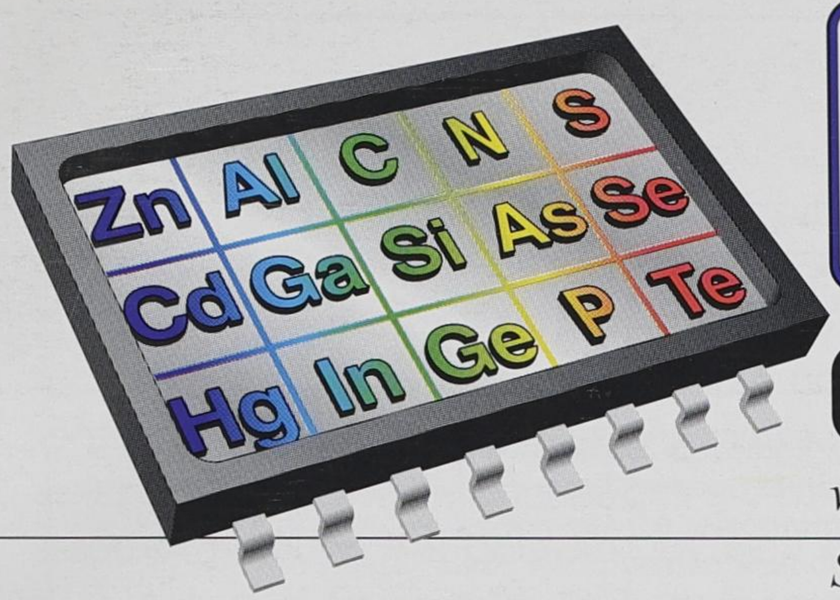


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September 2001 Volume 7 Number 8

GaAs fabs in Europe

Tunable lasers

LEDs for lighting

CS-MAX and Nitrides conference reports

Osram and Uniroyal take control

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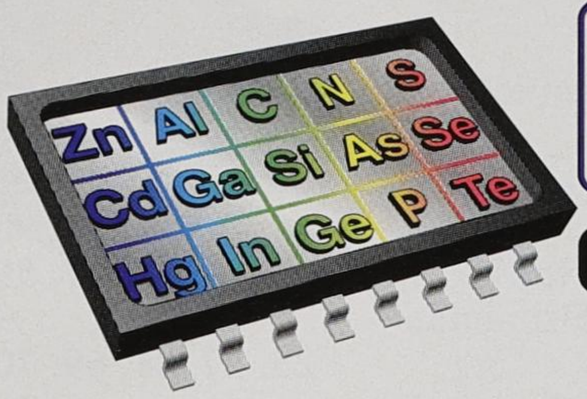
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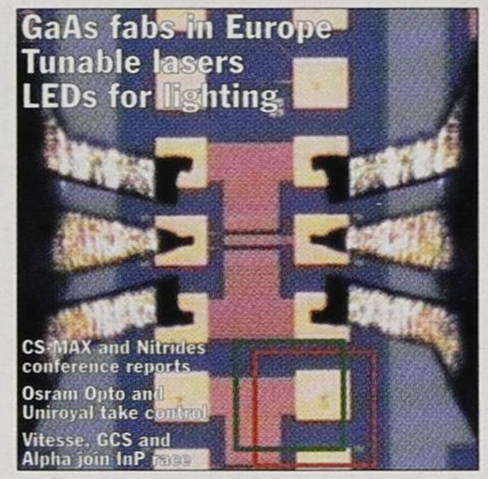
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SEPTEMBER 2001 VOLUME 7 NUMBER 8



COMPOUND SEMICONDUCTOR



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GaAs MANUFACTURING

53 European GaAs fabs still forging ahead
When talk turns to GaAs fabs and foundries, the first names that spring to mind are usually American or Taiwanese. However, Europe is no sleepy backwater as Jon Newey discovers.

81 The challenges of running a dual-use foundry for military and commercial users
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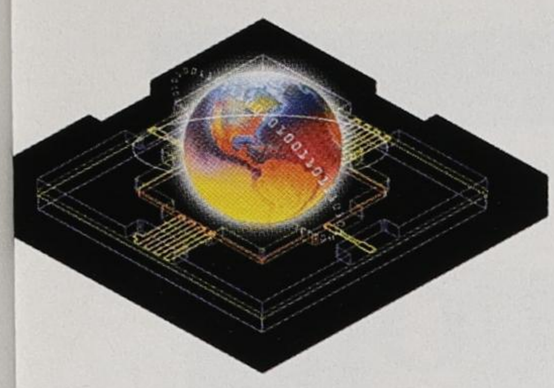
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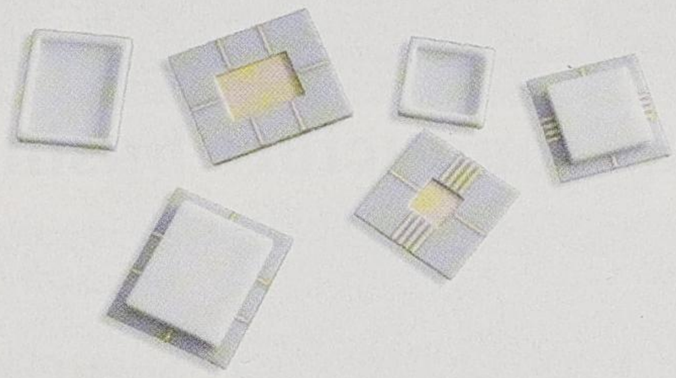


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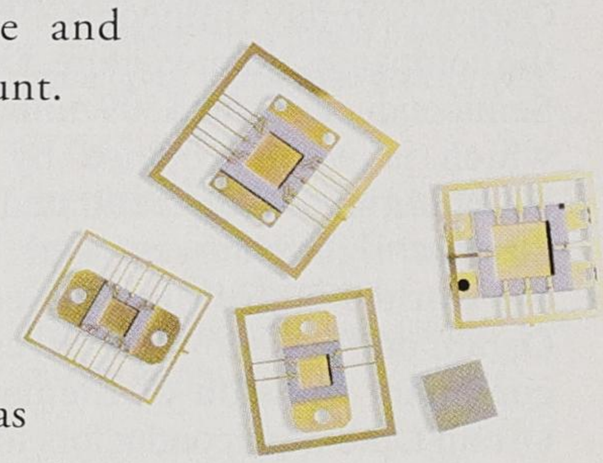
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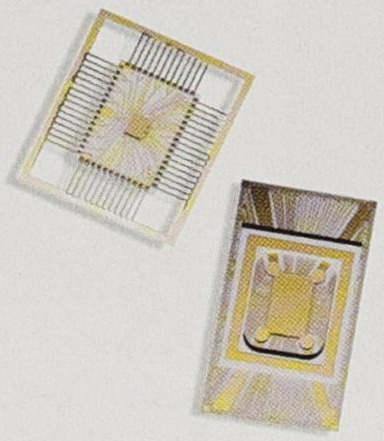
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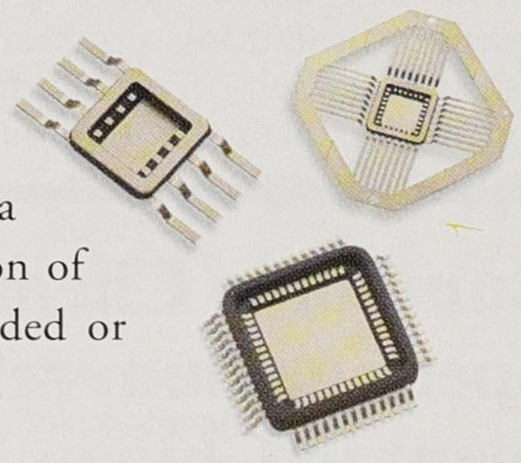
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Uniroyal buys Emcore's interest in UOE

Uniroyal Technology Corporation (UTC) has purchased Emcore's minority ownership in Uniroyal Optoelectronics (UOE), the joint venture established in 1998 to develop and manufacture high-brightness nitride-based LEDs. UTC, which owned 64% of UOE at the end of June, purchased the remaining shares from Emcore for just under 2 million shares of Uniroyal common stock.

"This is a unique way to maximize shareholder value for both Uniroyal Technology and Emcore," said Howard Curd, Uniroyal's chairman and CEO. "At the same time, we are pleased with the confidence Emcore has shown in Uniroyal Technology, and we look forward to a long-term relationship with them, both as a supplier and as a shareholder."

UTC's compound semiconductor and optoelectronics business segment includes UOE, Sterling Semiconductor, which manufactures SiC substrates and epiwafers, and NorLux, a subsidiary developing products for solid-state lighting applications. UOE recently completed the expansion of its epitaxy facility in Tampa, Florida, including the installation of several new reactors (see *Compound Semiconductor* August 2001, p19). The company's blue InGaN-on-sapphire LEDs exhibit brightness levels ranging from 3.5 to 4 mW in die form, and 8 to 10 mW in packages.

According to marketing communications manager Linda Emery, the company's long term strategic plan is to divest non-semiconductor related interests. "Our strategic goal is to become a pure-play high-technology company," she says. Last year, UTC sold its high performance plastics interest, and recently announced its intention to sell the specialty adhesives business, leaving coated fabrics as the company's last industrial business group.

UV Florida develops UV LEDs

UOE has announced a long-term collaborative project with three Florida universities to develop UV LEDs for white light emitters – see p19 for more details.

Osram takes control of Opto Semiconductors business

Osram is to buy Infineon's 49% share in the companies' joint venture, Osram Opto Semiconductors, for $509 million. Osram, which is wholly owned by Siemens, has traditionally concentrated on incandescent light sources, and is one of the world's largest lighting companies. Osram and Infineon, the divested semiconductor division of Siemens, set up Osram Opto Semiconductors to capitalize on the growing potential of semiconductor light sources.

The company manufactures high-brightness LEDs and also modules incorporating LEDs for lighting and signaling applications, as well as high-power laser diodes for pump sources and material processing.

This is a further move in Infineon's recent restructuring program that has also seen the sell-off of its infrared components business (see *Compound Semiconductor* August 2001, p31). To date, Infineon has shown no indication of divesting either its GaAs products group or its fiber-optic components business, which makes DWDM components and transceiver modules.



OSRAM OPTO SEMICONDUCTORS

LED modules provide a warning signal to passengers on the Stockholm subway.

The acquisition of Infineon's stake will strengthen Osram's position in the opto semiconductors market. "Osram is transforming itself from a traditional manufacturer of lightbulbs into a high-tech company," said Wolf-Dieter Bopst, president of Osram. "A major factor in this is the expansion of our business in semiconductor light sources."

New plant in Germany

Osram Opto Semiconductors recently announced that it is to build a huge new facility in Regensburg, Germany for the manufacture of LEDs, laser diodes and sensors – see p19 for further details.

Sumitomo Chemical opens gallium refining plant in China

Sumitomo Chemical Co is forming a joint venture in Shanghai, China for the production of high-purity gallium, beginning in the fall of 2001. Sumitomo Chemical will own 70% of the new firm, while the remaining 30% will be evenly split between Inabata & Co and the US chemical manufacturing group Technical Sourcing International. The Shanghai firm will build a factory with the capacity to refine 40 tons of high-purity gallium per year using Sumitomo Chemical's proprietary technology.

Sumitomo Chemical will handle the entire output from the Shanghai factory, selling most of the gallium to users in Japan for the production of compound semiconductor wafers and organometallic materials. The company already refines 40 tons of high-purity gallium at a factory in Japan and plans to boost that factory's capacity to 60 tons within the year, providing the company with a total capacity of 100 tons.

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NEL moves to 6 inch GaAs production

NTT Electronics (NEL) is in the process of shifting its fabrication to a 6 inch wafer facility to boost production, according to *FiberSystems International* magazine, a sister publication of *Compound Semiconductor*. NEL fabricates a range of GaAs ICs operating in the 2.5–20 Gbit/s range, and ships approximately 20 000 10 Gbit/s products each month. "Our IC sales have been doubling each year for the past few years," said Hiroyuki Kikiuchi, sales director of NEL's electronics business group. Around 60% of NEL's ICs, and 80% of its lasers, are sold to the domestic market (see *FiberSystems International* July 2001, p36).

Motorola to expand

Motorola Semiconductor Products Sector recently announced plans to phase out two silicon wafer fabrication lines in Mesa, AZ over the next few years. However, the company also stated that it plans to expand production at other facilities, including the CS-1 fab in Tempe, AZ that manufactures GaAs ICs.

Vitesse, GCS and Alpha join the indium phosphide race

Following closely on the heels of TRW spin-off Velocium, three other companies are moving InP towards commercial markets. Both Vitesse Semiconductor and Global Communication Semiconductors (GCS) have announced the availability of InP foundry services, while Alpha has also developed an internal InP process.

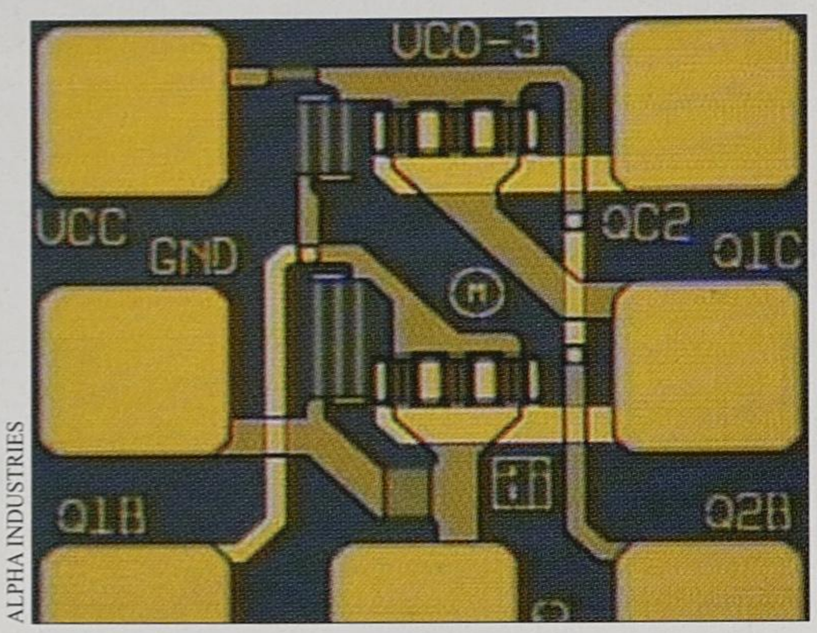
Vitesse launches foundry services

Vitesse is making InP foundry services available for high-performance IC designs, including SONET OC-768 (40 Gbit/s), 100 Gbit/s Ethernet, wireless and RF applications. Vitesse fabricates InP ICs using a proprietary process which it believes will drive oscillation frequencies above 250 GHz, while reducing power requirements five-fold.

Based on a vertical NPN bipolar transistor, Vitesse's process employs standard Si process equipment and manufacturing techniques on a 4 inch line in Camarillo, CA. Standard Al metallization is used instead of Au metals, lift-off and airbridges. The company says proprietary contact designs allow high-temperature processing and the use of Al interconnects and oxide dielectrics. Vitesse offers wafers or partnerships based on its current single HBT process, which features f_t and f_{max} values of 150 GHz and a breakdown voltage of 4.2 V. The company will also offer a double HBT process with a higher breakdown voltage, which will be ready later this year. A third process suitable for the integration of detectors and electronics is also available.

GCS offers InP HBT wafers

Foundry company GCS has added a new 4 inch InP HBT wafer process to its current portfolio of AlGaAs and InGaP HBTs, VCSELs, SAW filters and PIN diodes. For the last year the company has been working with strategic partners, including GTRAN, to supply InP HBT wafers from its foundry in Torrance, CA.



ALPHA INDUSTRIES

Demonstration VCO circuit produced using Alpha's new InP HBT process.

The proprietary InP HBT process employs a carbon-doped base for long-term reliability and features a 1.0 µm emitter width. The f_t and f_{max} values are above 160 GHz for operation at a current density below 75 kA/cm^2. GCS has now increased the current density to drive the f_t value above 200 GHz. The company says the emitter width is scalable to sub-micron size, allowing lower power dissipation and higher frequency circuits, including 40 Gbit/s ICs.

"It was a natural progression for GCS to develop an InP process to address the 40 Gbit/s requirement of OC-768 and PAs for 3G handset applications," said Owen Wu, GCS's CEO and president.

Alpha jumps on the InP bandwagon

Alpha Industries has also introduced an InP HBT process for analog chips used in the physical layer of next-generation 40 Gbit/s optical networks.

Alpha believes that InP delivers key performance advantages over competing technologies such as GaAs and SiGe, including the ability to manufacture smaller and more power-efficient products as a result of excellent thermal properties, higher threshold voltages and greater frequency response. Equally important, InP also enables the integration of electronic ICs and optoelectronic devices such as photodiodes.

"InP extends our semiconductor process technology arsenal, which already includes InGaP HBT, GaAs MESFET, GaAs PHEMT, silicon and ceramics," said Ding Day, Alpha's VP of Process Development. "This will enable us to manufacture devices with f_t and f_{max} values above 120 GHz, performance that is essential for high-speed data applications."

The process will take advantage of the automated production line at Alpha's fab in Sunnyvale, CA (formerly Network Device Inc), which currently runs various GaAs processes on 4 inch substrates with a capacity of 500–600 wafers per week. InP HBT epiwafers will be obtained from various suppliers, including Kopin.

According to L J Ristic, Alpha's chief technology officer, InP HBTs are ideally suited to analog functions such as TIAs, limiting amplifiers, laser drivers and modulators operating at 40 Gbit/s. "Our plan is to have an InP process developed by the first half of next year, and then to use the process to make devices towards the end of the calendar year 2002," said Ristic. "While the first devices will be single-HBT devices, our aim is to eventually produce double-HBT structures, which have a higher breakdown voltage."

Ristic added that for mixed signal circuits, which include clock data recovery and MUX/DEMUX functions, the performance requirements are not as stringent as for analog chips, which consume more power. "Mixed signal functions in the physical layer will be adequately served by InGaP HBT circuits or even SiGe ICs, which are currently available for OC-192 [10 Gbit/s] data rates," he said.

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Signal forms RF/microwave module venture

Signal Technology Corporation has entered into a strategic initiative with Northrop Grumman and Vitesse to leverage its defense-oriented wireless RF and microwave module technology into high-volume commercial markets for mobile phones and emerging wireless appliances. One of the major aims is to provide entire RF front-end modules in line with the shorter design lead times required by handset manufacturers.

As part of the venture, Signal Technology has entered into a 10 year license agreement that provides access to Northrop Grumman's 4 inch GaAs foundry processes. These include a PHEMT process with 0.25 μm T-gates for circuits in the 1–40 GHz range, and HBT processes employing 2.0 μm emitters for X- and Ku-band operation (up to 20 GHz). Northrop Grumman will also supply Signal with devices for up to 10 years, to support the company's growing line of wireless access products. In return, Northrop Grumman will conditionally receive a total of 1 million shares or 10% of Signal's common stock. Another key aspect will be the establishment of a joint technology working group to facilitate technology transfer to Signal, and also to provide Northrop Grumman's defense customers with access to a low-cost commercial production base.

Signal Wireless Group, headquartered in Danvers, MA, develops RF radio subsystems for fixed broadband wireless applications, in addition to switching/combining components and subsystems for digital PCS/cellular applications. On the defense side, Signal develops and manufactures RF, microwave and power conversion products for communications networks, electronic countermeasures, missiles, radar, intelligence and guidance systems.

"Offering GaAs module technology to cell phone makers is in line with Signal's growth strategy, which is to leverage our defense electronics heritage into the penetration of commercial wireless communications markets," said George Lombard, Signal's chairman and CEO. "With Jim DiLorenzo and his team's background in GaAs cell phone products, we believe it is an opportune time for Signal to apply this RF technology to 2.5G and 3G wireless handsets, as well as emerging wireless appliance markets."

Shared expertise with Vitesse

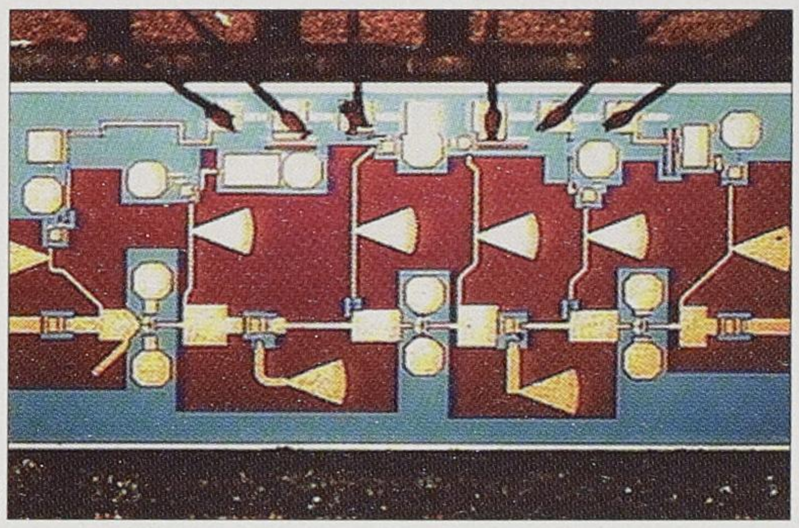
To date, Signal has employed its design capabilities to supply custom GaAs circuits largely for low-volume defense applications. The exclusive agreement with Vitesse will provide Signal with a high-volume supply of RFIC and MMIC wafers, and also provide Vitesse, which produces digital ICs, access to analog design expertise and Signal's customer base. The deal includes the transfer of Northrop Grumman's GaAs technology to Vitesse's 6 inch GaAs wafer line, and the production of Signal's MMIC designs for a period of 10 years. Vitesse will conditionally receive 500 000 shares or around 5% of Signal's common equity.

"From the Vitesse standpoint, there is great synergy with Signal Technology," said Vitesse CEO Lou Tomasetta. "By offering Signal our volume manufacturing expertise, this agreement offers us a route into wireless markets. We will gain from Signal's customer base and analog design experience, which is an area where Vitesse has less experience. Looking ahead, we see no technical roadblocks, and expect to have prototype parts that Signal can sample to its customers by the summer of 2002," added Tomasetta.

"We believe the wireless telecom market is poised for a rebound in terms of both infrastructure build-out and handheld appliance demand," added Signal's president and COO, Jim DiLorenzo. "In addition, creating the Northrop–Signal joint technology working group assures us of the earliest possible access to first-to-market design-in of evolving technologies vital to innovative products. These strategic advantages will position Signal to capture a meaningful share of the commercial market for wireless appliance components when worldwide demand growth resumes."

TRW InP chip in orbit around the Earth

An InP chip designed and produced by TRW is being flown on a scientific research satellite. Fabricated at TRW's 4 inch InP manufacturing facility in Redondo Beach, California, the MMIC low noise amplifier (LNA) circuit is part of a broadband radiometer being used by the Odin-1 science satellite. The device, a 3-stage HEMT operating in the 114–124 GHz range, offers a noise figure of less than 4.5 dB and gain of 14 dB. This enables the radiometer to detect very faint radiation emitted by interstellar oxygen, which could lead to greater insight into the formation and evolution of galaxies.



TRW

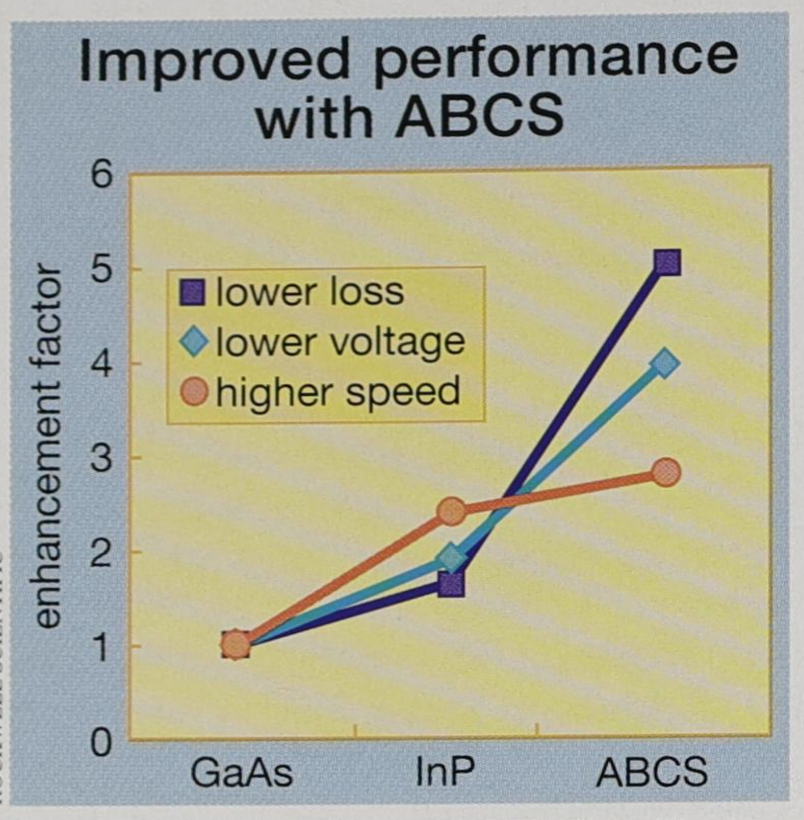
TRW's space LNA is based on a 0.1 μm InP HEMT process. The device features four 40 μm contact fingers in a 3.4 × 1.2 mm chip, and consumes just 30 mW of power.

Samsung orders Anadigics' MMICs

Anadigics has received production orders from Samsung for CATV tuner ICs for use in a new digital set-top box. Anadigics' ACU2109 upconverter provides the distortion and gain flatness performance required for simultaneous reception of 256-QAM digital and analog video signals, in turn enabling increased channel capacity for CATV broadcast services. This part is paired with the ACD2202 downconverter, which employs both GaAs and CMOS technology to provide dual synthesizer functions in a double conversion tuner (see p37).

Rockwell and UCSB develop Sb-based ICs

Rockwell Scientific Company (formerly Rockwell Science Center) has received a contract worth $6.4 million from the US Space and Naval Warfare Systems Center, under the sponsorship of DARPA, to develop ultra-low power ICs for use in high-speed digital and millimeter wave applications. A major objective of the program, which is scheduled to last 3 to 4 years, will be the development of ICs using antimony as a primary constituent. Rockwell Scientific will combine the properties of Sb-based ICs with new techniques of circuit fabrication currently being developed at the University of California at Santa Barbara (UCSB). The aim is to produce a robust, manufacturable circuit process, initially for insertion into defense and space applications. This will include mixed signal ICs used in high-frequency circuits operating up to 160 Gbit/s and low noise amplifiers (< 1 dB) used to amplify weak signals in front-end receivers. Markets also exist for high-speed (low-resolution) analog-to-digital converters used in digital oscilloscopes, in addition to digital cameras and CD players.



ROCKWELL SCIENTIFIC

Rockwell Scientific and UCSB will collaborate on antimony-based compound semiconductor (ABCS) systems to provide high-speed low-noise circuits. InAs/AlGaAsSb HEMTs and HBTs offer the potential for 4× lower operating voltage than GaAs devices, and a higher cutoff frequency and lower operating voltage than comparable InP HEMTs.

