s. Recent developments suggest that all of these will prove to be viable solutions.

Cielo launches serial transponder

At the recent Optical Fiber Communication conference (OFC), Cielo Communications launched a 10 Gbit/s 850 nm serial transponder (see front cover). The transponder is currently sampling to development partners with volume production commencing in July 2001. Picolight announced a similar product in August 2000, which will have general availability in the third quarter of 2001.

The product is designed for OC-192 very short reach (VSR), 10 Gigabit Ethernet and proprietary backplane interconnects up to 300 m in length.

Other products targeted at the VSR application use either 1310 nm serial or 850 nm parallel solutions. At present,



Fig. 1. Alvesta's four-channel parallel transceiver module contains arrays of four VCSELS and four detectors, and has a footprint of 0.61 × 1.36 inches.

1310 nm serial solutions suffer from high power consumption, and high testing and packaging costs associated with the use of edge-emitting lasers, while 850 nm parallel solutions involve more complicated interconnect designs using multiple components.

"Cielo's transponder takes the best from both worlds by offering a high-speed serial solution over MMF that is less expensive, requires less than half the

power, and is half the size of current alternatives" said Jeff Bisberg, product marketing manager at Cielo.

Blaze has a coarse solution

Blaze Network Products, a company based in Dublin, California, is one of the leading proponents of coarse WDM technology at 850 nm. Several other companies, including Agilent and Finisar, have announced longer wavelength CWDM products. Blaze's Afterburner XGSX transceiver (see page 43) combines four wavelength channels, each operating at 3.125 Gbit/s, and uses four VCSELS operating at 778, 801, 825 and 850 nm. The transceiver contains an optical sub-assembly (OSA) that contains VCSELS, drivers, detectors, TIAs, CWDM filters, and multiplexers and demultiplexers in a single, low-cost package. Blaze has developed an internal process to assemble the elements of the OSA using passive alignment. The company obtains oxide VCSELS from a number of suppliers, including Emcore (see page 13).

Blaze claims that the Afterburner-XGSX, which measures 1.2 × 2.57 × 0.53 inches, is the smallest pluggable 10 Gigabit transceiver in the industry. The

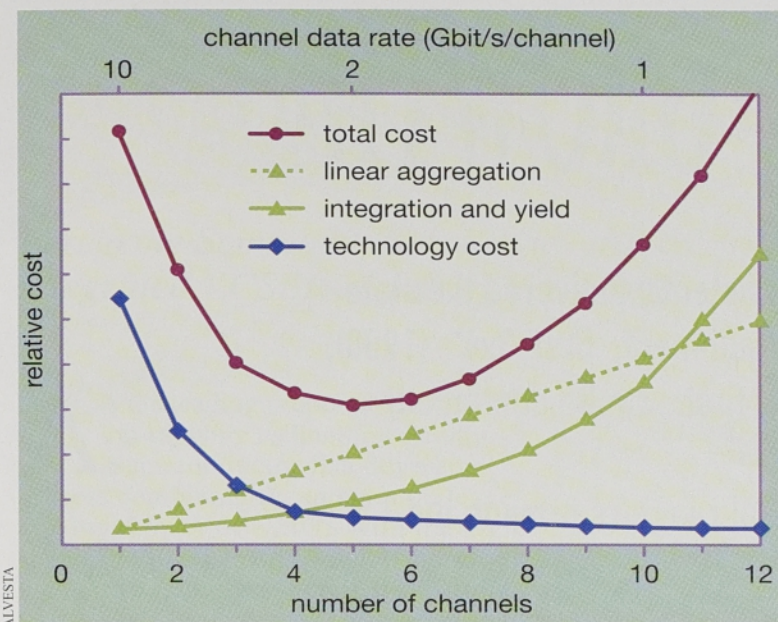


Fig. 2. The total cost of implementing a multi-channel 10 Gbit/s link is the product of the technology cost (which increases at higher data rates) and the aggregate component cost (which is higher when more channels are used).

initial pricing of the product is well below \$800 for modest volumes, and product shipments are due to begin in early June.

"Customers have been pushing the transceiver industry for years for higher port densities to support the increased numbers of links on the network," says Kirk Bovill, director of product marketing for Blaze. "While the initial implementations of 10 Gigabit Ethernet will not require a high number of ports per blade, they will in the near future."

Alvesta uses a four-channel format

At OFC, Alvesta announced the availability of its Model 3100 optical transceiver, which uses four channels and parallel optics to deliver an aggregate bandwidth of 10 Gbit/s. The transceiver (see figure 1) has a footprint of 15.5×34.6 mm (0.61×1.36 inches) and is priced in the \$300–600 range, depending on volume. Each module contains arrays of four 850 nm VCSELs and four PIN detectors, and transmission takes place over a 12-fiber ribbon (four fibers are used in each direction, and four are dark). This type of product was also the subject of a multi-source agreement between Agilent and Mitel (see *Compound Semiconductor* May 2001, p17).

Alvesta claims that their solution offers the lowest power consumption (less than 1.0 W) and lowest cost of any 10 Gbit/s solution.

Figure 2 explains Alvesta's contention that a four-channel parallel solution is more cost-effective than serial (one-channel) or 12-channel parallel solutions. A small channel count requires the use of high-speed components and leading edge technology, which is more expensive – this is represented by the curve labeled "technology cost". The cost of implementing more than one channel increases incrementally since more components are required – this is shown in the "linear aggregation" curve. In reality, the aggregate link cost is reduced in small arrays due to the benefits of integrating the components, while for larger arrays the opposite is true due to lower yield and increased assembly complexity. The "integration and yield" curve indicates the actual aggregate link cost. The "total cost" curve, which has a minimum in the four to six channel range, is the product of the technology cost and the aggregate link cost.

Two equipment suppliers, Force10 Networks and BrightLink Networks, have already chosen Alvesta's 10 Gbit/s Model 3100 optical transceivers for VSR applications.

Mitel's Smart OSA approach

Mitel is developing parallel fiber modules with aggregate bandwidths of up to 30 Gbit/s (for the 12-channel, 2.5 Gbit/s version). The company has developed its

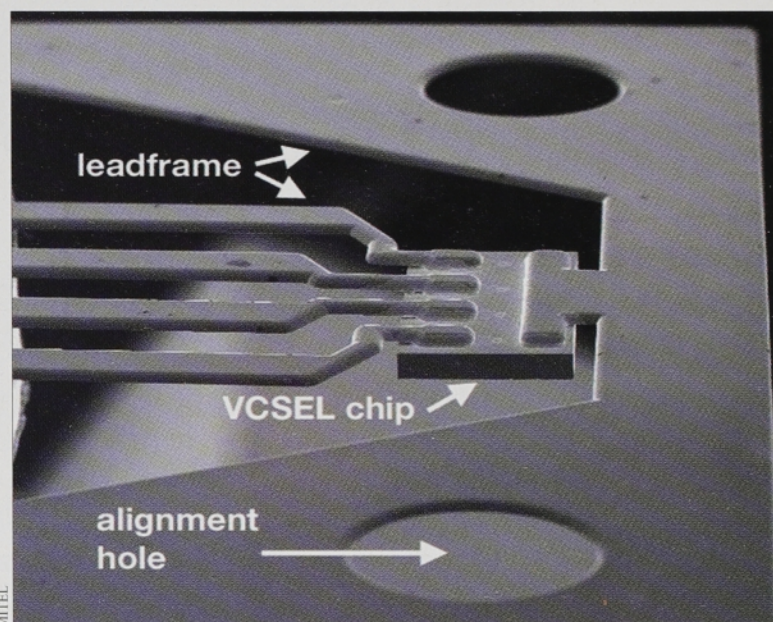


Fig. 3. Mitel's Smart OSA consists of a four-element VCSEL or detector chip attached to a leadframe. Holes in the leadframe correspond with pins in the connector, ensuring accurate alignment of the optical devices and the fibers.

Smart OSA high-volume manufacturing technology to accurately position the VCSELs or detectors with respect to the fiber arrays. The Smart OSA unit begins with a single chip containing an array of four devices, either VCSELs or detectors, spaced 250 μ m apart to match the spacing of fibers in a standard MTP or MPX connector. The chips are fabricated by Mitel. Using a solder reflow technique for very accurate alignment, one or more such chips are attached to a leadframe, as shown in figure 3. Because the two end elements are close to the edges of the chips, several chips can be combined to form an array with up to 12 elements. The leadframe also contains two circular alignment holes that correspond with guide pins in the MTP and MTX connectors – this ensures that the fibers in the connector align accurately with the optical devices. This approach results in a compact, simple and robust system, which is compatible with the high temperatures required for the reflow soldering process.

The use of chips with four devices allows several combinations of module to be built, namely transmitters and receivers with 4, 8 and 12 channels, or transceivers containing both four VCSEL and four detectors. Importantly, four-element chips have far higher yields than chips with arrays of eight or twelve devices.

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Peregrine sees through sapphire

Peregrine Semiconductor has leveraged its CMOS-on-sapphire technology to fabricate integrated VCSEL and detector arrays with silicon ICs, writes Tim Whitaker.

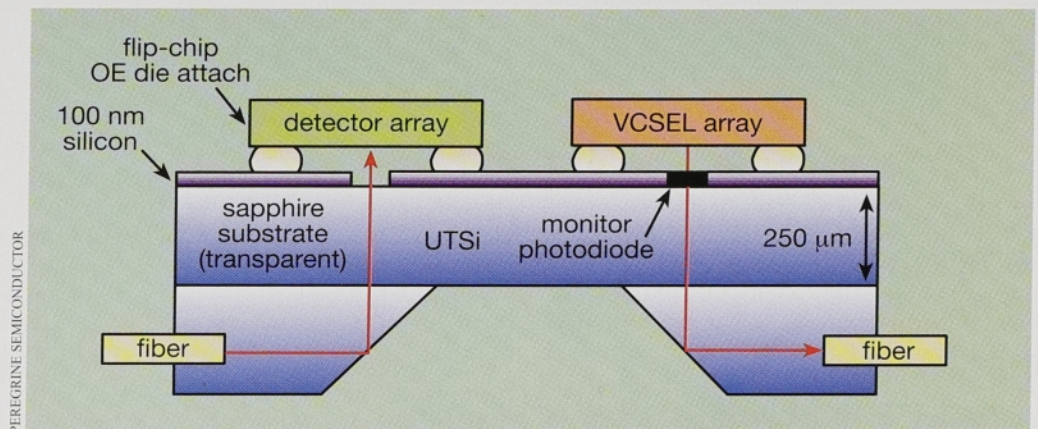
As the leading proponent of silicon-on-sapphire technology, Peregrine Semiconductor has developed a process combining the integration levels and low power of CMOS with the high speed and low parasitics that come from using an insulating sapphire substrate. However, sapphire is also transparent, which allows optical signals to pass through the substrate. Because of this, it is possible to fabricate modules in which arrays of vertical cavity lasers (VCSELs) and detectors are flip-chip bonded to the CMOS circuitry, with the fibers attached to the backside of the sapphire substrate as depicted in the figure, right.

“Packaging is the major issue in achieving high speed performance in an optoelectronic system,” says Ron Reedy, Peregrine’s chief technology officer. “Getting the full data rate electrical signals on and off the fiber is a problem that can not be done simply if the electrical packaging parasitics are in the way. Flip-chip packaging offers a good solution, but it must be based on a substrate with high speed, low power electronics and optical access between fibers, lasers and photodetectors.”

Module assembly

The starting point for the module shown in the figure is a sapphire wafer covered with an ultrathin (100 nm), high quality epitaxial silicon layer called UTSi. Standard CMOS processing is carried out on the UTSi layer to build ICs such as VCSEL drivers, amplifiers, clock and data recovery circuits, and serialize/deserialize elements. Peregrine runs a 0.5 μm version of the UTSi process at its 6 inch fab, which provides 3.125 Gbit/s operation at very low power. The company will soon introduce a 0.25 μm process for 12 Gbit/s operation, followed by 0.13 μm UTSi CMOS for data rates up to 40 Gbit/s.

Next, VCSEL and photodetector arrays are flip-chip bonded onto the CMOS



Cross-section through a parallel array of VCSELs and detectors bump-bonded to CMOS-on-sapphire substrate. CMOS processing on the ultrathin silicon (UTSi) layer provides high levels of on-chip functionality. Light is coupled into or out of the parallel fiber arrays through the transparent sapphire.

circuitry using standard gold-gold or gold-tin eutectic die attach techniques. For both transmitters and receivers, an open area is left in the silicon to allow light to pass through. On the transmit side, a small silicon monitor photodiode is included to measure the power output of each VCSEL. “We also build in feedback circuitry, which allows active control of each VCSEL in an array,” says Reedy. “This is useful for power monitoring, temperature or ageing compensation and eye safety control.”

Finding a way to couple light from the VCSEL into the fiber is a big challenge, but fortunately sapphire has some advantageous properties. When the VCSEL beam leaves the surface of the device it begins to expand; this expansion is modified by the sapphire, which has a refractive index of 1.76. “The thickness of the sapphire layer is such that by the time the beam emerges from the backside of the sapphire, the beam width is about the same as the core diameter of multi-mode fiber, i.e. about 50–60 μm ,” says Reedy. Because of this, there is no need to incorporate microlenses into the structure, although Peregrine has demonstrated

such lenses, and they would probably be required for single-mode fiber. “Although our initial products are aimed at short reach multi-mode fiber markets, this approach is directly applicable to receivers in single-mode systems, where parasitics at 10 and 40 Gbit/s are the most severe,” Reedy added.

Attaching the fibers

The module demonstrated by Peregrine at the recent Optical Fiber Communication conference (OFC) was slightly different from the one shown above, since it used fibers with end facets cut at an angle of 45° to change the direction of the light entering and leaving the fiber. The arrays of fibers are held in plastic V-groove holders with the same pitch (250 μm) as the VCSEL and detector arrays. Therefore, only a single alignment step is needed to position the plastic V-groove onto the backside of the sapphire. Again, the transparency of the sapphire helps by allowing alignment marks to be placed on the V-groove and on the top side of the substrate.

The arrangement shown is fine for 1-D arrays but is not suitable for 2-D arrays.

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"We've received a lot of inquiries about 2-D arrays," says Reedy. "For these, we'll use a different approach in which the fibers are butt-coupled to the backside of the sapphire."

Functionality

The module configuration allows a great deal of functionality to be integrated, as well as making it relatively easy to increase data rates by moving to faster CMOS processes. In addition to demonstrating VCSEL drivers, TIAs and limiting amplifiers, Peregrine is developing crosspoint switches, clock and data recovery ICs, MUX/DEMUX functions and integrated EEPROM (non-volatile memory). These can be seen as building blocks to more complex systems, ultimately offering fiber-in and fiber-out connections with high-speed electronics between. "Under this scenario, only relatively low speed control signals are required, thereby reducing power consumption, crosstalk, and size," says Reedy. "For example, you could build a 12 x 12 crosspoint switch between the detector and VCSEL arrays. The device would have fibers in and fibers out, with multiple functions carried out by the on-chip electronics. Functions such as routing, retiming, pulse shaping and jitter reduction could be done on-chip without handling high speed electronic signals anywhere but on the surface of the sapphire."

Starting with incoming optical signals, it would be possible to deserialize the

signals electronically on the surface of the chip, and provide relatively low speed digital outputs. "Router companies dislike having to deal with multi-GHz analog signals at the board level," says Reedy. "Crosstalk and power consumption cause real problems; they'd much rather get digital input/output signals." Peregrine expects these types of products to start sampling at the end of the year.

RF devices

While optoelectronic modules represent a new direction for Peregrine, the company continues to manufacture high performance RFICs using its UTSi CMOS-on-sapphire process. For example, Peregrine recently introduced a family of low insertion loss RF switches targeted at applications up to 2.5 GHz; the company claims these exhibit superior performance to GaAs switches. The SPDT devices have >36 dB isolation at 1 GHz and have single-pin control voltage levels that are CMOS compatible and readily interfaced with other CMOS devices. The switches also have extremely low power consumption, and are priced at 65 cents in volumes of 10k units. Peregrine also ships over a million mixer products per month with extremely high linearity (input IP3 of +38 dBm) and has recently announced a new mixer family with integrated high performance baluns (transformers). "This is an example of where our UTSi products are displacing GaAs and Si bipolar in certain high performance markets," says Reedy.

AraLight gets the Lucent spin

Lucent Technologies has founded a new venture, AraLight, which will use technology developed at Bell Labs to integrate very large numbers of VCSELs and detectors with prefabricated silicon ICs.

"We expect our higher port densities and smaller form factor will eventually allow us to develop products that have aggregate speeds of many terabits per second, all in a single compact package," says Michael Camp, CEO of AraLight.

AraLight is targeting the integration of 2-D arrays with many hundreds or thousands of optical channels, each with multi-GHz data rates. Innovative fiber array packaging is being designed to transport data to and from the optoelectronic-VSLI chips. The silicon ICs

themselves will have receiver and driver functionality capable of low power conversion of analog optical signals into digital electronic signals.

Like Peregrine, AraLight does not have any plans to manufacture optoelectronic chips. The companies have different approaches to getting light into and out of the bump-bonded VCSEL/detector/silicon structures; in AraLight's case, the GaAs substrate is removed to allow backside emission from the VCSELs.

Created by Lucent's New Ventures group, AraLight is located in Monroe Township, New Jersey. The company has received investments totaling some \$10 million, and its team has access to more than 70 patents.

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Tunable VCSELs: enabling wavelength-on-demand in metro networks

Tunable VCSELs offer a reliable, cost-effective way to dynamically provision bandwidth in metro networking systems, says Bandwidth9's Connie Chang-Hasnain.

An unquenchable thirst exists for bandwidth. Nowhere is this more evident than in the explosive growth of Internet traffic. This demand is driving the rapid development of DWDM networks: these systems now regularly handle more closely packed channels operating at speeds of up to 10 Gbit/s, with maximum channel counts reaching 200 per fiber. Currently the market for optical components for DWDM systems stands at around \$8–9 billion, and is expected to approach \$25 billion by 2004.

The metro environment

While a great deal of innovation and development has been focused on the deployment of long-haul optical systems, there also exists a growing demand for DWDM systems optimized for metro environments. Traffic patterns in metropolitan areas can be distinguished from long-haul data flow patterns largely by the uneven flow of data. The patterns are also differentiated by a need to accommodate multiple protocols and different quality-of-service requirements. These pre-requisites lead to a need for different hardware solutions. In short, metro DWDM systems should be smart and flexible.

Metro DWDM systems that are based on fixed wavelength add/drop nodes work well when a limited number of wavelengths and system reconfigurations are required. However, as the pattern of traffic and customer requirements change, costly and time-consuming system reconfigurations are needed. In addition, to limit downtime caused by system failures, carriers use spare components to establish infrastructure redundancy. In the case of laser sources, this requires a redundant line card with fixed wavelength lasers and filters for each working wavelength,

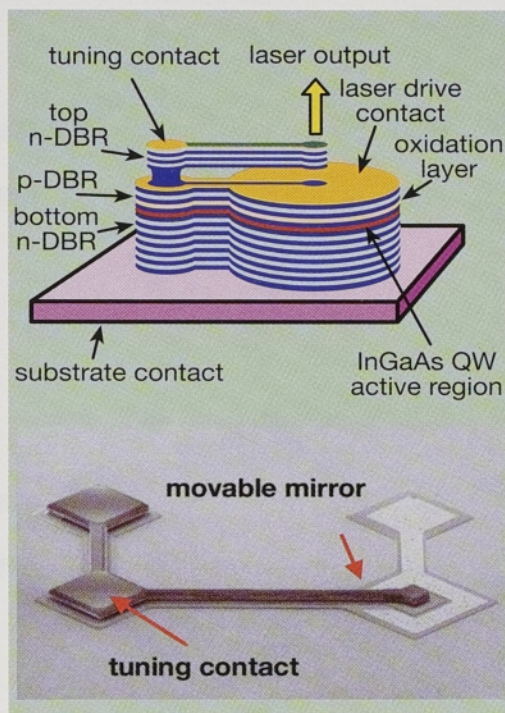


Fig. 1. Bandwidth9's mechanically-tunable VCSEL employs an electrically-pumped QW structure and GaAs/AlGaAs MEMS cantilever (see SEM image) to select the wavelength. As an electric field is applied, the position of the cantilever changes, altering the cavity length and wavelength. Direct modulation up to 2.5 Gbit/s is achieved by varying the pumping current through the quantum well.

DWDM systems now regularly handle more closely spaced channels operating at speeds up to 10 Gbit/s and channel counts of 200 per fiber.

which represents a large capital investment. Additional costs associated with this redundancy include those associated

with increased use of space and higher power consumption.

The tunable solution

The capital expenditure for fixed sources can be greatly reduced by using broadly tunable sources, which allow a single replacement or spare line card to be substituted for a wide range of wavelengths. Further cost reductions are possible if system reconfigurations can be implemented remotely and quickly.

Another cost-related issue facing providers of metro infrastructure relates to the fact that many customers employ systems operating at slightly different wavelengths. This requires locking equipment that allows the various systems to match wavelengths and "talk" to one another. The availability of tunable wavelength sources would eliminate such mismatch issues.

Remote access

For DWDM systems, while inventory reduction and lower system costs represent very considerable gains, an equally important benefit is afforded by tunable sources that offer remote access. The tunable laser can be reconfigured remotely, providing wavelengths on demand, and is able to dynamically provision, activate, deactivate and redirect data flow. In essence, this can be viewed as a physically connected fiber ring, over which there exists a connective mesh network that can be changed as needed.