Superior properties

The antimonide system being investigated employs AlGaAsSb confinement barriers and InAs active regions to make heterostructures that offer improved electronic properties compared to GaAs and InP. These properties include a higher electron velocity because the channel can be made with 100% indium, rather than 53% indium for lattice-matched InGaAs/InP devices. The higher In concentration increases the carrier velocities and raises the operating frequencies. In addition, the mobility is also as much as 5× higher than GaAs, which leads to a much lower channel access resistance and therefore improved RF gain.

Turn-on voltages are also reduced due to the smaller bandgap of InAs, leading to lower power consumption. The latter favors the device for high-speed, low-power circuits, but makes them inappropriate for high breakdown voltage applications. Both HEMT and HBT structures will be grown by MBE using UCSB's reactor, in addition to a new MBE reactor obtained for the project at Rockwell Scientific's facility in Thousand Oaks, California.

"Rockwell and UCSB will be working in parallel to develop device circuits and a manufacturing process for InAs/AlGaAsSb heterostructures," says Bobby Brar, manager of Advanced III-V Devices at Rockwell Scientific. "UCSB has a framework for a process already, and has for example demonstrated AlInAs/GaInAs HBTs with f_{max} values in excess of 800 GHz. Similar circuit designs for the new Sb-containing compounds will thus offer great benefits in terms of high-speed performance and low power consumption."

Some challenges ahead

"Sb-containing HEMTs and HBTs lead to a number of important gains, including the potential for millimeter wave devices with superior noise figures compared with InP HEMTs, but you also inherit a couple of disadvantages," says Mark Rodwell of UCSB's Department of Electrical & Computer Engineering. "Major advantages include an increased carrier velocity and 2D sheet carrier concentration, and reduced bulk and ohmic contact resistances." These properties together should provide an FET with a higher f_t value and lower source resistance, which are excellent parameters for achieving devices with low noise figures. However, the bandgap of the InAs channel is small and this leads to challenges in managing avalanche breakdown. "This breakdown phenomenon adds noise and offsets gains in noise figure," explains Rodwell. "In addition, the potential of the material system is also contingent on circuit design and other device specifications being met."

There is also the problem of suitable substrates. There is no insulating substrate lattice-matched to InAs, which is a requirement for HEMT devices used in RF applications. According to Brar, Rockwell Scientific will first employ lattice-matched conducting GaSb or InAs substrates to grow low-defect-density device layers. UCSB's wafer transfer process will then be used to remove the substrate before adding a suitable insulating substrate, such as GaAs. Rodwell notes that the transfer process is just one of the ways ahead, and device growth on GaAs substrates is also being investigated. However, work by Rodwell's group and others (i.e. HRL Labs and TRW) has resulted in high dislocation densities.

RFMD ships PAs for Sendo's handsets

RF Micro Devices has begun production shipments of MMIC PAs for use in Sendo's new S200 dual-band GSM (900/1800 MHz) mobile handset. Sendo, based in Birmingham, UK, is selling the new phones in the European and Asian markets.

"Our GaAs HBT power amplifiers provide Sendo a low-cost, high-performance solution that complements their emphasis on performance at a cost-effective price point," said Joe Grzyb, director of RFMD's PA product line. "We believe that handset manufacturers such as Sendo will continue to value RFMD's technology leadership and our ability to meet production requirements at cost-competitive prices."

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Filtronic announces strategic alliances

Financial results from Filtronic

Results for financial year ending May 31, 2001	Sales ($ millions) 2001	2000	Profit ($ millions)* 2001	2000
Filtronic plc	416.4	311.2	17.0	12.0
Filtronic Compound Semiconductor (FCS)	15.7	10.1	(20.9)	(11.5)

**Before goodwill amortization and impairment, and share compensation.*

The problems at Filtronic Compound Semiconductor (FCS) look closer to being resolved with the announcement of alliances with RF and microwave components manufacturer M/A-COM, and BAE Systems, a UK-based defense OEM. The separate agreements will see FCS supply large volumes of GaAs devices to M/A-COM for mobile handsets, WLANs and other commercial markets. The agreement with BAE Systems is for the development and supply of devices for defense applications. Filtronic had stated earlier this year that it was seeking partnerships to help stem losses at its GaAs MMIC production facility in Newton Aycliffe, UK (see *Compound Semiconductor* July 2001, p25). The table shows Filtronic's recently announced financial results, including a loss of $20.9 million from FCS before deductions.

"The combined effect of these agreements will be to improve the cash flow and profitability of the Newton Aycliffe operation significantly," said Filtronic's executive chairman David Rhodes. "The site is expected to move into profitability in the financial year beginning June 1, 2002."

"GaAs MMIC technology is a key element of many of our existing and future products throughout the company," added Christopher Snowden, CEO of FCS. "In addition to the needs of M/A-COM and BAE Systems, we will continue to fulfill Filtronic's increasing internal requirements. We remain confident that the high yields achieved at Newton Aycliffe, together with high-performance and highly competitive design processes, will address market conditions."

Although they have established separate agreements with Filtronic, M/A-COM and BAE Systems are linked by an agreement involving the former Sanders GaAs fab in Nashua, NH. In July 2000, it was announced that M/A-COM would share the new 6 inch wafer processing facility being built by Sanders; the following month, Sanders was acquired by BAE Systems North America. As well as its two GaAs fabs in Lowell, MA and Colorado Springs, CO, M/A-COM owns the former ITT GaAsTek facility in Roanoke, VA, although sources suggest that the Colorado facility is now closed.

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AOI gains funds for 1550 nm VCSELs

Applied Optoelectronics Inc (AOI), a company that manufactures mid-infrared quantum cascade lasers, has raised $10 million in a second round of funding and introduced its first VCSEL products, which operate at 1550 nm. This places AOI among the few companies, including Bandwidth9 and Nortel's CoreTek division, which are commercializing devices at this wavelength.

AOI's new single-mode VCSELs are based on an external cavity laser design, and target metro applications. According to the company, a planned expansion of its development activities and production capacity, primarily for packaging and testing, will help to meet demand for these devices, which it began shipping in prototype quantities last November. AOI received ~$7 million in first-round funding last year, and operates a vertically integrated 24 000 sq. ft manufacturing facility in Sugar Land, Texas (see *Compound Semiconductor* Dec 2000/Jan 2001, p23).

"This is a tremendous vote of confidence in Applied Optoelectronics and our VCSEL technology from our investors," said Thompson Lin, president and CEO. "With this infusion of capital, we will be able to accelerate the development and manufacture of new long-wavelength laser products. By leveraging our extensive experience in MBE growth of semiconductor laser structures, we have created a product that is squarely targeted at the metropolitan area network with link distances of 80 km or less."

VCSEL developments

According to AOI's director of marketing, Stefan Murry, the company is developing several different 1550 nm VCSEL designs. The device currently being shipped is an optically-pumped external cavity VCSEL. The company manufactures the VCSEL structure and obtains the external cavity components from an outside source. Featuring a tuning range of 25–30 nm, the VCSEL achieves an output power of 6 mW in CW mode. "We also plan to introduce a range of electrically-pumped monolithic 1550 nm devices with 1 mW output sometime towards the middle of next year," says Murry. "These will be 2.5 Gbit/s emitters, and will include single VCSEL devices, and tunable VCSELs."

The new monolithic VCSELs will employ InP substrates and contain InGaAsP active regions grown using the company's MBE systems. "We are addressing two major areas that have been preventing the proliferation of VCSELs at longer wavelengths," says Murry. "For the monolithically-grown DBR mirror stacks, we have improved the reflectivity of the layers, which has enabled us to reduce the total thickness of these stacks. This allows more heat to be removed from the active region, which is an important factor at longer wavelengths due to temperature-dependent losses such as Auger recombination. We have also optimized the active region by employing materials with improved gain properties compared to existing systems. The result is higher gain and lower loss, which increases the VCSEL output power."

Agere Systems files lawsuits against component rival Multiplex

Agere Systems has filed two lawsuits against Multiplex, a rival manufacturer of fiber-optic components. The first was filed in the US District Court for Delaware and alleges that Multiplex infringed four patents related to optical components and subsystems, including lasers and multiple quantum well modulators. According to Agere, the infringements relate to technology for pump lasers and for emitters used in short- and long-haul applications. Also included is technology designed to improve laser performance by reducing current leakage, and a method of improving waveguide structures.

The second lawsuit, for property theft, was filed at the Superior Court of New Jersey Chancery Division and alleges Multiplex has wrongfully possessed Agere optoelectronic device wafers and other related proprietary property. Agere is seeking monetary damages for Multiplex's infringement of its patents, and recovery of its property, in addition to an injunction against further infringements.

AGERE SYSTEMS

Multiplex has close links with Bell Labs, the research arm of Lucent Technologies which is also the parent company of Agere. Multiplex's CEO and president, Won Tsang, is the former head of the Semiconductor Photonics Department at Bell Labs. Tsang founded Multiplex in early 1998 together with several of his Bell Labs colleagues, including Tawee Tanbun-Ek, now VP of materials technology at Multiplex. According to the Multiplex Web site, Tanbun-Ek was "mainly responsible for the development of Lucent's major laser products, such as the 1550 nm directly modulated 2.5 Gbit/s laser and the 2.5 Gbit/s electro-absorption modulated laser." David Tzeng, VP of technology and manufacturing for photoreceivers, is also a former senior Bell Labs employee.

Agere launches transceiver range

Agere has upgraded its product line to include a new set of plug-in transceivers, 10 Gbit/s PIN receivers, and 2.5 Gbit/s receivers (see photo). Its NetLight 2417 transceiver range is now able to accommodate a temperature span of –40 to +85°C, making them suited for non-controlled telecom carrier environments, in addition to datacom applications. The R192P is the company's new 10 Gbit/s PIN receiver that forms part of a small-form-factor MSA with companies such as JDS Uniphase, Toshiba and Fujitsu. Finally, the 2.5 Gbit/s P172 APD detector also operates from –40 to +85°C.

OpNext closes $321 million investment

OpNext Inc, a supplier of active fiber-optic components and modules based in Eatontown, New Jersey, has received an investment worth $321 million from Clarity Group, a Los Angeles-based investment firm, and Marubeni Group, a trading house based in Japan. OpNext was formed from Hitachi's Fiber Optic Components business unit (see *Compound Semiconductor* Sept/Oct 2000, p43). The company says it will use the capital to expand manufacturing capacity, establish a worldwide sales and marketing team, grow its R&D program and develop new products.

OpNext manufactures a range of components, including 2.5 and 10 Gbit/s laser diode modules, transmitters and receivers, and is also collaborating with TRW's new telecommunication components company, Velocium, to develop 40 Gbit/s transceivers.

"Hitachi's heritage as a leader in semiconductors, optical lasers and transceivers, combined with a proven history of reliability and customer satisfaction, provides a tremendous base upon which OpNext will build its components and modules business," said OpNext chairman Masaaki Hayashi.

VSK moves into InP production facilities

VSK Photonics, a startup manufacturer of InP active optical components based in Lake Forest, CA, has moved into a new 21 000 sq. ft production facility. The company will produce InP-based photodetectors, modulators and lasers for transceivers and modules in 10 Gbit/s and next-generation 40 Gbit/s systems. Founded December 2000, VSK received $6 million in financing from Lighthouse Capital Partners to equip the new plant, which follows an $18 million investment earlier this year from Intel and Morgenthaler Ventures (see *Compound Semiconductor* May 2001, p15).

"From our beginnings as a startup with exciting technology, we have now reached the next stage of corporate maturity," said Don Ackley, president and CEO. "We are increasingly well-positioned to become an integral part of the communications industry's next growth phase."

Agility integrates modulators and amplifiers with its tunable lasers

Tunable laser manufacturer Agility Communications has successfully integrated an electroabsorption modulator into its widely-tunable sampled-grating (SG) DBR laser, which targets 2.5 and 10 Gbit/s metro core applications. Agility employs a monolithic InP device architecture to integrate functions such as modulation and optical amplification onto a single chip (see *Compound Semiconductor* November 2000, p34). A beta customer base of 30 companies includes startups such as Atoga, Network Photonics, and Mahi, which are currently sampling Agility's 4 mW C-band (1525–1565 nm) tunable laser.

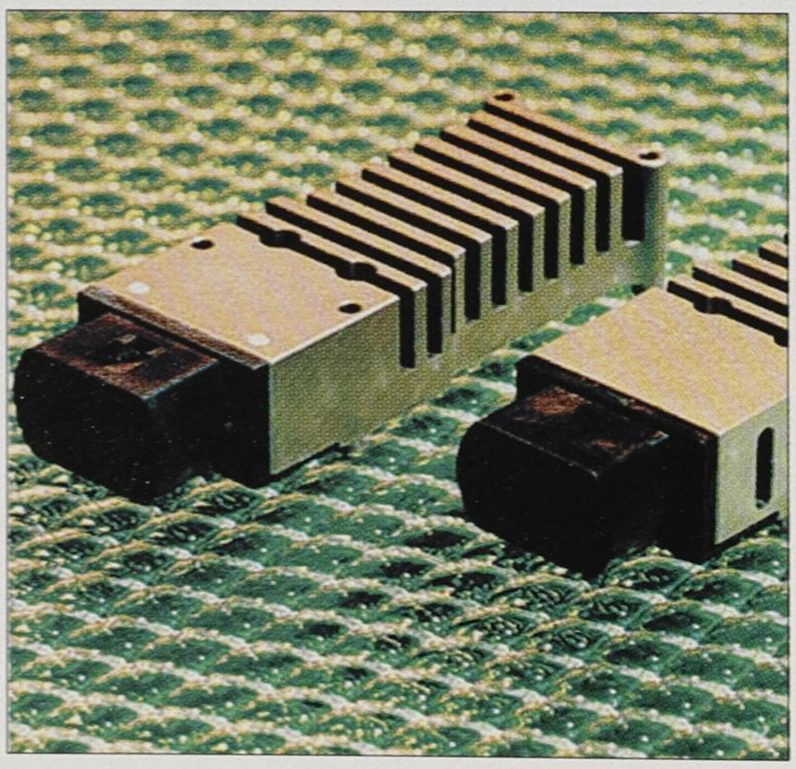
"The significance of the electroabsorption modulated laser technology is that we're able to integrate both the amplifier and modulator and still get the same yields we've achieved with our other lasers," explained Ron Nelson, Agility's president and CEO. "By integrating many capabilities onto one chip, we lower the overall capital and operating expenditures for carriers," he said.

In Agility's device, a semiconductor optical amplifier and modulator are integrated after the front mirror of the SG-DBR laser. The company says the inclusion of an optical amplifier compensates for a trade-off in power that occurs when designing with a wide tuning range cavity design, which in Agility's case includes 91 ITU channels spaced at 50 GHz with a side mode suppression ratio of 40 dB. The device offers over 18 mW of power across the C-band with less than 1.5 dB variation in power, and is housed in a 2 × 3 × 0.5 inch package.

Emcore unveils new 15 Gbit/s parallel optical interconnect

VCSEL device and array manufacturer Emcore has announced the production of 850 nm parallel optical array transmitter/receiver modules targeting high-speed data links, 10 Gbit/s VSR optical links used in optical interconnects, and datacom and telecom routers. The new transponder modules provide a data rate of 1.25 Gbit/s over 12 channels of multimode fiber ribbon cable to give an aggregate bandwidth of 15 Gbit/s. The power consumption is typically 2 W for the transmitter/receiver pair.

"In providing the market with a replacement for expensive serial interconnects, we have endeavored to ensure maximum manufacturing flexibility for our datacom and telecom customers," said Robert Bryan, VP of the company's Fiber Optics division. "The use of a ball grid array in Emcore's new product will ensure significantly easier manufacturing. Each module connects to external electrical circuitry using a compact BGA pattern on its underside, and therefore is one of the first optics that does not require special handling for insertion onto circuit boards. One of the many applications for these optics is to construct VSR transponders, which offer datacom and telecom equipment manufacturers significant cost and functionality advantages."



EMCORE

DRY IN/DRY OUT

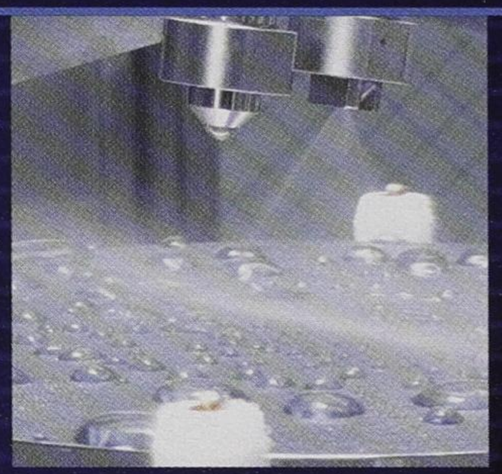
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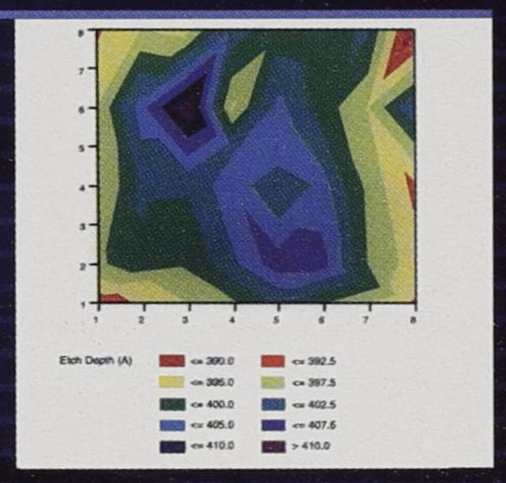
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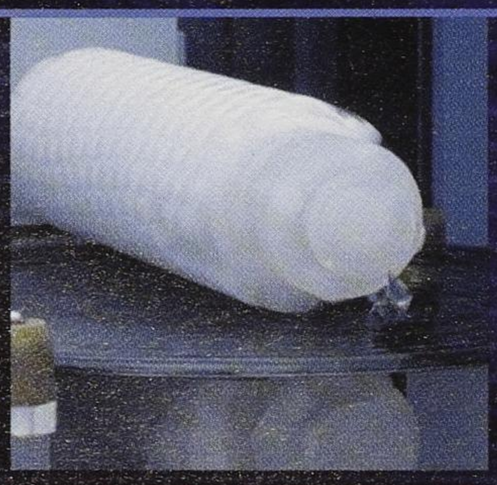
COMPLETE





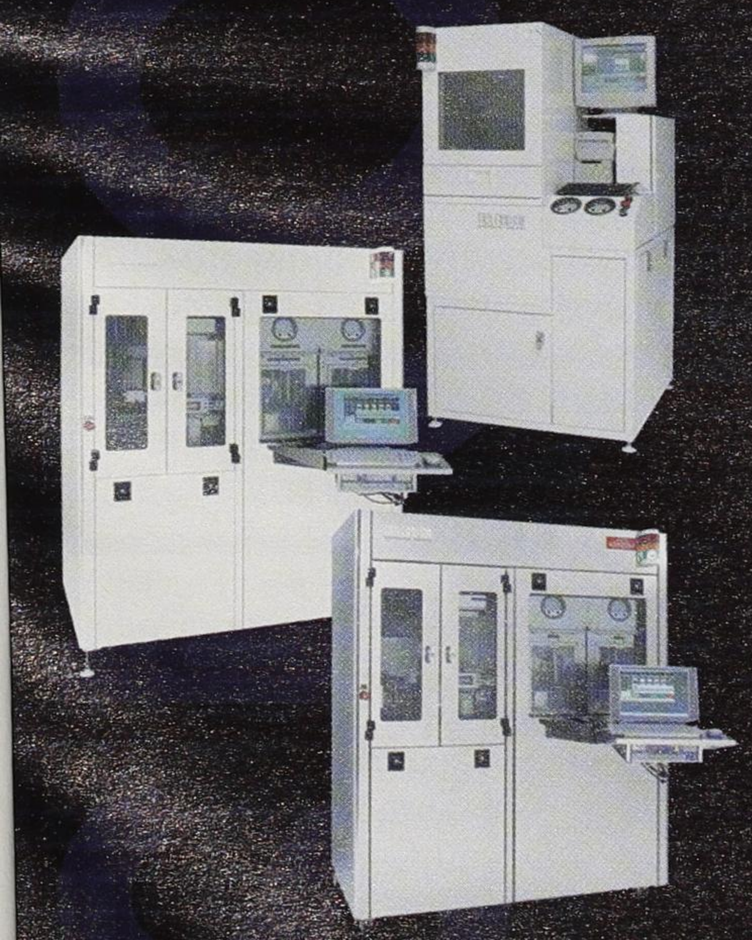
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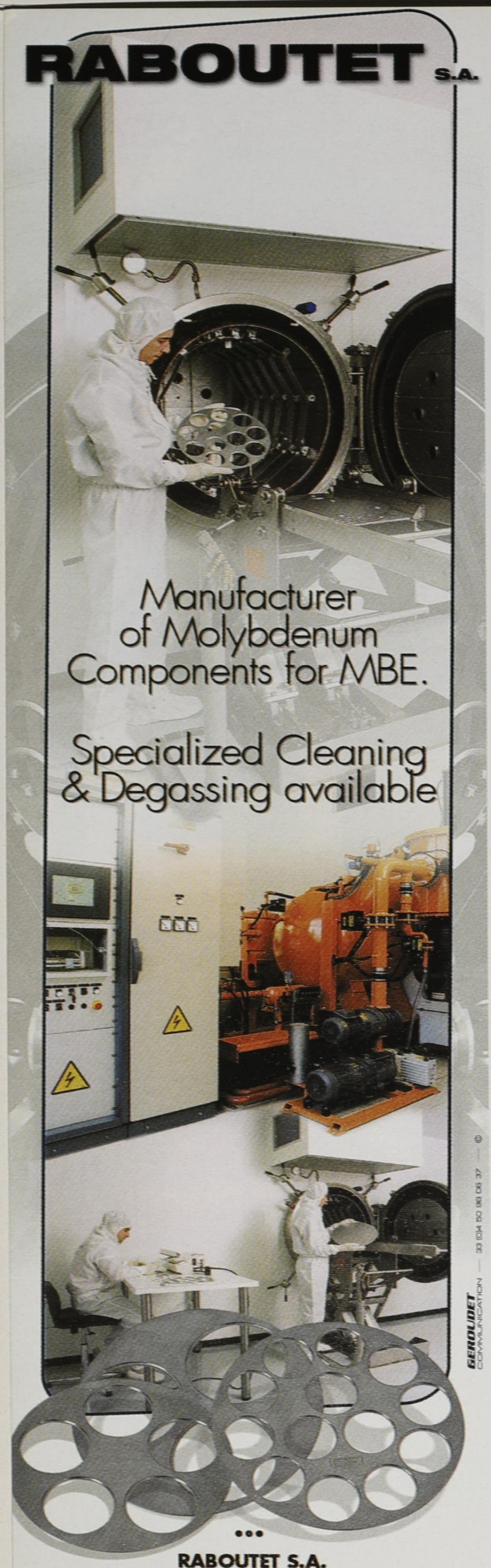
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Intense Photonics wins grant for optical switch

Intense Photonics (Glasgow, Scotland) has been awarded a $630 000 grant from the Scottish Executive to develop an optoelectronic packet switch. The device will integrate all of the components required for the routing of information packets on one monolithic chip. Intense sees this as the foundation for a new generation of optical network peripherals that will deliver very high bandwidth as and when organizations require it.

The project, expected to last 18 months, will use Intense Photonics' quantum well intermixing technology to monolithically integrate all the required devices onto one chip (see p63 for more details). These include lasers drivers and modulators, photodetectors, waveguides, multiplexers and demultiplexers. The resulting device will be one of the most highly integrated optical components ever made. "This is an ambitious project which will enable the world's telecommunications equipment makers to start building all-optical communication systems for mass markets," said Jim Ashe, VP of sales and marketing.

Alcatel sets new 40 Gbit/s world record

Alcatel has claimed a new world record in long-haul DWDM transmission by transmitting 32 channels at 40 Gbit/s over a distance of 2400 km in a laboratory demonstration. The 1.28 Tbit/s aggregate bandwidth was achieved using non-zero dispersion-shifted fiber and distributed Raman amplification. Raman amplifiers create less noise than EDFAs, a key feature for high-data-rate operation, and also allow for a significantly larger amplification bandwidth.

Agilent and Corning set to accelerate deployment of parallel-optics

Agilent Technologies (Palo Alto, CA) and Corning Cable Systems (Hickory, NC) are to provide a high-volume supply of new parallel-optics solutions, targeting high density interconnects for terabit switches and routers, server to server backplane interconnects and low-cost 10 Gbit/s SONET/SDH very short reach connections. Customers will gain access to Corning's passive optical technology and Agilent's active parallel-optics modules, which combine twelve 2.5 Gbit/s channels into discrete transmitter and receiver modules. These offer an aggregate data rate of 30 Gbit/s, and occupy only 1.5 inches of PC board.

"Agilent Technologies is the leading provider of high-speed active parallel-optics networking components," added Stuart Hoiness, VP of OEM sales and marketing for Corning. "As the industry's leading provider of passive optical products, we have invested heavily in both multi-fiber assembly performance and capacity, to support the industry's rapid move toward parallel networking. This alliance reassures customers of the availability of all the necessary active and passive products."

Nanovation fights to stay alive

Nanovation Technologies, which is developing photonic integrated circuits using a variety of material systems including InP, has filed a petition for bankruptcy protection in a US court. The filing, under Chapter 11 of the US Bankruptcy Code, gives the company 100 days to try to come up with a restructuring plan that will keep it alive. Nanovation, which has a 108 000 sq. ft manufacturing plant in Northville Township, Michigan, laid off two-thirds of its 169 employees at the end of July after its latest funding round fell through.

Alcatel Optronics acquires Kymata

Alcatel Optronics is to acquire privately-held Kymata (Livingston, Scotland), in a share exchange valued at $117 million. Kymata produces arrayed waveguide gratings for use in DWDM systems using silica on silicon technology. Alcatel Optronics is an established manufacturer of active components such as lasers, photodetectors and optical amplifiers. The acquisition is part of Alcatel Optronics' strategy to strengthen its planar waveguide expertise and passive component product lines with the aim of further integrating active and passive optical components.

"Kymata is a perfect match with Alcatel Optronics and will allow us to gain at least two years in time-to-market for planar products," said Jean-Christophe Giroux, CEO of Alcatel Optronics. "This acquisition is a crucial step in the implementation of our strategy of active/passive integration, which we consider to be key to the future. Kymata's high-end passive components complement our own high-end active component portfolio."

AXT debuts 1550 nm FP source lasers

AXT (Fremont, CA) has introduced a range of 1550 nm edge-emitting Fabry–Perot (FP) lasers operating at 2.5 Gbit/s for SONET transceivers used in metro and long-haul applications. Exhibiting a high-temperature power output of 10 mW at 85°C and peak linear power of 20 mW, these devices offer threshold currents of 10 mA and slope efficiencies of up to 0.5 mW/mA. The new laser is currently being sampled, with volume quantities expected later in the third quarter.

"We are very pleased with the performance of our new 1550 nm lasers," commented Morris Young, president and CEO. "In a very short period of time, we have developed a world-class product that has numerous uses in rapidly growing markets such as metro area networks. Our power output exceeds that of most other 1550 nm lasers currently available, and the efficiency is approximately 50% better than most. This will help our customers achieve more aggressive transceiver designs with fewer cooling requirements."