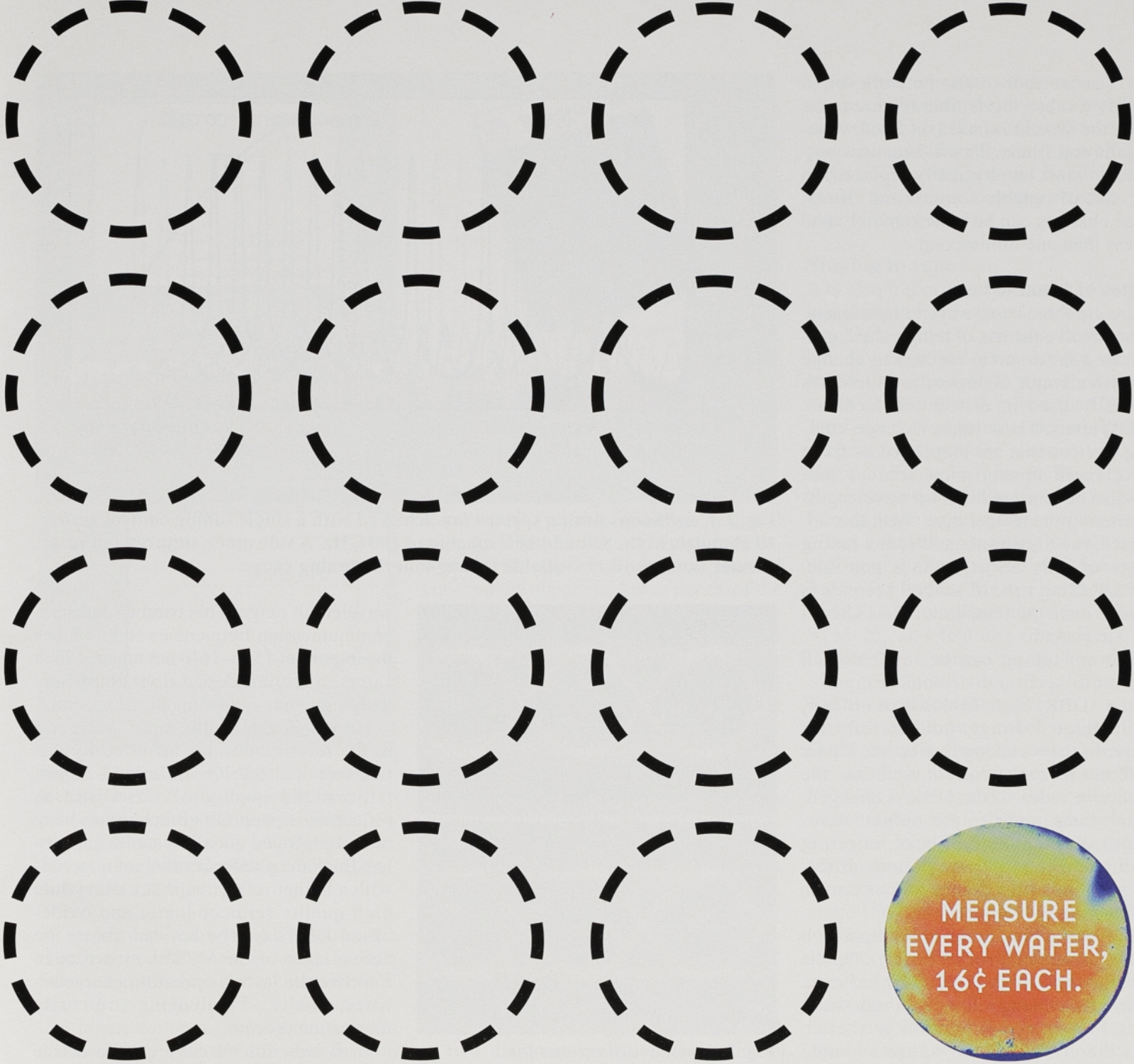
Even greater flexibility is possible if, in addition to tunable sources, tunable filters are included in the network. In this instance there is no need to pre-allot certain channels to particular fibers: any fiber can carry any wavelength.

This offers a major advantage. Typically it takes several weeks to remove or



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add a subscriber to the network, or to modify a subscriber's fiber requirements when the system is based on fixed wavelengths and filters. This is because components must be physically replaced. In the case of tunable sources and filters, these changes can be done remotely and in less than one millisecond.

Types of tunable laser

There are three basic ways to tune lasers: these involve the use of temperature, current or a mechanical method to change the wavelength. Temperature tuning is typically used in distributed feedback (DFB) lasers. These lasers are edge-emitting devices that are employed as fixed wavelength transmission sources that can also be tuned to different wavelengths by altering the temperature. With this approach, the disadvantage is that a tuning range of only about 5 nm is possible, and a settling time of several seconds is needed once the temperature has altered the wavelength.

Current tuning can be implemented in a multi-section distributed Bragg reflector (DBR) laser. In this kind of laser, an integrated Bragg grating reflector performs the wavelength selection. Under different levels of current injection, the refractive index of the DBR is changed, which then modifies the output wavelength. For this kind of laser, injecting multiple levels of current into different sections of the device allows a wide tuning range.

One of the limitations of this approach relates to the control of tuning. This is complex and often does not produce a continuous change in wavelength when one of the injection currents is altered. It is therefore difficult to use a simple universal wavelength locker with such a device.

Mechanical tuning is the most recent approach. This method employs a VCSEL in combination with a micro-electro-mechanical system (MEMS) tuning device. Unlike edge-emitting lasers, the VCSEL reflects light between two mirrors in a vertical cavity, emitting light vertically from the surface of the laser. With a MEMS structure it is possible to take advantage of this vertical cavity geometry, and the laser's upper mirror can be repositioned and adjusted using a cantilever (see figure 1).

The VCSEL possesses another major advantage compared to both DBR and

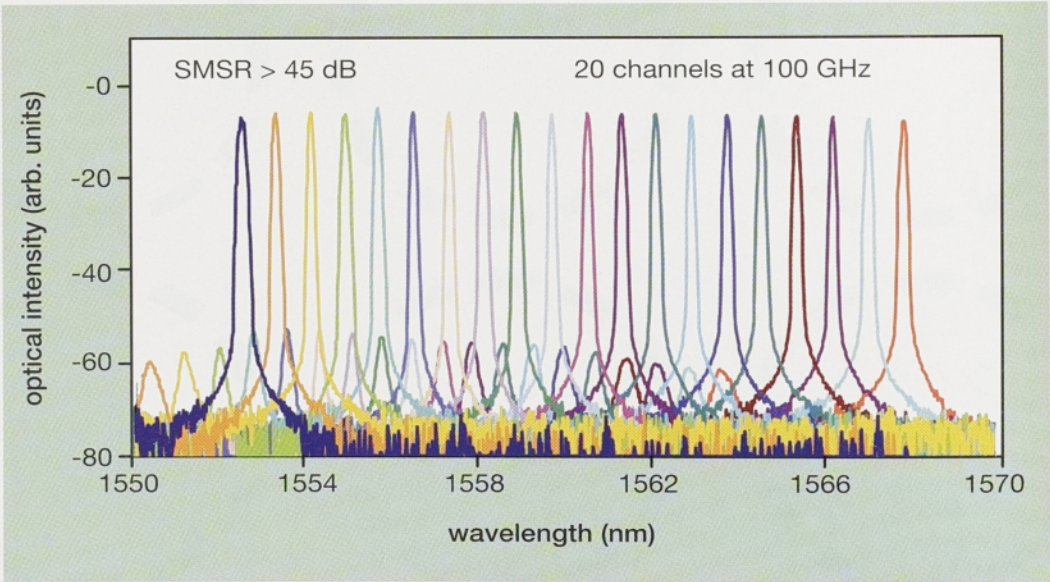


Fig. 2. Continuous tuning spectra are achieved with a single tuning control across 20 channels in the C-band at a spacing of 100 GHz. A side mode suppression ratio greater than 45 dB is available throughout the tuning range.

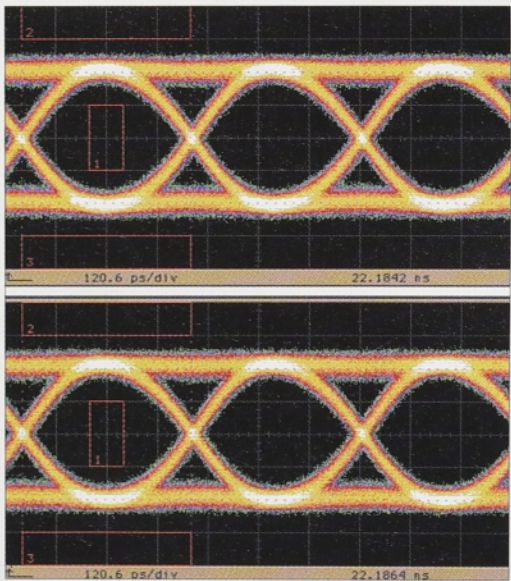


Fig. 3. Open eye diagrams for 1620.5 nm (top) and 1610.9 nm (bottom) attest to reliable 2.5 Gbit/s operation in the L band.

DFB lasers; at around 3 μm , its optical cavity is two to three orders of magnitude smaller. As a result, the VCSEL is intrinsically a single wavelength device. Therefore, adjustments to the cavity spacing cause continuous changes to the wavelength.

VCSEL fabrication

The key to implementing a mechanically tunable laser for DWDM applications is the ability to first fabricate a high-quality VCSEL operating in the 1.5–1.6 μm

wavelength range. This band targets telecommunication frequencies and includes the important 1530–1610 nm range, which caters to erbium-doped fiber amplifiers with high gain and wide optical spectra.

However, due to the small variation in the refractive index afforded by lattice-matched InAlGaAs/InAlAs superlattices, the quality of the DBRs as reflectors is poor. Other techniques have been employed to alleviate this problem, including wafer bonding of materials with a higher refractive index. But while high-quality semiconductor and oxide-based DBRs can be bonded above the active layer of the VCSEL structure to improve the laser's operating characteristics, this is a challenging and costly fabrication process.

In Bandwidth9's devices, the active region is typically comprised of strained InGaAs QWs, and the bottom DBR reflectors fabricated from lattice-matched InAlGaAs/InAlAs superlattices. The whole structure is based on a single epitaxial growth on an InP substrate.

Metamorphic mirrors

Bandwidth9 has improved the performance of these devices with a new proprietary design that includes a metamorphic (or non-lattice matched) top DBR mirror comprised of an AlGaAs/GaAs superlattice. A high-quality DBR can be fabricated with a relatively small number of AlGaAs/GaAs superlattice periods by exploiting the large change

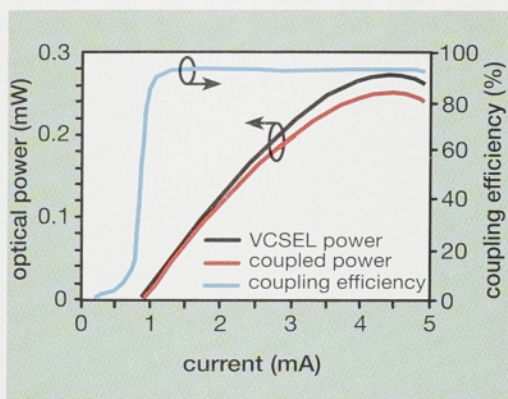


Fig. 4. VCSEL output power, power coupled into the fiber and the overall coupling efficiency as a function of current.

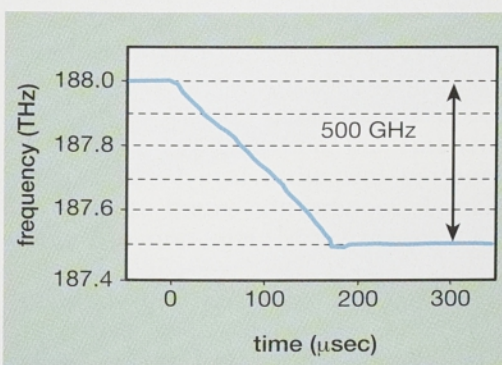


Fig. 5. The company's fast wavelength locking method employs a filtering process to rapidly damp transient ringing when changing wavelength. The system locks to within ± 2.5 GHz in less than 200 μ s.

in refractive index of AlGaAs as the aluminum content is increased. From a fabrication standpoint, the entire VCSEL structure – including the substrate contact layer, the upper tuning contact, the active layer, and the top and bottom DBRs – can be produced in a single MBE growth sequence.

The use of the high-quality metamorphic DBR above the active region greatly improves the laser performance: an output power of 0.45 mW with a threshold voltage of 1.7 V can be obtained for a 9 μ m aperture device. In addition, the current and optical confinement can be enhanced by sidewall oxidation.

In terms of the other key parameters of the device, a single transverse mode of operation is achieved, with a side-mode suppression ratio of 45 dB. The polarization mode suppression is 45 dB, and the operating parameters are maintained for temperatures up to 55°C.



Fig. 6. Bandwidth9's MetroFlex 2.5 Gbit/s tunable laser module.

Cantilever tuning

Bandwidth9's tunable VCSEL is designed with the DBR divided into three sections, with an air gap of about 1 μ m located between the upper and lower region of the top DBR. The tuning contact is a very basic MEMS structure manufactured from a simple GaAs/AlGaAs cantilever beam (figure 1). Applying an electrostatic force – which is obtained by applying a voltage to the tuning contact – can deflect this beam. This deflection changes the VCSEL cavity length, which in turn changes the wavelength of the device, allowing continuous tuning as a function of the applied voltage. The tuning spectra of a C-band VCSEL controlled by a single tuning voltage is shown in figure 2.

The tunable VCSEL can be directly modulated with high-speed data streams by varying the current through the QW region via the laser drive contact, in common with all directly modulated diode lasers. The direct modulation performed at two different lasing wavelengths in the L-band is shown in figure 3, where fully open eye diagrams attest to data rates of 2.5 Gbit/s.

As important as the ability to tune is the speed of tuning. The shorter the length of the cantilever, the greater its resonance frequency, and therefore the faster the cantilever can respond to a change in voltage. Research into differing cantilever lengths has shown that the frequency response of even the longest cantilevers (100 μ m), which also provide the largest tuning range, feature a resonant frequency of around 100 kHz. This allows a VCSEL to tune to a new wavelength in around 10 μ s. The shortest cantilever (25 μ m) is able to tune to a new wavelength in just 1 μ s.

Another inherent advantage springs from the circular nature of beam, which is controlled by the oxide aperture. This property considerably eases coupling of the VCSEL to a fiber, and Bandwidth9's device features a coupling efficiency of over 90% (figure 4).

Staying in tune

It is also important that once the desired wavelength has been selected, it can be quickly locked into position. Bandwidth9 has developed a locker for the tunable VCSEL that is able to lock to within a ± 2.5 GHz bandwidth in less than 200 μ s. This is achieved using a special filtering process that rapidly damps transient ringing (figure 5). This technology has been integrated into Bandwidth9's MetroFlex tunable optical transmitter, which offers continuous tuning and locking in less than 100 μ s (figure 6). Measuring 3 $\times$ 5 $\times$ 0.5 inches, MetroFlex is SONET and ITU-T compliant up to OC-48 and STM-16, and features the full C- and L-band tuning range.

Future applications

In the near future, other applications could benefit from tunable VCSELs. An example is optical cross-connects (OXC). Whether electrical or all-optical switch fabrics, OXCs are emerging as a way of handling high-density optical terminations typically found at the interconnection points between long-haul and metro DWDM systems. OXCs are used to regulate and re-route traffic across optical pathways. They also provide protection and restoration of the signal. These functions can be distributed throughout the metro DWDM transport network if tunable sources are used to control the selection of wavelength interchanging.

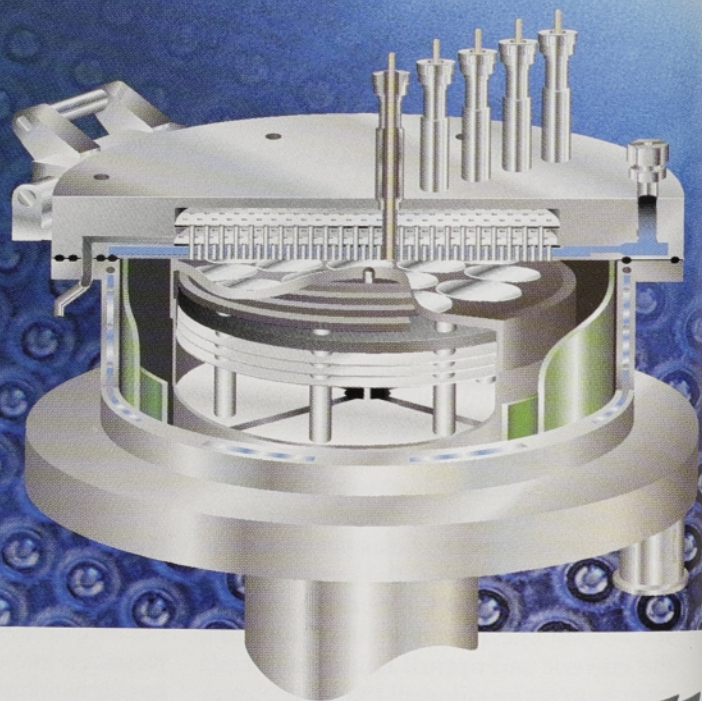
Wavelength tuning capabilities will also increase the degree of connectivity and number of logical connections, and will support a variety of protection and restoration methods on physical ring deployments. A combination of these currently distinct network elements could ease the migration to efficient implementation of metro WDM systems.

Connie Chang-Hasnain is CTO of Bandwidth9, Fremont, California. E-mail: cchang@bw9.com. This article is based on a presentation at the 2001 Key Conference, held 5–6 March in Key West.

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Deep thoughts on shallow dopants

The application of novel techniques, both theoretical and experimental, to the problems of doping wide bandgap semiconductors was the theme of the recent WideGap2001 workshop. Caspar Fall and Robert Jones report.

The WideGap2001 workshop held at the University of Exeter, UK, on 21–23 March, brought together 75 experimentalists and theoreticians from across the world to discuss the successes and current problems of doping a variety of wide bandgap semiconductors. The organization of this event was made possible by a grant from the European Science Foundation and the financial support of several industrial partners. Contrary to many conferences that are limited to one specific semiconductor material, WideGap2001 crossed material boundaries and focussed on defects and impurities in gallium nitride (GaN), silicon carbide (SiC), zinc oxide (ZnO) and diamond.

Some common problems

There is a great deal of interest in overcoming problems relating to shallow dopants in wide bandgap materials. For example, in GaN oxygen and silicon are known to be shallow donors but there are difficulties in finding efficient shallow acceptor dopants for creating p-type material. Magnesium and beryllium are favored but have high activation energies. In ZnO, an effective method to achieve p-type conduction is still eluding current researchers. In diamond, boron is a shallow acceptor but there are difficulties finding suitable shallow donors. Phosphorus and sulfur are key candidates and there is intense interest in optimizing their activity. Nevertheless, dopants in all these materials suffer from problems relating to solubility and the formation of complexes, for example with hydrogen which is a common impurity, or with native interstitials and vacancies.

Modeling methods

A striking characteristic of the WideGap 2001 workshop was the large number of theoretical groups represented. Physicists

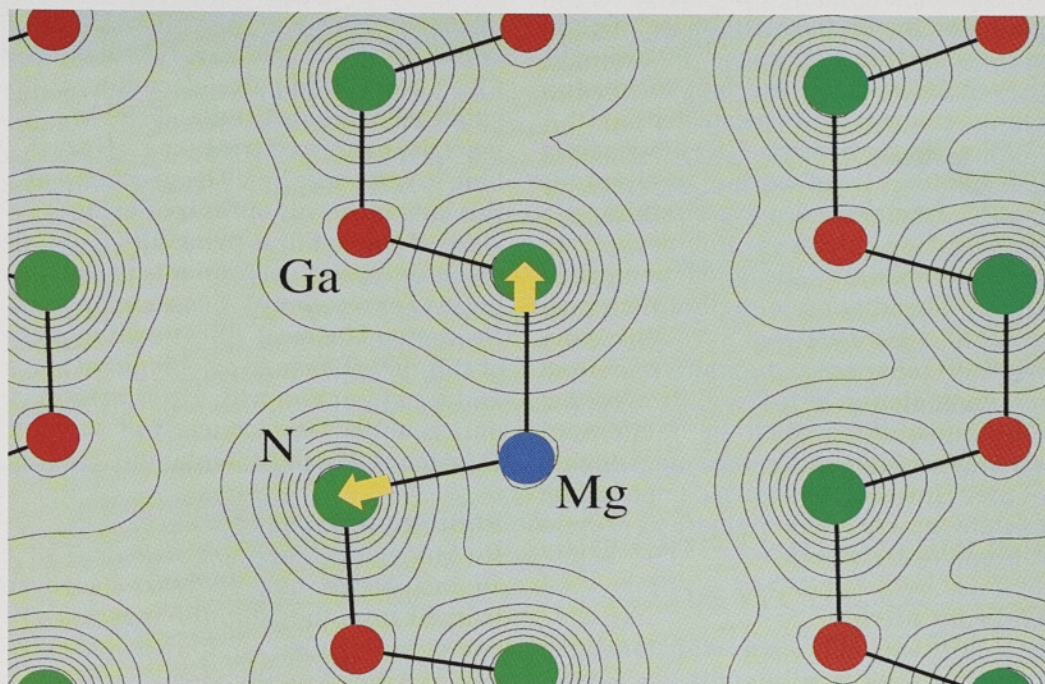


Fig. 1. Electronic charge density around a single negatively charged magnesium atom (blue disk) on a gallium lattice site in wurtzite GaN. The wurtzite c-axis is in the vertical direction. The gallium and nitrogen atoms are represented as red and green disks, respectively. The nitrogen atoms near the magnesium impurity are found to relax outwards with respect to their ideal lattice sites (yellow arrows).

are well aware that modeling from first principles is a very effective way in which dopant activity can be predicted. Combined with leading-edge computational resources, the so-called *ab-initio* codes can determine theoretically, amongst other properties, the structural, electrical, optical and vibrational characteristics of crystalline defects. The computed formation energies, equilibrium concentrations, diffusion paths, and behavior under applied stress of a variety of defects are often in excellent agreement with experiment, as are the calculated results of electron paramagnetic resonance experiments. Such valuable information helps to understand a wide variety of experimental observations and aims to predict the results of new ones. It is

significant that the shallow oxygen donor in GaN was first suggested from theoretical results.

In the fast evolving field of wide bandgap semiconductors, the experimental techniques employed to probe dopant activity are becoming more and more sophisticated. Not only are photoluminescence and photoconductivity studies routinely applied, but new methods such as positron annihilation, photoluminescence microscopy, and muon spin resonance can now provide equally valuable information.

Silicon carbide

The conference opened with a theoretical talk by Friedhelm Bechstedt (Jena, Germany) on deep level defects in several

SiC polytypes, focusing particularly on vacancies and complexes with boron. This was followed by other theoretical talks on SiC by Risto Nieminen (Helsinki, Finland) and Peter Deak (Budapest, Hungary), all of which highlighted the problems of doping and the formation of compensation centers such as vacancies. Nitrogen and boron incorporated on the silicon site are currently the best donors available. Hydrogen was also singled out as an important passivating impurity. By comparing the computed energetics of hydrogen interstitials with those of complexes containing hydrogen, for example, the tendency of hydrogen to form complex aggregates can be predicted.

John Steeds (Bristol, UK) emphasized the likely role of carbon interstitials in SiC luminescence by combining a transmission electron microscope to produce spatially localized controlled electron irradiation with photoluminescence microscopy. Bengt Svensson (Oslo, Norway) reported on the status of current ion implantation in SiC and showed that ion implantation was the method of choice for selective area nitrogen doping of SiC. However, unknown compensation centers are created which are at present difficult to anneal out.

Gallium nitride

In common with other wide bandgap semiconductors, gallium nitride is difficult to dope with good acceptors. James Speck (Santa Barbara, US) impressed the conference with MBE growth studies of GaN under gallium and nitrogen rich conditions and the success of introducing p-type dopants, such as magnesium, with resulting high hole densities and mobilities. Donat As (Paderborn, Germany) gave a talk on carbon doping of MBE-grown cubic GaN. This impurity was demonstrated to behave as a shallower acceptor than magnesium in cubic GaN. Incorporation of 10^{20} cm^{-3} carbon atoms has been achieved, although the activation efficiency is only about 1%.

Sergei Kucheyev (Canberra, Australia) highlighted the difficulties of eliminating lattice damage from ion implantation in GaN. The importance of dislocations in GaN thin layers was emphasized by Trevor Martin (DERA, UK), who reported experiments on high-power AlGaIn/GaN HFETs. Conduction parallel and perpendicular to the growth axis is found to be quite different.