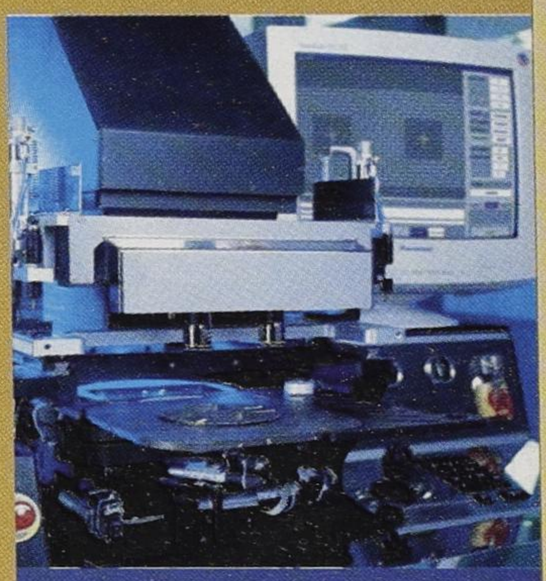
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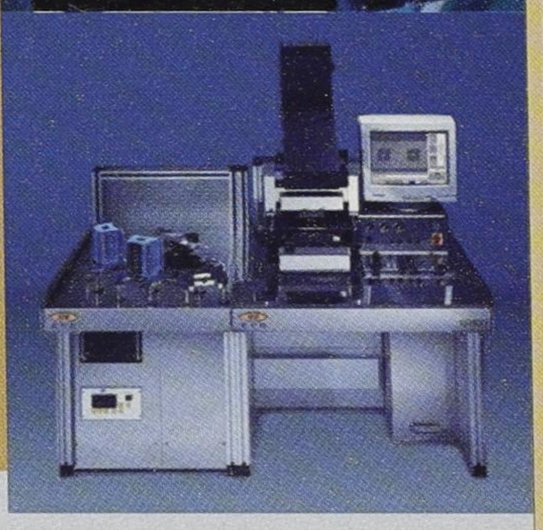
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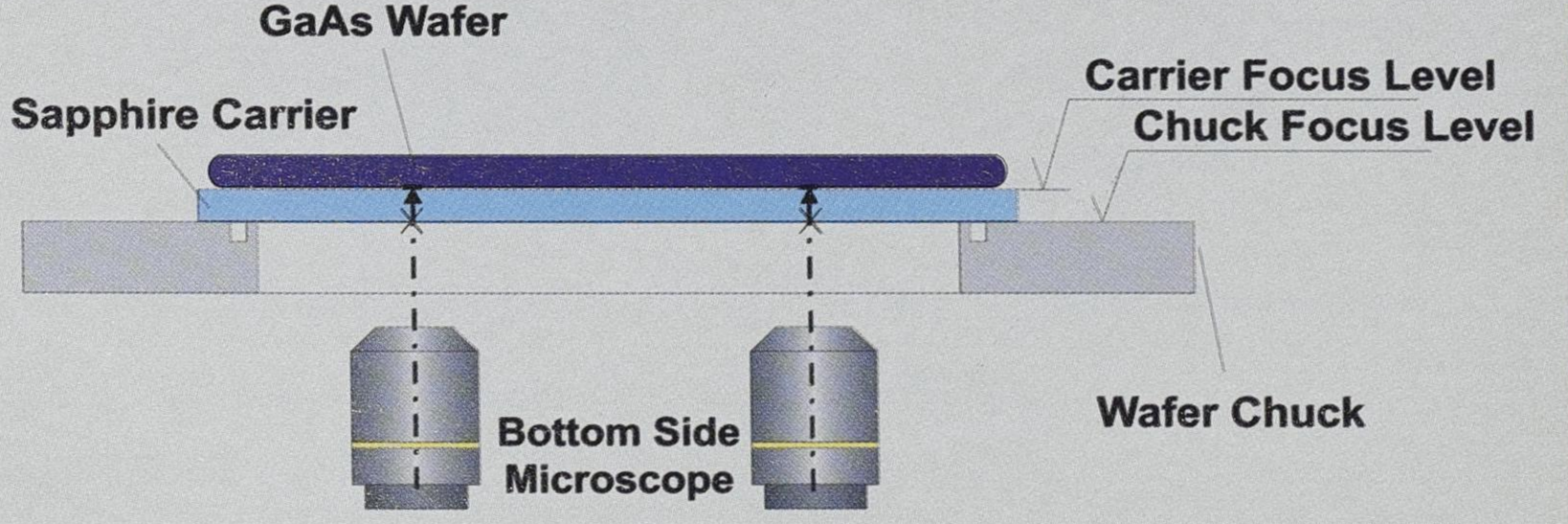
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Osram lays foundations of new LED plant

Osram Opto Semiconductors has laid the first stone of a new facility for fabricating chips for LEDs, laser diodes and sensors. Located in Regensburg, Germany, the 40 000 m^2 (~430 000 sq. ft) site is due to begin LED production at the end of 2002, at a cost for the first construction phase of around €120 million (~$105 million). The Regensburg site was chosen primarily as a result of the region's skilled workforce, but the company says the proximity of LED chip fabrication to its R&D department in Regensburg was also a contributing factor.

"By the time production is running we plan to have 1600 people working on this site, and we'll be creating around 500 new jobs," explained Osram president Wolf-Dieter Bopst. "The current site at Regensburg-West is not large enough to cope with the rapid growth in capacity. There are plans initially to run the factories in parallel, then switch production entirely to the new site at a later date."

UV Florida project targets ultraviolet LED development

Uniroyal Optoelectronics has announced a long-term collaborative project with three Florida-based universities to accelerate the development of UV LEDs for efficient white light emitters. Known as "UV Florida", the initial goal will be the development of AlGaInN LEDs operating from 350 to 400 nm in combination with tri-color phosphors. The company says UV LEDs packaged with such phosphors generate brighter, more efficient white sources than emitters based on the combination of a blue LED and yellow phosphor converter.

As part of the joint initiative, the University of Florida will focus on epitaxial growth and processing of UV LED devices, while the Universities of South and Central Florida will provide structural determination and electrical and optical characterization respectively. The project will be funded in part by a Florida State R&D incentive program, and supplement UOE's existing R&D program.



UNIROYAL OPTOELECTRONICS

"The development of efficient blue and even shorter wavelength solid-state light-emitting devices represents perhaps the most significant technological breakthrough in the last decade," said Tim Anderson, professor and chair of chemical engineering at the University of Florida. "This advance should have a broad impact on a variety of technologies, and UOE has the opportunity to become a major manufacturer of devices for this market."

Hong Kong University to develop blue and green LEDs

The Hong Kong University of Science and Technology (Kowloon, Hong Kong) has received HK$15 million (~$1.9 million) to develop and manufacture high-brightness blue and green LEDs.

The funding came from the Innovation and Technology Fund, an agency that incubates technology in the region, and was supplemented by sponsorship worth HK$4.5 million (~$570 000) from three local LED companies. These included LED lamp and display maker COTCO, LED producer Strong Base Investment and Lighthouse Technology, which also makes LED displays. The project is also supported by an equipment grant from Aixtron, while Epichem will assist with the supply of metalorganics.

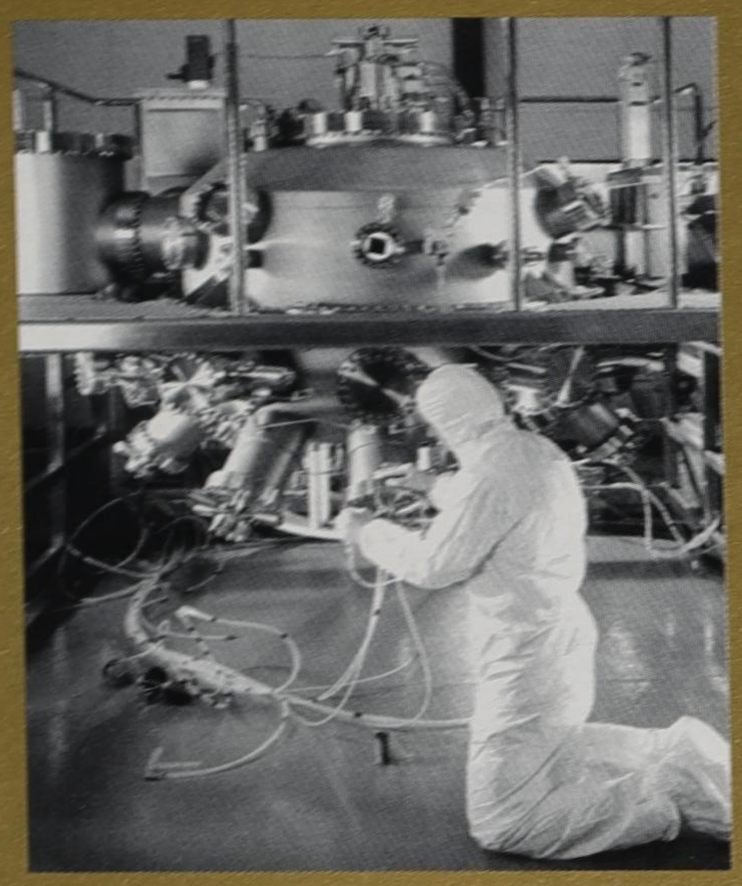
"Currently, local LED companies have to rely on overseas suppliers for processed LED chips, as Hong Kong lacks both the technology and infrastructure to develop its own inorganic LEDs," said project coordinator Kei May Lau. "Through this initiative we will design, fabricate and test prototype LEDs before transferring the technology to industry. Local companies can design their devices for their own specific applications to be integrated with their systems. Moreover, Hong Kong will also benefit from a pool of locally trained experts specializing in LED device design and processing."

Cree's high-power UV LEDs target illumination markets

Cree has introduced a new 405 nm UV LED for illumination markets, including automotive interiors, cell phone backlights and displays. The InGaN-on-SiC device provides an output of 12 mW at 20 mA, and employs a chip with a junction area of 240 mm × 240 mm. Cree claims the device is the brightest nitride-based LED currently available. The LED, which will be used primarily to produce white light in combination with a suitable phosphor, results from a collaborative R&D effort between Cree and the Advanced Technology Program of NIST, the US department for standards.

"UV LEDs offer a superior approach to producing white light compared with alternative methods using blue LEDs with a yellow phosphor coating," commented Jim Speck of UCSB's Solid State Lighting Center. "This is due to better color rendering, manufacturability, color temperature and control. Cree's UV chip will play a critical role in developing new white light applications." Cree is currently sampling devices and will begin volume production later this year.

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2 *An hydraulic trolley is rolled underneath and takes the weight of the bottom half of the growth chamber. The four locating bolts are quickly removed.*

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3 *The trolley is lowered at the touch of a button and the entire lower section of the growth chanber is wheeled out for easy cleaning and source loading.*

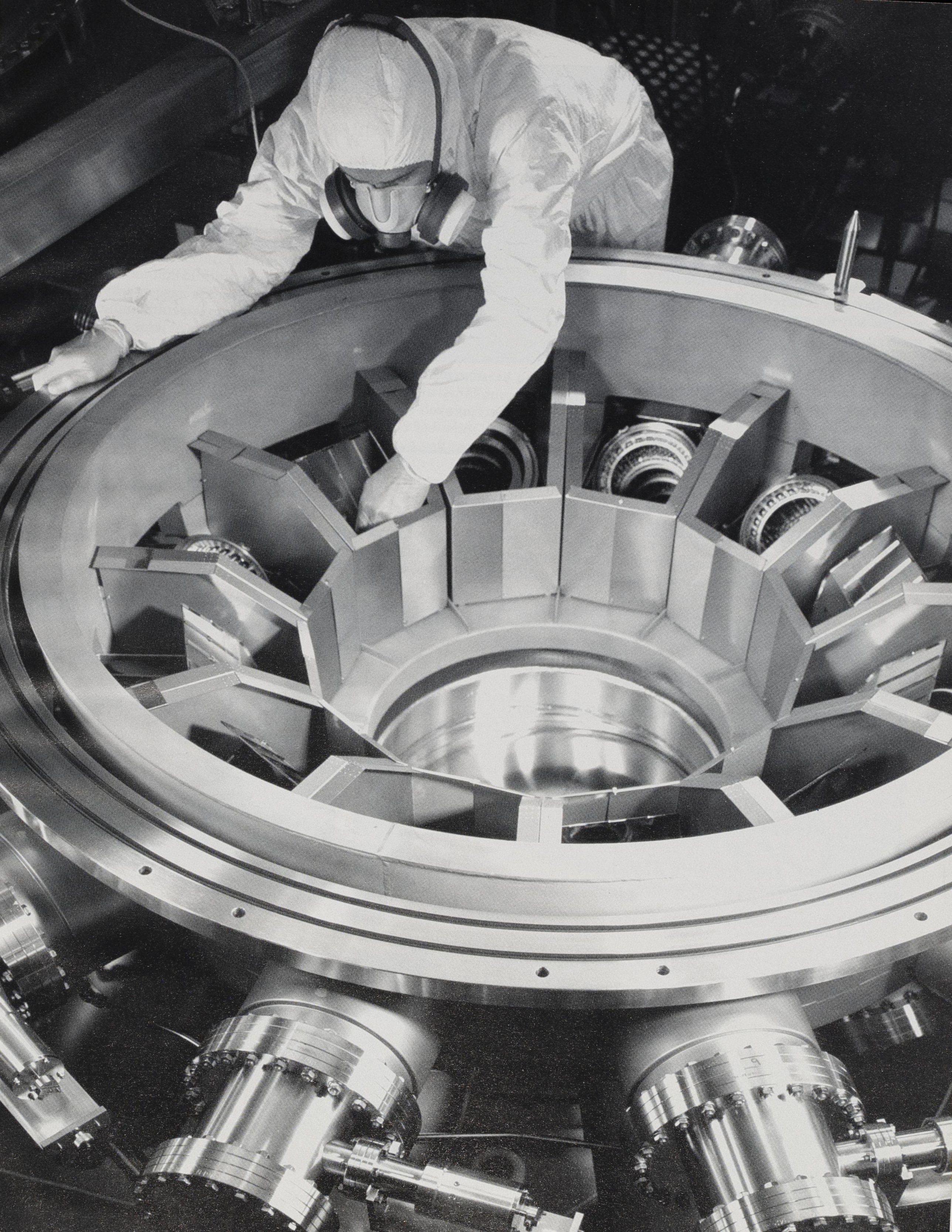
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Rohm forced to explain its actions in court case against Nichia

More information has emerged about Rohm's complaint against Nichia that was lodged with the US International Trade Commission (ITC) in December 2000. Although Rohm subsequently withdrew the complaint (see *Compound Semiconductor* June 2001, p10), an ITC judge has now ordered Rohm to explain exactly why the complaint was lodged in the first place. Nichia claims that Rohm "used the ITC to further an alleged conspiracy to exclude Nichia from the US market" and "improperly obtained and attempted to enforce patents that it knew were invalid".

In its original ITC submission, Rohm alleged that two of its US patents relating to nitride-based emitters were being infringed on by Nichia. Rohm sought damages and an injunction against Nichia to prevent importation into the US of certain of Nichia's LED products. The ITC has the power to block imports that can harm domestic industry in the US. Since Rohm and Nichia are both Japanese companies, the ITC would not normally have jurisdiction in such a case.

However, Nichia contends that Rohm fabricated the existence of a domestic industry by establishing a relationship with Cree, solely to invoke ITC jurisdiction in the case. In December 2000, three days prior to filing the ITC complaint, Rohm entered into several agreements with Cree (see *Compound Semiconductor* February 2001, p8). One of these granted to Cree an exclusive five-year license to use the technology disclosed in the same US patents that were at the center of the ITC complaint. Rohm and Cree also signed a purchase agreement for LEDs, and agreed to co-operate in the development of nitride-based lasers.

Court documents from the ITC state that "the allegations concerning the licensing arrangements between Rohm and Cree raise serious questions of potential abuse of Commission processes".

Nichia licenses LED color-change method

Nichia has licensed technology from researchers at Kyoto and Osaka universities in Japan that can be used to adjust the color of light emitted by LEDs. Kansai Technology Licensing Organization, which transfers technology from academia to industry, has applied for a patent in this area and will grant a non-exclusive license to Nichia. The technique combines the light from the LED and emission from rare earth complex ions embedded in a transparent plastic covering (see *Compound Semiconductor* July 2001, p15).

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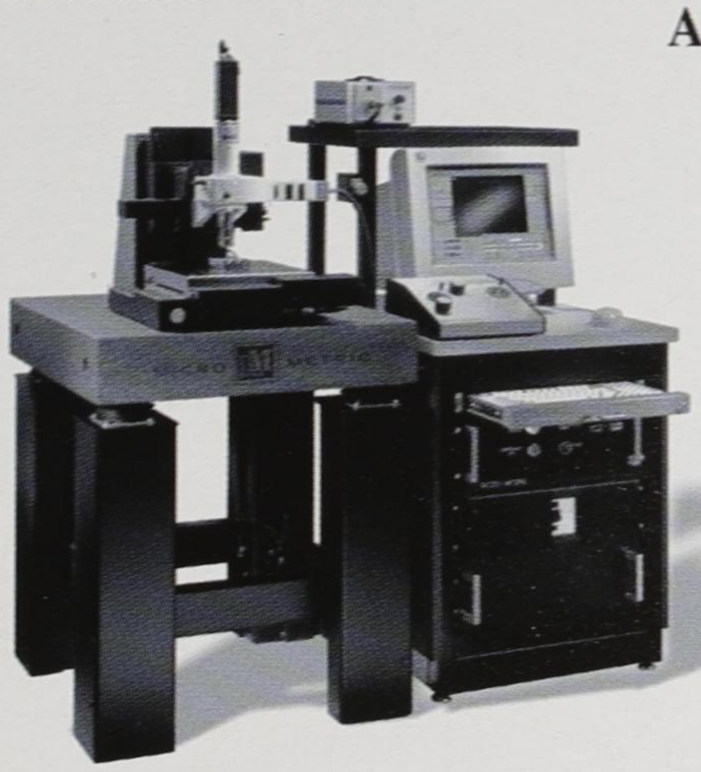
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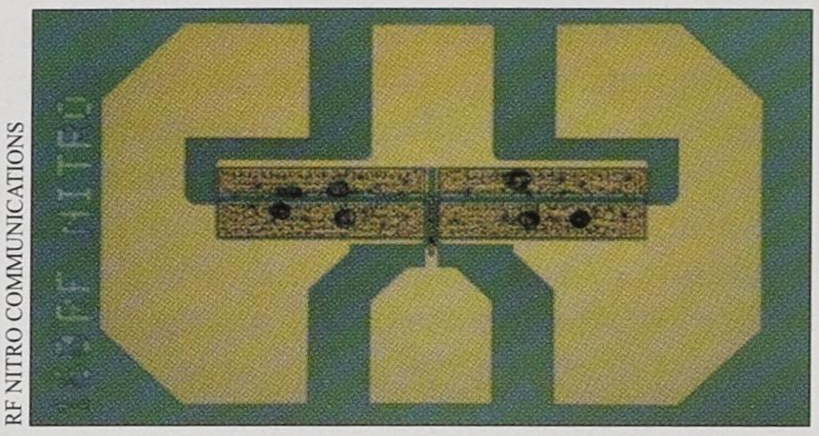
RF Nitro debuts GaN HEMT transistors

RF Nitro Communications, a manufacturer of GaN products based in Charlotte, North Carolina, has introduced its first AlGaN/GaN transistors. The company first demonstrated GaN-based VCOs in February of this year, and has now made available for evaluation prototype transistors fabricated on either sapphire or semi-insulating SiC substrates.

Applications for the company's HEMTs, which offer wide bandwidth operation and breakdown voltages approaching 100 V, include high power switching, driver amplifiers, electro-optical modulators and oscillators.

To date, RF Nitro has grown GaN devices by MOVPE in an 8 × 2-inch production reactor (see *Compound Semiconductor* Sept/Oct 2000, p17). The company says that its AlGaN/GaN-on-sapphire HEMTs offer the advantages of a low cost substrate, and deliver a power density of up to 2 W/mm at 10 GHz. AlGaN/GaN-on-SiC HEMTs dissipate more heat than devices grown on sapphire, and allow higher voltage operation, in addition to a power density of 6.6 W/mm at 10 GHz.

"Large-diameter sapphire costs approximately $100 per substrate, and GaN-on-sapphire offers superior insulating properties, lower defect density, higher frequency performance, and superior power performance over GaN-on-silicon approaches," said Joseph Smart, VP of advanced materials. "SiC substrates are expensive, but GaN-on-SiC offers the best combination of frequency and power performance for high-power applications."



RF Nitro has introduced prototype AlGaN/GaN HEMTs on sapphire and SiC. Power densities reach 6 W/mm for AlGaN/GaN-on-SiC devices, with breakdown voltages of 100 V and operation up to 10 GHz.

RF Nitro's NGN-125-D (Al)GaN-on-sapphire device features a coplanar design with a 1 mm periphery and gate length of 0.5 μm. Available in die form, the device provides a gain of 9.7 dB and saturated output power of 29 dBm, while the third order intercept (IP3) and noise figure reach +39.5 dBm and 3.5 dB, respectively (at 2 GHz). The cut off and maximum oscillation frequencies (F_t and F_{max}) are 16 and 26 GHz, respectively.

The company's (Al)GaN-on-SiC HEMT (NGN-225-D series) offers similar performance and features a 1.5 mm periphery, a gain of 8.6 dB and saturated output power of 31 dBm at 10 GHz. The IP3 value is 35 dBm and F_t and F_{max} are both 24 GHz.

Processing facility completed

RF Nitro has also completed a new facility for GaN epitaxy and wafer processing. Located at the company's headquarters in Charlotte, the facility houses class 10 and class 1000 clean rooms intended for the production of GaN-based heteroepitaxial structures and power transistors. The new facility will enable an expansion from 2 inch diameter epiwafer capability to 4 inch epitaxial growth using RF Nitro's patented high-throughput Flow Modulation Epitaxy (FME) technology.

According to VP of sales and marketing, B J Lyman, RF Nitro is currently using external foundry facilities to process its chips, and will begin producing 4 inch GaN epiwafers at its Charlotte facility by 2002.

"At present we have a prototype production facility that is undertaking high-frequency packaging of GaAs and GaN devices," says Lyman. "All of the NGN series of nitride products are presently at the evaluation stage, and we are now increasing the throughput of these devices to satisfy interest. In the near term, our GaN activity will evolve from discretes to MMICs, available in either chip or packaged form."

"This facility is indicative of our commitment to offer our customers a low-cost and high-performance GaN IC technology," added Jeff Shealy, president and CEO. "With this new facility, we will extend our market leadership from GaN epitaxial materials to GaN devices and amplifier circuits for wireless and wireline infrastructure."

Cree licenses "pendeo" patent for low-defect-density GaN growth

North Carolina State University (NCSU) has granted Cree an exclusive license for patented technology that allows the growth of low-defect-density GaN layers. Cree has licensed US patent no. 6,265,289, issued to NCSU on July 24, 2001, which describes methods of fabricating GaN layers and device structures using lateral growth from sidewalls into trenches.

The technique, known as pendeo-epitaxy, reduces the defect density of GaN grown on sapphire or SiC substrates. During conventional growth, lattice mismatch causes dislocations that propagate in the vertical growth direction, resulting in GaN with dislocation densities of around 10^8–10^9/cm^2. In pendeo-epitaxy, trenches are etched in a GaN layer and growth conditions are adjusted so that subsequent GaN growth occurs from the trench sidewalls (see *Compound Semiconductor* March 1999, p16). Since the dislocations do not propagate significantly in the lateral direction, defect densities are typically several orders of magnitude lower, which is important to the performance and longevity of certain devices, particularly lasers. The same effect is achieved using lateral epitaxial overgrowth (also known as LEO or ELOG), which requires the use of an SiO_2 or other mask.

Nitronex uses alternative technique

Cree is not the only company using the pendeo-epitaxy approach. Nitronex (Raleigh, NC), which is developing GaN-on-Si devices for RF and optoelectronic applications, has trademarked the term "Pendeo" to include its entire process from epitaxial growth to device fabrication. Nitronex has a number of patents in this area, including several licensed from NCSU.

A search of US patents unearths at least five documents covering pendeo-epitaxy and lateral growth recipes for GaN layers. All are assigned to NCSU, and some include authors who now work at Nitronex. While Nitronex has not revealed which patents it has licensed from NCSU, the company says there is no intellectual property overlap with Cree's technology. "There are many ways to grow lateral epitaxial layers of GaN," says Warren Weeks, who heads up Nitronex's optoelectronics division. In fact, Nitronex has filed patents on its own proprietary approach.

Low-defect-density lateral growth

As well as including lateral growth of GaN outwards from trench sidewalls, the patent licensed by Cree describes how further reductions in defect density can be achieved if masks with windows are subsequently deposited. The GaN layer grows upwards through these mask openings and then also grows laterally, forming an overgrowth layer of low-defect-density GaN material.

Alternatively, further growth in the vertical direction can produce a plurality of trenches, which are again used to grow lateral layers of GaN. Devices can then be grown on these surfaces.

"The issuance of this patent significantly extends Cree's portfolio of technology, critical in the development of high performance GaN-based devices," said president and CEO, Chuck Swoboda.

"Growing low-defect layers of GaN is essential to the realization of long-lifetime GaN-based laser diodes and other high-performance devices. We believe this patent strengthens our intellectual property position immensely, since it covers use of the patented process on any substrate."

Cree's first SiC Schottky diodes

Cree has begun shipping sample volumes of its first SiC Schottky diode chips. These will find application in high power circuits such as high frequency power supplies and motor controls. Typically, 50% of the power loss in a silicon PIN diode-based circuit arises because of the slow switching speed of the diode. SiC is able to operate at much higher speeds, virtually eliminating this source of power loss. It is expected that this will give an overall reduction in power consumption of between 4 and 7%, allowing smaller device sizes and reduced heat sink areas.

Initially two device types are being sampled, a 600 V, 1 A device and a 600 V, 4 A device. Cree are expecting to ramp up production during the first quarter of fiscal 2002, with additional products to be added over the next year.

In further news, a joint program with Kansai Electric Power Company has yielded record results for several high-power devices. A 6 kV MOSFET and a 5.5 kV JFET had on-resistances that were only 1/25 and 1/65, respectively, of the theoretical limit for the equivalent silicon devices. High voltage SiC PIN diodes have also been demonstrated with blocking voltages up to 19 kV, 50% over the previous record and double that from commercially available silicon devices.

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- Laser Diode Array

Laser Diode Array (Material:InP)

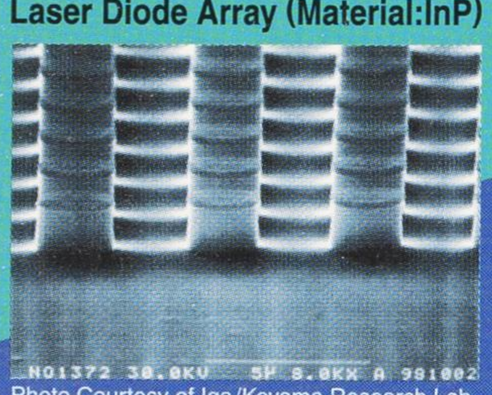


Photo Courtesy of Iga/Koyama Research Lab, Tokyo Institute of Technology



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NEC's spin-off takes shape

At the end of July, NEC's board of directors approved plans to transfer its compound semiconductor activities to a wholly-owned subsidiary, NEC Compound Semiconductor Devices Ltd, which will be established on 1 October 2001. Through this move, NEC aims to enhance the competitiveness of its optical and microwave devices business by concentrating resources and speeding up decision-making processes. The new company, headquartered in Kawasaki, Japan, will have working capital of ¥10 billion ($80 million) and estimated total assets of ¥28 billion ($224 million).

Pilot production at Knowledge*on foundry

Knowledge*on has commenced pilot operation of its new 6 inch InGaP HBT and MMIC foundry in Iksan, Korea. The operation, which is aiming for a capacity of 3000 wafers per month, will produce ICs for CDMA, GSM, Bluetooth and 3G applications, and 40 Gbit/s optical communications. In July, Knowledge*on announced a strategic partnership with Agilent Technologies to develop a design kit based on Agilent's Advanced Design System (ADS). This will provide MMIC and RFIC designers with easy access to Knowledge*on's InGaP/GaAs HBT foundry process. The two companies believe that this partnership will bring about an acceleration in growth of the GaAs pure play foundry business.

"We have made dedicated efforts to provide our customers with the best design-flow and design-support infrastructure to allow them to do their time-consuming design work with maximum efficiency," said Jae-Woo Park, Knowledge*on's CTO. "By supplying our foundry libraries embedded in the ADS design kit, RF engineers save time and money over the old method of working with raw foundry model libraries." With a pre-established design flow, designers are able to tackle the hardest circuit and system designs without worrying about the integrity of the design database.

Taiwanese foundries report progress

Global Communication Technology (GCT), one of Taiwan's new GaAs foundries, has raised an additional NT$750 million ($22 million) in capital, bringing its total funding to NT$2.2 billion ($64 million). Around half of the new funds will be used to buy equipment for GCT's GaAs operation, with a quarter each going to production of arrayed waveguide gratings and surface acoustic wave filters.

Another GaAs foundry in Taiwan, Suntek, has completed pilot production of 4 inch AlGaAs HBT wafers using technology transferred from Mitsubishi. Mass production will begin in October at an initial rate of 1000 wafers per month, rising to 5000 wafers per month at full capacity. The company also has plans to build a 6 inch fabrication facility (see *Compound Semiconductor* May 2001, p76), and is developing InGaP HBTs and other technologies.

More microelectronics news

NTT Basic Research Laboratories has developed a GaN/InGaN HBT with a gain of 20 for high frequency, high power applications. The device will find use in cellular base stations, WLANs and satellites, where its compact size and ability to handle high heat loads without cooling will save space and reduce costs.

A new GaAs MMIC from **Matsushita** has integrated into a single device, three functions required for transmission of video over fiber-optic networks. Intended for the home fiber-optic CATV market, the new device is 33% smaller than previous versions and halves the power consumption, operating at only 1.5 W.

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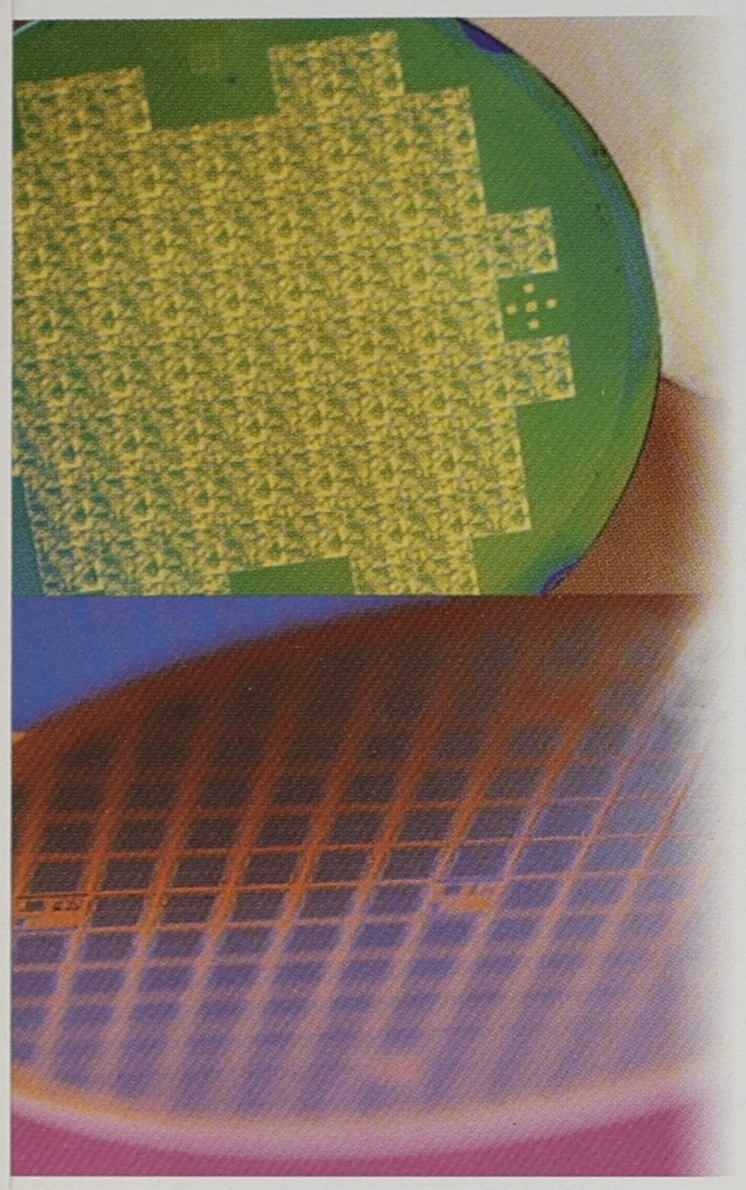
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News from wafer suppliers

Mitsui has invested $1 million in **Visual Photonics Epitaxy Company (VPEC)**, a Taiwanese epiwafer supplier. As part of the arrangement, Mitsui will market VPEC's products in Japan, Europe and the US, improving VPEC's visibility ahead of an expected share listing on the Taiwan Stock Exchange in September 2001. Mitsui is targeting annual sales of $50 million within three years; VPEC's sales in 2000 were $15 million.

Millennium Communication Co Ltd (M-Com) is an epiwafer specialist focusing on the fiber-optic communication market. Established in 2001 with $5 million in capital, M-Com operates a 1200 m^2 factory within the Hsinchu Industrial Park in Taiwan. The company, which employs around 20 people, quotes its production volume as 100–200 epiwafers per month. Somewhere around 97–99% of products are exported to markets in North America, Asia and Western Europe. M-Com manufactures epiwafers for a large variety of device types; these include edge- and surface-emitting lasers at 650, 850 and 980 nm, edge-emitters at 1310 and 1550 nm, InGaAs/InP and InGaP/GaAs PIN photodiodes, visible AlInGaP LEDs, and GaAs- and InP-based HBTs. Custom epiwafers are also available. For further information see www.geocities.com/mcommtw.

Tokyo Denpa has succeeded in producing a 1 cm^2 monocrystal of ZnO and is now trying to grow larger crystals with the intention of mass producing them within a year. ZnO is arousing interest because its wide bandgap makes it a candidate for production of blue LEDs and lasers. However, the development of devices based in this material system is hampered by a lack of suitable substrates, and Tokyo Denpa hopes that the availability of good quality single crystal ZnO will stimulate work in the area. Blue emitters using II-VI materials may eventually compete with GaN-based devices, where patent issues restrict market opportunities.

Semiconductor laser developments

Union Optronics (formerly Sirus Technology), Taiwan's largest manufacturer of red lasers, is planning to increase its output of 1310 nm lasers for the fiber-optic market from 10 000 to 200 000 units per month. The company, which has in-house epiwafer production facilities, was founded to produce 650 nm lasers for DVD players, and is now also developing VCSELs and PIN diodes.

A new laser diode from **Sanyo** has enabled the company to manufacture DVD drives with a 4× write speed, the fastest in the industry. In the device, laser light is confined within the active layer by controlling the refractive index of the cladding layers. This not only improves power emission by reducing loss from the active layer, but also makes the emitted beam shape less elliptical, effectively boosting output power by 20%. The output power of the laser is effectively 100 mW for a drive current of 150 mA. Reducing optical absorption at the facets has also increased the emitted power. This helps to lower the drive current required for a given output power, and improves the device lifetime.

Hitachi has developed a red laser emitting at 635 nm with a near circular beam. Most laser diodes have beams with aspect ratios around 3.5. Hitachi's new MARU Beam lasers have an aspect ratio of only 1.2, a figure claimed to be the best in the industry. Both products operate at 2.4 V and 25 mA with a 5 mW output power. Future plans are for higher output power versions and a reduction of the aspect ratio to 1.0.

Rohm has begun sampling an IR laser designed for CD-RW applications at 16× speed and higher. At 150 mW, the company is claiming the industry's highest output power for this class of device. The compact device comes in a 5.6 mm diameter package, operates at 120 mA and has a wavelength range of 780–788 nm. The device is fabricated using selective area epitaxy to give a reduction in optical power loss through absorption in the waveguides. Rohm guarantees 5000 hours of continuous operation thanks to the low optical density of the active region, which reduces catastrophic optical damage.

Fiber-optic products

NTT has developed a 1550 nm VCSEL requiring a drive current of 0.38 mA, which is only 1% of the current required for typical 1550 nm edge-emitting lasers currently used in long-distance fiber communications. Together with the more efficient fiber coupling inherent to VCSELs, the lower power consumption promises to offer cost reductions in optical communications systems. NTT's device features a lower GaAs/AlGaAs mirror wafer-bonded to an InP-based active region, with an upper dielectric mirror. The low power consumption is achieved by the use of a semi-insulating InP layer to define the active region. This confines the current to the active region and provides a light guiding effect, increasing the power efficiency of the device.

Increasing the levels of automation in fiber-optic component manufacturing is now recognized as crucial to lowering costs and improving uniformity and reliability. At present, fibers are often connected to components manually. **Toshiba Machine Co** has developed a device to automate fiber coupling by utilizing the control and alignment principles used in machine tools. The device positions the fibers in the placement grooves in components then welds them together using a laser.

Nissei Sangyo has recently made an agreement with US company **ADC** to import and to sell ADC's products in Japan. The contract covers ADC's wavelength-tunable transmitters and 980 nm pump lasers. Nissei Sangyo hopes sales of these goods in Japan will reach ¥300 million ($2.5 million) in the first year and ¥2 billion ($17 million) by 2003.

The Femtosecond Technology Research Association (FESTA), an organization of Japanese electronics companies including Toshiba, Fujitsu, Mitsubishi and NEC, has developed an ultra-fast semiconductor laser. Operating at the technologically important 1.5 μm wavelength, the device has been pulsed at a frequency of 480 GHz. FESTA claims that by incorporating the laser into a WDM system, an effective frequency of 1 THz may be achievable.

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Demand for 3G will aid components growth

Increased demand from the new generation of cellular handsets will fuel renewed growth for suppliers of components to handset OEMs, according to a new report from ABI. While recent market conditions have been difficult, long-term growth looks healthy as new subscribers are attracted by the new services on offer, and current subscribers upgrade their handsets. The report predicts the cellular IC market will double from $13.9 billion in 2001 to $26.4 billion in 2006.

The improved data services and increased functionality of 3G will push both silicon and GaAs IC manufacturers to higher levels of device integration. However, the delay in implementing 3G means that the development of integrated 3G IC products will also be held up. As a result, the bill of materials for 3G handsets when they do arrive will be higher than for the current generation, with the semiconductor value estimated at 49% more for 3G than 2.5G.

"*3G/Cellular Integrated Circuits*" is available from Allied Business Intelligence – see "www.alliedworld.com".

Fiber-to-the-building spurs US optical access growth

First mile connections to multi-tenant office buildings remain a strong growth area in spite of the overall slowing of growth rates in the fiber-optics industry. A new report from Communications Industry Researchers (CIR) sees the fiber-based competitive and building local exchange carriers (CLECs and BLECs) providing the impetus for growth in the optical access market. The report forecasts that fiber-to-the-building will spur this market to surpass $2 billion by 2005, with the number of fiber-connected buildings growing from 21 000 in 2001 to 43 000 in 2005. The table shows the different access systems: optical Ethernet systems will show the largest revenue growth, while free space optical access will develop a significant niche.

"*Optical Access: Next Generation Technology and Services in the First Mile*" is available from CIR – for further information see "www.cir-inc.com".

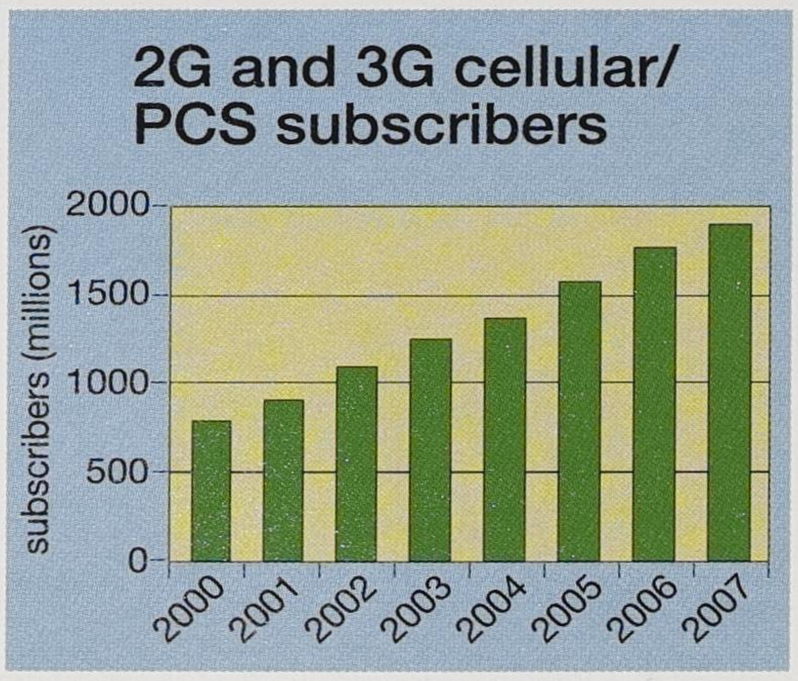
US optical access systems

Access system	Revenue ($ millions) 2001	2005
Optical Ethernet	66.4	447.2
SONET	668.4	851.1
WDM	53.6	168.9
Passive optical networks (PON)	48.9	396.3
Free space optics	22.3	289.5
Total optical access	**859.6**	**2152.9**

CIR

Wireless market looking healthy

Despite the economic slowdown in many areas of communication technology, the wireless market is still growing, according to a new study from Allied Business Intelligence (ABI). The narrowband market is evolving as carriers move to 2.5G and 3G networks. The study predicts that there will be more than 1.7 billion 2G and 3G cellular/PCS subscribers by year-end 2006, with 500 million of these using wireless Internet access. The move to the next generation of cellular technologies is good news for compound semiconductor IC producers, as infrastructure upgrades and replacement handsets will provide new orders.



ABI

On the broadband wireless front, local multipoint distribution services (LMDS), multichannel multipoint distribution services (MMDS) and unlicensed band fixed wireless are looking at healthy future growth, with the MMDS subscriber base expected to reach 14 million by 2007 (see *Compound Semiconductor* June 2001, p19). Fiber rings have been built out in many urban areas, but not connected to the last mile. Wireless broadband will allow operators to reach the local loop quickly and efficiently.

"*Wireless Systems Outlook*" is available from Allied Business Intelligence – see "www.alliedworld.com".

WDM leads growth in Asia-Pacific optical transport market

A new report from RHK shows that the market for wavelength-division multiplexing (WDM), SDH/SONET and DCS optical transport equipment in the Asia-Pacific region will grow 57% from the $3.9 billion spent in 2000, to $6.2 billion in 2001. The report predicts that the market will grow to $14.8 billion by 2004. This growth is being driven by deregulation of the markets in China and India, and increased Internet penetration.

The WDM segment is the fastest growing area of the Asia-Pacific market, and is expected to reach $1.4 billion in 2001. Lucent and Nortel lead the WDM market with shares of 33% and 11%, respectively. SDH/SONET is the second fastest growing segment, with equipment sales expected to reach $4.3 billion in 2001.

"*Optical Transport: Peoples Republic of China*" and "*Optical Transport: Japan and Rest-of-Asia-Pacific*" services are available from RHK – for further information see "www.rhk.com".

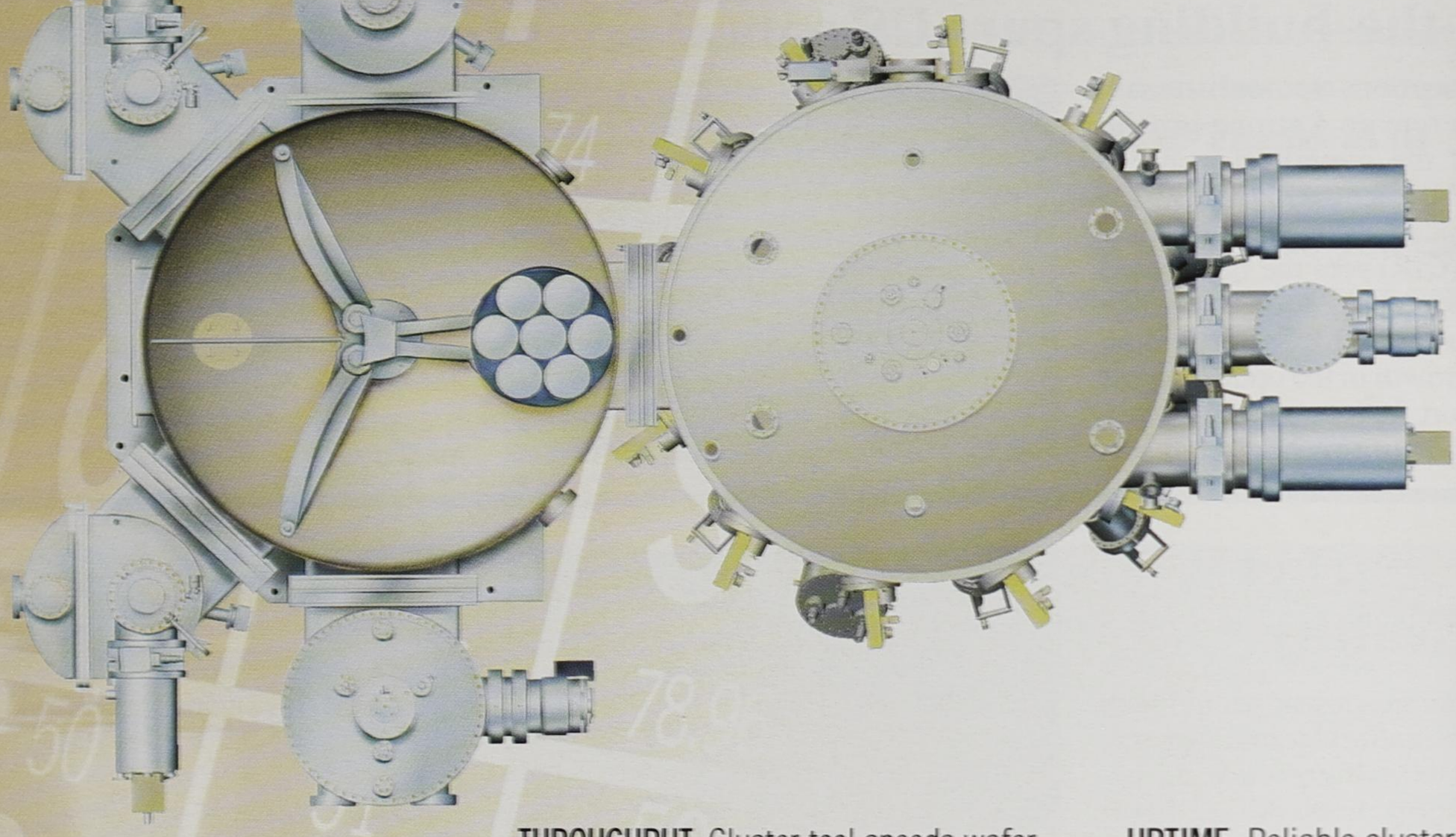
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Automotive radar drives mm-wave growth

According to a forecast released by Strategy Analytics, GaAs device demand from millimeter-wave applications will more than triple over the next five years. The market will grow from $530 million in 2000 to nearly $1.92 billion in 2005. Overall, transceiver shipments will grow from 1 million units to over 5 million units in 2005.

"Automotive radar based on 77 and 24 GHz will become the fastest growing market with a CAGR of 99%," said analyst Asif Anwar. Satcom and military markets are expected to show steady growth and the terrestrial point-to-point market will represent the second-largest millimeter-wave market.

"Broadband wireless (point-to-multipoint) solutions such as LMDS are currently failing to compete with cable modems and xDSL solutions and provide a cost-competitive alternative," Anwar continued. "This sector still holds potential but the major players have to converge on mutual standards for frequency and technology."

"GaAs Device Demand from Millimeter-Wave Applications" is available from Strategy Analytics – for further details see "www.strategyanalytics.com".

Optoelectronic ASICs surge forecasted

Application-specific ICs that control the optoelectronic layer in fiber-optic networks are a bright spot in the current industry gloom. According to a report from ElectroniCast, the global consumption of optoelectronic ASICs will climb at over 44% per year, from $1.32 billion in 2000 to $8.3 billion in 2005.

Amplifier and driver ASICs will continue as volume leaders, with a combined value share of 71% in 2000, but will decline to 46% by 2005. These components will be replaced by integrated multifunction ASICs, which include parallel links containing multiple channel transmit/receive units. This new category will reach 14% over the study period.

"This explosive growth will be driven by a very rapid expansion of transceivers and transponders in metro/access and intra-equipment links," said ElectroniCast founder and chairman Jeff Montgomery. "Plus there will be a significant shift to higher-priced ASICs for 10 and 40 Gbit/s systems, and to increased functionality ASICs used in 256 × 256 parallel links."

Speed and integration favor InP

Silicon's market share (including SiGe) is expected to drop from 86% to 68% by 2005, with increasing uptake of GaAs and InP ASICs in laser drivers, TIAs and limiting amplifier functions. The leading manufacturer of GaAs optoelectronic ASICs last year was Vitesse, with around one-third of the market.

InP will become much more significant as more 40 Gbit/s circuits are deployed. In addition, InP lends itself to integration with other optoelectronic components such as PIN detectors and TIA circuits. "For the major vendors, optoelectronic ASICs represent at best only 10% of their business volume," Montgomery continued. "I would expect some of these players to put more emphasis on this sector in future."

"The Optoelectronic ASICs Forecast" is available from ElectroniCast – for further details see "www.electronicast.com".

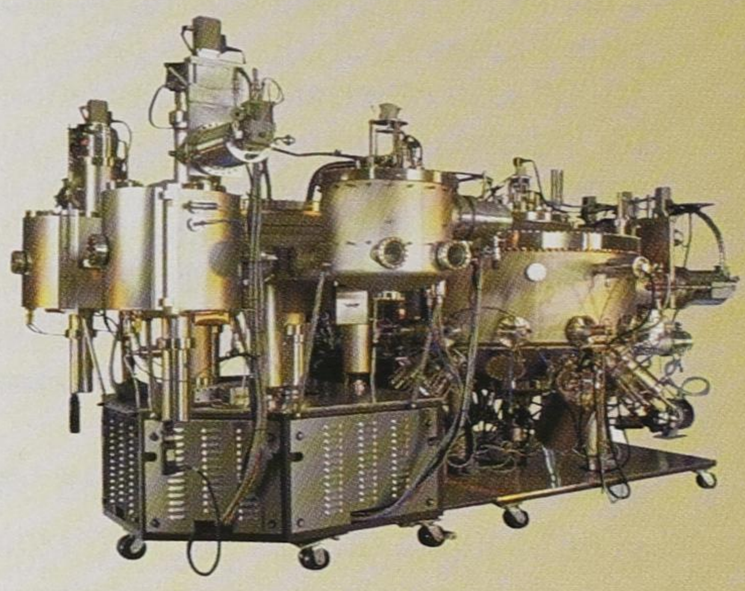
Asia-Pacific wireless user numbers grow

Starting from a low penetration level of ~7% in 2000, the Asia-Pacific region will expand 20% annually in the next five years, increasing its wireless penetration to more than 15%. A three-part report from The Yankee Group puts the final tally of wireless subscribers in the region at 575 million by 2005, which is a result of robust economic growth and an expanding addressable population base. The key drivers for mobile adoption are telecom deregulation, prepaid services, decreasing handset prices and service charges, and the development of mobile data services. Japan and China will generate around 40% of the global wireless infrastructure spending from 2001 to 2005.

"Asia-Pacific Wireless Market Overview 2000–2005" is available from The Yankee Group – see "www.yankeegroup.com".

TODAY

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Philips Analytical opens Arizona facility

Characterization and metrology tool supplier Philips Analytical has opened a new 10 000 sq. ft office and demonstration facility located in Chandler, Arizona. Built to support growth in semiconductor equipment markets, the company's new center will support the Americas region and solidify its existing links with the semiconductor R&D and production facilities in the West and Midwest regions of the US.

"Philips Analytical made a strategic choice to expand its semiconductor office in this part of the US as a result of its centralized location," said Gjalt Kuiperes, general manager for the Americas. "The new facility enables us to better support our semiconductor and data storage customer base and also provides easy accessibility to Texas and California."

Now fully operational, the new facility combines a complete demonstration and application fab, including a full range of semiconductor metrology tools and analytical instrumentation.

JMAR accelerates XRL prototype development

JMAR Technologies (San Diego, CA) has received almost $7.8 million from DARPA, the US defense funding agency, to construct an engineering prototype for an X-ray lithography (XRL) system.

The company, which received $9 million just three months ago from the same agency, is accelerating development of its XRL system for high-speed circuits used in telecommunications applications. JMAR believes XRL will be well suited to producing GaAs ICs with critical device dimensions ranging from 130 to 70 nm.

JMAR has steadily increased the power output of its large-field XRL source, which is used to collimate 1 nm X-rays onto a mask/wafer target. The company is now targeting an output power of 45 W for subsequent integration into a photolithographic stepper produced by SAL (Burlington, VT).

SAL acquisition goes through

In related news, JMAR has completed the purchase of SAL (see *Compound Semiconductor* May 2001, p25). The business will now be known as J-SAL.

August system used to inspect VCSELs



August Technology (Bloomington, MN) has received an order for a defect inspection system from a VCSELs manufacturer. August's NSX tool (above) performs automated inspection of wafers, die, and bumps with a feature resolution of 0.5 μm.

"The flexibility of the NSX has allowed us to pursue applications in new and emerging market segments, such as VCSELs, and successfully implement the systems into non-silicon production environments," said VP of sales and marketing, Mayson Brooks.

Aixtron reactors for PLI and University

The **Hong Kong University of Science and Technology** (Kowloon, Hong Kong) has purchased an **Aixtron** AIX 2000 HT reactor with a capacity for 6 × 2-inch wafers. The system will be used in the manufacture of blue and green LEDs (see LED news, p19).