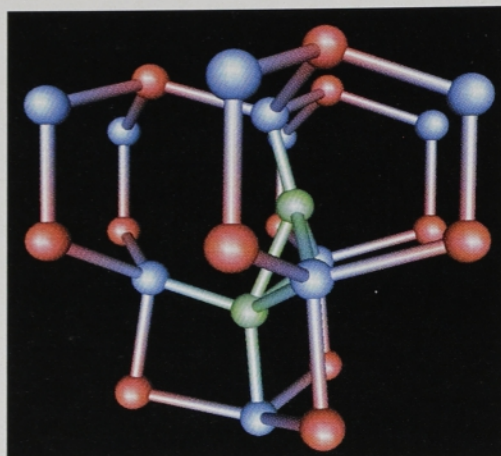


Fig. 2. Beryllium pair defect at a gallium atom substitutional site in wurtzite gallium nitride (red = Ga, blue = N, green = Be). The geometry of this structure was optimized using state-of-the-art first-principles techniques, and corresponds to the lowest energy complex containing two Be atoms. The local vibrational modes of this defect have been computed and a comparison with experimental data is under way. Courtesy of C Latham, Helsinki, Finland.

Photoluminescence

Bo Monemar (Linköping, Sweden) gave an instructive talk on what has been learned from the photoluminescence of common dopants, such as the shallow donors silicon and oxygen. Progress in identifying the optical signatures of these impurities was reported. Kimmo Saarinen (Helsinki, Finland) highlighted the use of positron spectroscopy in identifying vacancies. Baiba Berzina (Riga, Latvia) discussed optical centers in aluminum nitride, demonstrating the importance of vacancies and oxygen impurities with a view to using this material in dosimetric applications.

Vibrational spectroscopy

Bernard Clerjaud (Paris, France) showed what could be extracted from local vibrational mode (LVM) spectroscopy of impurities in GaN, finding vibrational modes of magnesium and beryllium complexes possibly linked with oxygen. Hydrogen is known to play a crucial role in the common passivation of magnesium acceptors in GaN, requiring annealing to be performed before p-type conduction is observed. A local vibrational mode at 3125 cm^{-1} has been attributed to a magnesium-hydrogen complex. Crucially, the

orientation of the electric dipole induced by this vibration has also been measured, challenging conventional wisdom about the atomic structure of this defect, and allowing comparisons with theoretical models of hydrogen-magnesium complexes to be tested. Chris Van de Walle (Xerox, US) and Caspar Fall (Exeter, UK) reported theoretical models seeking to reconcile the experimental observation with the results of simulations.

A typical result from a first principles calculation is shown in figure 1, where the electronic charge density around a single magnesium atom in GaN is shown. The stronger electronegativity of nitrogen is seen to lead to a strong localization of the electron density around the nitrogen atoms. This information can lead, for example, to predictions of the preferred positions of a supplementary H^+ atom, which is expected to reside in regions of high electronic density. Conversely, H^- interstitials may be expected to diffuse down the c-axis channels in the wurtzite structure, where the electronic density is low.

The high-pressure, high-temperature growth of bulk GaN was discussed by Stanislaw Krukowski (Warsaw, Poland). Using such conditions, oxygen can easily be incorporated as a donor. Magnesium acceptors are also readily introduced but beryllium doping has remained elusive using this growth technique. Chris Van de Walle and Risto Nieminen independently argued from first principles calculations that beryllium doping of GaN might be hindered by the tendency of beryllium atoms to form compensating interstitials rather than substitutional acceptors. Beryllium might favor an interstitial site, with pairs of impurities readily formed, as shown in figure 2. This may explain the low observed doping efficiency of beryllium.

Zinc oxide

Chris Van de Walle reviewed his new theoretical results on native defects in zinc oxide. With a bandgap and lattice parameter similar to those of GaN, ZnO is being seen as a material for future applications. The origin of n-type conduction in ZnO was examined and, contrary to GaN, hydrogen was singled out as a shallow donor in this material. This talk was followed by one from Philip King (ISIS Facility, UK) who experimentally confirmed this result. Indeed, muon spin

spectroscopy has confirmed the prediction of a donor level at 0.019 eV below the conduction band, associated with hydrogen. Danie Aurret (Pretoria, South Africa) reported on deep level transient spectroscopy studies of other levels in ZnO induced by proton irradiation. Zinc oxide is found to be remarkably radiation hard compared to GaAs or GaN.

Co-doping

There is current interest in co-doping wide bandgap semiconductors. This involves including two or more impurities (sometimes both donors and acceptors) in the crystal, with the aim of increasing the electrical activity of the dopants. Hiroshi Katayama-Yoshida (Osaka, Japan) gave an interesting talk on his theory of co-doping to produce effective acceptors in wide bandgap materials. Shallow level defects might be made by complexes such as N-Al-N defects in ZnO, and Mg-O-Mg defects in GaN. There is experimental evidence that magnesium and oxygen co-doping in-

creases the hole concentration in GaN. A striking feature of Katayama-Yoshida's talk was the number of patents secured for the effect, a first in this field for a theoretical physicist.

Jörg Neugebauer (Berlin, Germany) gave the results of an impressive set of calculations on the interaction between dopants and crystal growth surfaces, explaining why rough and smooth crystal faces occur under different growth conditions. These calculations may pave the way to an alternative theory of co-doping magnesium and oxygen in GaN, where the presence of surface oxygen may encourage the incorporation of magnesium. This would be especially true if oxygen and magnesium had surfactant and anti-surfactant roles, respectively.

Summary

Chris Van de Walle summed up the meeting in this fast evolving field as one which had successfully brought together groups having interests in different materials and experience with different techniques of

doping. It will be judged successful if the methods used in one area are used in others. Certainly, co-doping should be tried in silicon carbide and theorists encouraged to analyze the difficult problems of dopant incorporation and surface effects. These obstacles will need to be overcome in the drive towards nanostructures built from wide bandgap materials.

Further information about this research can be found in the conference proceedings, which will be published by Institute of Physics Publishing in a special issue of *Journal of Physics: Condensed Matter*. The conference Web site at <http://widegap2001.ex.ac.uk> features a full list of abstracts and some three-dimensional interactive graphics of atomic structures of defects similar to that shown in figure 2.

Caspar J Fall and Robert Jones are with the School of Physics at the University of Exeter in the UK.

Tel: +44 (0)1392 264 198;

e-mail: widegap2001@excc.ex.ac.uk.



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Compound Semiconductor Manufacturing Expo

July 9–11, 2001
Boston, Massachusetts



The inaugural Compound Semiconductor Manufacturing Expo (CS-MAX) will be held at the Hynes Convention Center in Boston, Massachusetts, on July 9–11, 2001. The purpose of CS-MAX is to discuss large-volume manufacturing of all types of compound semiconductor devices.

The timing of the CS-MAX conference could not be better. Shipments of compound semiconductor devices have doubled in the last two years (reaching \$18 billion), and they are predicted to double again by 2003. Compound semiconductors are the fastest growing segment of the semiconductor industry, and they play enabling roles in many of the world's most strategically important technologies.

As a necessary consequence of this growth, the compound semiconductor

industry is transforming itself by emphasizing high-volume manufacturing techniques. A new base of common knowledge and a new infrastructure are needed to support these efforts.

CS-MAX is the first conference that attempts to bring together the three major device types that are currently in large-volume production – transistors/integrated circuits, laser diodes and fiber-optic components, and LEDs – as well as today's most commercially important materials systems: GaAs, InP, GaN and SiC.

The technical program

The technical program, which is described in detail on the following pages, consists of 100 papers discussing the manufacturing of compound semiconductor devices.

The exhibit

The exhibit is an important component of the CS-MAX event, providing a showcase for new ideas about how to increase the productivity of compound semiconductor fabs. Nearly 100 companies are expected to participate. The list includes every major manufacturer of compound semiconductor-related materials and processing equipment. Special, deeply discounted registrations are available for attendees who are interested solely in visiting the exhibit hall.

The courses

The educational opportunities at CS-MAX include major multi-presenter workshops and targeted single-presenter tutorials, as well as free seminars conducted by leading suppliers to the industry. A complete list is given in the box below.

CS-MAX short courses

Monday July 9

08.30–13.00

Plasma processing of III–V microelectronic devices

Instructor: Stella Pang,
University of Michigan
Registration fee: \$150

09.00–13.00

Introduction to fabrication and packaging of laser diodes and VCSELs

Instructor: Kurt Linden, Axcel Photonics
Registration fee: \$150

14.00–17.00

Application of manufacturing software to fiber-optic component manufacturing

Presented by Datasweep
Free seminar

Tuesday July 10

08.30–12.30

Exhaust gas management for compound semiconductor epitaxy and device processing

Presented by BOC Edwards
Free seminar

09.00–13.00

CAD for compound semiconductor MMICs

Instructor: Wolfgang Bosch, Filtronic
Registration fee: \$150

14.00–17.00

Process and device simulation for compound semiconductors

Presented by Silvaco International
Free seminar

Wednesday July 11

08.30–15.00

Manufacturing indium phosphide ICs

Led by Owen Wu,
Global Communication Semiconductors
Registration fee: \$175

09.00–15.00

The roadmap for solid-state lighting

Led by Arpad Bergh, OIDA
Registration fee: \$175

Course descriptions are
available on the Web at

["www.cs-max.com/courses.htm"](http://www.cs-max.com/courses.htm)

For more information about CS-MAX, visit the conference Web site at ["www.cs-max.com"](http://www.cs-max.com).

CS-MAX PROGRAM

Track 1

Microelectronics
Chair: Alan Swanson
BAE Systems

Track 2

Fiber Optic Components
Chair: Mark Itzler &
Bedwyr Humphreys
MetroPhotonics

Track 3

LEDs
Chair: Steve Denbaars
Cree Lighting

Track 4

Characterization
Chair: Fred Pollack
CUNY

Track 5

Epitaxy
Chair: Rajaran Bhat
Corning

Monday July 9th

Plenary session:
GaAs IC Manufacturing
9.00–11.00

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Break

Processing and
Packaging I
11.15–12.30

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Foundry Services for
Epiwafer Requirements
11.15–12.30

Lunch 12.30–14.00

Processing and
Packaging II
14.00–15.40

—

Plenary session:
LED Manufacturing
14.00–16.00

Characterization
Techniques I
13.30–15.15

Epi Equipment I
14.00–15.15

Break

Processing and
Packaging III
16.00–17.40

—

Characterization and
packaging of LEDs
(joint session, Track 4)
16.15–17.55

Characterization and
packaging of LEDs
(joint session, Track 3)
16.15–17.55

Epi Equipment II
15.30–16.45

Reception in the Exhibit Hall 17.30–19.00

Tuesday July 10th

GaAs Fab
Management
9.00–10.40

Characterization and QC of
Optoelectronic Wafers
(joint session, Track 4)
9.00–10.40

Gas Purification Issues in
LED Manufacturing
(joint session, Track 5)
9.00–10.40

Characterization and QC
of Optoelectronic wafers
(joint session, Track 2)
9.00–10.40

Gas Purification Issues
in LED Manufacturing
(joint session, Track 3)
9.00–10.40

Break

Qualification and
Characterization of
IC Wafers
(joint session, Track 4)
11.00–12.40

Devices
11.00–12.40

Epitaxy for LEDs
(joint session, Track 5)
11.00–12.40

Qualification and
Characterization
of IC Wafers
(joint session, Track 1)
11.00–12.40

Epitaxy for LEDs
(joint session, Track 3)
11.00–12.40

Lunch 12.30–14.00

Growth of
Heterostructure Epiwafers
(joint session, Track 5)
14.00–15.40

New Tools for
Fiber Optic Component
Manufacturing
14.00–15.40

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Characterization
Techniques II
14.00–16.05

Growth of
Heterostructure Epiwafers
(joint session, Track 1)
14.00–15.40

Break

InP and
Metamorphic ICs
16.00–17.40

Plenary session: Fiber
Optic Component
Manufacturing
16.00–18.00

Reception in the Exhibit Hall 17.30–19.00

Wednesday July 11th

Plenary session: Fab
Management Principles
Applied to III-Vs
(joint session, Tracks 2 & 3)
9.00–10.40

Plenary session: Fab
Management Principles
Applied to III-Vs
(joint session, Tracks 1 & 3)
9.00–10.40

Plenary session: Fab
Management Principles
Applied to III-Vs
(joint session, Tracks 1 & 2)
9.00–10.40

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Gas Management
Issues
9.00–10.40

Break

Plenary session:
Technologies for
Manufacturing III-Vs
(joint session, Tracks 2 & 3)
11.00–12.40

Plenary session:
Technologies for
Manufacturing III-Vs
(joint session, Tracks 1 & 3)
11.00–12.40

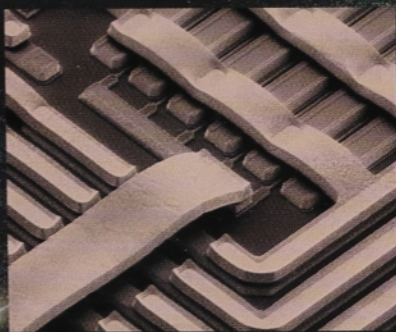
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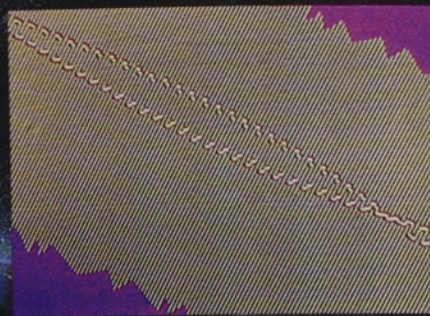
Metalorganics
for MOCVD
11.00–12.15

Lunch 12.30–14.00

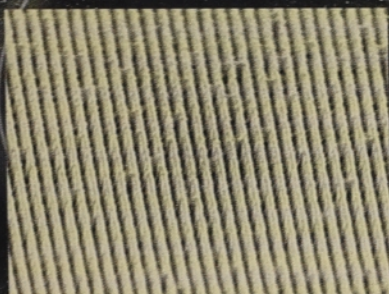
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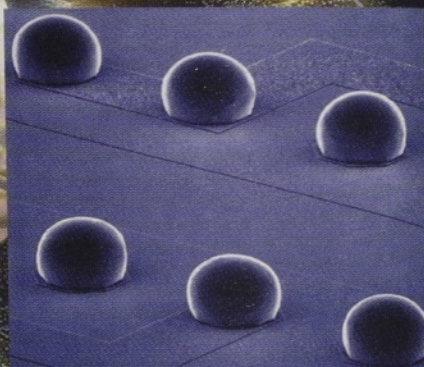
Air bridge on high speed GaAs device, courtesy of M/A-COM



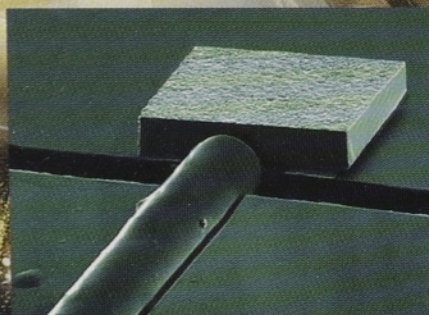
Saw filter, courtesy of AME Space



DFB Grating



Wafer bumping, courtesy of IZM/TU Berlin



Laser diode

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Monday July 9th 09.00–11.00

Track 1 – Microelectronics

Plenary Session on GaAs IC Manufacturing

Chair: Alan Swanson, BAE Systems

Monday 09.00–11.00

09.00 Mainstream Manufacturing: GaAs IC Production in a 6 Inch Fab

Patrick H Jenkins

Vitesse Semiconductor Corporation

As the first IC manufacturing site in the world using 6 inch GaAs substrates in production, Vitesse's Fab 2 in Colorado Springs has a wealth of experience in volume production using large diameter compound semiconductor substrates. A review of the critical performance indicators demonstrates the advantage of internal manufacturing capabilities for core technologies. The capabilities of the GaAs MESFET technology support continuing product performance improvements in components for optical networks. The future outlook for Fab 2 calls for performance improvements in GaAs MESFETs and a look at InP as it scales into volume manufacturing.

09.30 The Fabless RF Component Model: Strategies and Tactics

Robert Van Buskirk

Stanford Microdevices, Inc

This presentation will begin with a brief company description and follow with an overview of the fabless operating model employed by Stanford Microdevices (SMDI). This operating model overview will describe for the audience the company's product portfolio, process technologies currently in production, as well as in R&D, and the company's packaging and testing operations supporting the fabless model.

A discussion of the evolution of the fabless operating model will follow along with a discussion of the financial and strategic benefits of this operating model.

The final part of the presentation will feature a discussion of the key strategies and tactics required for successful fabless model execution. This section will also cover relevant lessons learned over years of successful utilization of this highly flexible and efficient operating model.

Questions from the audience will be encouraged.

10.00 From 6 inch Silicon to 6 inch GaAs with a High Productivity, High Yield Approach

Richard Kerrigan

Filtronic Compound Semiconductors Ltd

The presentation outlines the process of converting the former Fujitsu Newton Aycliffe silicon DRAM Fab to 6 inch GaAs while still endeavouring to maintain the high productivity, high yield approach and systems well established in silicon manufacturing.

There were several main areas of the project, all designed to meet the requirements of the original business plan, which called for the creation of a Fab capable of running 30k wafers per annum.

The various areas that will be covered are:

- Defining an equipment set

- Designing the layout of the Fab
- Obtaining the equipment set
- Recruitment
- Training
- Process start-up
- IT systems
- Cost awareness

This presentation will detail the advancement and progress of the project.

10.30 The Foundry Model: a Winning GaAs Manufacturing Solution

Peter Cheang

WIN Semiconductors Corp

In addition to the exponentially growing cellular handset market, more consumer and commercial applications find their dependency on GaAs technologies to meeting product performance needs. As a result, the GaAs semiconductor industry has witnessed an explosive growth in the past few years. Many integrated device manufacturers are looking for reliable partners for second source, while fabless design houses are looking for dedicated foundry partners. In response to the market demand for low cost, high quality GaAs wafer manufacturing solutions, WIN Semiconductors established a pure-play 6 inch GaAs MMIC foundry business in Taiwan.

In this paper, we shall discuss the dynamics of the market situation, the driving force for foundry service demand, the advantages of 6 inch foundry service and the technologies available in Taiwan.

CS-MAX organizing committee

Marie Meyer, founder and managing editor, *Compound Semiconductor* magazine, Beverly, MA
Alan Swanson, director, Microwave Electronics Group, BAE Systems, Information & Electronic Warfare Systems, Nashua, NH

Mark Itzler, VP and chief technical officer, JDS Uniphase Epitaxx, West Trenton, NJ

Bedwyr Humphreys, director of process development, MetroPhotonics, Ottawa, Ontario

Steve Denbaars, professor, UCSB, and technical advisory board, Cree Lighting, Goleta, CA

Freed Pollack, professor, Brooklyn College, CUNY, New York, NY

Rajaran Bhat, research fellow, Corning Inc, Corning, NY

CS-MAX is organized by *Compound Semiconductor* and Institute of Physics Publishing

Monday July 9th 11.00–13.00

Track 1 – Microelectronics

Processing & Packaging I Chair: Kim Conway, Alpha Industries Monday 11.15–12.30

11.15 Unified Process Technology Based on the Dummy Gate for Optical and Wireless Communication Devices

Shigeru Nakajima and Yoshihiro Saito
Sumitomo Electric Industries Ltd

We have developed a dummy gate process, which we call a single resist-layered dummy gate (SRD) process, for LDD structure MESFETs. The features of the SRD process are (1) superior device characteristics, (2) high uniformity of device characteristics across the wafer and from wafer to wafer, (3) realization of 0.2 μm gate by using optical lithography, and (4) precise control of the gate length by in-line SEM measurement.

High speed ion-implanted MESFETs with a self-aligned LDD structure have been produced for optical communications. The 4 inch diameter vertical boat (VB) grown semi-insulating substrates are used for taking into account the development of a 6 inch diameter line in the near future.

High power and low distortion MESFETs with asymmetric LDD structures also have been produced for wireless communication.

11.40 Enhancement-mode PHEMT Processing Technology for High Efficiency Power Amplifiers for Wireless Communications

Gene Tkachenko, T H Kao, J B Lee, J Gering, C Wei and D Bartle
Alpha Industries

Enhancement-mode PHEMT (E-PHEMT) process technology will be presented. This technology is based on double selective dry etching, 0.5 μm T-shaped gate, low temperature PECVD SiN passivation and epitaxial structure optimized by physics-based simulations. This process is fully compatible with Alpha's established high volume and low cost D-PHEMT process.

In addition to the single supply operation, this technology features high amplifier efficiency, especially at low voltages and ability to integrate PA with a switch, LNA, attenuator on one chip without sacrificing individual chip performance, for a complete front-end solution. Device performance highlights include $I_{\text{dss}} = 10 \text{ mA/mm}$, $I_{\text{max}} = 380 \text{ mA/mm}$, $G_m = 500 \text{ mS/mm}$ and $V_{\text{bd}} > 15 \text{ V}$. Excellent parameter uniformity across the wafer is achieved due to the fully selective nature of the process.

A typical 4 mm E-PHEMT on-wafer loadpull characteristics demonstrate excellent output power density and power-added efficiency: 220 mW/mm with associated PAE = 65%, when matched for P_{out} and 150 mW/mm with PAE = 76%, when matched for PAE at 3.2 V and 900 MHz. Power-added efficiency above 70% is preserved even when the operating voltage is dropped to 1 V, which favors E-PHEMT over an HBT. An E-PHEMT single-supply GSM power amplifier with an integrated VVA delivered 35

dBm with PAE of 55% and gain of 30 dB at 3.2 V.

12.05 Using X-ray Lithography in GaAs IC Fabrication

Don Bailey, Bob Selzer, Ken Mason
SAL, Inc

Richard Foster, Richard Forber
JMAR Research, Inc

Proximity X-ray Lithography has been proven as a capable means of manufacturing semiconductor circuits with sub-100 nm critical features. Early systems, utilizing the "compact ring" synchrotron as the light source, were viewed as overly complex and expensive. This perception has inhibited any widespread acceptance of this technology. This paper explores the X-ray Point Source system and its application in the production GaAs IC devices.

The ongoing evolution of projection optical lithography from DUV to EUV technologies, and its inevitable march toward shorter and shorter wavelengths, continues to converge on the X-ray node of the spectrum. (248 nm $\Rightarrow$ 193 nm $\Rightarrow$ 157 nm $\Rightarrow$ ~14 nm $\Rightarrow$ 1 nm). Over a decade of experience and development has resulted in the successful integration of all the technology components: X-ray source, stepper, resists and defect-free masks. X-ray Lithography has gone beyond the "feasibility" stage of the other NGL tool approaches, and has been proven to work. It is a production ready technology.

A fully integrated X-ray lithography system, utilizing point source X-radiation, provides a platform for both production and R&D demands. A system such as this has been operational at BAE Systems in Nashua, NH for over a year.

This paper will present results from the point source X-ray system installed at BAE Systems, and describe the newer Laser Plasma X-ray point source system and its capabilities.