Princeton Lightwave Inc (PLI), a vertically integrated manufacturer of InP components based in Cranbury, New Jersey, has bought two AIX-2400G3 MOCVD reactors from **Aixtron**. The new systems will allow PLI to ramp production of the company's recently introduced range of EDFA and Raman pump modules, broadband gain chips, and high power distributed feedback laser modules.

Fitel Technologies, the US arm of Furukawa Electric, based in Clinton, NJ, has named **John Rogers** as its CEO. Rogers has 22 years telecommunications industry experience, including director of market management and OEM sales for Lucent.

John Brewer has been appointed as VP of product marketing for wireless applications at **Nitronex**, a developer of GaN-on-silicon products. Brewer has more than 18 years experience with RF and semiconductor technologies, and joins Nitronex from Tropian, an RF semiconductor company which he co-founded.

Trion Technology, a manufacturer of plasma etch and deposition equipment based in Tempe, AZ, has appointed **Forrest Van Benthuysen** as VP of sales and marketing, and **Curt Larson** as director of operations.

John Murphy has been appointed as president of **PerkinElmer**'s Optoelectronics business, based in Fremont, California. Murphy will oversee the unit's telecom, digital imaging and specialty lighting groups, which had sales of $500 million in 2000.

Geoffrey Brown is to be VP of business development and sales at the new San Francisco office of **Optillion**, a Swedish manufacturer of 10 Gbit/s Ethernet optical transceivers.

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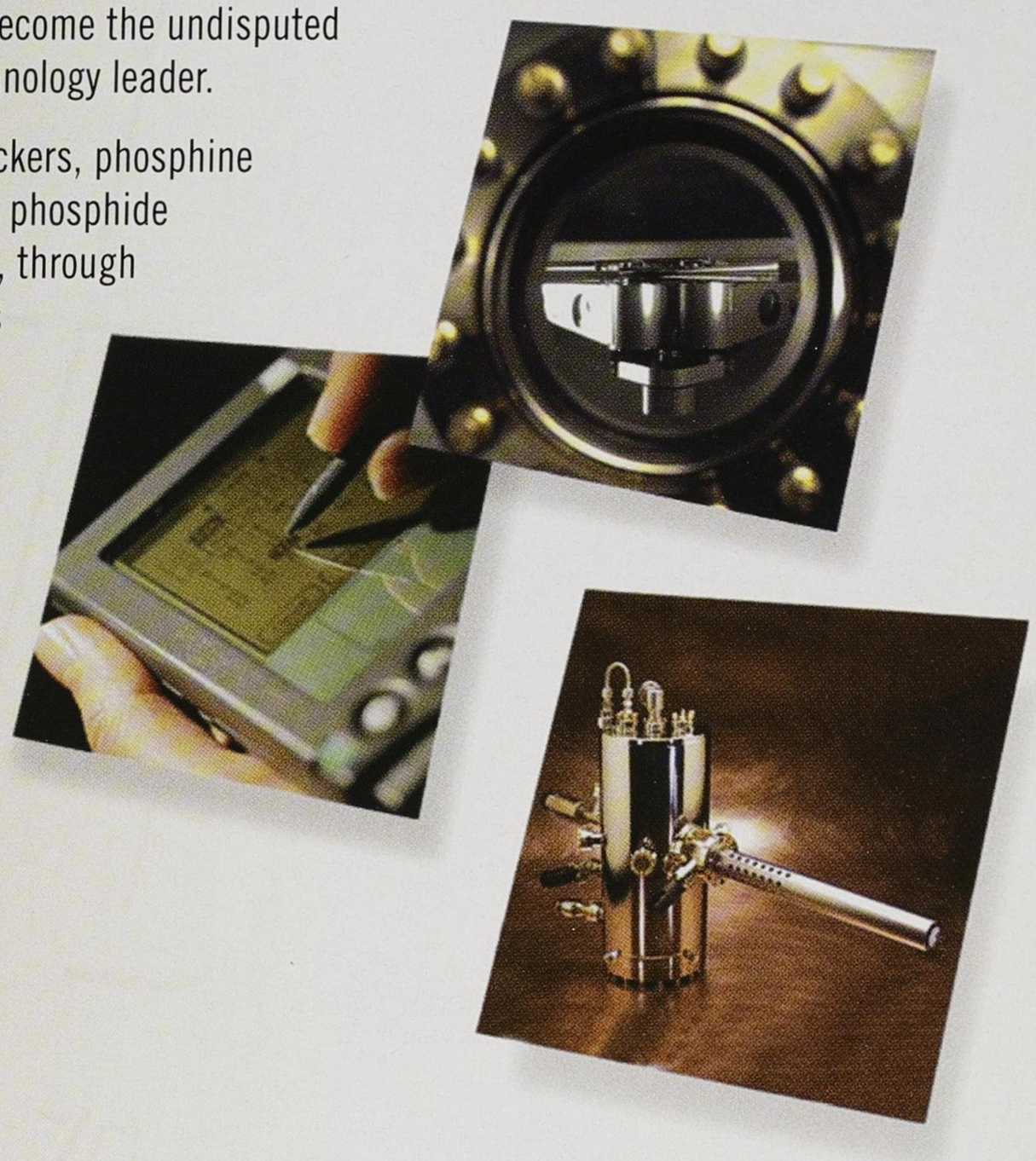
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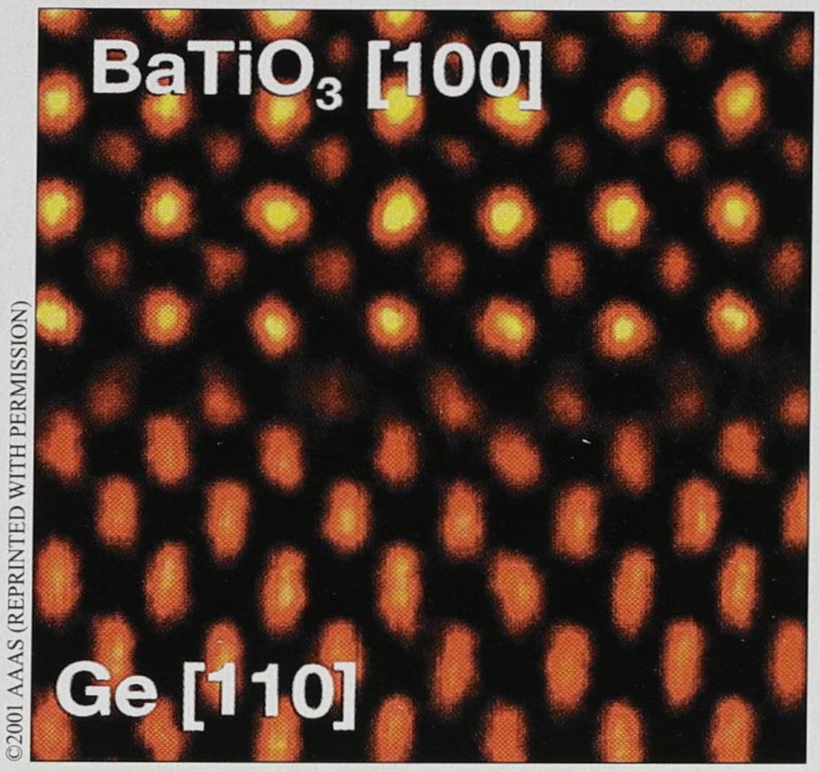
Single crystal oxides help silicon's advance

The ubiquitous Si/SiO_2 interface is struggling to meet the demands of shrinking feature sizes in silicon microelectronics. ***Bob Metzger*** *takes a look at an interesting alternative.*

While the high quality of the Si/SiO_2 interface, coupled with the large bandgap of SiO_2, and favorable band offsets, permits the manipulation of charge at the Si/SiO_2 interface through applied voltage to the gate, source and drain of a MOS structure, this interface is not perfect. As a consequence of the amorphous (SiO_2)/crystalline (Si) interface, defects are generated due to steric hindrance and bond coordination at that interface. High quality Si/SiO_2 interfaces typically exhibit an interface state density in the mid-to-low $10^{10}cm^{-2}eV^{-1}$ range. These interface states can result in performance limitations at high electric fields (and therefore at high power, small geometries, or a combination of the two). As any III-V researcher well knows, one way to reduce interface state densities is to form the interface with two lattice-matched crystalline materials.

Researchers at Oak Ridge National Laboratory are investigating crystalline replacements for SiO_2 in the formation of interfaces with both Si and SiGe. By removing the amorphous element to the interface, the interface defects generated as a result of steric hindrance and bond coordination could be entirely eliminated. This would open the way for the type of bandgap engineering of interfaces that is common in III-V materials.

Referred to as crystalline oxides on semiconductors (COS), the crystalline oxide is expressed as $(AO)_n(A'BO_3)_m$, where n and m are the number of atomic plane repeats of a given oxide, AO is an alkaline earth oxide, and $A'BO_3$ is a perovskite oxide. A and A' are elements or combinations of elements from group IIA of the periodic table (Ba, Sr, Ca, and Mg), and B is a group IVA transition metal (such as Ti or Zr). Grown by MBE, in which $(AO)_n$ and $(A'BO_3)_m$ can be shuttered on and off, these alloys can be formed to cover the entire lattice range from Si to Ge (5.43 to 5.65 Å). The perovskite oxides typically used are $CaTiO_3$, $SrTiO_3$ and $BaTiO_3$, which are all mutually soluble in each other. As an example, mixing a 60/40 ratio of Ca and Sr results in a perovskite oxide with a lattice constant of 3.84 Å that rotates 45° to match silicon's 5.43 Å lattice constant. A Z-contrast image of a $BaTiO_3$/Ge interface is shown in figure 1, illustrating the high degree of crystalline perfection possible at the interface between a perovskite oxide and a semiconductor.



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Fig. 1. Z-contrast image of perovskite oxide heteroepitaxy on Ge showing the ability to manipulate the interface at the atomic level.

While the perovskites may have the desired band gaps and dielectric constants to make them candidates for a crystalline oxide in a COS structure, their band alignment and offset are highly unfavorable. This means that little or no barrier is generated to restrict the transfer of an electron across the perovskite dielectric. However, by introducing an alkaline earth oxide between the perovskite and the Si or SiGe layer, and varying its thickness, the resulting bandstructure can be modified to inhibit the transfer of electrons.

A COS dielectric consisting of two monolayers of $Ba_{0.75}Sr_{0.25}O$ at the interface of Si, followed by 52 monolayers of $SrTiO_3$, was used in the fabrication on a 50 μm channel length FET. The device showed a peak mobility of 321 cm^2/Vs, the highest value obtained for any non-SiO_2 gate dielectric. At high fields ($> 5 \times 10^5$ Vcm^{-1}), where interface scattering dominates, the mobilities approach that of state of the art SiO_2/Si interfaces. In another experiment, to determine the feasibility of inserting a thin alkaline earth oxide at the semiconductor interface to inhibit leakage, layer thicknesses ranging from 1 to 7 monolayers of BaO were used beneath a 250 Å $BaTiO_3$ layer. Over this range of increasing BaO thickness for a structure grown on Ge, leakage current was reduced by six orders of magnitude, illustrating that the alkaline earth oxides can modify the interface bandstructure to inhibit electron transfer across the crystalline oxide.

To investigate interface state densities in such structures, high frequency and low frequency C-V measurements of a 250 Å $BaTiO_3$/Ge structure were made. The resulting interface state density was below the level of detectability for the equipment used, indicating a value of $< 1 \times 10^{10}$ $cm^{-2}eV^{-1}$, which is comparable to, or even better than, that achievable with an SiO_2/Si interface.

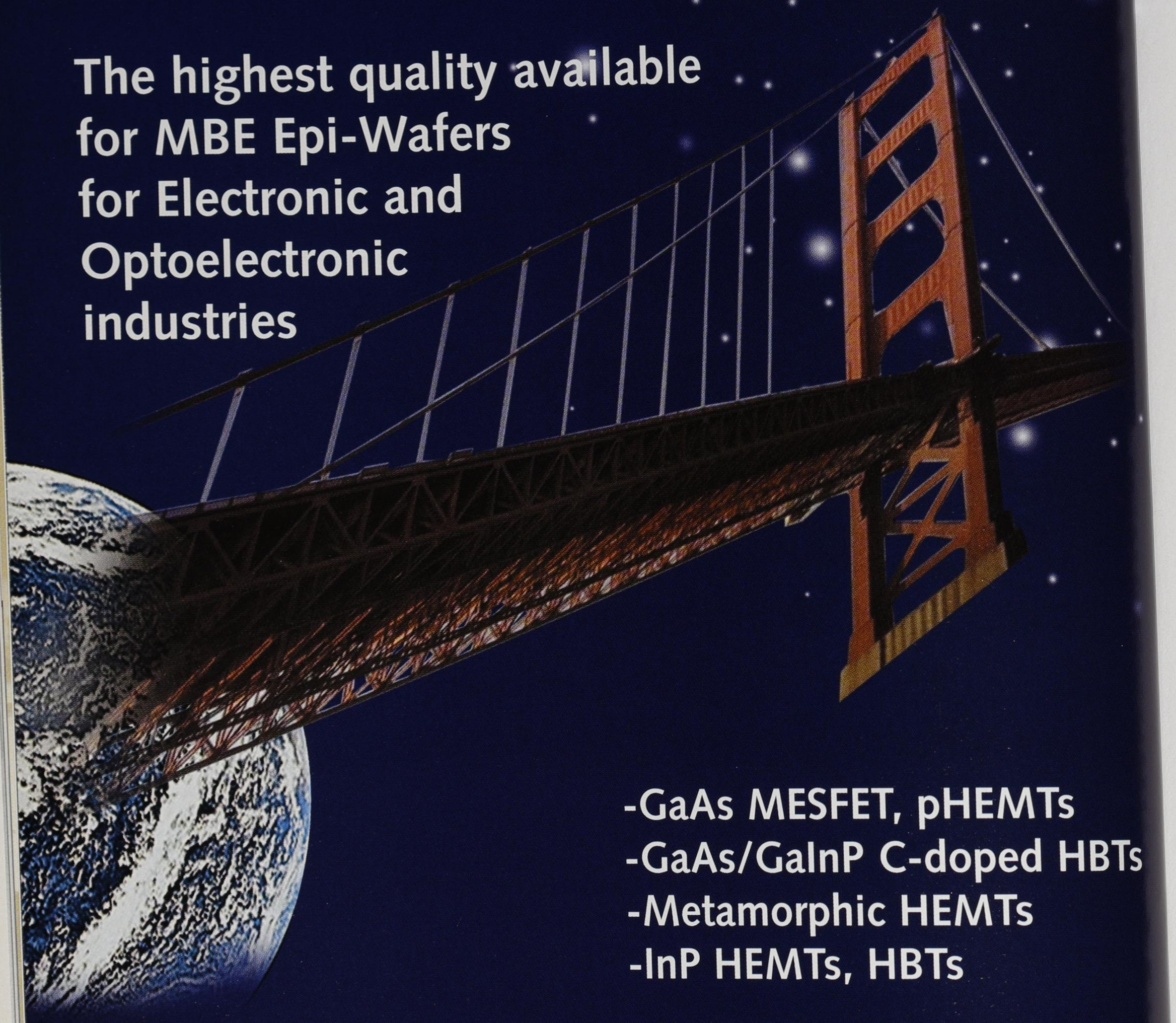
This work is still in its early stages, and experiments to determine the trade-off between interface state densities and leakage currents (by varying the thickness of the alkaline earth oxide layer) have yet to be concluded. However, this technology opens the way for a much greater control of the properties of the oxide-semiconductor interface, and allows for the fabrication of narrow insulating layers within Si structures. This could enable a whole new range of Si-based device structures.

Further reading

R McKee *et al.* 2001 Physical structure and inversion charge at a semiconductor interface with a crystalline oxide *Science* **293** 468.

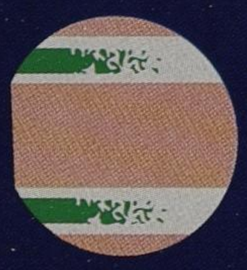
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WIRELESS PRODUCTS

Anadigics CATV downconverter

Warren, NJ. Anadigics' new downconverter and dual synthesizer IC is engineered for set-top boxes, CATV tuners and cable modems. Leveraging the company's GaAs and CMOS



technology, the ACD2202 integrates an LNA, balanced mixer, the active circuits for a local oscillator, and a dual synthesizer into a 28-pin SSOP surface-mount package. The double-conversion architecture eliminates the need for production alignment, and provides a flat gain response that enables cable operators to monitor systems remotely.

Employing a single +5 V supply, the ACD2202 offers 10 dB of conversion gain, an 8 dB noise figure and a local oscillator phase noise of –90 dBc/Hz (10 KHz offset). The typical total power consumption is 600 mW. The integrated design significantly decreases the number of external components, reducing the cost and complexity of the tuner.
www.anadigics.com

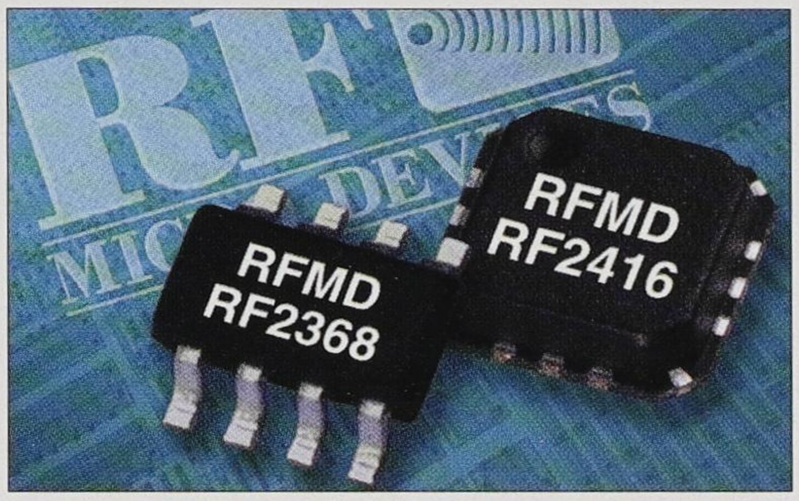
New GaAs MMIC products from UMS

Orsay, France. United Monolithic Semiconductors (UMS) has released several new GaAs-based products, including a wideband LNA that employs the company's self-biasing technology to remove the need for external tuning components. The CHA2069RAF operates from 18–31 GHz, with a gain of 19 dBm and noise figure of 3 dB. Output power at 1 dB gain compression is 9 dBm. The CHA2098aRBF is a broadband three-stage buffer amplifier. The device operates from 20–40 GHz with an 18 dB gain and output power of 15 dBm.

Meanwhile, the CHA3093c is a medium power four-stage amplifier manufactured using UMS' power PHEMT process. This device operates over the same frequency range with a 21 dB gain and output power of 20 dBm. An 8.5 GHz frequency divider is also available that features an input frequency range (F0) of 1.0–8.5 GHz and output power noise level (F0/4) of –2 dBm.
www.ums-gaas.com

RFMD single- and dual-band LNAs

Greensboro, NC. RF Micro Devices has introduced two new LNAs for GSM, DCS and PCS handsets. The RF2368 is a single-band LNA for DCS or PCS, while the RF2416 is a dual-band version that covers GSM, DCS or PCS handset applications. The RF2416 offers 1.4 dB



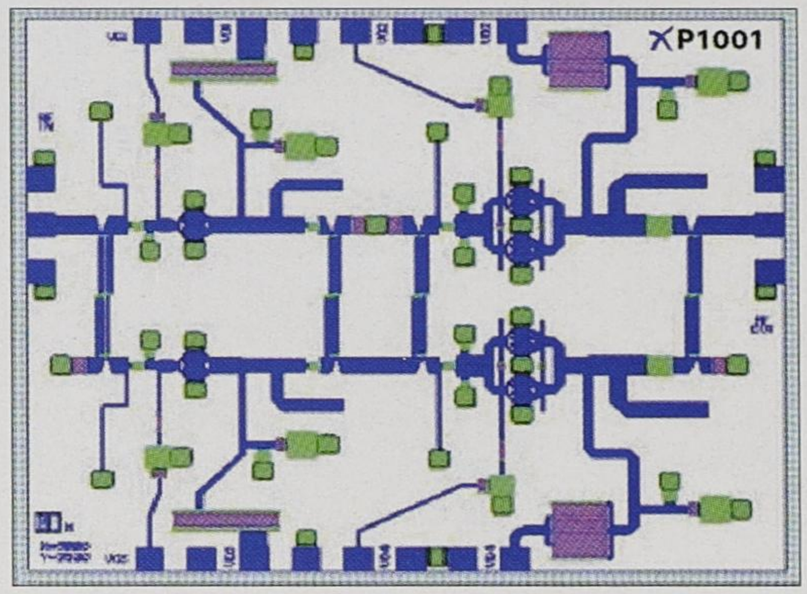
noise figure and 15.5 dB of gain in the 950 MHz GSM band. In the 1800 MHz DCS and 1900 MHz PCS bands, the device provides a 1.5 dB noise figure and 17.5 dB of gain. The RF2368 offers similar performance with a 1.6 dB noise figure and 18 dB gain for the DCS band, and 16.5 dB gain in the PCS band.

Both devices offer a selectable gain bypass mode with a gain reduction step of 21.5 dB. This feature enables a step reduction in system gain, meeting gain control requirements and lowering system power consumption by reducing the linearity requirements further down the receiver chain.

Manufactured using RFMD's GaAs HBT process, both devices operate from a 2.7 V supply and are available in a 1.6 × 3 mm SOT 8-pin plastic package (RF2368) or 3 × 3 mm 12-pin leadless plastic package (RF2416).
www.rfmd.com

Mimix offers 26–40 GHz PAs

Houston, TX. Mimix Broadband has introduced a GaAs MMIC two-stage PA featuring a third order intercept point



(IP3) of +36 dBm. Optimized for linear operation, the device is based on an externally manufactured 0.15 µm gate length GaAs PHEMT process, and covers the 26–40 GHz bands. The XP1001 operates with a small signal gain of 12 dB and includes Lange couplers to achieve good input/output return loss. Applications include millimeter-wave point-to-point radio, LMDS, SATCOM and VSAT. A version is also available with an on-chip temperature compensated output power detector.
www.mimixbroadband.com

FIBER-OPTIC PRODUCTS

Si-on-sapphire ICs from Peregrine

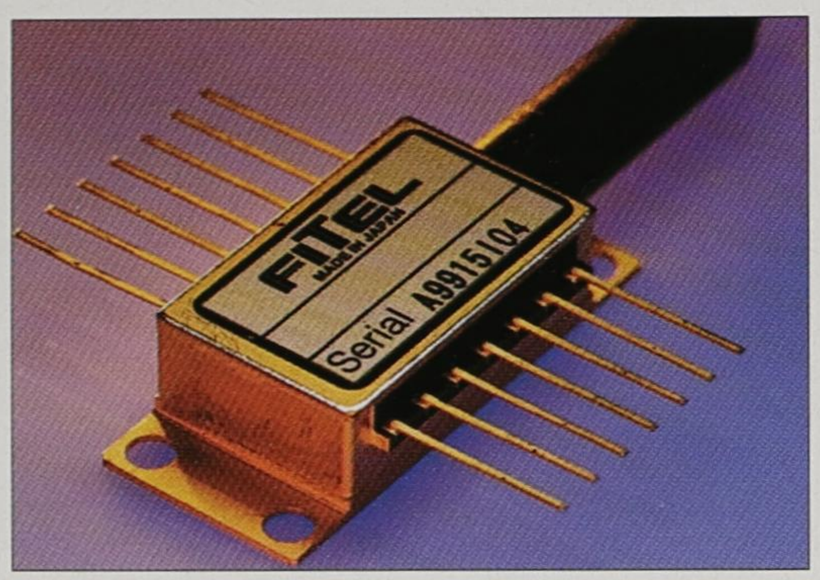
San Diego, CA. Peregrine Semiconductor is offering what it describes as the first successful high-volume production process featuring thin layers of silicon on sapphire. Peregrine has proven its patented Ultra-Thin-Silicon (UTSi) SOS RF/CMOS process by fabricating its PE412x family of mixers, which have shipped over 1 million units. These MOSFET quad mixers are applicable to PCS and 3G

base station receivers and exhibit a linearity (IP3) of over +30 dBm at 1.8–2.0 GHz (conversion loss = 7.6 dB).

In addition, Peregrine's new portfolio also includes a single 3.3 V supply quad TIA with integrated post amplifier operating at data rates from 155 Mbit/s to 2.7 Gbit/s, and a 12-channel VCSEL laser driver operating up to 3.125 Gbit/s on a single die. The latter device targets VSR links, features a low power (100 mW per channel) architecture, and simplifies designs by reducing power supply and cooling requirements. These products will be available in the third quarter of the year.
www.peregrine-semi.com

Fitel unveils DFB laser series

Clinton, NJ. Fitel Technologies has released a new series of distributed feedback (DFB) laser diodes for WDM transmission systems. Manufactured by parent company Furukawa Electric, the

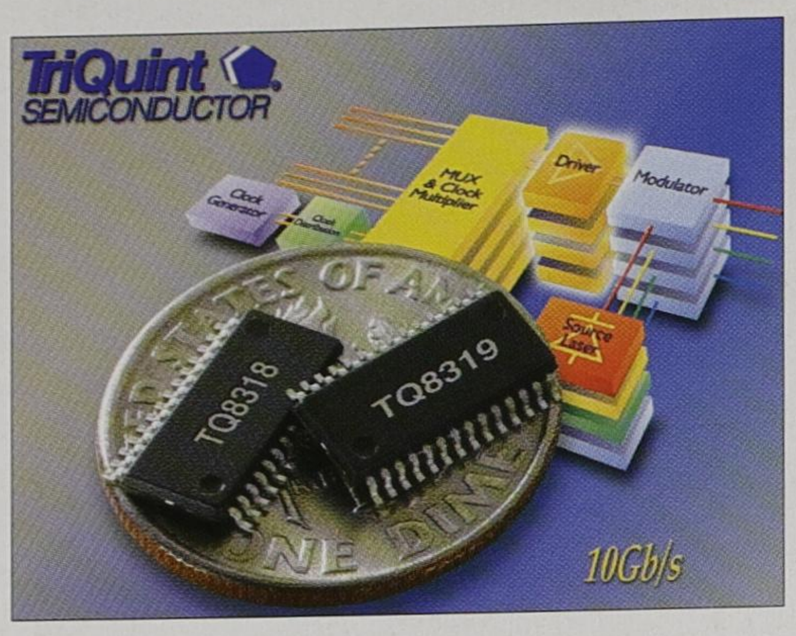


new lasers include a series of 1550 nm CW and directly-modulated DFBs for OC-48/STM-16 (2.5 Gbit/s) DWDM transmission systems. The series is available in power outputs from 10 to 40 mW.

Fitel has also unveiled a 1550 nm DFB laser with an integrated wavelength monitor for high-speed, long-haul optical networks. Furukawa currently holds nearly 70% of the total market share for 14xx nm pump lasers. Full production is scheduled for the end of the year.
www.fitel.com

Triquint reveals electro-optic drivers

Hillsboro, OR. TriQuint's new TQ8318 and TQ8319 ICs are 10 Gbit/s electro-optic drivers designed for metro and long



haul DWDM applications employing SONET/SDH OC-192/STM-64, including FEC rates up to 10.8 Gbit/s.