Exhibit hours

Monday July 9	10.30–19.30
Tuesday July 10	09.00–19.00
Wednesday July 11	09.00–14.00

Track 5 – Epitaxy

Foundry Services for Epiwafer Requirements

Chair: Raj Bhat, Corning

Monday 11.15–12.30

11.15 Networking Systems to Facilitate Statistical Process Optimisation in a Foundry Operation*E W Griffiths, H R Williams and A J Pearce
IQE (Europe) Ltd*

A system enabling statistical monitoring of III–V epitaxial growth processes is described. The role played by statistical methods in optimising any industrial/technological process with its consequent beneficial effect on profit is discussed briefly, and the difficulties of establishing a “traditional” SPC system in an outsourcing plant, such as IQE, are highlighted. The paper also deals with the architecture of the networked system in the context of company specific constraints. The consequence of IQE’s somewhat unique position as a pure outsourcing foundry, more traditional SPC techniques will only partially address the problems faced by a company dealing with an unusually varied product list.

The paper describes a more holistic approach to SPC, where data from reactors is directly related to characterisation data. This approach allows for a more fundamental understanding of the process. Once the essential input/output parameters are elucidated, a real-time SPC feedback loop may be initiated in order to affect reactor responses according to pre-determined relationships

In recent years, the demand of high precision, uniformity, and consistency epitaxial wafers for both Microelectronics and Optoelectronics has been rapidly increased due to (1) The advancement of epitaxial technologies (e.g. MOCVD & MBE). More difficult structures like heterojunction requires abrupt interfaces and complicated structures like DBR requires rapid variation of composition and layer thickness with extremely high precision control, which can not be handled by the traditional epi technology (e.g. LPE). (2) The availability of commercial large scale reactors or systems (3) Higher device and circuit performance requirements, like higher frequency, speed, bandwidth, sensitivities, and other optical properties, which can not be satisfied with traditional non-epi substrate materials and technologies (e.g. Diffusion or Ion-Implantation).

More and more professional epi houses have been started worldwide in the past 10 years, especially in the last 2 years. However most of the companies started with their epi technology without having the high volume manufacturing experience. To demonstrate small quantity of high quality epi materials simply can not guarantee the capability of producing thousands and thousands wafers with both quality and consistency. In this conference, an experience of establishing a successful mass production capability in VPEC will be presented.

11.40 Establishment of High Volume III–V Epi Manufacturing Capabilities in Taiwan*Michael H T Yang, Jim J S Liu, James C H Huang, Grace M F Huang
Visual Photonics Epitaxy Co. Ltd***12.05 High Volume and Flexibility in an MOVPE Foundry***J H Ermer, J M Lacey and M Haddad
Spectrolab, Inc*
Abstract not available.

Monday July 9th 14.00–16.00

Track 1 – Microelectronics

Processing & Packaging II

Chair: Fabian Radulescu, TriQuint Semiconductor

Monday 14.00–15.40

14.00 GaAs Etch Problems under High Volume Production Conditions*Jiang Wang, Sam Momy, Nercy Ebrahimi
Conexant Systems Inc*

In the last two years, during Conexant’s steep production ramp, some etch issues were observed that were not apparent during low volume production. In the wet etch processes, base pedestal (BP), emitter mesa (EM), and collector contact (CC), mouse-bites, protrusions and undercut were detected. These problems occurred intermittently. A series of SEM inspections revealed that EM etch blocking was caused by partial dissolution and flow of photo resist during the wet etch. CC gross undercut

was a result of poor photo resist adhesion. BP mouse-bites and protrusions were caused by resist adhesion and residues left from previous step. Addition of some key process steps resulted in the complete elimination of these issues and significant defect reduction and improvement in yield.

14.25 Reduction of Manufacturable Plated Linewidth in GaAs MMICs by Modification of Base Metal Process*L K Hanes, D LeBlanc, C Shepard, C Carpenter,
J Haanpaa, T Hand, W Kopp, and J Walling
Alpha Industries, Inc*

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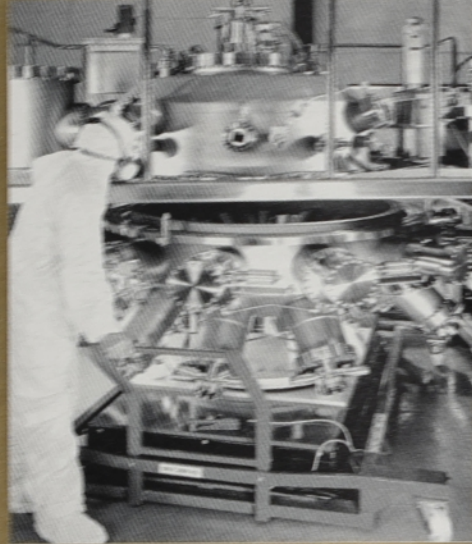
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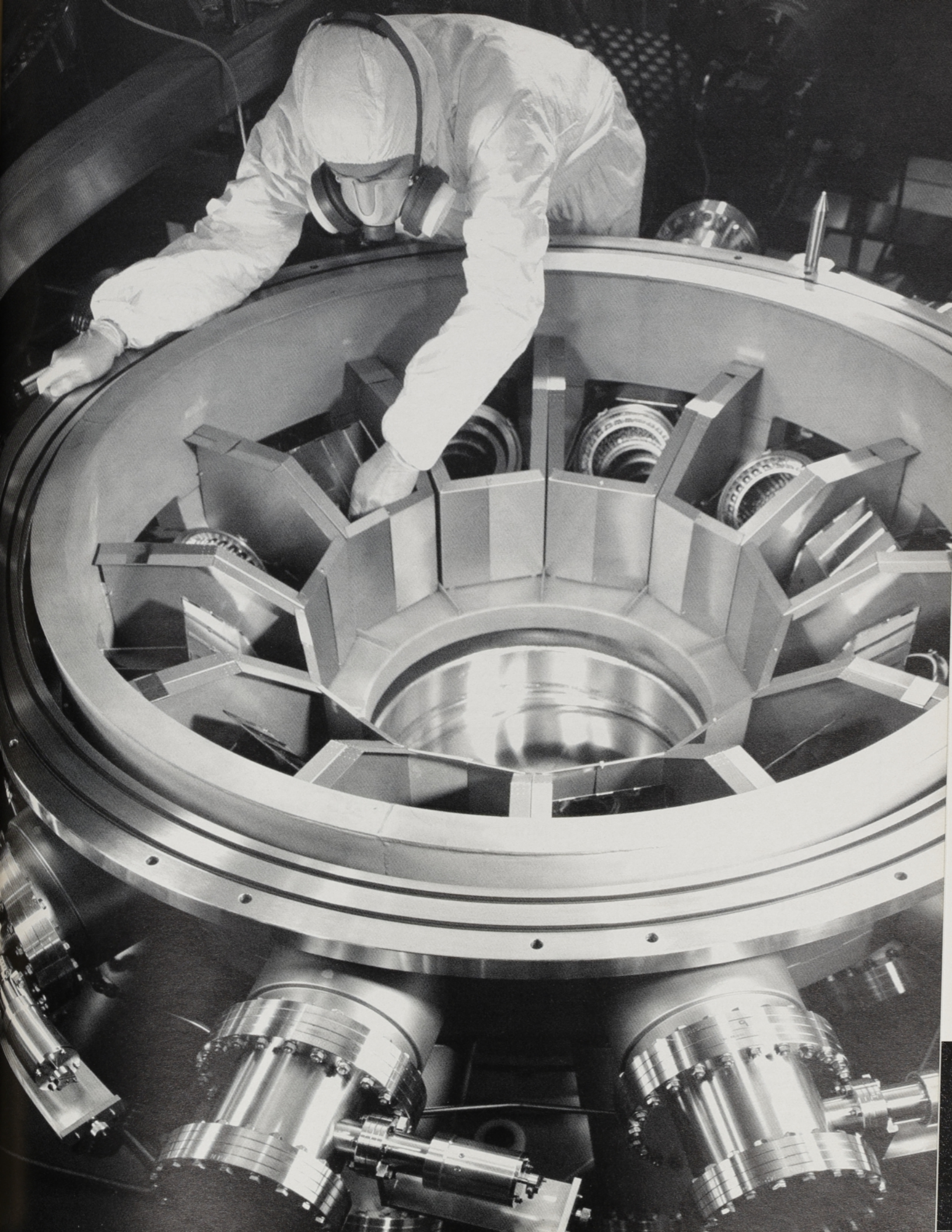


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dimensions on GaAs MMICs continue to shrink in order to pack more die onto each wafer, thereby reducing chip cost. As a result established processes may reach their limits, requiring a replacement process with greater capability and latitude. While this effect is well known in photo-lithography it can also extend into other process areas and determine the choice of materials and etchants.

The baseline process at Alpha Industries, like most GaAs processes, utilizes a plated metal for the final frontside metal for the formation of transmission lines, bondpads, contacts to active devices, and capacitor top plates. In this paper we will describe our efforts to aggressively reduce plated FET contact dimensions by 50% and the resulting problems that were uncovered in the post-plating etchback of the base metal.

14.50 High Performance, High Productivity Interconnect by Sputtered Metal and Dry Carbon Dioxide Lift-off Techniques

David Butler

Trikon Technologies

Peter Graham, Marjorie Burtch

Eco-Snow

In traditional III-V manufacture, interconnect formation normally uses evaporated metal deposited over patterned resist. The bulk of resist and metal is then removed by wet solvent stripping, sometimes followed by a water based mechanical scrub to clear residual metal. While satisfactory for small-scale output, there are a number of issues that make such approaches unattractive for volume production, such as wafer breakage and high labour costs of evaporators. Further, in terms of device performance, the water based scrub step can cause corrosion issues, leading to device degradation.

This paper reports on work aimed at developing a high performance, high productivity interconnect scheme. Two separate technologies were focused upon; the replacement

of evaporators with a highly automated, high throughput sputter cluster tool, and the use of a novel dry CO₂ snow clean to remove unwanted metal from over the photoresist, facilitating easy solvent removal of the resist.

The presentation will discuss the application of Si production techniques to III-V manufacturing lines. Results will be presented on the integration aspects of resist profiling, sputter deposition and dry CO₂ metal removal.

15.15 Production Plasma Etch Process Solutions for GaAs Integrated Circuit Fabrication

L G Jerde, Y K Cho, M Rousey-Seidel and P F Werbaneth
Tegal Corporation

Plasma etch process applications for production gallium arsenide integrated circuit fabrication range from relatively straight-forward, non-critical etches to very demanding, critical etches. These substantial differences in requirements lead to the selection of very different plasma etch systems in order to develop and realize optimized, cost-effective process solutions for these applications. Photoresist descum and PECVD nitride etch, for example, are fairly simple, non-critical etch applications that are usually best performed in a relatively simple and inexpensive, non-load-locked single wafer etch tool.

GaAs backside via and front side mesa, however, are critical etch applications that have fairly demanding requirements. Sophisticated processes that utilize toxic gas chemistries are needed to meet these requirements. These processes, in turn, require the use of sophisticated, load-locked etch systems. We have developed etch tools and processes to meet the production requirements for each of these plasma etch applications. In this paper we discuss the production etch requirements, process development considerations and etch system selection criteria for each application. The process results that have resulted from this work will also be presented for these applications.

Track 3 – LEDs

Plenary Session on LED Manufacturing Chair: Steve Denbaars, UC Santa Barbara Monday 14.00–16.00

14.00 Manufacturing InGaN LEDs

Kiyoshi Komatsu

Nichia Corporation

Nichia is recognized as the world leader in InGaN LED and laser diode technology. In 1993 and 1994, Nichia developed the world's first high brightness InGaN blue and green LEDs. In 1995, Nichia demonstrated the world's first InGaN violet laser diode operating in pulsed operation at room temperature. In 1996, Nichia developed a white LED by covering an InGaN blue LED with phosphor (thereby mixing blue light and down-converted yellow light to create white light). In 1998, Nichia developed the world's first InGaN yellow LED. And in 1999, Nichia began commercial sales of InGaN violet and blue laser diodes.

In this session, Nichia presents the history of InGaN LEDs, current LED products line-up and prospect of the future InGaN LED market.

14.30 Design and Manufacturing of AlInGaN-based High Brightness LEDs

Heng Liu, William So, Xian An Cao

AXT, Inc

AlInGaN-based high brightness LEDs are becoming more and more important due to the availability of color blue and green offered by this material system. Although the bandgap of this material system covers basically from deep UV to the whole visible spectrum, the useful range at this moment is 380–540 nm. In the last few years, there has been huge investment being made in building up the manufacturing of these devices.

However, compared to many other existing LED technologies such as LPE, VPE of GaP-based LEDs as well as MOCVD of AlInGaP-based LEDs, the cost to make blue and green LED is much higher. Many issues need to be addressed before a cost effective manufacturing can be achieved.



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n-type : Te or undoped

p-type : Ge doped

Polycrystalline ingots, slices or granules

✓ Gallium Antimonide

n-type : Te doped

p-type : Zn or undoped

Polycrystalline ingots, slices or granules

✓ Indium Arsenide

n-type : S or undoped

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In this presentation, we will show experimental data demonstrating the challenges of current manufacturing process for AlInGaN-based LED. Also, we will present some design rules in all fabrication steps to optimize LED performance.

15.00 The Production of New Generation AlGaInP High Brightness LED

*Jen-Chau Wu, Holin Chiang, C S Chiang,
S W Chu, H T La*

United Epitaxy Company, Ltd

New generation AlGaInP LED, with 2 to 4 times intensity brighter than the current product, has been produced in UEC. This paper will focus on the aspects of the major manufacture breakthroughs, including structure growth, chip process and testing, that bring the new devices into production. The device performance and the reliability evaluation results are also discussed to meet requirements of the emerging markets.

15.30 LED Manufacturing in Taiwan

Jlm Y Chi and Ming-ying Hsieh
Industrial Technology Research Institute

In the last five years, the LED industry in Taiwan has grown rapidly and attracted large investments from the Taiwanese Government and private sector. Many startup companies are formed in all areas of LED manufacturing from epitaxy and wafer fabrication to packaging and assembly. At the present time, more than 20 companies in Taiwan are devoted to the epitaxial growth and wafer fabrication and more than 30 companies to the packaging and assembly. The revenue generated by these companies has also grown from 24 billion NTD (~\$800M) in 1999 to 30 billion NTD in 2000 with a growth rate of 25%. A large portion of this revenue is from exporting to the world markets. For the current year, the growth is estimated to be about 13% with the annual revenue growing to 33 billion NTD, taking into account the anticipated worldwide economic downturn currently in progress.

Track 4 – Characterization

Characterization Techniques I Chair: Fred Pollak, Brooklyn College Monday 13.30–15.15

13.30 Trends in Characterization of III–V Materials and Devices

I D Calder

Nortel Networks Optical Components

As the compound semiconductor industry moves from small scale fabrication of specialty devices to large scale volume production, materials characterization must keep up with this trend. At the same time, there is an intrinsically greater probability of material, process, and structural variations in III–V device fabrication than in the silicon industry. As a consequence, the industry needs a large toolkit of analytical techniques, available throughout the production process, in order to maintain control over processing and performance.

This comprehensive approach requires the characterization of:

1. Crystal structure and orientation, defectivity, and resistivity of bare wafers;
2. Epitaxial layer structure, composition, doping, impurities, strain, defectivity, and surface morphology;
3. Process issues, including device and metallization structure, defectivity, and contamination;
4. Root cause of device degradation and failure.

The range of analytical techniques required to satisfy these needs will be described, then the focus of the talk will turn to current and future trends in analysis. The most important of these trends exhibit increased requirements for:

1. Wafer mapping, especially with high spatial resolution;
2. Scanning probe (AFM based) techniques;
3. Site specific analysis of devices and device structures;
4. Multivariate computer simulations, especially of spectral measurements;
5. Improved standardization and calibration of measurements.
6. In line and in situ process characterization.

The challenge of the next few years will be to integrate

new techniques and new equipment into the process flow while providing increased measurement reliability, low cost, and rapid turnaround.

14.00 X-ray Diffraction for QC: Finding the Best Technique

P LaPuma, R Eisenhower, U Preckwinkel
Bruker-AXS

Among the many methods available for performing quality-control measurements, X-ray diffraction is one of the most time-honored. Nonetheless, continuing improvements in X-ray sources, optics, and measurement techniques are being made. In particular, improvements in high-resolution (i.e. low beam divergence together with high beam monochromaticity) and texture X-ray methods have enabled the technique to become an increasingly convenient and powerful tool in the analysis of compound semiconductors. Our presentation will not only focus on the latest technical developments, such as improvements in X-ray optics that greatly speed up measurement times, but will also be tutorial in nature, helping to guide the industrial user through the many X-ray measurement techniques available. In particular, the material parameters that will be addressed include atomic composition and uniformity, degree of crystalline perfection or amorphousness, layer thicknesses and roughnesses, strain, relaxation, and lattice mismatch. Particular technical highlights will include measurement automation, beam compressors, and mapping of patterned wafers.

14.25 Broadband Spectrophotometry Brings Integrated Metrology onto the Fab Floor

Rebecca Mirsky
Al Shugart International
Rahim Forouhi
N & K Inc



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To date, compound semiconductor manufacturers have faced significant barriers to integrating conventional metrology instruments into processing tools. While conventional integrated metrology methods that use reflection spectrometry and ellipsometry have been effective in a very focused R&D environment, the criteria for effectiveness in the manufacturing environment are very different. For example, a viable metrology system suitable for integration into manufacturing must be cost effective, adaptable, compact, easy to use, and robust. Furthermore, it must be easy to maintain and readily configurable for various process settings, and capable of accurate and reliable measurements over the full range of material types and film thicknesses. Finally, the physical model applied to the measurement data must be valid, especially if the substrate is rough, or the film stack is multilayer, ultra thin, or when the interface between layers is not smooth.

Broadband spectrophotometry is a materials characterization method that is capable of combining R&D-level precision and fabrication line practicality. We will present data that demonstrate that this technology, when used in conjunction with a valid physical model,

produces accurate, precise, reproducible results for optical properties and film thicknesses for virtually any combination of thin films, substrates and structures.

14.50 Defining the System Requirements of a Photoluminescence and Reflectance Mapping System

Clive Meaton

Accent Optical Technologies

As the volumes of compound semiconductor wafers increases wafer yield becomes ever more important. The ability to carry out non-destructive assessment quickly on whole wafers to map the morphological, structural, electrical and optical properties is critical for the profitable manufacturing of semiconductor wafers. In recent years there have been significant developments in the sophistication of optical assessment tools used for production. Fully automated tools are now available which can load wafers from cassettes and map the reflectance response or the photoluminescence response of a 6-inch wafer in a matter of a few minutes. In this paper the functionality of a high-speed photoluminescence/reflectance mapping system is described.

Track 5 – Epitaxy

Epi Equipment I

Chair: Allan Hanson, M/A-COM

Monday 14.00–15.15

14.00 Productivity for Epi Manufacturing – Equipment and Support

Bernd Schulte

Aixtron AG

In the last 15 years, Compound Semiconductors have been successfully transferred from research to mass production scale. Nowadays, we can find products based on compound semiconductors in our everyday live such as UHB-LED lighting applications, laser diodes for optical storage or fiber communications, and transistors for high frequency wireless communication. That increasing need for compound semiconductor devices together with the pressure to continuously reduce the costs per device, enhance the development of MOCVD equipment with higher productivity. The productivity of a MOCVD tool is primarily driven by the capacity of wafers per run, the uniformity of the wafers, the number of runs per day.

This presentation will address the development of new MOCVD equipment and supporting systems with increased productivity in mass production of compound semiconductors.

to mass production. We have commercialized MOCVD grade AsH_3 for laser manufacturing by reducing moisture in AsH_3 in the mid.-1980s, and developed Super-grade AsH_3 for HEMT by eliminating Si impurity in the early 90s. We have also developed S-grade and Ultra-luminous-grade PH_3 for AlInGaP laser or HB-LED, and S-grade NH_3 for GaN Blue LED in the mid.-1990s.

In our talk, I will present other details of our practices in the Japanese compound semiconductor industry.

14.50 Epi Layer Temperature Measurement and Control in Large Scale MOCVD Manufacturing

Jeff Bodycomb, Vadim Boguslavskiy, Mikhail Belousov, Jeff Ramer, and Richard Hoffman

Emcore

Epi layer temperature control is a vital requirement for growing reproducible structures. Wafer temperatures can vary significantly from those measured by close proximity thermocouples (TC) or optical pyrometers. The insulating layers (low pressure gas, susceptor, and wafer carrier) between the thermocouple and the wafer leads to measurement errors, particularly when the environment of the chamber changes such as during gas switching. Optical pyrometers will measure the combined wafer carrier and wafer temperature and be affected by deposits on the wafer carrier. Emcore recently developed emissivity compensated pyrometer known as RealTemp for use in multiwafer, rotating disk reactors which provides accurate measurement of the wafer surface temperature during growth. We can also use this more accurate temperature data to control wafer surface temperature and therefore structure.

14.25 Integrated MOCVD System Engineering and Fab Management

Koh Matsumoto

Nippon Sanso Corporation

Nippon Sanso Corporation is one company that has a total system, which includes MOCVD, Specialty Gases, Cylinder Cabinet, Abatement, Piping Construction, Safety Control Management and Fab Design.

We have developed an application specific technology for specialty gases, MOCVD and abatement systems through close cooperation with customers from R&D stage

Monday July 9th 16.00–18.00

Track 1 – Microelectronics

Processing & Packaging III
Chair: Lisa Aucoin, Raytheon
Monday 16.00–17.40

16.00 Pre- and Post-Metal Deposition Processes Associated with the Lift-off Process Layer

John Lamb

Karl Suss America

Telecom device fabrication is in transition from manual, small lot production to high-volume production. As GaAs (and other III–V) fabs move past the 1000 weekly-wafer-start threshold, cassette-to-cassette production is an economic necessity. Incompatibility between etchable metals (Al) and most III–V substrates positions lift-off metalization as a key process layer. This paper describes and compares known techniques for both pre- and post-metal deposition processes associated with the lift-off process layer.

Pre-metal deposition processes to generate retrograde profiles during lift-off: There are a number of accepted techniques to generate the retrograde resist profile necessary for lift-off. The paper illustrates and compares the wafer processing materials and processes in use today (resists, resist treatments, develop processes), and illustrates the pros and cons of competing methods with emphasis on volume production.

16.25 Back-side Processing of GaAs Wafers

Henry Hendriks, Jim Crites, and Bharat Patel

M/A-COM: Tyco Electronics

John Moore

General Chemical

Back-side processing of GaAs wafers includes all the manufacturing process steps from just after final front-side electrical test through die separation and packaging. The back-side process flow of a typical GaAs Fab can be separated into two major branches. The first branch is for GaAs die that do not require back-side via holes or metallization. The main process steps involved are wafer thinning, dicing, die inspecting, and packaging. The second branch is for die that require back-side metallization and in most cases through substrate via holes. This branch involves several additional process steps including wafer / carrier mount, back-side photoresist mask definition, via hole etch, photoresist strip, oxygen plasma clean, seed layer deposition, and electroplating.

This presentation will focus on several key backside process steps that have historically presented problems and review some of the recently available options that can be implemented to increase yield and throughput.

16.50 Assembly and Packaging of Gallium Arsenide Wafers

Gunasekaran Muthusamy and Christian Andrada

ST Assembly Test Services, Ltd

Gallium Arsenide (GaAs) is a semiconductor material that generates less heat at high frequencies. In the past, applications has been restricted to military due to high manufacturing cost resulting from poor and unpredictable

yield. Recent breakthrough in the wafer manufacturing process has made high volume commercial product viable with wafer sizes of up to 6 inches. Demand for GaAs products has soared with explosive growth in communication sector that demanded an ever-increasing performance. GaAs wafers are toxic and very brittle making it difficult to assemble due to risk of breakage and die cracking. This paper will discuss the special requirement needed to package GaAs wafers and the recent advancement in assembly processes that made it possible.

17.15 Determining Compound Semiconductor Component Reliability

Roland Shaw, Paul Friedman

Maxwell Technologies

New consumer, commercial, and aerospace wireless (RF) products require components that support high operating frequencies. To achieve this performance, products must utilize components and monolithic microwave integrated circuit (MMIC) devices made from compound semiconductors. The resultant devices must maintain a level of reliability mandated by the overall reliability of the end products into which they are designed.

In this paper, the disparity between reliability results obtained from a test system that employs only DC bias and one that applies real-world RF power will be discussed. In addition, this paper will describe the system used to produce the results of the RF reliability testing. This system exercises components with DC and RF signals under a highly controlled temperature environment, reduces operator involvement, and increases the flexibility of performing reliability testing for both R&D and manufacturing operations.

Reception in the Exhibit Hall

Monday and Tuesday

17.30–19.00

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Track 3 – LEDs

Track 4 – Characterization

Characterization and Packaging of LEDs

Chair: Jeff Krogen, Tecstar

Monday 16.15–17.55

16.15 Luminous Intensity and Colorimetry**Calibrations of LEDs at NIST***C Cameron Miller and Yoshi Ohno***National Institute of Standards and Technology**

Light Emitting Diodes (LEDs) are unique light sources and are very different from traditional lamps in terms of physical size, flux level, spectrum and spatial distribution. In this presentation, the first of two describing the efforts to develop standards for LED characterization at NIST, we will discuss calibrations for luminous intensity and colorimetry.

The transfer of photometric scales from luminous intensity standard lamps to LEDs are not trivial, and large discrepancies among companies have been reported. The CIE has established two standard measurement conditions, ILED A and ILED B for individual LEDs with diameters less than 10 mm. These standard measurement conditions do not use point source conditions and should provide better agreement in LED luminous intensity measurements.

The National Institute of Standards and Technology has established a capability for calibrating the luminous intensity of LEDs using the detector-based method. We have built a tentative measurement set up for LED measurements in the NIST photometric bench and made the calibration service available. A dedicated small photometric bench for LED measurements is to be built. The calibration service available for LED luminous intensity, has an overall uncertainty of 1.5% for LEDs with a special base, and 3 % for normal bare LEDs with no alignment aids.

16.40 Luminous Flux Calibrations of LEDs at NIST*C Cameron Miller and Yoshi Ohno***National Institute of Standards and Technology**

The luminous flux (lumen) is one of the most important characteristics of Light Emitting Diodes (LEDs), and is commonly measured using integrating sphere photometers. Large variations of measurement results are reported among different manufacturers and users of LEDs. There are issues such as the LED mounting geometry (4pi, 2pi), treatment of backward emission, the best integrating sphere geometries, etc. While these issues are to be resolved, there is an urgent need for standard LEDs in order to certify measurement accuracy in industrial laboratories.

In this presentation, the second of two describing the efforts to develop standards for LED characterization at NIST, we will discuss measurement procedures developed at NIST to to calibrate total luminous flux of LEDs using the existing NIST 2.5 m integrating sphere.

17.05 LED Metrology: How is the Optical Characterization of LEDs Tied in from the Wafer Test to the Packaged LED to the QC lab to User's Incoming Inspection?*Tim Moggridge***Instrument Systems**

LED manufacturers who are targeting high value markets such as cell phone displays, automotive displays, LED indoor and outdoor displays and more recently illumination applications will know that clients want consistent and uniform product. Many of these installations in aesthetic electronic products are constrained by the application to have a narrow acceptable range for chromaticity and intensity.

This paper discusses the metrology and the associated photometric and colorimetric quantities that must be tracked from wafer test through end-customer acceptance test. Techniques employing good LED measurement metrology throughout a company's process and throughout the industry will improve quality and enhance harmony between clients and suppliers.

17.30 Packaged LEDs Finishing at High Speed*Remy Degen and Yves Pelletier***Ismecca Europe SA***Michael Hoss***Instrument Systems GmbH**

As more and more LEDs being shipped are packed in embossed carrier tapes, it was logical for the worldwide largest tape and reel manufacturer to develop handlers dedicated to these products.

As with every market where high volume of devices have to pass through several operations before being sent to the end-users, integrated process is one of the option allowing to reduce assembly cost.

During this presentation we will describe how it became possible to replace three or four stand alone machines with one automatic piece of equipment providing the LEDs test, marking, inspecting, grading and final packing.

Exhibit hours

Monday July 9	10.30–19.30
Tuesday July 10	09.00–19.00
Wednesday July 11	09.00–14.00

Track 5 – Epitaxy

Epi Equipment II

Chair: Peter Velling, Innovative Processing

Monday 15.30–16.45

**15.30 Enabling High Volume MBE Production:
A Roadmap for the Future***Michael F Levy***Riber**

This paper will present what we believe to be the key success factors needed to ensure the continued development of production MBE. Drawing upon over 20 years of experience in the manufacture of MBE systems, we will share our vision, as the market leader, of how the MBE systems supplier of the future will have to evolve to better serve the ever-changing compound semiconductor market.

The core of this paper will describe the roadmaps we have created for our systems, software, components and service offerings. The strategies behind our most recent investments will be discussed, with an emphasis on the development of our new application laboratories that address key strategic material systems. The status of our work-in-progress will be presented. The importance of being active in the research/development/production market segments will be highlighted with recent success stories from the field.

**15.55 A Review of the Production Aspects of MBE
Technology***Dave Narum***Applied Epi, Inc**

Numerous emerging devices based on novel material systems in the electronic and optoelectronic markets are moving into high-volume production. The presentation will examine MBE's critical role in the commercial success of these emerging devices. The paper will explain how MBE delivers the unmatched material quality, growth uniformity, dopant flexibility, reproducibility and interface abruptness these devices require. These MBE technical strengths, plus the economic advantages of new multi-wafer MBE systems, are responsible for numerous groups choosing MBE to grow these devices. A cost of ownership review will illustrate how today's higher-volume MBE systems – which feature 7 × 6 inch wafer configurations, higher-capacity sources for longer campaigns, and higher wafer yield – lower the cost of growing these devices with MBE.

**16.20 Dynamic Secondary Ion Mass Spectrometry
Used as a Process Monitoring and Troubleshooting
Tool for Compound Semiconductor Epitaxial
Growth***Temel H. Büyüklımanlı***Evans East**

Dynamic Secondary Ion Mass Spectrometry (SIMS) is a unique technique often used to investigate the elemental structure of solid materials with depth. It has the sensitivity to detect parts per billion concentrations as well as to quantify atomic percent level matrix compositions. Layers of several nanometers to micrometers thickness can be characterized using proper SIMS analytical protocols. This ability to resolve concentration and thickness (or depth)

ranges has made SIMS the routine technique for in depth chemical characterization for semiconductor materials. In a single analysis SIMS can determine most of the dopant and impurity concentrations and thicknesses of the individual layers grown.

SIMS analyses of HEMT samples require sufficient depth resolution (layer definition) to identify minute changes in the doping profiles of the grown epitaxial films. Separate high precision SIMS protocols have been developed to characterize layers that are usually much thinner than those found in a typical HBT structure. This resolving power of SIMS allows comparison of Si delta doped layers found in the HEMT samples to investigate possible sources of a transistor characteristics problem.

Proceedings

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Tuesday 10th 09.00–11.00

Track 1 – Microelectronics

GaAs Fab Management
Chair: Guoliang Zhou, Alpha Industries
Tuesday 09.00–10.40

9.00 Increasing Capacity Together With Reducing Cycle Time. A Look at Productivity Improvement Process at GaAs Wafer Fab

Wladyslaw Danielak, Lynn Weckwerth
Nortel Networks Ltd

Ariel Meyuhas, Noam Porat

Max International Engineering Group

Nortel HPOCS GaAs product line is in a growing market environment and its manufacturing facility was facing the challenge of keeping up with ever increasing demands. The Ottawa Ontario facility was in a stage where equipment and operational capabilities were the limit. As a result, the utilization of the manufacturing tools and the optimization of the resources were critical for meeting demands, achieving maximum capacity while reducing Fab cycle time and assuring on time delivery.

Key objective of Wafer Fab as a GaAs HBT provider, was ramping its capacity to 2X (bottleneck utilization at 80% or more) while reducing its cycle time to 4X, and minimizing additional equipment purchases through operational productivity improvement within a year's time.

To achieve this goal, it was decided to implement a structured improvement process. The results achieved demonstrate a measurable capacity increase together with reduced cycle time for the Nortel GaAs IC's Wafer Fab.

9.25 The Challenges and Benefits of Running a Dual Use GaAs Foundry

Lisa M. Aucoin

Raytheon RF Components

Most GaAs wafer fabrication facilities in existence today cater mainly to the commercial marketplace for applications ranging from discrete FETs to cellular telephone power amplifiers. As wafer volume and market driven price pressures increase, GaAs wafer manufacturing tends to follow the trend of the silicon industry: dedicated fabrication facilities for each process. This model allows the manufacturing operation to focus exclusively on the yields and cycle times of a single process in order to drive wafer cost down. For those foundries producing modest volumes and serving military and commercial customers, unique challenges to the silicon-like model exist. These issues include the optimization of the equipment capacity for multiple processes in order to maximize use of installed capital, measuring the overall yield health of the facility when running multiple processes each at differing levels of maturation and prioritization of wafers in the process line. Along with the challenges come some equally unique solutions around work in process flow (WIP), implementation of preventative maintenance programs and machine retooling and the measurement and reduction of cycle times. The continuous introduction of higher performance processes required for military applications is a significant benefit.

9.50 Manufacturing HBTs for Wireless and Broadband Applications

Wu-Jing Ho, Mike Sun, Juntao Hu, Chang-Hwang Hua, and Ding Day

Alpha Industries, Inc

Steve Sprinkle, Pat Reginella, Joe Gering, and Paul
Alpha Industries, Inc

HBT technology becomes a great enabler for the wireless and broadband communication markets due to its highly controllable device manufacturability with super performance for its linearity, efficiency, power capability, bandwidth and phase noise characteristics. The manufacturing of HBTs becomes increasingly cost-effective, based on the availability of high throughput epitaxial techniques and high volume production capability with high processing margins and relaxed dimension controls. At Alpha Industries a non-self-aligned InGaP HBT process technology has been developed and characterized in production for implementing the carbon-doped MOCVD InGaP HBT epitaxial structures. Issues important for manufacturing of HBTs and their prospects for applications are discussed.

10.15 Roles for Compound Semiconductors in the NEMI Technology Roadmaps

Herbert S. Bennett

National Institute of Standards and Technology

The National Electronics Manufacturing Initiative (NEMI) is an industry-led consortium with approximately 60 member institutions from industry, government, and academia. NEMI members identify the future needs of the North American electronics industry, reach a consensus on technology and infrastructure gaps, and then help eliminate key technical and business gaps. Technology roadmaps are essential for today's business models because as Avtar Oberai, a founding director of SEMATECH, stated in 1999 "No one is big enough to drive the totality of the infrastructure and pre-competitive investments on their own." Among the NEMI roadmaps, the RF Components Roadmap addresses the role of compound semiconductors in meeting the market drivers for low cost, hand held and mobile, cost/performance, and harsh environments products. In this talk, highlights from that roadmap will be given.

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The Technology of Choice for Compound Semiconductors

Track 2 – Fiber Optic Components

Track 4 – Characterization

Characterization and QC of Optoelectronic wafers
Chair: Fang Yang, Corning Lasertron
Tuesday 09.00–10.40

9.00 FTIR Characterization and Control of Compound Semiconductor Epi Layers

Peter Rosenthal, Peter R Solomon, Sylvie Bosch-Charpenay, Victor Yakovlev

MKS Instruments

The manufacturing of many Opto-Electronic components starts with the production of compound semiconductor epi layer stacks. The eventual component yield depends on maintaining accurate thickness and doping concentrations for each layer. To satisfy this need, a new Fourier Transform Infrared (FTIR) based metrology tool has been developed for non-destructive characterization of these layers. While FTIR has been used in semiconductor manufacturing, it has not been widely applied to compound semiconductor epi layer stacks because of: 1) the optical complexity of the film stacks, 2) sample-dependent stray light reflected internally from the sample backside, and 3) the lack of robust models of the variable optical constants of the layer materials. These limitations have been eliminated with recent advances that employ state-of-the-art FTIR reflection spectroscopy combined with advanced model-based analysis and the use of optics tailored for high accuracy front-surface-only measurements of thin films.

9.25 Non-Destructive, Non-Contact Optical Measurement of Majority Carrier Properties in Compound Semiconductors

J E Maslar, W S Hurst

National Institute of Standards and Technology

Transport of free carriers is central to the operation of all optoelectronic devices and critical for device fabrication is the measurement of carrier properties. Hall or capacitance-voltage measurements, traditionally used to obtain this information, are techniques requiring electrical contact. This precludes their use in situ during growth or processing and, typically, even their use on actual device layers. As an optical technique, Raman spectroscopy does not suffer from these limitations. However, a number of issues have limited the utilization of Raman spectroscopy. In order to evaluate the potential of Raman spectroscopy as a probe of majority carrier properties, these issues are being systematically addressed. The status of this investigation will be discussed, including in situ measurements at thermal chemical vapor deposition temperatures, measurements of buried layers in high electron mobility transistor structures, and development of new and sophisticated fitting procedures that uniquely utilize complex spectral models to incorporate both carrier and temperature dependent effects.

9.50 Materials Characterization for High Volume Compound Semiconductor Manufacturing

Patrick Van Lierde

Charles Evans & Associates

The requirements for high volume manufacturers present unique challenges to the materials characterization service

industry. The response time and data quality are both critical to allow producers to monitor their products efficiently. Secondary Ion Mass spectrometry has proven to be an excellent tool to meet these demands. High levels of precision can be maintained on a routine basis while keeping response time within a 24 hour window. This has proven to be extremely valuable by manufactures of LEDs, laser diodes and VCSELs.

10.15 Effects and Estimation of the Random Variation of the Epitaxial Layer Thickness in 850 nm VCSELs

Bong-Cheol Kim, Jeong-Hwan Son, Bum-Joon Kim

PROWTech Inc

Sung-Han Kim, Sang-Bae Kim

Ajou University

Vertical cavity surface-emitting lasers (VCSELs) rapidly become a dominant optical source in local area networks and optical interconnections after a long period of extensive research efforts. Advantages of the VCSELs making this rapid commercial success a reality include suitability for mass production, low cost, and superior performance. On the other hand, the VCSELs require high precision epitaxy technologies, because their performance critically depends on the details of the multi-layer structure. Moreover, with the advent of wavelength division multiplexing (WDM) technology also in 850 nm wavelength range, the wavelength accuracy of VCSELs becomes increasingly important. Our objective is to investigate the effects of the random epi-layer thickness variation, and to propose a simple method of estimating the degree of the thickness variation. Because the degree of the thickness variation determines the wavelength accuracy, threshold current distribution, uniformity, and production yield, the results of this study will be quite useful in estimating both the required precision and the ability of thickness control of the epitaxy technology for VCSELs.

Reception in the Exhibit Hall

Monday and Tuesday

17.30–19.00

Track 3 – LEDs

Track 5 – Epitaxy

Gas Purification Issues in LED Manufacturing
Chair: Christine Wang, MIT Lincoln Laboratory
Tuesday 9.00–10.40

9.00 Cost of Ownership Issues in Gas Purification*Eric Bretschneider***Uniroyal Optoelectronics**

In compound semiconductor growth, the choice of gas purification methods has traditionally been based solely on technology. Little attention has been paid to the operating cost associated with different gas purifiers. In order to compete in high volume markets, the operating cost and specifically the cost of ownership should be a crucial factor in selecting a gas purification method. Accordingly, a detailed study has been completed to compare the cost of ownership for a variety of gas purification methods at varying gas flow rates. Depending on the volume of gas being purified, the cost of ownership for different purification methods can vary widely. The impact of bulk compressed or liquid gas and point of use versus bulk purification on the cost of ownership will also be discussed.

9.25 Delivery of Liquefied Compressed Gas at High Vapor Flowrates*Jayne Cantu***Praxair Inc**

There is a growing need in semiconductor manufacturing to deliver specialty gases to the point-of-use at high flowrates (~500 slpm) that are not obtainable from conventional compressed gas storage vessels. Conventional compressed gas storage vessels (cylinders and ton containers) contain a liquefied gas under its own vapor pressure at ambient temperature. As the vapor is withdrawn from the vessel, the liquid evaporates at an equivalent rate. In the absence of external heat transfer to the vessel, this evaporation consumes energy from the remaining liquid and causes the liquid temperature to drop leading to a corresponding drop in the vapor pressure. Further vapor withdrawal eventually subcools the liquid and the flow of vapor stops.

Experiments were conducted to evaluate the feasibility of using conventional ton containers in conjunction with carefully controlled external heat sources to deliver high flowrates of ammonia. High vapor flowrates were obtained by using a simple heat source and controlling the surface temperature of the vessel. The flowrate was found to be a function of the temperature difference between the surface and the bulk ammonia in the container, as expected for pool boiling. This novel method and apparatus does not require the use of new or modified storage vessels and can deliver a large range of vapor flowrates from the conventional compressed gas storage vessels thus minimizing the capital investment required to obtain high vapor flowrates.

9.50 Bulk Specialty Gas Systems For Ammonia: Gas Phase Delivery vs. Liquid Phase Delivery

Belgin Yucelen, Robert Torres, Joseph Vininski, Hans Funke, Virginia Houlding

Matheson Tri-Gas

The compound semiconductor industry is requiring higher flow rates of ammonia with lower, more consistent impurity levels. This present trend has challenged gas suppliers to develop high flow delivery systems for ammonia. Bulk specialty gas systems (BSGS) that can deliver much higher flow rates are now beginning to replace the traditional cylinder delivery systems due to their lower cost of ownership, increased safety, product quality, and consistency. Currently, the most common gas delivery system requires the ammonia to be vaporized within the bulk container and delivered throughout the gas distribution system. This traditional gas phase delivery system has demonstrated many problems due to the inability to maintain flow for long periods of time. Additionally, the gas delivery system exhibits inconsistent impurity concentrations. A moisture spike has been observed and correlated at a flow rate range for a typical ammonia BSGS when delivered from the gas phase.

A newly developed liquid phase delivery system was designed and tested to obtain information on the moisture and temperature variations for ammonia.

Results from the gas and liquid phase delivery systems will be compared and the advantages of the newly developed system will be discussed.

10.15 Performance and Cost of Ownership Models for Nitrogen, Ammonia and Hydrogen in MOCVD Processing

Jeffrey Spiegelman and Dan Alvarez, Jr
Aeronex, Inc.

The authors will present data for purifier use with Nitrogen, Ammonia, and Hydrogen in MOCVD processing. Data presented will encompass results from studies between Aeronex and Dr. Steven Denbaars and Dr. Jim Speck from UCSB, Dr. Alan Bandy from Drexel University and work by Dr. Dan Alvarez from Aeronex. Performance data will examine ammonia and nitrogen purity for use with InGaN films. Cost of ownership models will examine significant differences between different catalytic, palladium cell, and getter technologies. Variables effecting cost of ownership include purchase price, operating costs, direct gas costs, reliability, safety, and hazardous wastes.

Exhibit hours

Monday July 9	10.30–19.30
Tuesday July 10	09.00–19.00
Wednesday July 11	09.00–14.00

Announcing Purification for MOCVD Production Tools

Aeronex Infinity Gas Purification Systems provide a continuous supply of pure gas at ambient temperature

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As the process moves from R&D to Production, demand increases for purified nitrogen, hydrogen, and ammonia. Previous purification technologies required halting the process to replace the purifier bed. Today's process engineers require a high flow of pure gas and continuous up-time to maximize return. To meet these challenges Aeronex has developed the Infinity GPS™, which delivers a continuous supply of ultra pure gas without interruption.

Performance

Aeronex purifier technology sets the standard for pure gas. The patented media removes contaminants such as moisture, oxygen, CO, CO₂, and hydrocarbons from gas or

liquid sources. This unique inorganic media operates at room temperature and handles high flows at very low pressure, a requirement for next generation MOCVD equipment.

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The Infinity accommodates different gas grades from either liquid or gas sources to significantly reduce

your total tool operating costs through reduced cylinder change-out and lower gas costs. The purifier is hydrocarbon free, removing the possibility of expensive tool repair or chamber clean-up from system upsets. The



result: reduced liability, lower operating costs, and increased product throughput.

Safety

Safety is a major concern at Aeronex. By enabling gas purification at ambient temperature and low pressure, safety is increased. The Infinity GPS regenerates in-situ, so technicians are no longer routinely exposed to process gas during purifier change-out.

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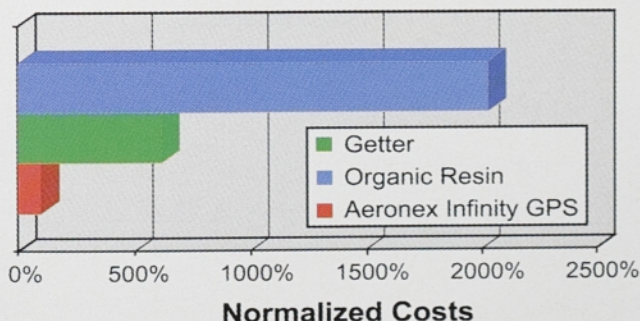
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Tuesday 10th 11.00–13.00

Track 1 – Microelectronics

Track 4 – Characterization

Qualification & Characterization of IC Wafers

Chair: Iain Calder, Nortel

Tuesday 11.00–12.40

11.00 Quantitative X-ray Analysis of GaAs- and InP-based HBT for Rapid In-production-line Material Qualification

Peter Velling

IPAG - Innovative Processing AG

The qualification of complex device layer sequences is a very important issue for process optimization and reproducible growth. A detailed analysis of complex device heterostructures is necessary for statistical process control but is often done by destructive techniques. Non-destructive X-ray characterization is an established technique enabling the determination of layer parameters in highest accuracy. However, a detailed quantitative X-ray analysis is usually only carried out for special test structures like superlattices. Usually X-ray diffraction analysis becomes qualitative or is thus reduced to a comparison of fingerprints for complex layer sequences. In fact explicit extraction of individual layer parameters like thickness and strain from X-ray scans is time consuming and often fails in total if a manual procedure is carried out. This work presents a quantitative analysis of complex device heterostructures by X-ray diffractometry using an automatic procedure for calculation of layer parameters. The applicability of the automatic X-ray analysis as a powerful tool for rapid quantitative material qualification will be discussed and the impact of this proposed technique on process control and cost reduction will be addressed.