Based on the company's GaAs MESFET process, the new ICs feature rise and fall times of 32 ps at 35 ps input rate, a single-ended modulation voltage of 1.0–3.0 V and a differential output of 2.0–6.0 V peak-to-peak. Also built in is an integrated 0.0 to –1.0 V offset and back-terminated 15–60 mA modulation current for 50 Ohm loads for the TQ8318. The TQ8319 offers 30–120 mA of modulation current for 25 Ohm loads. Both devices operate at +3.3/–7.5 V.
www.triquint.com

New telecom devices from Alcatel

Paris, France. Alcatel Optronics has released the 1906 OFA, a single channel EDFA amplifier dedicated to high bit-rate systems used in metropolitan links and optical cross-connects. The company's amplifier achieves +18 dBm (63 mW) of optical output power in the C-band (1528–1565 nm) using a single 980 nm pump module. Manufactured in-house, Alcatel's pump module maintains a noise figure of <5.5 dB and consumes 3.5 W.

Designated the 1915 DMO, Alcatel's 10 Gbit/s high-speed PIN photodiode and preamplifier is designed for metropolitan and long haul DWDM terrestrial applications. This new device handles bit rates up to 12 Gbit/s, facilitating forward error correction, and employs a 16-pin standard package for operation as low as –18 dBm. In addition, a bit error rate performance of 10^{-12} is designed to match ITU requirements for I-64.2, S-64.2 and L-64.2b metropolitan and long-haul applications.

Finally, the company has also introduced a 2.5 Gbit/s DFB integrated laser module emitting in the 1260–1360 nm window for distances over 40 km.
www.alcatel.com

InGaAs monitors and receivers

Princeton, NJ. Sensors Unlimited has unveiled a 10 Gbit/s PIN receiver module that complies with OC-192/STM-64 SONET/SDH specifications, making it ideal for long haul and metro systems. Integrating the company's InGaAs pin diode with a GaAs HBT preamplifier, the SU-10PSR features a responsivity of 1 A/W at 1550 nm, dark current of 10 nA and optical sensitivity of –24 dBm. The device operates in the 1280–1625 nm range for use in multi- or single-mode applications.

The company has also introduced an InGaAs-based multi-channel power array monitor for DWDM, add/drop multiplexers and EDFA gain monitoring applications. Available with 8, 12 or 16 fiber ribbon pigtail formats, the array is designed to monitor in C, L or S bands (1280–1620 nm). Available in a hermetically sealed 19 × 21 × 7 mm package, the SU-008-MCPM features a maximum adjacent (zero bias) cross talk of –35 dB, dark current of 300 pA, and responsivity of >0.85 A/W.
www.sensorsinc.com

Emcore debuts GaAs photodetector

Somerset, NJ. Emcore has unveiled a new 10 Gbit/s GaAs photodetector for multi-mode fiber-optic applications. The new photodetector partners the company's recently introduced 10 Gbit/s oxide VCSEL, and forms part of a matched transceiver device suited to VSR applications such as serial links, LANs for Gigabit Ethernet and Fibre Channel, Infiniband and OC-192. The photodetector offers a bandwidth of 8.5 GHz and minimum responsivity of 0.5 A/W. It features an aperture size of 60 µm, dark current of less than 0.2 nA and capacitance of typically 0.23 pF. The accompanying 10 Gbit/s VCSEL supplies an output power of 1 mW and 3 dB bandwidth over 10 GHz.
www.emcore.com

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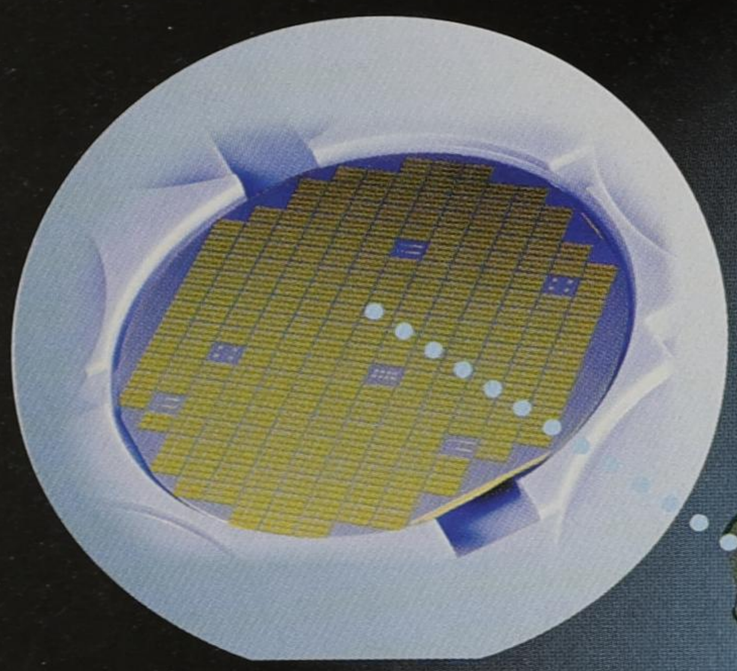
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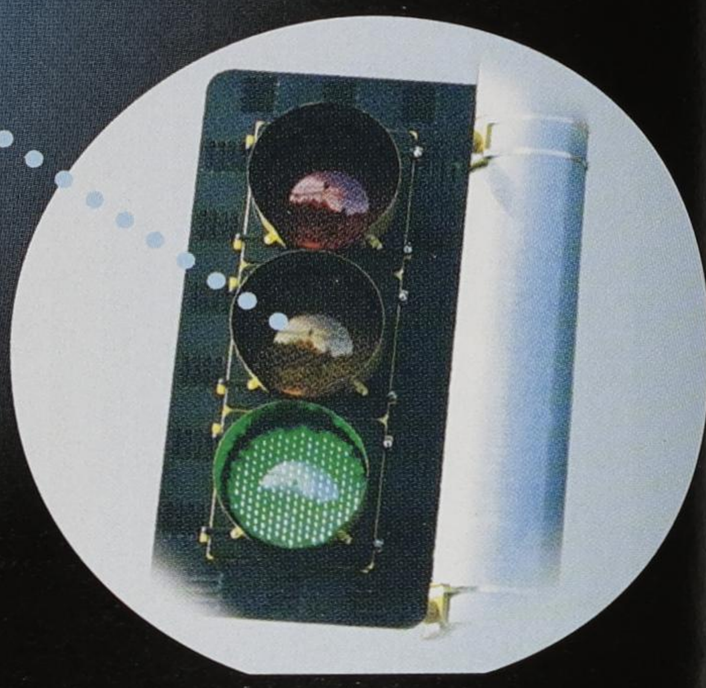




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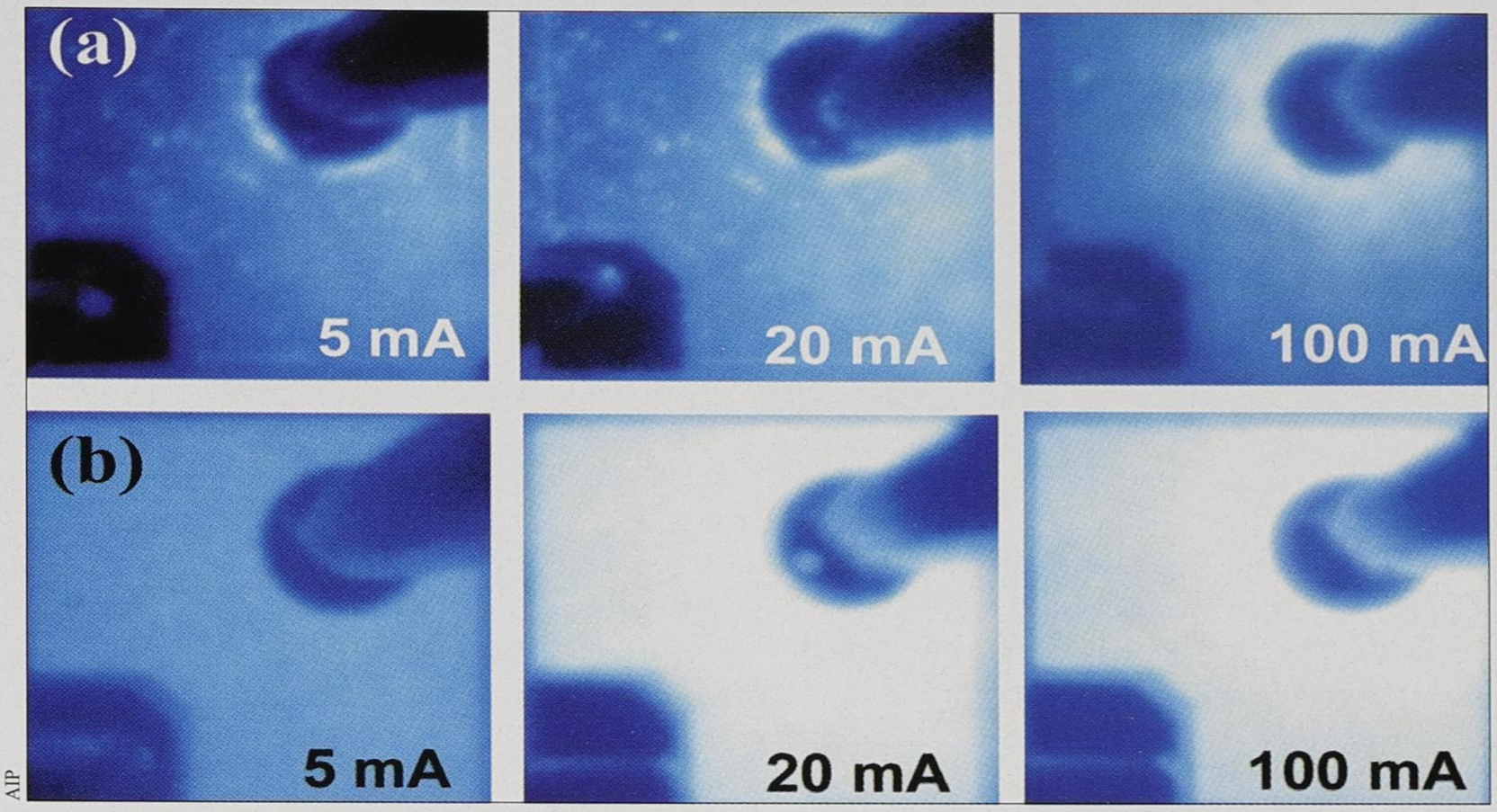
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LED tunnel junctions spread the charge

One of the limitations of conventional GaN-based LEDs is the low conductivity of p-type GaN:Mg used as the top contact layer. A large area p-type ohmic contact is required to spread current from the p-bonding pad across the junction area to prevent current crowding in the high-resistivity GaN:Mg. This electrode must be semi transparent for maximum light emission.

A group at Chonbuk National University, Korea, have published a method to facilitate lateral current spreading by reducing lateral hole conduction (*Appl. Phys. Lett.* 2001 **78(21)** 3265). This involves using buried tunnel contact junctions on the p-side. A reverse biased tunnel junction (TJ) supplies holes to the p-type crystal above the active region by lateral electron currents. This allows the use of a low resistivity n-type GaN contact layer that further facilitates current spreading, and also the use of an n-type ohmic contact. Device fabrication is simplified as only n-type ohmic contacts are needed, resulting in a single metalization process. The TJ concept has been demonstrated for GaAs-based edge-emitters and VCSELs, but this is the first reported use for GaN-based LEDs.

At 4.9 V (20 mA), the operating voltage of a TJ-LED is higher than that of a conventional GaN-based LED (4.5 V at 20 mA). This is as a result of a series resistance across the tunnel junction. However, the light output of the TJ-LED is twice that of a conventional LED. This is because there is no need for a large metal contact to spread current, and light emission occurs across the whole junction area because of the low resistivity n-type contact layer. Figure 1 shows the blue light emission at 5, 20, and 100 mA for (a) a conventional LED without a semi-transparent electrode and (b) a TJ-LED. At 100 mA operation, the emission is slightly more intense around the electrode. This is the result of current crowding in the n-type GaN contact layer. The uniformity of the radiance was further increased in the TJ-LED by increasing the doping level of the n-type GaN to improve its conductivity.



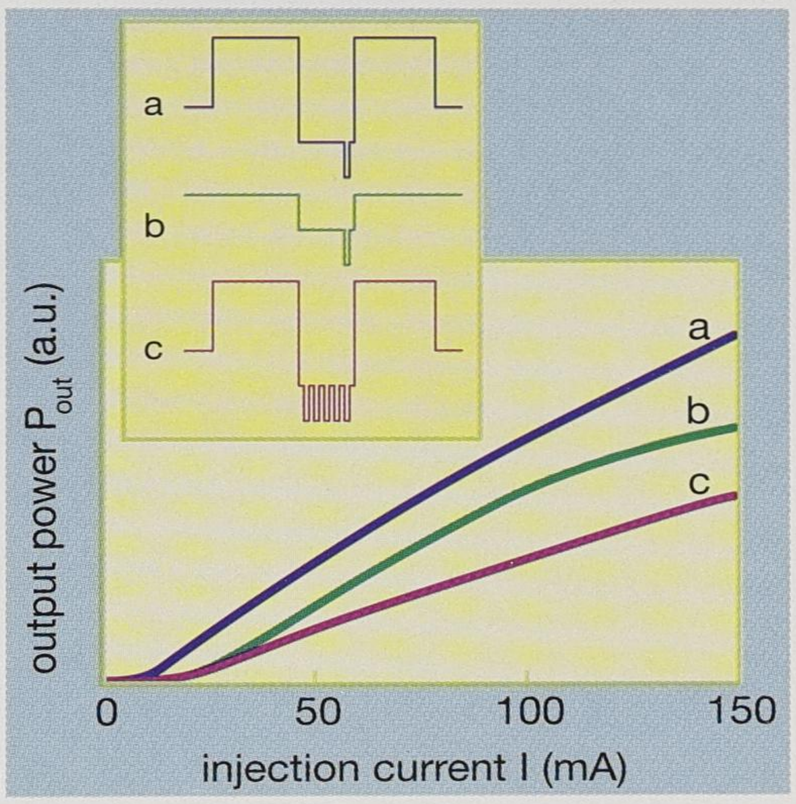
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Light emission images of (a) conventional and (b) tunnel junction GaN LEDs.

NTT achieves 1 mW output from AlGaN-based UV-LED

Toshio Nishida and colleagues from NTT Basic Research Laboratories in Japan have reported an AlGaN-based SQW UV-LED with an output power of 1 mW. Room temperature CW operation gives a peak wavelength of 341–343 nm (*Appl. Phys.Lett.* 2001 **78(25)** 3927).

The device is grown by MOCVD on a SiC substrate. The backside contact is provided by a conductive AlGaN (18% Al) buffer layer with a short period (3 nm) alloy superlattice giving transparent and conducting p-side cladding. The active regions of the structures consist of 2 nm thick $Al_{0.06}Ga_{0.94}N$ SQWs with $Al_{0.12}Ga_{0.88}N$ barriers. Current confinement is provided by 20 nm thick n- and p-type $Al_{0.3}Ga_{0.7}N$ layers below and above the SQW structure.



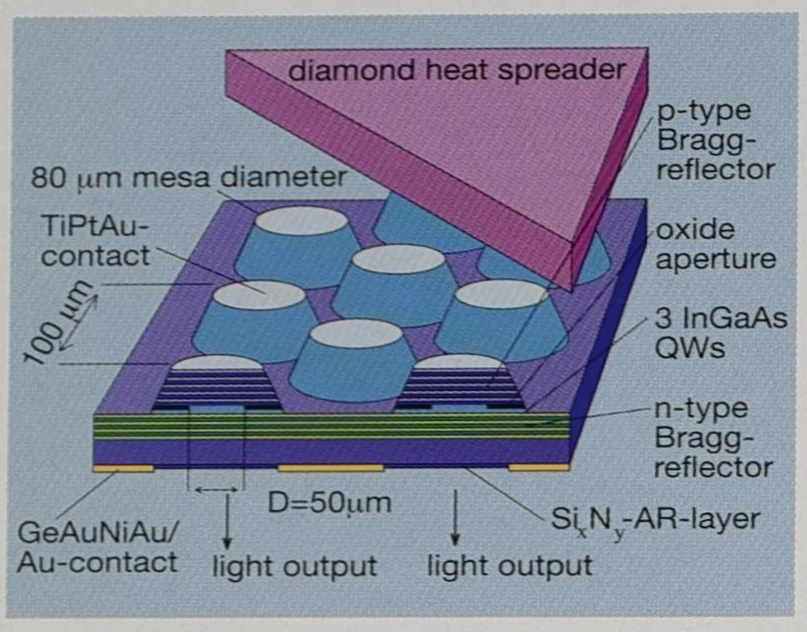
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I-L characteristics of three UV-LED structures under RT, CW operation. (a) SQW with carrier confinement, (b) SQW without carrier confinement and (c) MQW with carrier confinement.

The figure shows the I-L curves for three different LED structures tested under RT, CW operation: the inset shows the band structures of the devices.

LED (b), which does not have carrier confinement layers, begins to show saturation at 100 mA injection current. Without confinement, carriers are spilling over from the SQW to the other side of the p-n junction. LEDs (a) and (c) are carrier-confined and show near linear characteristics up to 150 mA, though slope efficiency for LED (c) is lower than LED (a). This is ascribed to the optical reabsorption in the upper QWs. LED (a) did not show saturation until an injection current of 400 mA was reached. At this point, the output power was 1 mW. This output power is almost 10 times at half the injection current than that previously reported by this group.

High-power 980 nm VCSEL arrays in demand



IEEE

Cross section of the oxidized 19 VCSEL array. A diamond heat spreader and copper heat sink play an important role in removing heat from the array, which provides a highly-circular 100 μm spot leading to power densities in excess of 10 kW/cm^2.

Investigations into both edge-emitting laser diodes and VCSELs are being driven in part by demand for compact, high-power devices for use in materials processing, printing, medical applications and free-space data transmission. This paper by Miller and colleagues from the University of Ulm (*Phot. Tech. Lett.* 2001 **13(3)** 173) describes an array consisting of 19 high-power VCSELs operating at 980 nm.

The devices were grown by MBE and contain C-doped upper Bragg reflectors made up of 30 pairs of $Al_{0.9}Ga_{0.1}As$/GaAs layers. The active region comprises three 8 nm thick $In_{0.2}Ga_{0.8}As$ quantum wells. Above the p-type cladding, a 30 nm thick layer of AlAs is added, which is partially wet etched at 410°C after mesa etching to form 50 μm apertures, which are spaced 100 μm apart. The total array size was 0.64 mm^2. Backside light emission through the 150 μm thick GaAs substrate is facilitated by an n-type DBR with only 20 Si-doped mirror pairs with the same composition as the p-type reflector. The GaAs substrate was coated with an anti-reflection layer and the device also employs a diamond heat spreader and copper heat sink.

Each device provides 1.08 W of CW output at room temperature and 1.4 W at a heat sink temperature of 10°C, corresponding to a total power density for the array of 1 kW/cm^2. A beam divergence of 16° FWHM was also achieved, and the circularly symmetric far-field pattern allows for simple focusing of the beam with power densities of over 10 kW/cm^2. Long-term testing has shown the device to be reliable for at least 10 000 h, with less than 1% degradation in output per 1000 h.

Superlattices improve electrical properties

The low doping efficiency in III-nitrides is an inherent property of a deep acceptor in wide bandgap materials. For the p-type dopant Mg in AlGaN, the activation energy increases with Al content, which leads to a decrease in the doping efficiency compared to bulk GaN. J Sheu *et al.* (*Elec. Dev. Lett.* 2001 **22(4)** 160) describe the incorporation of Mg-doped $Al_{0.15}Ga_{0.85}As$ strained-layer superlattices (SLS) to improve p-dopant activation. Hall measurements showed a higher conductivity as a result of improved Mg activation efficiency, which was associated with strain-induced piezoelectric fields in the AlGaAs SLS.

The authors (from Taiwan's National Central University and Epistar) applied the same AlGaN SLS design to a blue InGaN/GaN LED, and were able to reduce the operating voltage from the 3.8 V typical of conventional devices to 3.0 V (at 20 mA). Grown on a sapphire substrate, the LED consisted of a nucleation layer and thick Si-doped GaN layer, followed by 5 $In_{0.3}Ga_{0.7}N$/GaN QWs (3 nm wells, 7 nm barriers). A layer of Mg-doped GaN was followed by the AlGaN/GaN 10-pair SLS (in the ratio 16 nm : 8 nm) and a NiAu transparent contact.

Considerable improvements in the electrical properties were measured: the hole carrier concentration was 3×10^{18}/cm^3, or 30 times that of a bulk AlGaN layer. In addition, a very low contact resistance of 4×10^{-6} Ω.cm^2 and series resistance of 18 Ω were obtained, compared to 40 Ω in an AlGaN device without the SLS.

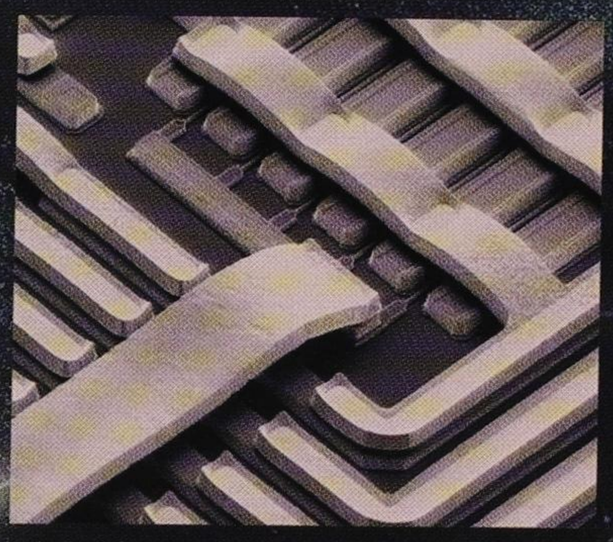
ELO-GaN improves laser facets

The performance of violet laser diodes has been improved using epitaxial laterally overgrown (ELO) GaN as a substrate for the subsequent deposition of active layers. ELO-GaN is known to show lower dislocation density than GaN deposited directly onto sapphire substrates, leading to improved device lifetimes. Further increases in lifetime can be achieved if device operating currents are reduced. The operating current of a laser diode is directly related to the quality of the mirror facets. A paper by Tojyo and colleagues of Sony Shiroishi Semiconductor, Japan (*Jap. J. Appl. Phys. Pt. One* 2001 **40(6A)** 3206) describes a method of forming much improved laser facets on ELO-GaN.

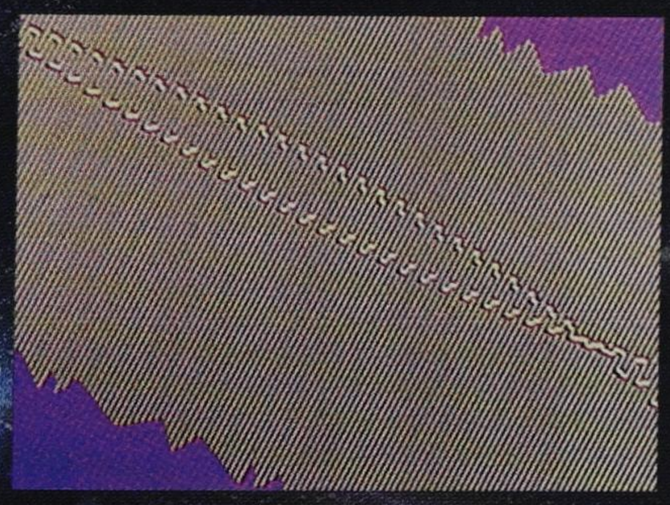
Photoluminescence measurements at 362 nm were made on the ELO-GaN layers. The photoluminescence intensity distribution was taken along a line perpendicular to the ELO stripes. The photoluminescence intensity in the ELO region was three times that of the seed region and 30% greater than the region where adjacent ELO wings coalesce. Since photoluminescence intensity is closely related to defect density, the wing regions should contain a relatively low number of defects. This was confirmed by comparing plan view TEM shots of the ELO wing regions and seed regions. AFM measurements of the cleaved facets of InGaN laser diode structures grown on ELO-GaN and sapphire substrates were also compared. The Ra roughness of the laser facet in the sapphire sample was 10 nm, which would cause mirror losses of between 2–3%. In the ELO sample the Ra roughness was <1 nm.

Light output versus current (L-I) characteristics for a laser diode grown on material from the ELO-GaN wing regions was compared with diodes from GaN grown directly onto sapphire. The threshold currents for the ELO-GaN laser diode and sapphire laser diode were 53.4 mW and 57 mW, respectively and slope efficiencies were 1.21 W/A and 0.92 W/A, respectively. Lifetime tests showed the laser diode grown on the ELO-GaN still functioned after 1000 hours operation at 50°C with a constant output power of 30 mW.