11.25 Overview of Flatness Characterization as it Relates to Compound Semiconductor Lithography

James N Greene and Louie Denes

Corning Tropel Corporation

An overview of the optical issues associated with major photolithographic processes, including full field, stepper and scanner as they relate to compound semiconductor wafer flatness is discussed. Industry trends toward larger wafer diameters and higher device densities have adverse effects on lithographic image fidelity. Understanding how wafer flatness relates to both the lithographic process and the feature density requires consideration of these issues. This paper discusses wafer flatness measurement techniques and how they impact the lithography process. The most common measurement concepts in use today include capacitance, normal incidence interferometry, grazing incidence interferometry and air gauging. To match the best measurement concept to each compound semiconductor device family, one must compare the lithography issues to the benefits and limitations of each measurement concept.

11:50 Topographic Assessment of EL2 and Implantation Dose Homogeneity in Semi-Insulating GaAs Wafers

Peter Hiesinger, Stefan Mueller and Wolfgang Jantz

Fraunhofer Institut Angewandte Festkoerperphysik

High speed analog and digital circuits are fabricated on semi-insulating GaAs substrates. An important wafer quality requirement is the homogeneity of the bulk material parameters, foremost the electrical resistivity. It is determined by the concentration and the ionization degree of the intrinsic deep donor EL2. Characteristic near-infrared absorption bands are used to evaluate these quantities.

The EL2 Absorption Topography system IAF-EAT is a production control system for semi-insulating GaAs. It has been developed and constructed to meet the demanding specifications of leading producers of GaAs substrates. The computer controlled system is designed for routine production control measurements, but also supports the development of innovative fabrication processes.

12.15 Dynamic I(V) Behavior of Some Contemporary Semiconductor Devices

Peter Ladbrooke

Accent Optical Technologies

The dynamic I(V) characteristics of contemporary semiconductor devices can be very different from their static (or dc) characteristics. Such differences, which are known as "dispersion", arise from the different ways in which self-heating and deep levels (or traps) respond dynamically to fast signals compared with dc. Dynamic I(V) measurements show how devices ranging from PHEMTs and HBTs to lasers will behave in practical high-frequency circuit applications. Examples include negative differential conductivity in some PHEMTs, an inability to cut off some HBTs, non-diode-like gate current in compound semiconductor FETs and HEMTs, and separation of the individual contributions to dispersion from deep levels and self-heating.

Proceedings

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Track 2 – Fiber Optic Components

Devices

Chair: David Christensen, NIST

Tuesday 11.00–12.40

11.00 Volume Manufacturing of 1.3 μm AlGaInAs Lasers for Fiber Optic Communications*Chun Lei, Hongyu Deng***Finisar Corp**

High performance and low cost lasers are highly desirable for fiber optic communications. While 850 nm VCSEL can serve as a low cost light source for multi-mode and short distance links, long wavelength VCSEL still has much challenge ahead. In this talk, we report performance, reliability and manufacturability of 1.3 μm AlGaInAs edge emitting lasers for multi-mode and single-mode links. The performance of these lasers at OC48 and OC192 will also be discussed.

11.25 Fabrication of High Reliability 850 nm and 1310 nm PIN Photodiodes Operating up to 10 Gb/s*Mark Gottfried, Alex Ceruzzi, Steve Edwards, Steve Schwed, Xiang Gao, Peggy Hess, Paul Rotella, Jr***Emcore Corporation**

PIN photodiode arrays have become a key enabling component in broadband solutions for data communication and telecommunication systems. Their popularity comes from the devices' utility, as well as the PIN design being conducive to high volume manufacturing. The challenges for the PIN manufacturer include developing a quality based process that produces low cost, reliable diodes while offering customers a product they can easily integrate.

This paper will discuss the manufacturing of high reliability GaAs-based and InP-based PIN photodiode arrays. We have produced both 850 nm and 1310 nm PIN photodiode arrays operating up to 10 Gb/s with high yields that pass Telcordia 85 °C/ 85% relative humidity tests without hermetic packaging. In addition, we will show data comparing the following Zn-diffusion processes for InP-based planar photodiodes: sealed ampoule, spin-on-Zn dopant, and diffusion in an MOCVD reactor.

11.50 Technology and Telecommunication Applications of Indium Gallium Arsenide Photodiode Arrays*Marshall J Cohen***Sensors Unlimited, Inc**

Indium gallium arsenide (InGaAs) has long been the detector material of choice for telecommunications both in the form of PIN and avalanche photodiodes. Single-element InGaAs photodiodes are used in receivers, transceivers and transponders. More recently, InGaAs photodiode arrays have found wide use in building and monitoring optical networks. Linear photodiode arrays are used as spectroscopic detectors to monitor the integrity and performance of wavelength division multiplexing sources and erbium doped fiber amplifiers. Two-dimensional arrays are used to measure the beam profiles of laser diodes, to assemble and align optical components and to monitor the performance of optical cross-point matrices and add-drop multiplexers. In this presentation, we will summarize the status of InGaAs photodiode array technology and describe the range of telecommunications applications.

12.15 Challenges and Solutions for VCSEL Manufacturing*Geoffrey B Rosenthal; Bing Liang***AXT, Inc**

As VCSEL devices are adopted as the preferred laser technology for a greater number of data communication and sensing applications, there are ever increasing demands placed on VCSEL manufacturers to deliver high quality devices in high volumes. Numerous manufacturing hurdles must be overcome in order to meet or exceed the quality, reproducibility and reliability performance of VCSEL devices in a large scale manufacturing environment. The VCSEL Technologies division of AXT, Inc. has made significant strides in these areas to increase manufacturability and yields for both oxide and ion-implant confined VCSELs. Areas of focus have been numerous, but include such challenges as MOCVD growth performance, VCSEL processing, and device testing.

Track 3 – LEDs

Track 5 – Epitaxy

Epitaxy for LEDs

Chair: Heng Liu, AXT

Tuesday 11.00–12.40

11.00 High Volume AlInGaP LED Manufacturing Experience with 95 × 2 inch MOCVD Reactor*Clint McCreary, Jeff Krogen, and Kerri Wilkerson***Tecstar Inc**

Tecstar has been producing large volumes of compound semiconductor devices since 1982, primarily for the space Photovoltaic industry. Recently, Tecstar has entered the optoelectronic market with 590–645 nm AlInGaP LED structures. We will present our experience with the Aixtron

3000 Epitaxial Reactor to produce 95 × 2 inch wafers per run and over 6000 2 inch wafers per month per reactor. Full load thickness uniformity of GaInP and AlInP is less than 0.5% (SD/Avg.), Full load wavelength uniformity for complete devices is less than ±1.0 nm. Statistical analysis of a large population of wafers has shown a process capability (Cpk) of >3.0 for forward voltage, >1.0 for wavelength uniformity, and > 0.5 for brightness uniformity. For a period of production, an average OEE

(Overall Equipment Effectiveness) value of >62% was attained with a peak one week value of >70%. These data combine to demonstrate the high yield and reproducible nature of our manufacturing foundry.

11.25 **Multiwafer Growth of Group III Nitrides for LED Application in the Close Coupled Showerhead MOCVD Reactor**

B. Marheineke, E J Thrush, L Considine, J T Mullins

Thomas Swan Scientific Equipment Limited

M Kappers, N Sharma, C J Humphreys

University of Cambridge

M Dauelsberg

Aixtron, AG

Low cost of epitaxy and high yield are key issues to low cost, high volume production of devices such as blue, green and white LEDs based on Group III Nitride materials. Here the challenge to MOCVD reactor technology is to offer stable process conditions in a wide parameter window together with uniform and reproducible deposition and low precursor consumption. The Close Coupled Showerhead (CCS) MOCVD Reactor is designed to combine simplicity with scalability to meet these demands to a production tool.

We will present the jetting, mixing and decomposition behaviour evaluated using a three-dimensional modelling approach. Real-time in-situ monitoring using a laser based interferometer gives added insight into the mechanisms controlling the growth process and permits efficient mapping of the growth parameter space.

11.50 **New Developments in SiC**

Hiromu Shiomi

SiXON Ltd

Sixon is a new venture in the development, manufacturing and marketing of electronic devices made from silicon carbide (SiC). It incorporates its proprietary technology to produce silicon carbide for use in power systems and other applications. The company also manufactures n-type 6H SiC substrates, semi-insulating 6H SiC substrates and n-type 4H SiC substrates directed toward optoelectronic, microwave and power applications. Here is our status of the development and road map in near future.

12.15 **Development and Manufacturing of GaN and AlN Epitaxial Wafers**

Vladimir Dmitriev

TDI, Inc

GaN, AlN and SiC epitaxial wafers are in short supply for a large and rapidly growing market in compound semiconductor devices based on wide bandgap electronic materials. TDI is developing a high-quality, high-rate, simple and controllable advanced epitaxial processes for volume production of wide bandgap semiconductors, in particular GaN, AlN, and SiC, which are the key components for blue/UV LEDs and laser diodes, UV detectors, and novel power/RF devices. In this report we review state-of-the-art of GaN and AlN epitaxial technology including HVPE, MOCVD, and MBE. Main technical issues and latest results on manufacturing technology for GaN and AlN epiwafers will be presented.

Tuesday 10th 14.00–16.00

Track 1 – Microelectronics

Track 5 – Epitaxy

Growth of Heterostructure EpiWafers

Chair: Henry Hendriks, M/A-COM

Tuesday 14.00–15.40

14.00 **Inline Quality Control During MBE Production of AlGaAs/InGaAs pHEMTs Epi-wafers**

Guoliang Zhou and William Quinn

Alpha Industries, Inc

With the requirements of migration from the second generation to the third generation of cell phones, pHEMTs manufacturing is continuously being driven towards smaller gate length and newer device structures such as enhancement-mode pHEMT. As a result, pHEMTs production is facing tougher challenges for high yield, high reproducibility, and high reliability to meet cost and performance requirements. We present here the status of MBE production of AlGaAs/InGaAs pHEMTs at Alpha Industries. The results of monitoring and controlling of structural and electrical parameters for different types of pHEMTs, especially the impact of etch-stop layer to the device quality and yield control are compared. Also discussed is the effort of implementation of non-destructive monitoring tools.

J-L Guyaux, H Lareche, J-Ch Garcia, B Courboules Picogiga

Carbon doped GaAs base can be easily grown by MOCVD but the HBT shows some drawback such as burn in effect, current gain drift and in a certain extend, reliability problem which are thought to be related to the incorporation of hydrogen in the grow process. Therefore, hydrogen free carbon doped GaAs has been grown by MBE and many HBT studies have been published. However, the published results show poor HBT electrical characteristics compared to MOCVD material. In this paper, we will present the results achieve on GaAs /GaInP carbon doped HBT grown by solid source MBE on multi-4 inch and multi-6 inch machines on the commercial basis. Figure of merit of our transistors will be presented and compared to state of the art HBT. We will present an overview of the material quality: tight control of the thickness, doping levels and composition over wafers, uniformity. The specific advantages of the MBE HBT will be point out, in particular the surface morphology of the GaInAs cap layer, the absence of ordering effect in the GaInP ($E_g \sim 1.89$ eV) emitter, the absence of hydrogen in the base ($< 1 \times 10^{17} \text{ cm}^{-3}$)

14.25 **Carbon Doped GaAs/GaInP HBT Volume Production by MBE: A Breakthrough**

within the entire range of carbon doping level ($1e19$ - $2e20$).

14.50 Cost-Effective, High-Volume Molecular Beam Epitaxy Using a Multi 6-inch Wafer Reactor

Ren Jenkins, Larry Leung, Damian Davison, Arthur Cornfeld, Frederick Towner, and Dave Hartzell*
IQE Inc

Demand for GaAs based devices and circuits has driven the industry to increasingly larger diameter substrates for cost-effective, high-volume production. IQE Inc., a division of IQE plc has recently developed the technology to grow epitaxial structures on 150 mm (6-inch) GaAs substrates using a multi 6-inch wafer MBE platform with material characteristics exceeding those achieved on a multi 4-inch platform. The new platform is configured to produce four 6-inch epiwafers per platen and is projected to produce up to 21,000 wafers per year. This paper presents the methodology that was chosen to qualify the reactor for production. Discussions focus on machine performance, material quality, and capability. In-depth discussions of capacity, throughput, and reproducibility are

included. The advantages of using statistical process control for high-volume production are presented.

15.15 High Volume Manufacturing of Heterostructure Device Wafers for Advanced Microelectronic Applications

Matthew Micci

Kopin Corporation

The rapidly expanding market for wireless and high speed fiber optic systems continues to drive demand for advanced, compound semiconductor based circuits. The commercial and consumer nature of these markets necessitates that high quality complex heterostructure device wafers be produced in high volume and at low cost. To this purpose, wafer production systems must be implemented that are predictable and scalable. Strategies to implement this program include efficient growth process design, standardization of production and test tools, further automation of the process from heterostructure growth through to test, fast cycle device testing and characterization and SPC driven process control.

Track 2 – Fiber Optic Components

New Tools for Fiber Optic Component Manufacturing

Chair: Seppo Orsila, Modulight

Tuesday 14.00–15.40

14.00 Successful Implementation of Manufacturing Execution Systems in Fiber Optic Component Manufacturing

Greg Sowle

Camstar Systems, Inc

Morris St. Angelo

Unifi Technology Group

This paper describes the application of collaborative manufacturing execution software to single-and multiple plant environments, with a focus on application of the technology to the specific processing and business needs of high-volume fiber optic component manufacturing. Solutions will be shown for yield improvement, process repeatability, quality control, product traceability and other issues critical to high-volume manufacturing of semiconductor products for the optoelectronics market.

14.25 Quantifying Cost, Yield, and Volume Improvements Using Automation in Fiber-Optic Component Manufacturing

Randy Heyler

Newport

The pressure to increase volume, improve yield, and reduce the manufacturing cost of optoelectronic devices for optical networks is driving a push towards automated manufacturing of these devices. Of significant interest are the inspection, assembly, test, and material handling of these devices, especially across the back-end manufacturing processes of fiber pigtailed opto-electronic components.

Many factors contribute to the effectiveness and leverage of automation for these devices, including device design, equipment and process technology, machine utilization, and material handling strategies.

This presentation will provide an overview of commercially available back-end automation equipment and technology, which has been specifically designed for opto-electronic component manufacturing, and establish realistic guidelines and criteria for the selection of automation level in terms of product design and manufacturing process maturity.

Finally, real-world examples will be used to quantitatively compare different approaches to automating various assembly and test processes for various opto-electronic devices.

14.50 “Work Cell” Design and Implementation for Flexible, Cost-Efficient Manufacturing of Fiberoptic Components

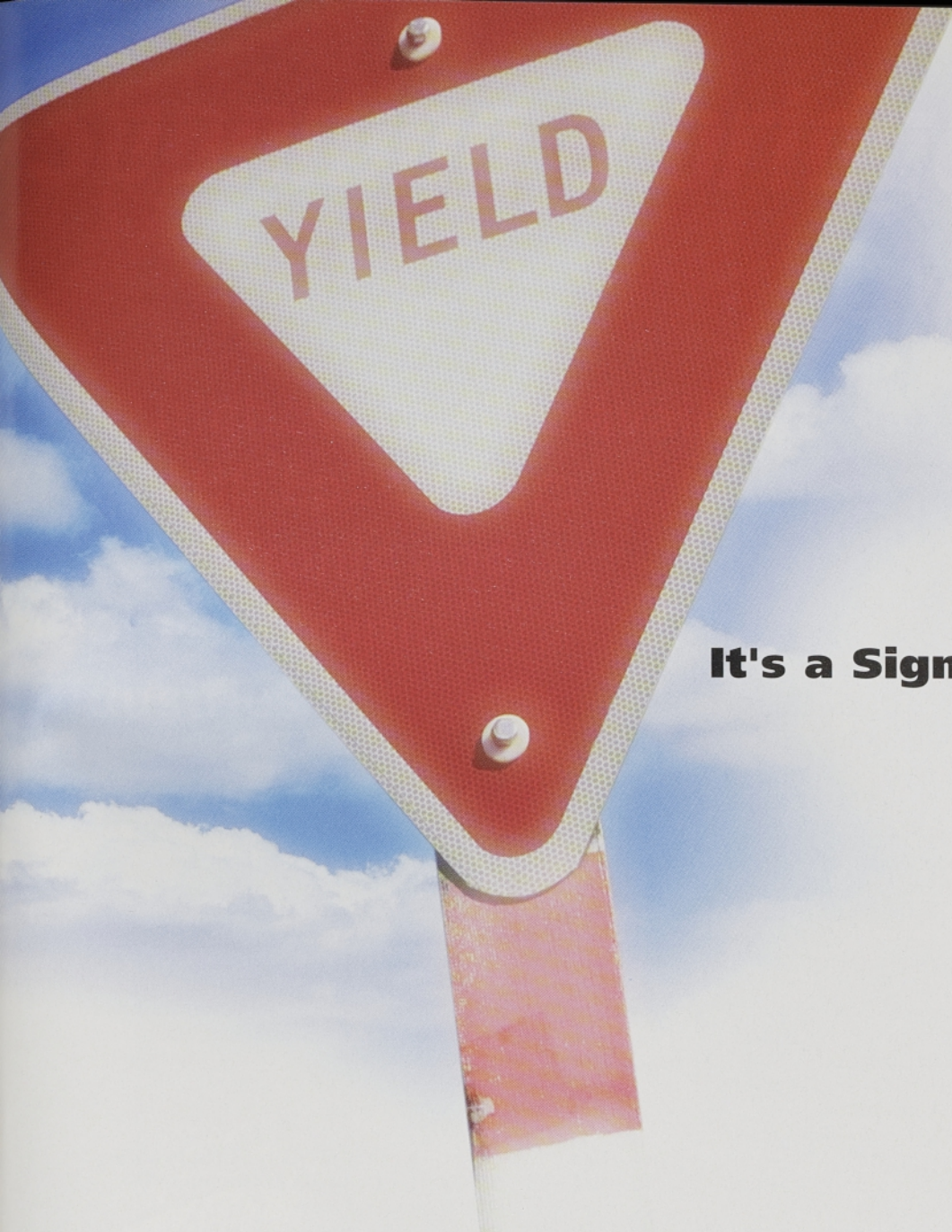
Dan Courtney

JDS Uniphase

Erez Hacohen

Kulicke & Soffa Industries, Inc

The presentation will explain how JDS Uniphase, a world-renowned supplier of optical receivers and monitors used in the fiber optic communications industry, developed and implemented a unique “work cell” model for flexible manufacturing with equipment and support provided by Kulicke & Soffa. JDS Uniphase uses an open space factory, arranged in U-shaped “work cells”, each containing complete phases of raw materials manufacturing, assembly, test, inspection and packaging, so that each cell produces complete product that is packaged and ready for shipment. The audience will gain an understanding, from both a conceptual and practical perspective, as to how a global leader in high-volume, fiberoptic component manufacturing designed and implemented the “work cells” to meet specific objectives for cost control, quality, flexibility,



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throughput and scalability, and how K&S supplied dicing and wire bonding equipment, along with the technical assistance needed to achieve these goals.

15.15 New Technologies for Packaging High Speed, High Power Optoelectronic Devices

Juan L Sepulveda, Jeffrey A Karker, Kirankumar H Dalal and Clark M Steddom

Zentrix Technologies Inc

Copper matrix composites, using tungsten as reinforcement (Cu/W), have been used during the last two decades providing good thermal dissipation and thermal expansion match to package common semiconductor laser dice. This technology has been applied to the manufacturing of advanced subassemblies for optoelectronics modules such as amplifiers, transmitters, receivers, modulators, lasers, pump lasers, and tunable lasers.

Powder metallurgy (P/M) based Cu/W composites exhibiting thermal conductivity (TC) around 200 W/mK and a fine microstructure are becoming the standard material for optoelectronic carriers and mounts. Coefficient of thermal expansion (CTE) for these materials is kept in between 6 and 9 ppm/°C. New heterogeneous assemblies making use of Cu/W composites, metallic copper, other metals or alloys, and metallized multilayer ceramic pads have been developed recently. Using the low CTE of tungsten based composites, the excellent TC of copper, and the amenability of Kovar for laser spot welding, a new family of brazed optoelectronic carriers or subassemblies has been developed. Several solutions involving the use of copper and copper/tungsten composites are presented including an innovative P/M design approach based on functionally grade materials.

Track 4 – Characterization

Characterization Techniques II

Chair: Marshall Cohen, Sensors Unlimited

Tuesday 14.00–16.05

14.00 Contactless Electromodulation and Surface Photovoltage Spectroscopy for the Room Temperature, Nondestructive Characterization/Qualification of Wafer-Scale III–V Device Structures

Fred H Pollak

New York State Center for Advanced Technology in Ultrafast Photonic Materials

The nondestructive characterization/qualification of complex semiconductor multilayer structures is a crucial step in the fabrication of modern day electronic, optical and opto-electronic semiconductor devices. Improvements in their quality and yield, with resultant increase in performance and reduced cost, will rely on wafer-scale characterization methods that are informative, nondestructive, convenient, easy to use, and inexpensive.

This talk will review the use of contactless electromodulation (photorefectance and contactless electroreflectance) and surface photovoltage spectroscopy for the production line evaluation of important structural/device parameters for III–V wafers. These relatively simple and compact methods are already being employed by more than two dozen companies world-wide.

Spectrum Analysis (QMSA) in conjunction with variable magnetic field Hall measurements that provides for the extraction of individual carrier mobilities and densities for multi-carrier devices. Temperature (2 – 400 K) and magnetic field (0–9 T) dependent Hall measurements and QMSA results for InP HEMT and GaAs multi-quantum well devices will be presented. The reliability and sensitivity of QMSA and variable field measurements show that this technique is a powerful measurement methodology for routine electrical characterization of multi-carrier semiconductor devices for both research and industrial QC/QA applications.

14.50 Using Automatic Mercury C-V Probe for Profiling and Mapping Carrier Densities of Compound Semiconductor Epitaxial Layer

James T C Chen, Tatiana Dimitrova

Four Dimensions, Inc

An automatic mercury ring-dot probe was used to make C-V plots at multiple sites on several kinds of compound semiconductor epi wafers. Carrier density profiles and wafer maps of vertically averaged carrier density were extracted from these C-V plots. The materials of these epitaxies are GaAs, AlGaAs, GaN, InP, SiC, and Si. The number of epi layers may be up to three. The substrate may be semi conducting or semi insulating.

The methods and results of these measurements will be presented. Safety advantages of this ring-dot mercury probe will be discussed.

14.25 Characterization of Multi-Carrier Heterostructure Devices with Quantitative Mobility Spectrum Analysis and Variable Field Hall Measurements

Gang Du, J R Lindemuth, and B C Dodrill

Lake Shore Cryotronics, Inc

K Vargason and Y C Kao

Intelligent Epitaxy Technology, Inc

D A Cardimona, C P Morath, and P Varangis

Air Force Research Laboratory

Hall measurements at a single applied magnetic field are incapable of characterizing the multi-carrier properties of heterostructure devices such as HEMT and multi-quantum wells because the measured parameters are averaged over all carriers. In this paper, we demonstrate a novel characterization technique, Quantitative Mobility

15.15 A New Optical Sensor for Real Time in-situ Endpoint Monitoring During Dry Etching of III–V Ternary Multi Stack Layers

Eric Teboul

Jobin Yvon, Inc

Ramdane Benferhat

Jobin Yvon, Inc

Jewon Lee, Dave Johnson, John Donahue, Jay Sasserath

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Unaxis, Inc

There has been a great demand for improved endpoint detection techniques for advanced etching of III-V ternary multi stack layers. Current etch rate and end point monitoring techniques are based on three methods. The first is to use timed or a blind etch as it is known; this offers no monitoring of the etch process. The second is to use optical emission spectroscopy (OES) which is a secondary measurement of the process and requires a large open area, fast etch rate, and a detectable emission line from the etch products. The third is laser interferometry, a primary measurement, based on light interference of reflected beams from several layers in the stack.

A new in-situ endpoint system utilizing a 905nm laser interferometer will be described that allows the ability to follow dry etching of III-V ternary multi stack layers. Endpoint detection techniques on various $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with different compositions (i.e. $x = 0.3 - 0.92$) and different types (n- or p- AlGaAs) are examined.

15.40 Non-Destructive Sheet Resistance or Resistivity and Mobility Characterization Techniques for Compound Semiconductors

Tom Ellington

Leighton Electronics

Sheet resistance and electron mobility are useful quality control metrics for increasing yields in compound semiconductor wafer production. However, the standard techniques for making these measurements – use of a four-point probe for sheet resistance, or Hall measurements for mobility – are destructive and are therefore not suitable for use in a high-volume production atmosphere.

In this presentation we will review the latest improvements in sheet resistance measurement systems, including tools with automatic wafer handling capability for all sizes of compound semiconductor wafers. A new instrument for contactless mobility measurement at room temperature will also be discussed, as well as application of these techniques for process control in compound semiconductor fabs.

Tuesday 10th 16.00–18.00**Track 1 – Microelectronics****InP & Metamorphic ICs**

Chair: Wu-Jing Ho, Alpha Industries

Tuesday 16.00–17.40

16.00 InP HBT IC Technology for Future High-Speed Communications

C H Fields, M Sokolich, and S Thomas

HRL Laboratories

In future wireline and wireless communications systems there will be an increasing need for circuitry capable of 40, 80 or 100 Gbps data rates.

Several issues need to be addressed to achieve manufactureable technologies at such high clock rates. The underlying device technology must have sufficient cutoff frequency. Cutoff frequencies (both f_t and f_{max}) of roughly twice the clock rate and careful design should suffice. InP based HBT IC technology is ideal for these applications because only InP based HBTs have demonstrated clock rates in excess of 70 GHz with MSI levels of circuit complexity.

HRL has developed InP-based HBT technology that is capable of supporting these needs. We have demonstrated InP HBTs with cutoff frequencies $f_t > 200\text{GHz}$ and with $f_{max} > 300\text{GHz}$ as well as fully static dividers operating at 72.8 GHz. The level of maturity of InP HBT IC technology makes it a strong candidate to support the needs of future communications requiring 100GHz logic.

We will review the device and circuit issues that have enabled us to exceed 70 GHz clock rates and we look forward to what must be done to surpass 100 GHz clock rates. The development trends indicate that 100 GHz clock rate circuit demonstration is imminent.

16.25 Production of MHEMTs for Microwave and Millimeter-wave Applications

Colin S Whalen, Philip C Balas, Lisa M Aucoin

Raytheon RF Components

In the past few years, Metamorphic HEMTs (MHEMTs) have become a popular topic at all of the major compound semiconductor conferences. The MHEMT technology has demonstrated the ability to displace InP HEMTs for microwave and millimeter-wave applications ranging from transimpedance amplifiers for the optical fiber market to 77 GHz low noise amplifiers for the automotive market. Use of GaAs substrates and scalability to 6 inch wafers dominate the reasons why MHEMTs offer an attractive alternative to InP HEMTs from both a cost and a yield perspective. Beyond the substrate issues, MHEMTs offer wafer processing advantages over InP HEMTs that are more aligned with the standard processes used in GaAs PHEMT wafer fabrication facilities. These aspects will be discussed in concert with standard process flows and positive impact to yield. Key to any new process introduction is a demonstration of reliability.

16.50 Metamorphic GaAs ICs and Metamorphic Technology on Germanium

Raf Vandersmissen, Dominique Schreurs and Staf Borghs
IMEC

For almost a decade InP based HEMTs have shown to be the best performing three-terminal devices. It combines high gain with low noise levels, resulting in excellent performance in the microwave and millimeter wave range. Despite its convincing performance level, InP is unlikely to break through in mass-market applications such as automotive radar and LANs because of several practical reasons (price, brittleness and size of substrates).



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Over the last years, the technology of metamorphic GaAs based HEMTs has matured, demonstrating performance levels close to InP with fT values of typically 200 GHz. In these devices, the advantages of the GaAs substrate are combined with the performance level of InP based heterostructures, yielding way to production for consumer applications.

In this paper, we will present the integration of these metamorphic devices monolithically into high-gain amplifiers in the Q- and W-band. A comparison between MMICs on LM InP and Metamorphic GaAs shows a performance in the range of InP based circuits. The Q-band amplifier even outperformed its InP counterpart.

17.15 **Metamorphic HBT's for New Wireless and Fiber-Optic Telecommunication Applications**

W K Liu, D Lubyshv, X-M Fang, and T Yurasits

IQE

InP-based HBTs are prime candidates for applications in new wireless and 40 Gb/s fiber-optic telecom products.

The ability to commercialize this device is currently limited by the cost, availability, and brittleness of larger diameter InP substrates. Furthermore, many GaAs-based device fabrication facilities have converted to six inch diameter equipment and lack the ability to process smaller wafers. To specifically address these issues, a growth technology has been developed which allows the growth of InP-based HBTs on GaAs substrates via a metamorphic buffer layer. HBTs, produced using this technology, which have demonstrated DC performance comparable to HBTs grown lattice-matched on InP substrates.

Although this technology was originally developed on a single three inch diameter wafer platform, it has now been transferred to a larger production tool capable of producing 5 six inch diameter wafers per growth run. The X-ray diffraction data indicates the device epitaxial layers are fully relaxed. Both carbon and beryllium have been used as p-type base dopants. SPC data will demonstrate that this technology has matured to a reliable and reproducible manufacturing process for HBTs.

Track 2 – Fiber Optic Components

Plenary Session on Fiber Optic Component Manufacturing

Chair: Mark Itzler, JDS Uniphase

Tuesday 16.00–18.00

16.00 **Commercialization of VCSEL Technology**

Jim Tatum

Honeywell

Honeywell introduced the world's first commercial VCSEL product in 1996, a proton implanted VCSEL operating at 850nm, which has evolved to completely displaced edge emitting lasers in short wavelength data communications. The ever-increasing need for bandwidth has driven the need for higher speed lasers, and laser arrays, as well as other laser wavelengths. This talk will address the commercialization of the latest VCSEL technology, and its implementation into high volume manufacturing.

16.30 **Indium Phosphide Photonic Integration for DWDM Applications**

Charles Huang

Anadigics

The exponential growth of Internet is the engine of change for both electronics industry and world economy. Optical fiber OC-192 (10 Gb/s) and OC-768 (40 Gb/s) DWDM system is the most efficient way to provide this insatiable demand for bandwidth.

Lithium niobate is the current technology of choice for long and very long haul 10 Gb/s DWDM external laser modulator applications. Unfortunately, lithium niobate is not semiconductor, therefore it can't be integrated with other active optical components.

Semiconductor material such as Indium Phosphide (InP) can provide all-in-one integrated functions that includes light generation, detection, amplification, modulation and switching, as well as passive splitting, combining and routing. It can be used to make, on a single substrate, high-speed modulators, switches, amplifiers, detectors as well as waveguides for interconnect. As such, it's ideally suited

for high volume production.

In this article we'll present in detail the design issues of an InP laser modulator. We will pay special attention to its integration with other optical transmitter components.

17.00 **An Integrated 150mm Opto and MMIC Process Line**

W A Phillips

Marconi

The increasing demand for high data rate telecom traffic is fuelling an expansion in opto-electronic production volumes. The work reported here describes the setting up of a line to process both opto and MMIC GaAs components. The decision to upgrade to 150 mm was dominated by two factors: the value of bigger wafers in providing a basis for true monolithic integration and increased optical functionality in photonic devices, and the recognition that silicon processing tools and techniques could be accessed at 150 mm. However, the task was complicated by the need to retain a production capability for 2 inch InP and 3 inch GaAs wafers, together with a R&D capability at all three wafer diameters.

Initial fabrication of modulators has now started, with full wafer production expected at the end of the year. Both lessons learned from the silicon industry and the use of process modelling and simulation have been invaluable in setting up the capability.

17.30 **Advances in Photonic Computer Aided Design**

Matthew Goodman

Telcordia Technologies

This talk will provide perspectives from a hierarchical photonics design environment, and will discuss the efforts of the PCAD Consortium to improve the usefulness of design tools for photonic devices and circuits.

Wednesday 11th 09.00–11.00

Track 1 – Microelectronics

Track 2 – Fiber Optic Components

Track 3 – LEDs

Plenary Session on Fab Management Principles Applied to III-Vs

Chair: Bedwyr Humphreys, MetroPhotonics

Wednesday 09.00–10.40

9.00 On the Fast Track: Tapping into the Power of SPC and Demand-Flow Tools to Jump Start Production

Tom Dearmin

Lasertel

Many of the same production tools taken for granted by silicon chip makers for decades are now being implemented by high-power semiconductor laser companies. As the industry matures, methods for epitaxial growth and processing are shifting from the “black arts” to a more predictable, controlled environment, resulting in higher volume, more efficient costs and improved reliability.

One of the key tools is the use of statistical process control (SPC) throughout the semiconductor laser production line, starting with wafer growth; continuing through photolithography, etching and sputtering; and finishing with final packaging and fiber coupling. As we narrow the acceptable range of variation and as we document normal parameters, we can standardize processes. Machines can be calibrated more accurately. Preventative maintenance is scheduled more consistently. Formulas for applying metals and the complex ratios for layering and temperature control can be broken into a series of simplified steps. The end result is that as processes are tracked and continuously improved, technical staff can turn more of the operation over to trained operators and technicians. Production gets streamlined, volume goes up, and price goes down.

9.25 Database Centered Manufacturing

Seppo Orsila

Modulight, Inc

Silicon industry is enjoying the benefits of industry standards for production tool automation since long time. The advantages of automation are obvious. As volumes are increasing in fiber optic industry more attention is paid to automation of process steps. However, most of the focus has been in the automation of single process steps while automation of information flow and management is often given less consideration, even though it is a crucial part of the process automation.

We decided to implement a system, which takes not only data but also process instructions and characterization results in to a central relational database. The centralized database allows not only static analysis of process afterwards. It is also rather simple to implement business logic, which reduces the necessity of engineer involvement in simple routine tasks and decision-making. Proper data management also allows automated equipment to generate instructions to each other thereby reducing the possibility of human error and increasing throughput. Finally, full traceability is achieved throughout the manufacturing

chain. This allows multidimensional on-the-fly statistical analysis of all variables for factual decision-making process.

9:50 Advanced Resource Modeling – The First Step for Productivity Improvement

Oded Tal

MAX International Engineering Group

Fab operational efficiency can be the difference between beating the competition or looking for excuses. The quest to become number one in productivity is a long and hard process. We suggest taking the expressway. Understanding the real capabilities and relations of your resources will give you the breakthrough to generating opportunities faster than you can exploit them. To run your operations in an effective manner there is a set of parameters you need to know and understand. Tools, operators, technicians, and all other support staff should be geared toward a streamlined manufacturing process.

To fully understand the environment we suggest going through the following stages:

- Mapping the process flow fully capturing all relevant process and tool related data.
- Creating a tool list based on the process flow.
- Modeling all tools and creating a fab wide capacity model
- Creating a resource allocation model for operators and all other support staff.

10.15 Utilising a III–V Optical Foundry for Rapid Time to Market

Neil P Martin

Compound Semiconductor Technologies

The presentation will acquaint the audience with the concept of the III–V optical foundry and attempt to define its roles within the developing market, with references to the evolution of the silicon market. Specifically it will highlight some of the challenges of providing such a service to the optical components suppliers across a number of compound semiconductor materials.

The presentation will focus on the core business and technology model of the foundry and discuss some of the peculiar challenges and issues to be addressed, now and in the future. The speaker will show the tangible time to market advantages obtain through case studies. Benefits to start-up companies and their fenders will be shown.

Future developments in the telecom optical device, process and manufacturing technologies of III–V semiconductors and their impact on the general market development as well as the specific foundry model will be discussed.

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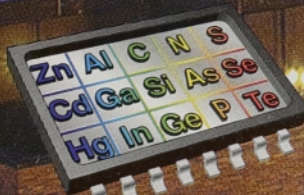
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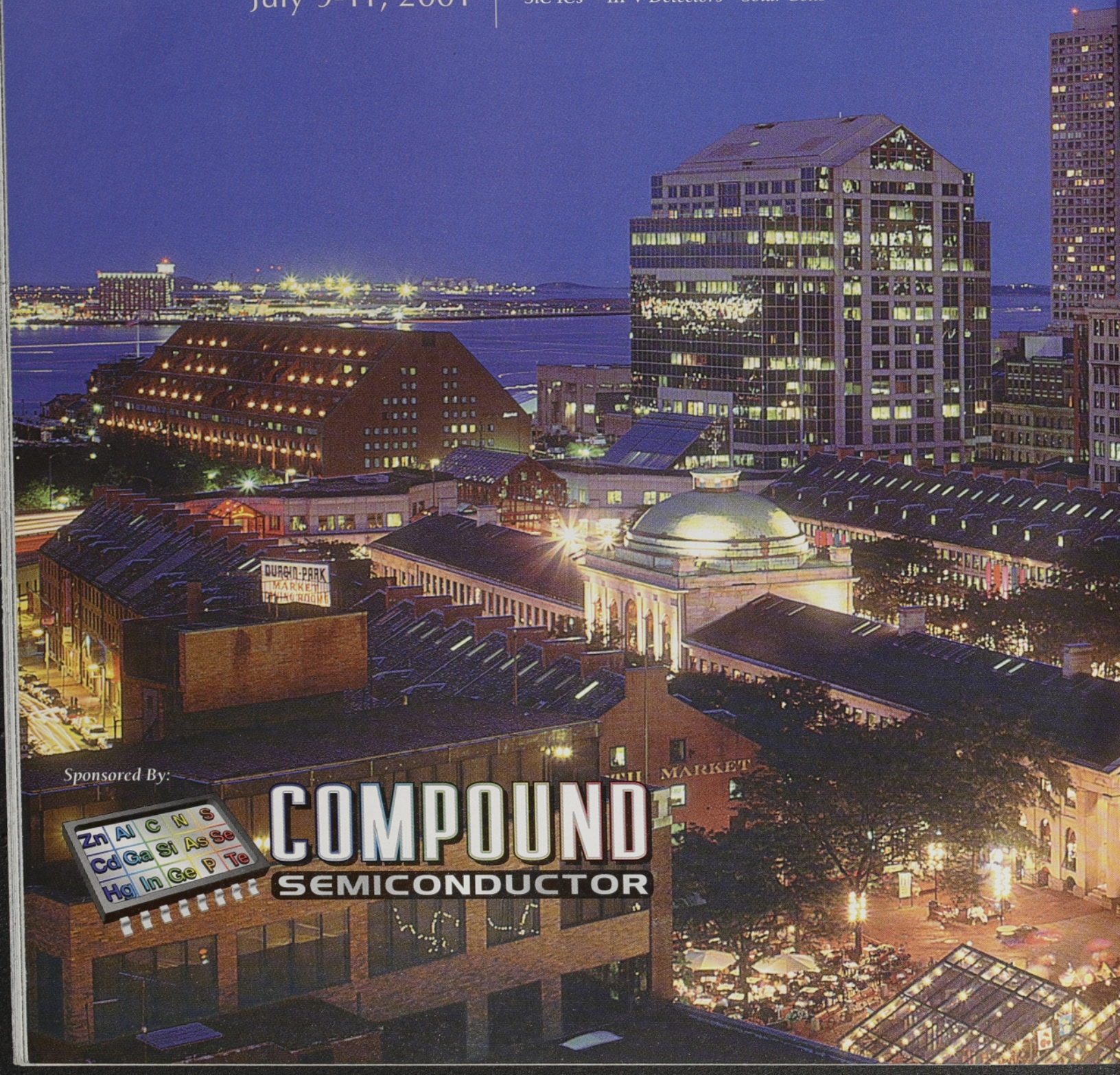
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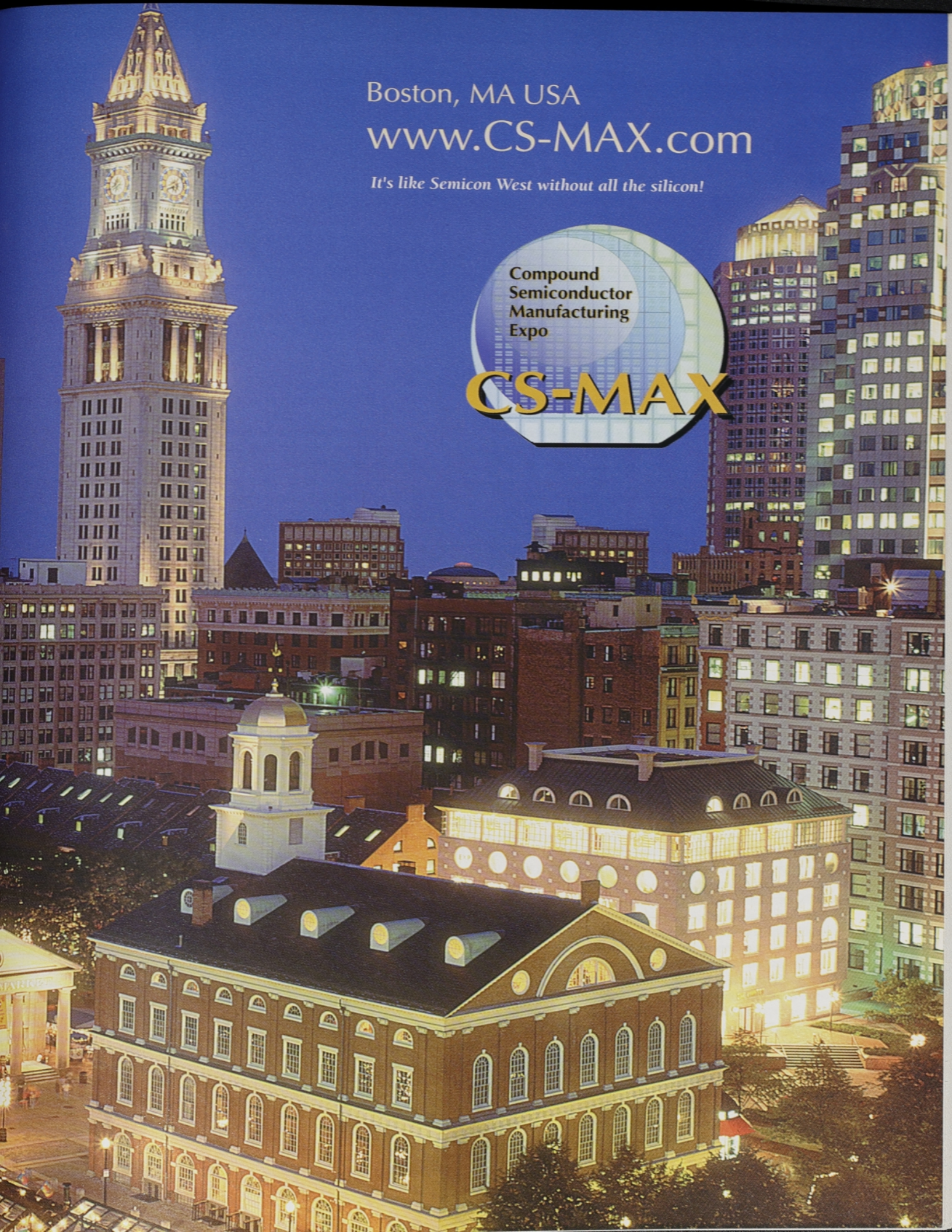
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Track 5 – Epitaxy

Gas Management Issues

Chair: Eric Bretschneider, Uniroyal Optoelectronics

Wednesday 9.00–10.40

9.00 Safer Delivery of Hydride Gases for III–V Manufacturing*Jim Dietz, Kent Carpenter, Russell Frye, Luping Wang, Mike Wodjenski, and Karl Olander***ATMI, Inc**

The risks associated with using the highly toxic gases common to compound semiconductor manufacturing can be greatly reduced using sub-atmospheric pressure gas sources. Removing pressure as the motive force in gas releases allows new options as to the location of materials, quantities stored and the type facilities required. By employing DOT exempt cylinders for sub-atmospheric pressure packaging, bulk arsine systems capable of delivering 175 pounds of arsine are possible. The problem of low differential pressures between the sub-atmospheric source and the process limiting deliverable quantities and flow rate is overcome using an extraction system to augment gas delivery. A mechanical pump, located between the gas source and the reactor, provides flow rates of 10 SLPM and allowing multiple tools to be connected to the same gas source. A typical sub-atmospheric pressure hydride gas installation is reviewed.

The paper examines the safety and risk comparisons of sub-atmospheric pressure delivery versus high-pressure cylinders, gas purity and process data and productivity benefits of bulk gas sources.

9.25 Safe Integrated Management of MOCVD Exhausts*Mike Czerniak***BOC Edwards**

The exhaust gases from most MOCVD processes pose considerable challenges to vacuum pumps and gas treatment systems because of their flammability (hydrogen and hydrides), metalorganics can be pyrophoric, phosphorus is pyrophoric, toxicity (particularly hydrides) and tendency to block pipework (especially phosphorus). Conventional technologies for pumping and abatement are reviewed, especially how these factors can combine to result in system downtime and loss of potential wafer throughput which is especially important in a high volume production environment.

Integration of a high temperature process pump with an inward-firing adiabatic combustor minimises the maintenance impact of MOCVD processes whilst removing the process gases to below TLV (including the removal of hydrogen to below LEL). This product, the Zenith from BOC Edwards, has demonstrated improved uptime (>98%) and safety in the two years since its introduction.

9.50 Control of Moisture in Group V Hydride Gases and Gas Delivery Systems*Virginia Houlding, Tadaharu Watanabe, Dan Fraenkel, Joe Vininski, Robert Torres***Matheson Tri-Gas**

Control of impurities during epitaxial growth is a critical path to yield improvement in compound semiconductor device manufacture. Oxygen, perhaps the most important

killer impurity in epitaxial films, can come from three major contaminant sources. The first source is oxygen-containing impurities present in the process or carrier gases. A second contaminant source is the reaction products of Group III or Group V source gases with trace environmental O₂. A third source is moisture generated by reaction of hydride process gases with the walls of nominally “dry” gas delivery system components. One of the largest moisture contributors is the particle filter.