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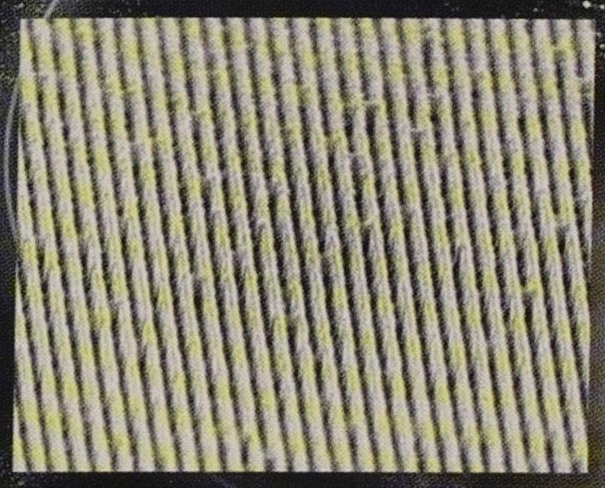


Air bridge on high speed GaAs device, courtesy of M/A-COM

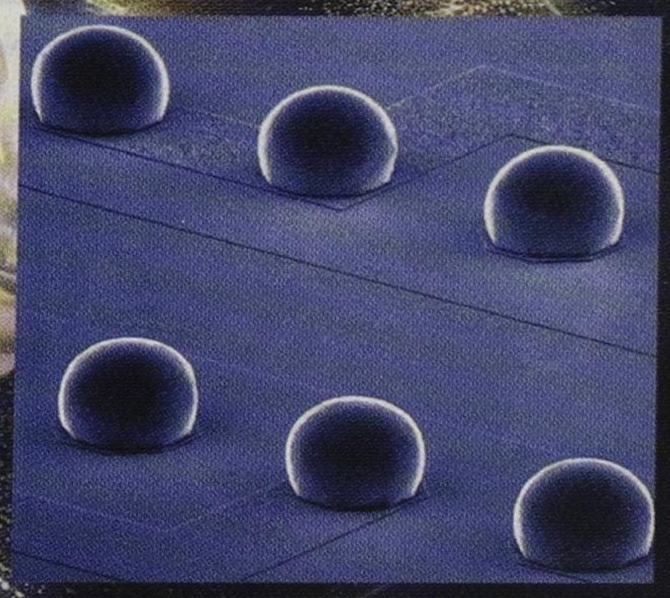


Saw filter, courtesy of AME Space

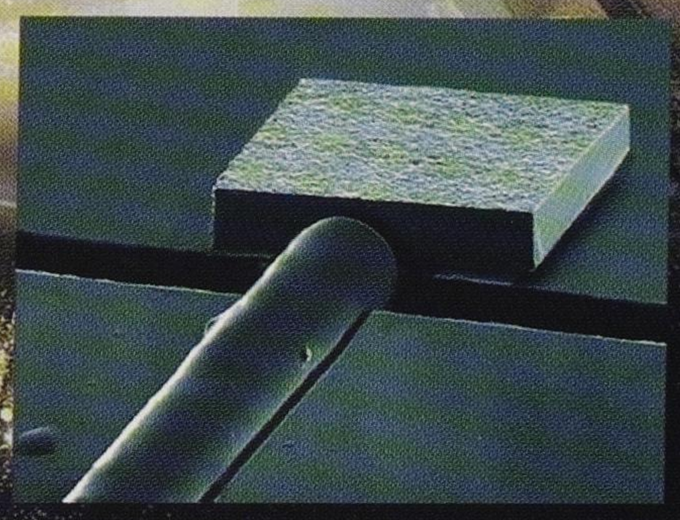




DFB Grating



Wafer bumping, courtesy of IZM/TU Berlin



Laser diode

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Nortel integrates SOA with gain-coupled tunable DFB laser

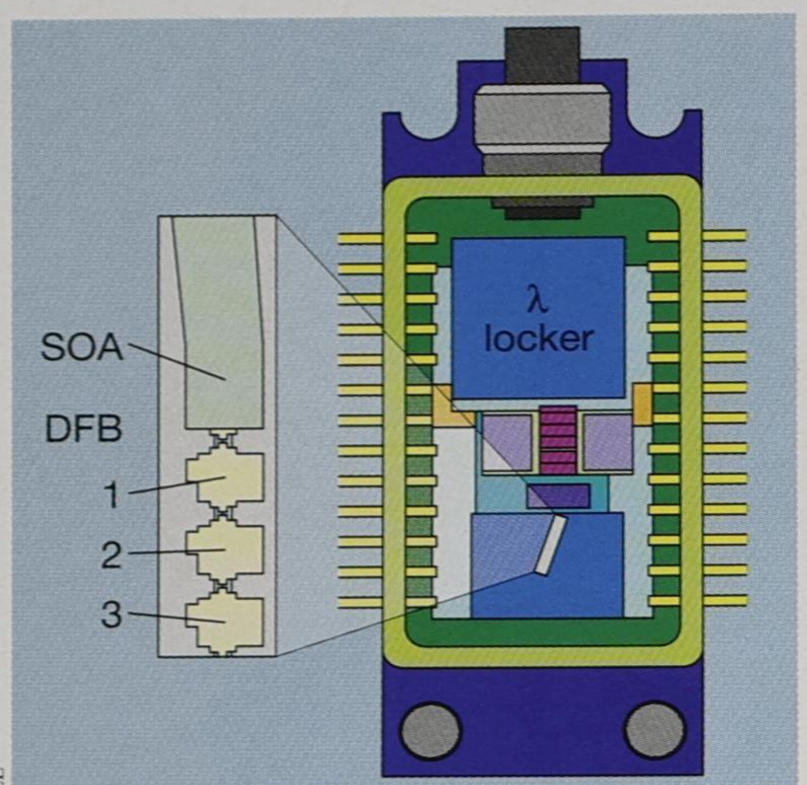


Fig. 1. Nortel's tunable laser consists of three separately addressable GC-DFB lasers and SOA in a fiber-pigtailed butterfly package.

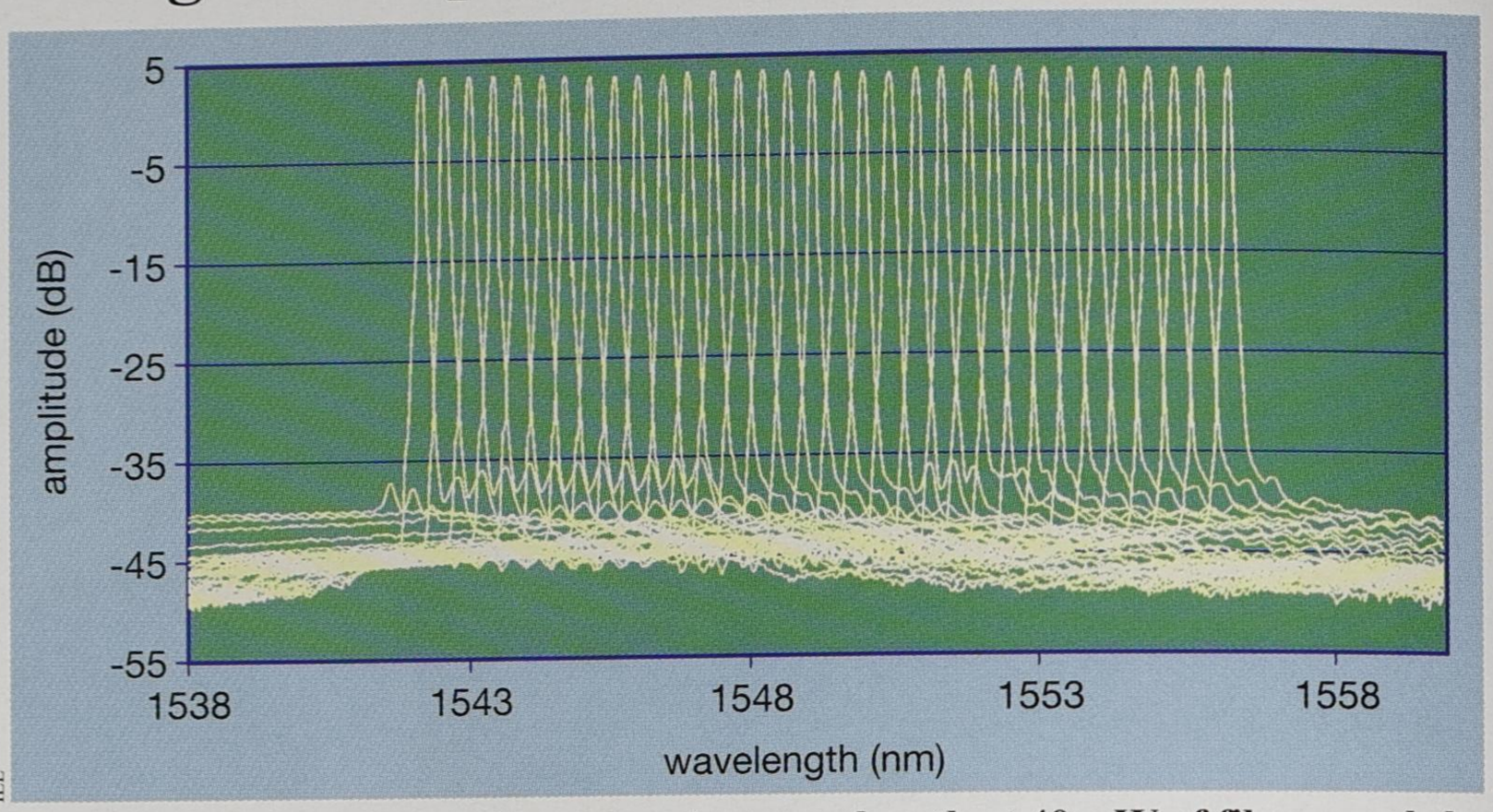


Fig. 2. The superposition of power against wavelength at 40 mW of fiber-coupled power for all 34 ITU channels. Linewidth is below 10 MHz for a 75 mA DFB section bias, decreasing to 5 mA for 90 mA bias.

Tunable lasers are crucial to the development of adaptable optical networks. DWDM systems will need to utilize tunable sources in order to be rapidly reconfigurable, and to offer flexibility for channel assignment, and cost savings through reduced component inventories. Researchers at Nortel Networks have reported a three-section, gain-coupled distributed feedback (GC-DFB) laser, monolithically integrated with a semiconductor optical amplifier (SOA), with over 40 mW of frequency-locked fiber-coupled power for 34 consecutive International Telecommunications Union (ITU) channels (*Elec. Lett.* 2001 **37(11)** 691). The SOA not only provides high output power, but can also adjust amplitude to compensate for laser aging, equalize channel amplitudes, and attenuate the signal during network insertions or reconfigurations.

The tunable laser consists of a 1.5 mm-long ridge waveguide, angled SOA output section, and three separately addressable GC-DFB lasers (figure 1). Fabrication of the monolithic chip requires only two MOCVD growth steps and so lends itself to high-volume production. The active chip and wavelength-locker optics are co-packaged within a fiber-pigtailed, 26 pin butterfly package measuring 12.7 × 30 mm.

The grating pitches in the DFB sections are chosen to produce emission at increasing wavelength in steps of 4.8 nm. A particular ITU frequency is accessed by selecting the DFB section having an emission wavelength nearest the ITU frequency of interest. Fine-tuning onto that frequency is done by adjusting the chip heatsink temperature. When operating DFB sections two or three, the preceding DFB section or sections are biased to transparency. Heatsink temperature is variable from –5 to +50°C, meaning each DFB section can access ~5 nm continuously. The total tuning range is therefore 3 × 5 nm giving 15 nm, minus the two ~0.2 nm spans over which adjacent DFB sections overlap.

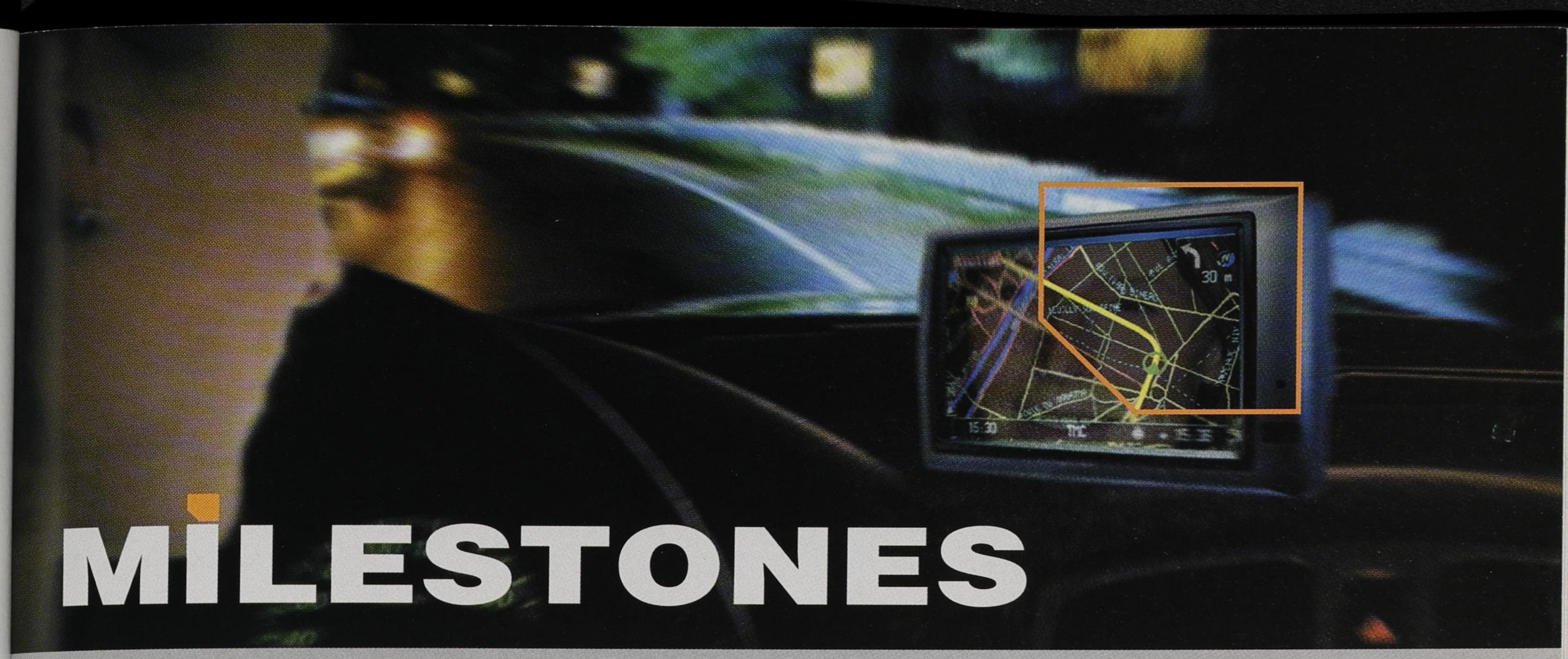
Output power is adjusted by selecting an SOA bias current. At low bias current or voltage, the SOA can heavily attenuate. 40 mW of fiber-coupled power is achieved with an SOA bias of 250–500 mA. The superposition of power against wavelength at 40 mW of fiber-coupled power is shown for all 34 ITU channels in figure 2. Side mode suppression ratio (SMSR) is below 37 dB on all channels, and linewidth is below 10 MHz for a 75 mA DFB section bias, decreasing to 5 mA for 90 mA bias. The relative intensity noise spectrum collected at 40 mW for all channels was better than –118 and –141 dB/Hz at frequencies below and above 200 MHz, respectively.

DFB and SOA sections were aged separately. SOA reliability was tested by fabricating Fabry–Perot lasers from the SOA material. A burn in period gave less than 4% reduction in efficiency. A further 2200 hours of aging at 100°C with a current density equivalent to an SOA operating at 500 mA, gave no further changes.

The DFB-laser sections were aged for 2200 hours at 100°C at a bias of 150 mA. The estimated chip lifetime for a module power of 40 mW with SMSR of > 34 dB is over 24 years when operating at a frequency corresponding to a heatsink temperature of 50°C.

High-temperature operation of VCSELs

In order for components such as VCSELs to be suitable for commercial applications, they must be capable of operating over a wide range of conditions. F Peters and H MacDougal of Gore Photonics reported 850 nm oxide-confined VCSELs that retain sufficient bandwidth for 10 Gbit/s operation up to 150°C (*Phot. Tech. Lett.* 2001 **13(7)** 645). Since the limiting factor for high-frequency operation is generally either poor thermal characteristics or parasitics, high-speed devices are designed with small mesas to limit parasitic capacitance. A semi-insulating substrate is utilized, and an air-bridge is used to reach the completely isolated top contact. Because the size of the top contact is very small, the resistance of the DBR mirror becomes significant; this was minimized by optimizing the doping in the DBR.



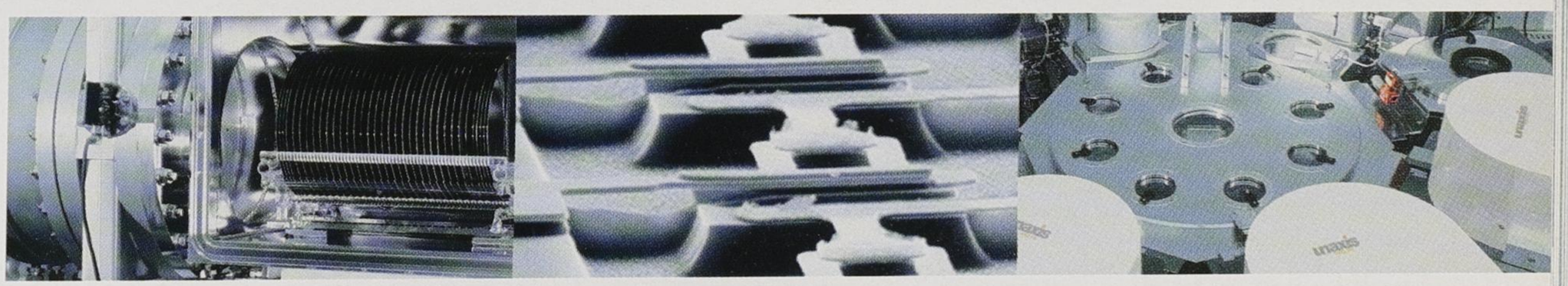
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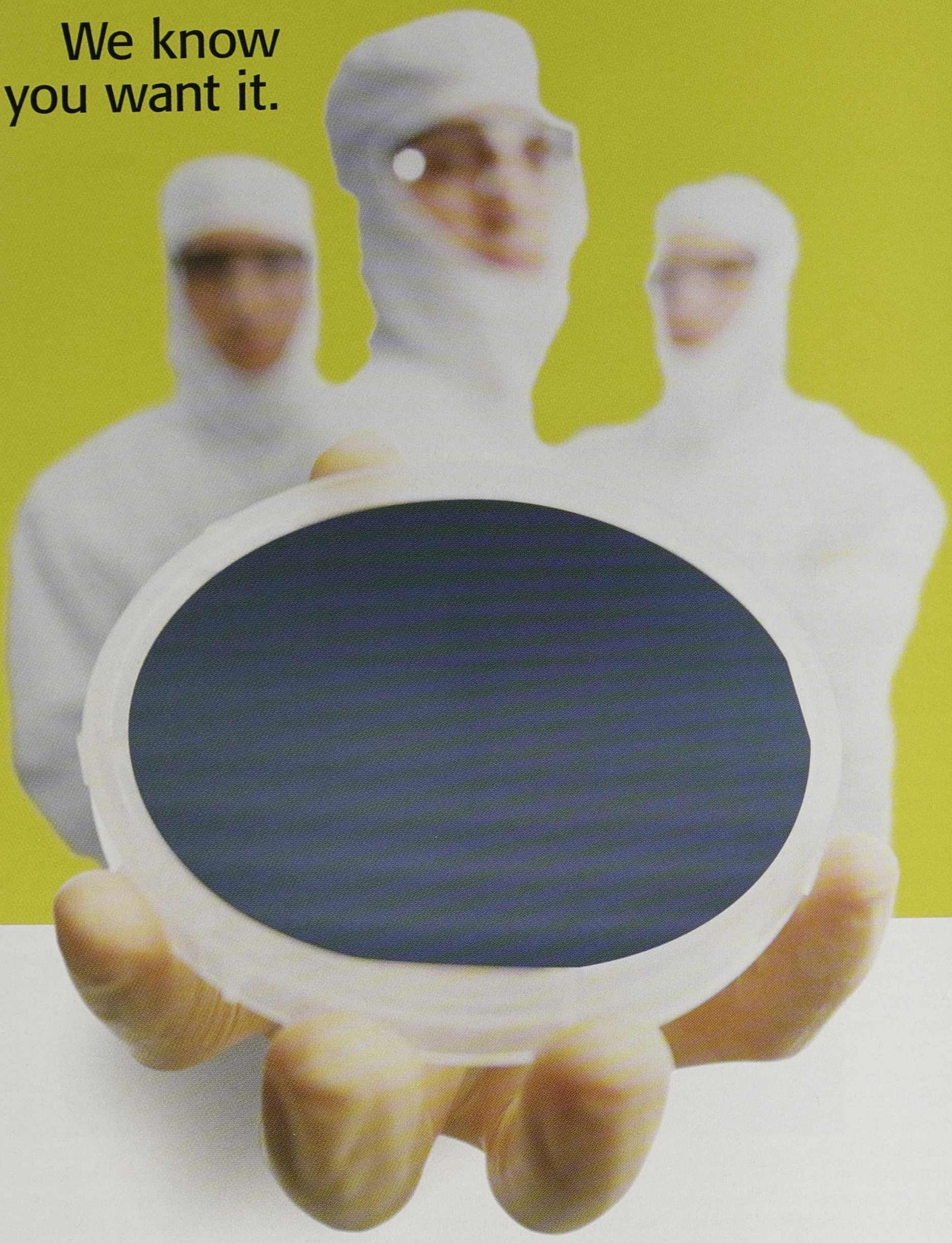
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CS-MAX highlights manufacturing issues

The inaugural CS-MAX show provided a forum to discuss high-volume manufacturing issues across the whole compound semiconductor industry, including GaAs devices, fiber-optic components and LEDs. ***Tim Whitaker, Richard Dixon*** *and* ***Jon Newey*** *report.*

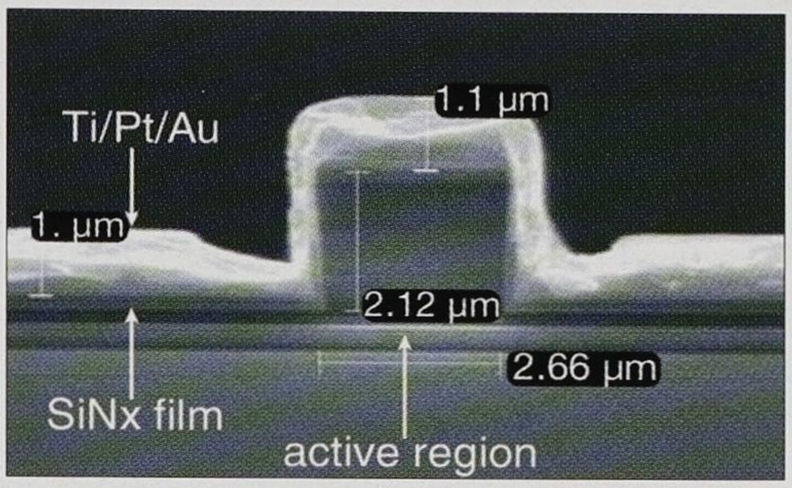
Many technical conferences in the compound semiconductor industry focus on a single material system, or a single epitaxial technique, and tend to have a research-oriented feel. In contrast, the Compound Semiconductor Manufacturing Expo (CS-MAX), held for the first time in Boston on July 9–11, addressed high-volume manufacturing issues of the type that are becoming increasingly important as the industry expands and matures.

Running alongside an exhibition featuring over 100 companies, the technical program at CS-MAX comprised 95 papers and was organized into five tracks – microelectronics, fiber-optic components, LEDs, epitaxy and characterization. In addition, a number of short courses and seminars were held on areas such as exhaust gas management, process and device simulation, manufacturing InP ICs, and the roadmap for solid-state lighting.

The technical program was composed of talks from industry-leading device manufacturers – Honeywell, Vitesse, Nichia, Nortel and Alpha, to name just a few – as well as representatives from companies supplying materials and equipment. At the time this provoked some lively debate, for example when Jeff Spiegelman of Aeronex advocated his company's nickel/titania catalyst technology for hydrogen purification, and was questioned closely by those with a vested interest in the incumbent palladium membrane technology.

GaAs IC manufacturing

Opening the program, Patrick Jenkins described Vitesse Semiconductor's experience in establishing the world's first 6 inch GaAs fab at Colorado Springs, as well as the company's decision to introduce a 4 inch InP process at its facility in Camarillo, CA. Vitesse's manufacturing focus contrasts strongly with Stanford



FINISAR

SEM cross-section showing ridge waveguide structure employed in Finisar's 1300 nm AlInGaAs Fabry–Perot and DFB lasers.

Microdevices, which operates on a fabless model and uses different foundries (including RFMD, TRW, Nortel, GCS and TriQuint) for its various RF process technologies. Bob Van Buskirk, CEO and president, described the advantages of this approach, which include process flexibility, diversity and neutrality; low investment levels and low technical risk; efficient asset utilization; and timely evolution to new technologies. Key lessons are that it is expensive to qualify a new process or foundry; that cycle time is critical and foundries have their own set of priorities (to other external companies and sometimes to internal customers); and that frequent technical contact is critical. Also, designers should be encouraged to be technology-neutral, and intellectual property should be protected.

Fiber-optic components

Chun Lei of Finisar Corporation discussed uncooled long wavelength Fabry–Perot (FP) and DFB lasers manufactured by the company's Demeter Technologies subsidiary. Compared to InGaAsP buried heterojunction devices, said Lei, AlInGaAs FP and DFB lasers offer higher optical gain and speed, improved temperature performance, higher reliability and easier manufacturing. Based on a ridge waveguide design, Finisar's 1.3 μm AlInGaAs FP and DFB lasers have a chip size of 250 × 250 μm, with an active stripe width of ~3 μm (see figure, left). Both DFB and FP designs can be operated at 2.5 Gbit/s from –40 to +85°C, and up to 75°C at 10 Gbit/s. The AlInGaAs FP laser operates at 10 mW with an MTTF of 8×10^6 hours at 85°C. At 100 mA, the DFB structure is centered on 1283 nm, and offers a side mode suppression ratio of 47 dB at 25°C, and 42 dB at 100°C.

Mark Gottfried described Emcore's PIN photodiodes. Devices operating at 850 nm and 3.125 Gbit/s are grown by MOCVD on 4 inch semi-insulating GaAs substrates, and typically feature 2–3 μm layers of n-GaAs followed by a 1.5–3.5 μm i-GaAs absorber and thin (< 0.4 μm) p-type top GaAs layer. A mesa structure design is chosen to reduce parasitic capacitance by placing bond pads directly on the substrate. The 10 Gbit/s design replaces the GaAs epilayers with AlGaAs, making the p- and n-layers more transparent and increasing the responsivity. At both data rates, the diodes featured a responsivity of ~0.50 A/W, and dark current (–1.6 V) of 0.2 nA. According to Gottfried, 1310 nm InP-based photodiodes are less mature devices than their GaAs counterparts. An n+ InP buffer is grown before the i-InGaAs absorber, which is followed by a p+ InP layer and InGaAs cap. The devices feature a responsivity of over 0.9 A/W, capacitance of 0.6 pF and dark current less than 2 nA. In die form, reliability of 3400 hours has been demonstrated at 85°C and 85% humidity. This could lead to moisture-resistant photodiodes that alleviate the cost and yield issues associated with hermetic packaging.

Light-emitting diodes

In the plenary session on LEDs, Kiyoshi Komatsu of Nichia described his com-

pany's manufacturing capabilities for high-brightness LEDs, which now includes a 46 500 m^2 building in Tatsumi. Komatsu estimated that the efficiency of white LEDs will increase steadily, reaching 60 lm/W in 2010, at which time costs will fall so that these devices will offer 100 lumens/dollar.

Heng Lui of AXT's LED division described the design and manufacturing of AlInGaN-based LEDs. In the area of MOCVD growth, in-wafer uniformity, run-to-run reproducibility and throughput of commercial machines all require improvement. During chip processing, there is a lack of pattern recognition systems to identify bad chips, making this a labor-intensive procedure. Due to the nature of the material, dicing losses and costs are high. Test and measurement also needs improvement; for example, there is a weak correlation between chip I-V figures and light output power from the lamp. Degradation is also a major issue that requires better understanding, and possibly the introduction of a better reliability test.

Roger Wu described UEC's fourth-generation AlInGaP LED (see p51), while Jim Chi of the Industrial Technology Research Institute gave some information on Taiwan's burgeoning LED industry. At least 20 companies are now producing LED chips and epiwafers in Taiwan, while many more are packaging the devices. According to Chi, Taiwan's main strengths are the availability of capital and the low cost mindset, while weaknesses include a lack of intellectual property, inadequate R&D and a shortage of engineers. As well as price erosion and the current economic downturn, problems for Taiwan include the strong IP position of companies such as Nichia in the area of GaN technology, and the ongoing national white LED programs in other countries. However, large market growth presents a strong opportunity; Chi predicted that Taiwan's overcapacity situation will be consolidated, low-cost products will open new applications, and manufacturing relationships with mainland China will become increasingly important.