In this work we have characterized the generation of gas phase moisture in hydride gas delivery from two sources: cylinders and particle filters. Data from AsH₃ and NH₃ cylinders show that the intrinsic moisture from a gas cylinder increases significantly as the cylinder is depleted. Particle filters dried down by standard inert gas procedures are shown to produce large moisture spikes when exposed to AsH₃ or NH₃. The results show a dramatic difference between metal and Teflon particle filters in hydride gas service.

We have also studied the moisture control performance of three new Point-of-Use (POU) hydride gas purifiers recently developed by the Advanced Technology Center at Matheson Tri-Gas.

10.15 On the Suitability of Getter Purified Hydrogen for the LP-MOVPE of AlGaAs: A Comparison to Pd-Diffused Hydrogen*S Guadagnuolo and G Vergani***Saes Getters SPA***H Hardtdegen, R Schmidt and K Wirtz***Research Center Juelich**

Diffusion through a very thin Pd foil is a well-accepted method for the purification of hydrogen carrier gas in MOVPE. However, due to the foil's mechanical fragility pinholes and cracks can form, which may go unnoticed until damage is done to the metalorganic source compounds as well as to the deposited layers. Pd cell failures can thus cause relatively high costs for production due to unnoticed bad quality and MO source contamination, let alone the ever increasing cost of palladium and thus the foil.

Therefore purifying methods such as getter columns, which will chemically bind the impurities irreversibly are a welcome alternative to Pd diffusion. Some test data will be presented on the quality of getter purified H₂ as tested with some of the most sophisticated and state of the art techniques for UHP gases. This data will analytically prove the quality of the getter purified H₂ carrier.

Exhibit hours

Monday July 9	10.30–19.30
Tuesday July 10	09.00–19.00
Wednesday July 11	09.00–14.00

Wednesday 11th 11.00–13.00

Track 1 – Microelectronics

Track 2 – Fiber Optic Components

Track 3 – LEDs

Plenary Session on Technologies for Manufacturing III-Vs

Chair: Wayne Liu, Corning Lasertron

Wednesday 11.00–12.40

11.00 Incremental Automation in the Compound Semiconductor Fab

Emmett Hughlett

Karl Suss

Producers of Compound Semiconductor Devices (CSD) are challenged to adapt production practices to an expanding market. CSD demand worldwide drives an accelerated market progression from low volume, low standardization products to high volume, commodity level products.

Hence, economy of scale and best production practices play a critical role in the future viability of our industry's Integrated Device Manufacturers (IDM) and foundries. The jumbled-flow, job shop production fab of the early 1990s is superseded by connected/paced flow-line production.

The CSD producer's world of low volume, high price products is giving way to the new primary goals of low cost, high volume products. This paper reaffirms the volume manufacturer's maxim that cycle time (CT) minimization supplants high equipment throughput/utilization, leading edge processes, and frequent inspection as core competencies on the volume production line.

This paper details how the available incremental levels of automation are economically and rationally applied to the compound semiconductor device producer's manufacturing technology roadmap.

11.25 III-V Thin Film Transfer as an Enabling Technology

Carlos Mazure and Frédéric Dupont

Soitec SA

Deposition techniques like chemical vapor deposition (CVD) offer to the semiconductor industry the initial flexibility to deposit thin films of key materials on many kinds of substrates. The homoepitaxy or heteroepitaxy techniques using CVD or Molecular Beam Epitaxy (MBE) add the flexibility to get a pure monocrystalline thin film but with a major limitation: the starting substrate has to be monocrystalline.

The missing technology has been the one which allows the growth of a thin monocrystalline film on any kind of substrates. Hydrogen induced splitting of a given wafer (which is known today as Smart-Cut), discovered at the LETI laboratory in 1991, provides this unique opportunity.

Therefore, a new technique is offered today to the semiconductor industry which enables the development of substrate solutions tailored to specific applications, for example the combination of high quality III-V thin films on Si substrate.

11:50 Bonding and Lithography Process Technology for Compound Semiconductors

Christian Schaefer, Friedrich Paul Lindner

EV Group

Paul A Lamm

EV Group US, Inc

The tremendous growth of compound semiconductor process technology in the past two years has required the development of a wide variety of specific wafer processing tools. This paper reviews the differences in compound semiconductor processing equipment compared to IC processing. New approaches in CS manufacturing equipment as well as the need for automatic processing of small wafer diameters and even pieces will be discussed.

Traditionally compound semiconductor wafers have been processed on manual equipment. Use of 2 to 6 inch wafers (InP, SiC, GaAs etc.) at relatively low volume allowed for use of R&D systems and manual handling. High volume production however cannot be achieved with systems that still exist from the times where Si was 2 inch or 3 inch diameter. A high level of automation and reliability known from IC industry is nowadays available and specifically configured to meet the needs of compound semiconductor processing. Double sided processing of ultra-thin substrates drives the need for temporary wafer bonding and de-bonding. Several techniques have been developed to temporarily mount a compound semiconductor wafer to a carrier substrate. The paper will give an overview of fully automated technologies used for temporary bonding including the various different types of intermediate layers.

12.15 Compound Semiconductor EHS Challenges

Brett Jay Davis

Motorola

The toxic, flammable and pyrophoric chemicals used in compound semiconductor (CS) manufacturing pose complicated challenges for environmental, health and safety (EHS) professionals. With the expected rapid growth of the CS market, the Semiconductor Environmental, Safety and Health Association (SESHA, formerly SSA) has committed to developing a network for CS EHS professionals to share best practices and develop new solutions.

Environmental challenges are multiplying, reinforcing the need for the SESH network. POTWs are considering lowering the wastewater discharge limits for arsenic and ACGIH is lowering the TWA-TLV for arsenic. Product content requirements may prohibit the use of some chemicals used in CS manufacture. And take-back rules may require the disposal or recycling of returned product.

Track 5 – Epitaxy

Metalorganics for MOCVD

Chair: Tim Whitaker, *Compound Semiconductor* magazine

Wednesday 11.00–12.15

11.00 Metalorganics Safety and Handling

Gregory M. Smith

Akzo Nobel

Most of the metalorganic compounds used in MOCVD processes are very reactive materials. This reactivity results in two specific primary hazards: ignition and fire on exposure to air (pyrophoricity) and explosive reactivity with particular incompatible materials (such as water). These hazards are well known— as the result of 40 years of experience with these materials in industrial settings – and successful strategies for managing these hazards exist.

This paper summarizes qualitative and quantitative data available on the reactivity of these materials; it summarizes appropriate general safety practices, appropriate materials of construction, and appropriate personal protective equipment; finally, it also summarizes appropriate fire-fighting techniques and extinguishing materials for use in the event of a fire involving metalorganics.

11.25 Group V Metalorganics for High Volume Manufacturing of Compound Semiconductors

Arnd Greiling

Mochem GmbH

In the last years the safer, more efficient liquid group-V-MO's have successfully been introduced in high volume manufacturing of compound semiconductors.

This success is based on a unique quality specification, which will ensure the requested consistent high-quality of the source materials for metal organic vapor phase epitaxy (MOVPE) of III/V-device structures. Routinely every batch of these MO's have to be tested using MOVPE growth followed by film characterization of reference material systems.

Significant advantages of epitaxial-tested based quality standards for compound semiconductor manufacturing (improvements of safety in supply, storage & handling of MO's, cost-reduction in process, reduced waste, increasing system uptime and improved performance) will be discussed.

11.50 Automated Bulk Distribution System For Liquid Organometallics in MOCVD Production

Ravi Kanjolia, Stan Pryll, Richard Pearce

Epichem, Inc

Lindsay Smith, Graham Williams

Epichem Ltd

The epitaxial growth of compound semiconductors in modern facilities is demanding increased throughput with decreased downtime and inherent process safety. The constant change-out of small organometallic toolbubblers impacts all of these areas adversely. Interrupting processes to replace these source bubblers frequently results in increased CVD equipment downtime, an increase in human traffic in the clean room, and lower overall throughput.

The III–V market is expected to pattern the roadmaps

and best practices set by the more mature silicon semiconductor industry. The bulk distribution concept is commonplace in the silicon industry to deliver electronic chemicals to tools in a safe and efficient manner.

These issues are now addressed in MOCVD production facilities by EpiFill, which is Epichem's automated organometallic source bubbler refill system. The EpiFill is designed to automatically dispense liquid organometallics, upon demand, from a bulk reservoir into the tool bubblers on multiple MOCVD reactors reducing process downtime. EpiFill minimizes the handling of pyrophorics, and increases process efficiency. A Cost-of-Ownership model will be presented to demonstrate the areas where efficiencies can be achieved.

CS-MAX organizing committee

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Alan Swanson, director, Microwave Electronics Group, BAE Systems, Information & Electronic Warfare Systems, Nashua, NH

Mark Itzler, VP and chief technical officer, JDS Uniphase Epitaxx, West Trenton, NJ

Bedwyr Humphreys, director of process development, MetroPhotonics, Ottawa, Ontario

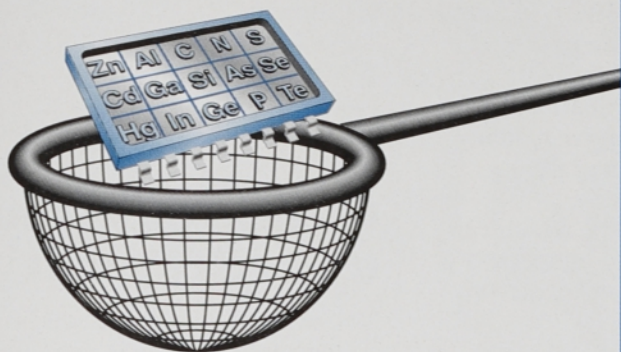
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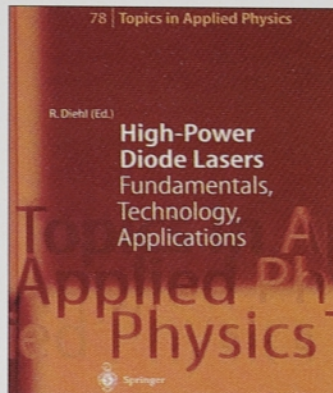
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BOOK REVIEW

High-Power Diode Lasers – Fundamentals, Technology, Applications



As editor Roland Diehl notes, steady increases in the performance of high-power laser diodes has allowed these devices to compete in applications that are traditionally the stronghold of solid-state lasers. As more opportunities open in areas as diverse as cosmetic surgery and materials processing (e.g. laser marking, drilling and welding), a thorough treatment of the performance and reliability of

semiconductor lasers is particularly timely. Over 10 chapters, Diehl's book explores the leading edge of epitaxy, device design, heat removal and packaging, but also includes an introduction to the physics, design and high-power operation.

Also covered are broad-area diode lasers, tapered emitters and tunable laser bars. A final chapter on new concepts deals with diode-pumped solid state lasers, laser active waveguides, double-clad fiber lasers and the thin disk laser.

Roland Diehl (Ed.) 2001. Fraunhofer Institute, Freiburg. Springer ISBN 3-540-66693-1 (260 figures and 20 tables).

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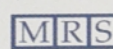
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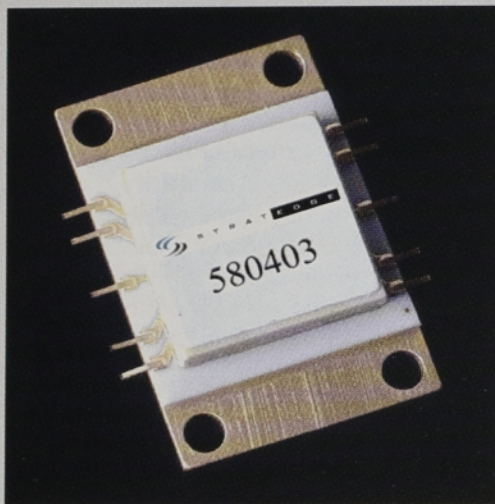
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StratEdge launches mm-wave package

Designed with the thermal management needs of power amplifiers in mind, StratEdge's new millimeter-wave (26–31 GHz) leaded package (part



number 580403) is the first leaded product for commercial applications in the Ka-band. Prior to this, leaded packages from StratEdge were only available from DC to 23 GHz.

The 580403 can be used to package power amplifiers, low-noise amplifiers and switches, and can be customized for MCMs. Using a standard copper composite base, the company's package also incorporates its microstrip-imbedded microstrip-microstrip transition design. A plastic cap lid finishes the structure and provides protection for the device. The final outside dimension is $11.43 \times 11.43 \text{ mm}^2$.

Contact Tim Going, StratEdge, 4393 Viewridge Avenue, San Diego, CA 02123, USA
Tel. +1 858 569 5000
Fax +1 858 560 6877
E-mail t.going@stratedge.com

New Karl Suss probes reduce device failures

While ball grid arrays (BGAs) are designed to house higher densities of ICs and telecom devices, the ability to perform testing at these densities

becomes increasingly difficult. Karl Suss has introduced the PA200BGA to assess BGA structures prior to the packaging process. This can save additional processing steps and eliminate device failures. The automatic probe system features a robotic loader and pre-alignment function that uses programmable probe heads, which can be switched automatically between carrier and BGA measurement set-ups.

Contact Veronica Miller, Karl Suss America, 228 Suss Drive, Waterbury Center, VT 05677, USA
Tel. +1 800 685 7877
Fax +1 802 244 5103
E-mail vmiller@suss.com

Keithley controller auto-tunes TECs

The model 2510-AT from Keithley Instruments is an auto-tuning source meter designed for both production testing and control of thermoelectric coolers (TECs) used in telecom applications. Combining temperature control and measurement capabilities, the 2510-AT enables control of wavelength and light intensity output.

The 2510-AT can also be integrated with other instruments in a Light-Intensity-Current-Voltage test stand. With a maximum output of 50 W, the unit's programmable power, current and temperature limits offer maximum protection against laser diode damage.

A function has also been included to enable more accurate testing of the TEC Peltier heater/cooler following assembly in laser diode modules, where physical damage of the TEC can occur.



Contact Ellen Modock, Keithley Instruments, 28775 Aurora Road, Cleveland, OH 44139-1891, USA
Tel. +1 440 498 2746
Fax +1 440 248 6168
E-mail emodock@keithley.com

Optical power meter tests telecom devices

A new multifunctional hand-held optical power meter with a 30 mm diameter integrating sphere-based detector is now available from Gigahertz-Optik. Designed for telecommunication testing, the P-9710 contains an InGaAs detector



(850–1700 nm) and measures the output power of bare and connected fibers, laser diodes, and LEDs in the 20–60 dBm range.

Contact Bob Angelo, Gigahertz-Optik, 5 Perry Way, Newburyport, MA 01950, USA
Tel. +1 978 462 1818
Fax +1 978 462 3677
E-mail b.angelo@gigahertz-optik.com

Trikon releases new plasma etch products

Trikon Technologies has introduced two new plasma etch products for compound semiconductor and silicon applications. The Omega fxP is a multi-chambered cluster tool that combines its Omega plasma etch sources with a Brooks MX 800 wafer handler. The Omega system

offers up to six process modules, wafer alignment and cool-down with two vacuum cassette stations.

A single chamber format is available that uses an enhanced version of Trikon's Omega 201, featuring the company's plasma source and MORI plasma-enhanced RIE and ICP system. Both the Omega fxP cluster tool and the single-chamber Omega 201 feature Windows NT control software, advanced electrostatic chucks and low footprint, in addition to dynamic notch/flat alignment and wafer cool-down.

Contact Dave Thomas, Trikon Technologies, Ringland Way, Newport, NP18 2TA, UK
Tel. +44 (0)1633 414027
E-mail dave.thomas@trikon.com

SSEC's processors use even soak timing

Addressing applications for metal lift-off and resist stripping, Solid State Equipment Corporation's solvent processors employ an "even soak" timing step during solvent immersion batch processing.

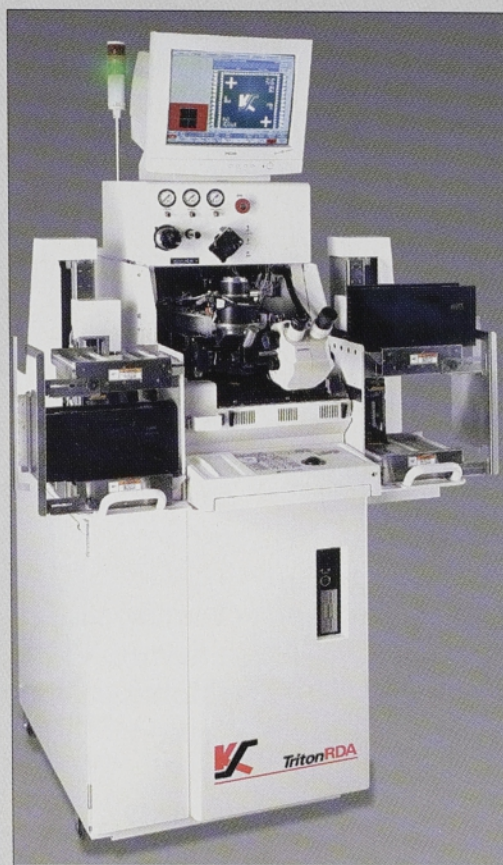
Able to handle wafers up to 300 mm and glass panels up to 1 sq. m, the company's system employs the batch immersion with controlled agitation and heating of the solvent bath. This complements its single-wafer processing systems, where each wafer is treated individually in a processing and rinse chamber.

Contact Terri Kolodziejski, Solid State Equipment, 185 Gibraltar Road, Horsham PA 19044, USA
Tel. +1 215 328 0700
Fax +1 215 328 9410
E-mail t.kolodziejski@ssecusa.com

New ribbon bonder provides deep access

K&S Triton's ribbon deep access (RDA) bonder is an automatic wedge bonder designed to bond wireless, optoelectronics and other devices.

As the name suggests, the RDA offers deep bonding access and a 90° wire feed angle to enable bonding of packages with deep cavities. The company says



the combination of wedge bonding technology, looping control and ribbon wire provide significant performance and reliability advantages.

Contact Henri Van Parys, K&S Triton, 2101 Blair Mill Road, Willow Grove, PA 19090, USA
Tel. +1 215 784 6000
Fax +1 215 784 6167
E-mail parys@kns.com

Pyramid probes place contacts accurately

Complex IC designs call for ever-smaller pitches and bond pads, which make it difficult to perform on-wafer testing. The traditional method uses needle probe cards and becomes impractical for more than about 500 bonding pads, but current designs require many thousands of contacts for as many as 500 to 1000 pads per die.

Cascade Microtech's new thin-film Pyramid Probe Card for on-wafer testing solves this problem for production environments: the company's probe uses a membrane core that is processed photolithographically, resulting in

contacts that are placed 10 to 15 times more accurately than hand-positioned needle probes. And because the contact area is smaller, the pyramid probe causes less pad damage, making it suitable for high-speed testing of wireless and telecommunications ICs, says Cascade Microtech.

Another feature of the probe is a low contact resistance: 15 mΩ compared to up to 3 Ω for a needle probe.

Contact Ellen Payne, Cascade Microtech, 2430 NW 206th Avenue, Beaverton, Oregon 97006, USA
Tel. +1 503 601 1181
Fax +1 503 601 1002
E-mail ellen_payne@cmicro.com

August Technology inspects wafer bumps

August Technology's 3Di-8000 is a high-speed bump and wafer inspection system incorporating a 3-D Rapid Confocal Sensor with 2-D bump and active die inspection.

The 3Di-8000 measures the height and co-planarity of solder and gold bump interconnects in packages or circuit boards. Wafers can be analyzed in a range of diameters from 75 to 300 mm.

"The bump height is critical to the functionality of devices using wafer-level interconnect technology," said product manager Dan Nelson. "The 3Di-8000 enables bump height detection and combines high speed with an accuracy of greater than 2 μm."

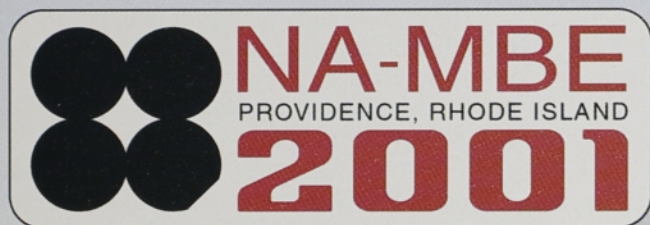
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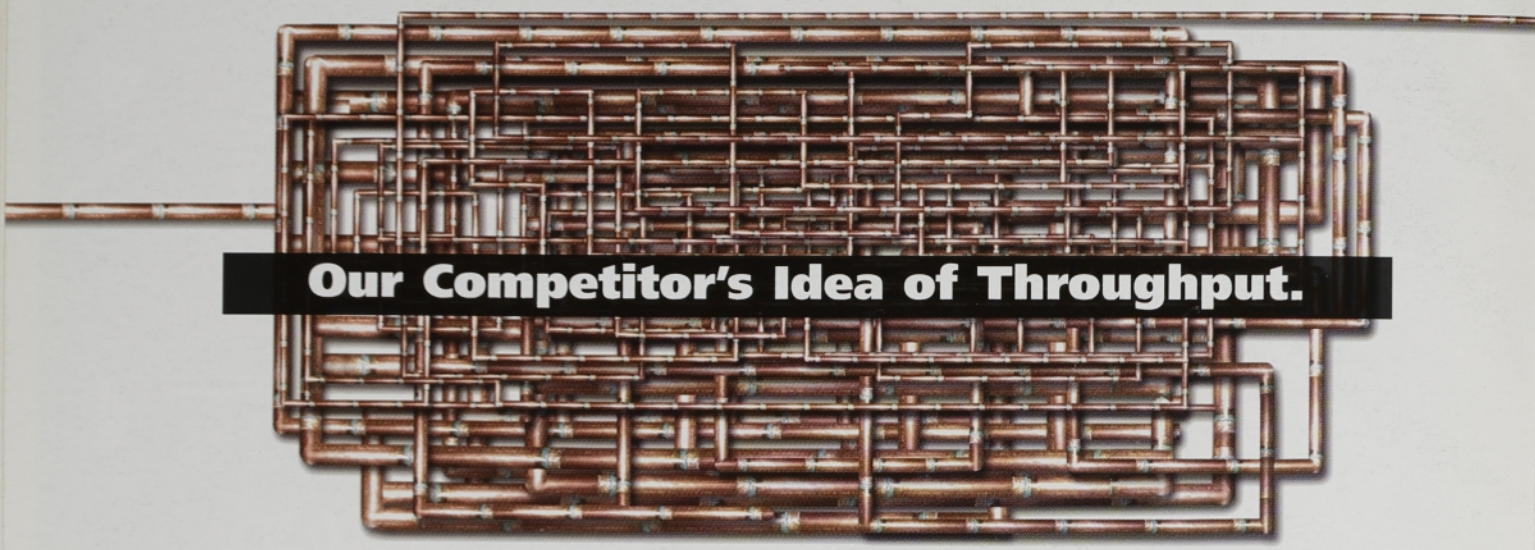
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