Processing and packaging

Larry Hanes of Alpha Industries described manufacturing issues associated with shrinking the metallization line dimensions of the company's GaAs MMICs. Alpha chose to scale the source-drain fingers in its FET device from 6 μm down to 3 μm, with the aim of increasing the chip yield from 6 inch GaAs substrates. The first of the new devices featured severe delamination of the smaller plated metal fingers, which were made from a titanium-gold plated stack. On analysis, these contacts appeared to have undergone undercutting during etching. The undercut was traced to the titanium: in 6 μm wide contacts, the undercut had not been sufficient to lead to delamination. Alpha considered several approaches, including wider contact and alternative etches, but settled on a replacement for the Ti layer, choosing to employ a TiW:Au plated base metal instead of Ti:Au. The move to TiW:Au required no mask or design rule changes.

MOCVD and MBE

The vital importance of accurate temperature measurement and control during MOCVD growth was highlighted by Jeff Bodycomb of Emcore. Real wafer temperatures are known to vary significantly from the readings given by commonly-used thermocouples and pyrometers. Bodycomb explained how Emcore set about correcting for this variation using an emissivity-compensated pyrometer. Known as RealTemp, this device takes readings at high speed enabling its use in multiwafer rotating disk reactors, where it measures the temperature and uses the data to control surface temperature and therefore the grown structure. When growing laser test structures, changes in surface temperature when gas switching occurred could be readily seen. Using RealTemp allows temperature swings to be compensated for, giving much more uniform temperature throughout the growth runs. Laser wavelength variation from wafer to wafer was much reduced as compared to thermocouple-controlled growth.

A number of contributions discussed MBE's ascendance from a costly, slow research tool to a true production technology. The advent of large multiwafer reactors with high-capacity sources has lengthened campaign times and increased throughput to make it a cost-competitive epitaxy technique. Applied Epi's Dave Narum discussed the emerging generation of devices and their increasingly stringent demands, including lower noise, higher power and higher frequency. Narum translated these needs into the challenges that device structures are now placing upon MBE. These include maintaining a smooth surface during metamorphic growth, composition control for graded layers, dopant control ($< 10^{16}$ in collectors, $> 10^{19}$ in base regions) and abrupt interfaces. The incorporation of nitrogen plasma sources for the emerging class of devices requiring nitride growth was discussed.

Characterization of IC wafers

Innovative Processing AG (IPAG), a spin-off from the University of Duisburg, Germany, was formed at the end of last year to commercialize InP and GaAs devices, including PIN photodiodes and HBT driver ICs. The company has access to ~3000 sq. ft of class 10 and 100 clean room space, MOVPE and MBE growth, circuit design and a processing line. The company's first products, PIN diodes operating at 10 and 40–50 Gbit/s, are expected at the end of this year. One of the founders of the company, Peter Velling, described a novel approach to X-ray characterization. Detailed quantitative analysis of epilayers is usually carried out for test structures that are then used to fingerprint and model subsequent data sets from complex layer structures. Extraction of fully quantitative data is often time-consuming. IPAG's method enables fully quantitative measurements to be automatically extracted from X-ray rocking curves without fitting the data to models. This means rapid qualification of structures such as HBTs, enabling the technique to be used in process control. Analysis of an InGaP/GaAs:C device showed that the observed X-ray intensities resulted from tensile strain in the base layer caused by carbon on arsenic sites, and surface roughness resulting from the formation of islands at the p+-GaAs:C interface of the InGaP/GaAs (emitter/base) structure. Overall, no degradation in the performance of GaAs HBTs was noted, and these devices were reported to offer a robust process with f_t and f_{max} values in excess of 120 GHz.

James Greene of Corning Tropel, a manufacturer of substrate flatness measurement equipment capable of assessing 120 wafers per hour, described how different measurement techniques impact the lithography process. Capacitance, normal and grazing incidence interferometry, and air gauging each have benefits and limitations and can be matched



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to different compound semiconductor device families.

Peter Hiesinger from the Fraunhofer Institute described the development of the EL2 Absorption Topography System, which uses IR absorption to measure the uniformity of the EL2 intrinsic deep donor across a GaAs wafer. This mid-gap donor occurs when an As atom sits on a Ga site. The concentration and ionization degree of this donor determines the semi-insulating properties of a wafer and is controlled by the Ga/As ratio during growth. The uniformity of this donor is crucial to the operation of RF devices made on semi-insulating GaAs substrates. Data from the tool showed a lateral resolution down to 30 mm and reproducibly gave variations as low as 1%. Differences in EL2 uniformity in LEC- and VGF-grown wafers were shown before and after annealing. Though annealing improved EL2 uniformity, it also reduced resistivity.

Fab management

Several sessions looked at the issues of productivity, cycle times and efficiency from a number of different perspectives. Mary Young of Nortel Networks discussed how the goal of doubling fab capacity and halving cycle time had been meet by working with a consultant, MAX International Engineering Group, to implement an Overall Resource Effectiveness scheme. This monitored how all resources were being used, not just equipment, to identify and quantify bottlenecks. It also monitored how implementing a structured improvement process eventually lead to the goals being achieved.

Lisa Aucoin of Raytheon RF Components described the challenges of running a fab dedicated to a number of low-volume processes at different levels of maturity, for military and commercial customers. This limits the usefulness of a silicon-like model of a dedicated facility for each process (see p81).

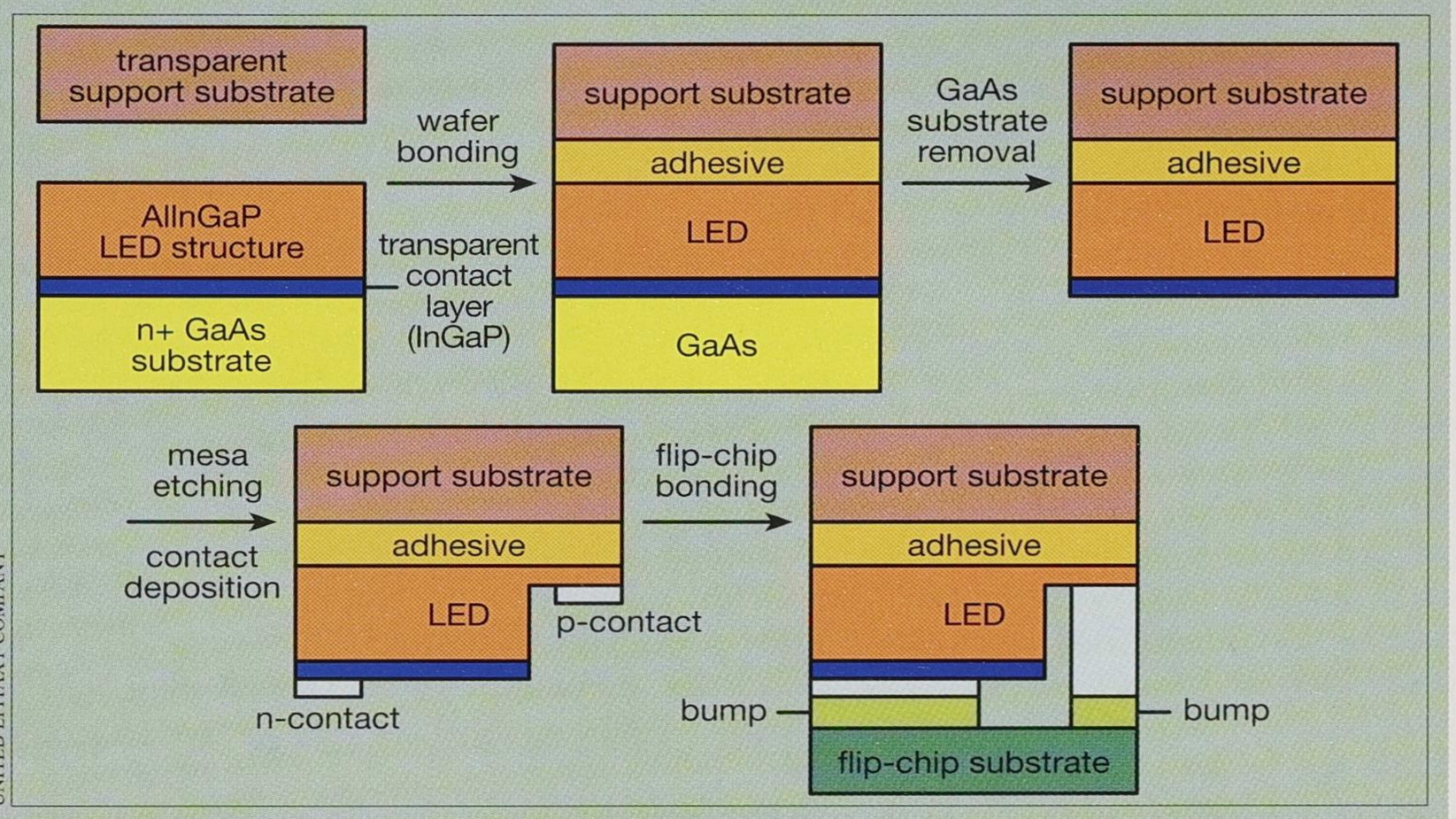
In the fiber-optic arena, Tom Dearmin of Lasertel discussed the role of statistical process control when establishing a new company (see *Compound Semiconductor* August 2001, p61). Seppo Orsila described how Modulight is using database-centered manufacturing to reduce operator involvement in routine tasks and simple decision-making, thereby reducing human error and increasing throughput.

UEC unveils new wafer-bonded AlInGaP LED structure

United Epitaxy Company (UEC) used the CS-MAX stage to announce its fourth-generation AlInGaP LED structure, which it hopes will challenge the highest performance devices developed by LumiLeds Lighting (see *Compound Semiconductor* April 2001, p59).

A key feature of AlInGaP devices, which are grown on absorbing GaAs substrates, is the need to extract light efficiently from the device. LumiLeds uses a wafer-bonding approach to replace the GaAs wafer with a transparent GaP substrate, and also employs relatively complex chip-shaping techniques. An alternative approach, which was used by UEC in its first AlInGaP devices, is to incorporate a DBR structure above the absorbing GaAs substrate to reflect light back towards the top surface. UEC's second-generation device included surface roughening to reduce the effect of total internal reflection, while a further iteration also incorporated a current-confining layer (see *Compound Semiconductor* Dec 2000/Jan 2001, p13).

For its fourth-generation device, UEC has also moved to a wafer-bonded approach. However, rather than using direct bonding of a semiconductor (GaP) wafer, UEC has developed an indirect bonding process to join the wafer to a transparent substrate such as sapphire or glass. The process sequence, shown in the figure, was described by Roger Wu, manager of UEC's Epitaxy Department. The AlInGaP LED epitaxial structure is grown on an n^+-GaAs substrate, and includes a transparent InGaP contact layer adjacent to the substrate. The structure is coated with an adhesive polymer and wafer-bonded with unaxial pressure at elevated temperature. Next, the GaAs substrate is removed, and a mesa structure is etched to allow p- and n-contact formation.



Process sequence for UEC's fourth-generation wafer-bonded AlInGaP LED.

The adhesive has to meet some stringent criteria, in particular good chemical resistance, thermal stability and optical clarity. A low cure temperature and small volume shrinkage during curing are also required, as is the ability to bond to various substrates. Reporting that the adhesive polymer successfully passed various tape lift-off, high temperature and chemical stability tests, Roger Wu showed photos of LED wafers bonded to glass and sapphire substrates. Encouraging performance results similar to those obtained from UEC's third-generation devices (>40 lm/W at 625 nm) were reported. Flip-chip bonding to a suitable substrate (see figure, final step) is predicted to give rise to further performance increases.



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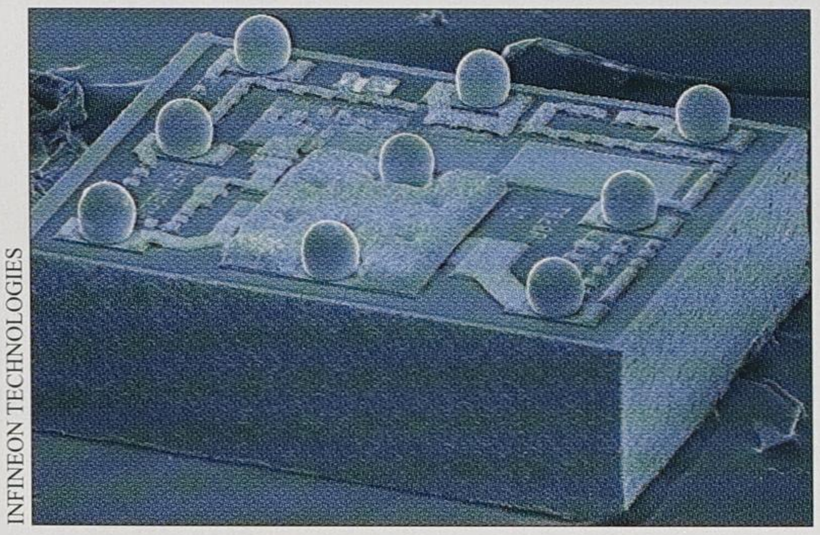
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European GaAs fabs still forging ahead

When talk turns to GaAs fabs and foundries, the first names that spring to mind are usually American or Taiwanese. However, Europe is no sleepy backwater as ***Jon Newey*** *discovers.*

Europe has always been at the forefront of the worldwide research and development effort that has made GaAs a mainstream technology and continues to push devices to higher performance levels and into new applications. Despite the current malaise in the global microelectronics business, and especially in the markets that GaAs relies upon, the European GaAs industry, whilst feeling the pinch, seems to be coping. Compared with the US or Japan, overall production capacity is small. However, a number of facilities are producing a variety of products and developing new processes to keep up with emerging applications, with the aim of reaping the benefits when the market upturn arrives.

What follows is a look at Europe's larger players, examining what they do and where they are heading in a fast changing industry. The focus is on manufacturing and omits much of the activity in small-scale production and those organizations that exist mainly as research and development bodies. Obvious examples might be university research departments, or ventures such as Opto+, a joint R&D effort between France Telecom and Alcatel working on devices for high-speed optical communications networks.



INFINEON TECHNOLOGIES

Fig. 1. Infineon's T628 flip-chip version of its Bluetooth PA. The chip area is 0.6 mm^2 and has leadless bumps for mounting on ceramic modules.

Infineon Technologies

As would be expected from Europe's largest volume producer of GaAs ICs, Infineon runs an extensive range of processes to address the mobile handset, broadband wireless access and automotive radar markets. In common with its competitors, Infineon runs well established MESFET processes and has qualified HBT and PHEMT processes in recent years, with others still in development. Production is now concentrated in a purpose-built 6 inch fab in Munich.

The proprietary double Ge/Si contact implantation, one ohmic gate metal (DIOM) MESFET process is for production of devices for microwave applications up to 20 GHz. A variant of this, DIOM-low voltage mobile (DIOM-LVM), yields MMICs optimized for low-voltage mobile phone equipment with supply voltages down to 2.4 V. MESFET-based products include LNAs, and PAs for mobile phones, base stations, CATV and other applications.

Although MESFETs form an important part of Infineon's product line, Martin Wimmers, senior manager for product marketing, explained, "The main technologies in the future for Infineon will be HEMT- and HBT-based GaAs products."

InGaP/GaAs HBT processes have been established for mobile phone and Bluetooth applications. PHEMT process variants have been optimized for applications in mobile communications, millimeter-wave (20–40 GHz) communications and automotive radar at 77 GHz. Infineon has also realized the potential of enhancement mode (E-mode) PHEMTs and has such a process in development.

Moving to modules

There is gathering momentum towards a more modular approach to components for wireless and fiber-optic applications. This has been evidenced by a number of recent mergers that have seen GaAs MMIC producers such as TriQuint merge with filter manufacturers such as Sawtek in order to position themselves better as suppliers to handset OEMs. Infineon has not ignored this trend, launching a tri-band MESFET-based PA module earlier this year. The module employed a low-temperature, co-fired ceramic substrate. "We believe that Infineon needs to offer 50 Ω matched devices today and in the future because the market requires it. The base technology for this can be modules made with ceramics and/or multi-chip plastic packages," added Wimmers. PAs for Bluetooth applications already come in a flip-chip version with leadless bumps for mounting on ceramic modules (see figure 1).

Infineon's well established name in the GaAs IC business and its size have not made it immune to the market turbulence of the past year. This has not deflected the company from its chosen market and it still seems to have every confidence in the future. "We have put our GaAs business on a broad basis, and we still believe that it should be this way in future," said Wimmers. Certainly the drop in the mobile market has had an influence on Infineon, but the main growth area for its business is expected to come from this area. "Infineon has a well balanced product portfolio and very good system know-how, and we think we are well prepared to benefit from any upturn in the semiconductor market," he added.

United Monolithic Semiconductors

Formed in 1996 as a joint venture between Thomson CSF (now Thales) and EADS (formerly Daimler Chrysler Aerospace), United Monolithic Semiconductors (UMS) has become one of the primary suppliers in the markets on which it focuses. In fact, UMS claims to be the number-one supplier – with 80% of the world market – of GaAs devices in automotive applications. A recent market

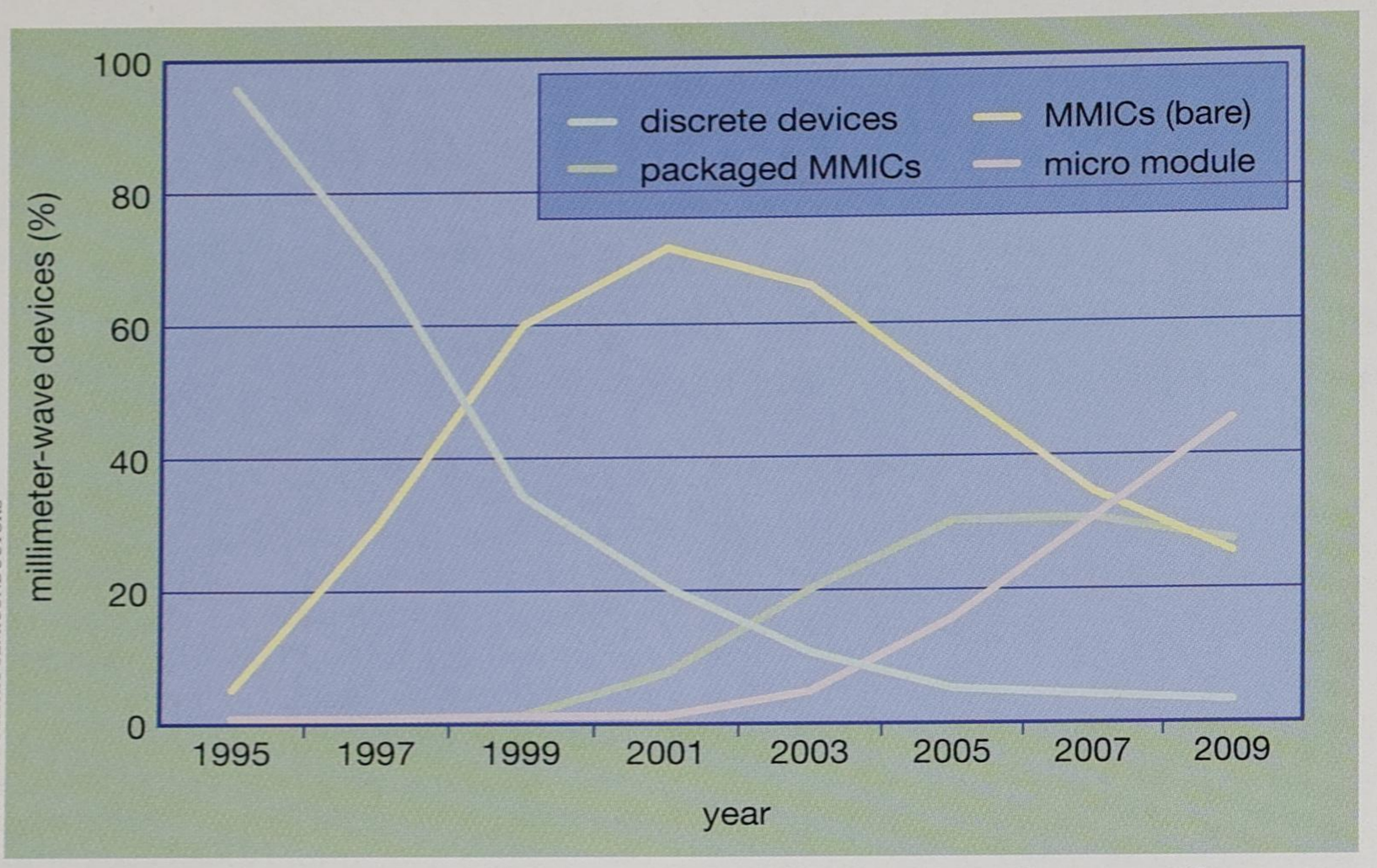


Fig. 2. The evolution of millimeter-wave MMIC technology. Almost totally dominated by discrete devices in the mid-1990s, a move to packaged MMICs and micro-modules is being pursued by many manufacturers.

analysis report indicates that this is a good position to be in (see p31). It predicts that automotive radar is set to become the fastest growing millimeter-wave market.

The company is split over two sites in Ulm, Germany and Orsay, France. The German facility performs front-end processing on a 4 inch line, with 10 000 wafer starts per year. The French plant performs back-side processing, including wafer thinning, via hole etch, metallization and wafer level test.

UMS's standard products account for 55% of all business, with the remainder coming from its foundry service. Over half of all its business is done within Europe. UMS has three main markets, namely wireless telecom networks (local multipoint distribution services [LMDS], multichannel multipoint distribution services [MMDS] and VSAT), automotive (collision avoidance radar, keyless entry systems and short-range communications for automated road tolling) and optical communications (Gigabit Ethernet and OC-192 and OC-768).

PHEMT processes run in single-recess and double-recess versions for LNAs and high-power applications respectively. A new 0.25 μm gate length, power PHEMT processes is under development to increase breakdown voltage (BV_{ds}) from 12 to 18 V. Latest results have shown that BV_{ds} is reproducibly above 20 V. The first products guaranteeing BV_{ds} of 18 V from this process will be available early next year. The first MHEMT MMIC demonstrations are expected early next year with process qualification scheduled for late 2002.

An InGaP/GaAs HBT process is in an advanced stage of development for high-power amplifiers and VCOs operating up to the Ku band. The first products are expected to be available early in 2002.

Packaging and modules to cut costs

In common with others, UMS is attempting to position itself better in the value chain by moving to module production and incorporating packaged MMICs into RF subsystems (figure 2). The first goal of this activity is to offer a complete family of packaged MMICs for 26–28 GHz radio links for wireless network applications such as LMDS. The packaged chipset will include all the necessary circuits for manufacturing modules using surface mount technology, avoiding the cost to the customer of wire-bonding bare MMICs in a clean-room environment. "We strongly believe that this will turn out to be a real breakthrough, enabling us to reduce very significantly the costs at the system module assembly level and perhaps enabling the real take-off of millimeter-wave telecommunication systems in high volumes," said Dominique Pons, director of R&D and strategic marketing.

The cost of modules can be further reduced by using UMS's self-biasing MMIC technology (figure 3, p57). This removes the need for further tuning after module assembly and eliminates up to eight additional passive components per MMIC. Flip-chip mounting using solder bumps is seen by UMS as a way to reduce assembly costs, though considerable effort is still required to make this a high-volume production technology.

UMS is not sitting idly as other technologies nudge into the traditional territory occupied by GaAs. A program is underway to develop high-power devices using the GaN/AlGaN material system. GaN HEMT technology is firmly embedded in the UMS technology roadmap, though technological challenges and uncertain market demand mean commercialization of the process is unlikely before 2004. "We definitely believe this is an important topic for the future and want to be ready in time," explained Pons.

Marconi Optical Components

Activity in electronic materials has a long history at the Caswell, UK site, beginning in 1940 when the Plessey Company set up a development laboratory. Between 1940 and the present there have been a number of divestments and mergers between companies resulting in the activities at Caswell changing name and ownership. This activity includes the merger of GEC with Marconi and later Plessey. In 1999, British Aerospace (BAE) bought GEC's defense electronics business to form BAE Systems. The non-defense activities came within the new publicly traded Marconi company. The current business, reshaped to focus on components for optical networks and trading as Marconi Optical Components (MOC), came into being in November 2000.

Despite the company's new name, GaAs MMICs for the wireless market currently provide MOC with an underpinning technology and sales base. Processes are run on both 6 and 3 inch lines and include PHEMT, HBT and MESFET, with a MHEMT process in development. Device wafers are provided by in-house MBE and MOVPE activity. Standard products include amplifiers, switches and broadband attenuators. The target markets for these are wireless local-area networks and MMDS.

A 0.5 μm gate length MESFET process yields amplifiers for frequencies up to 20 GHz. For higher frequencies, a 0.25 μm

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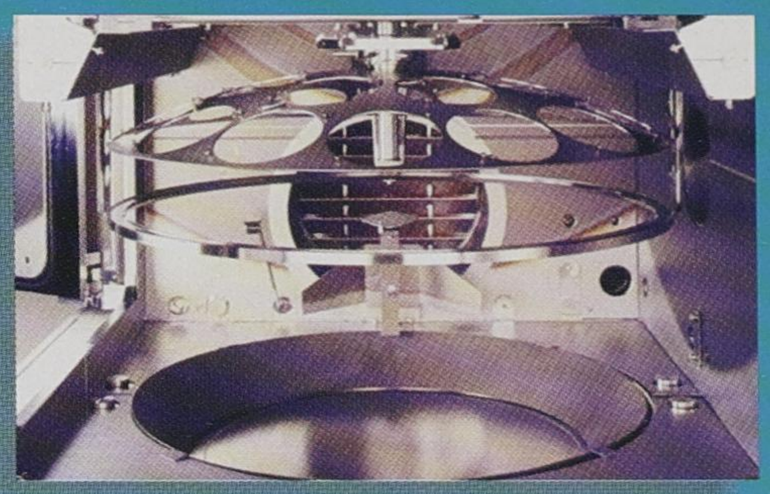
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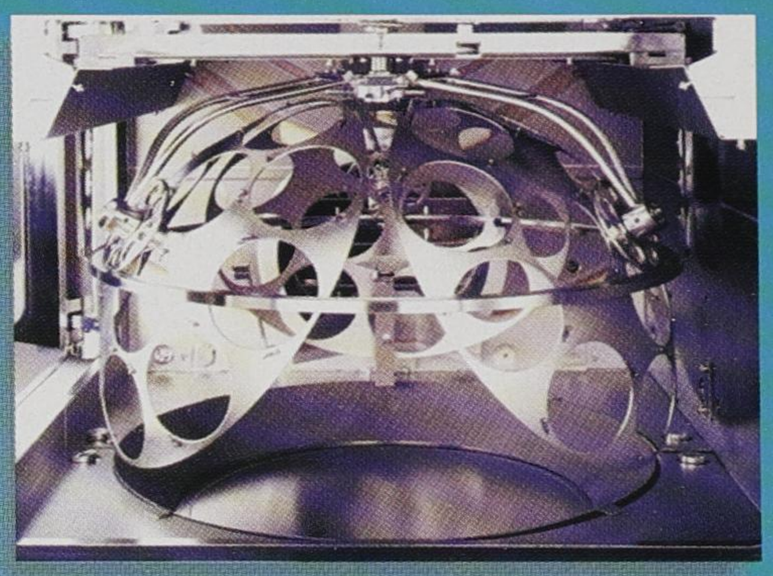
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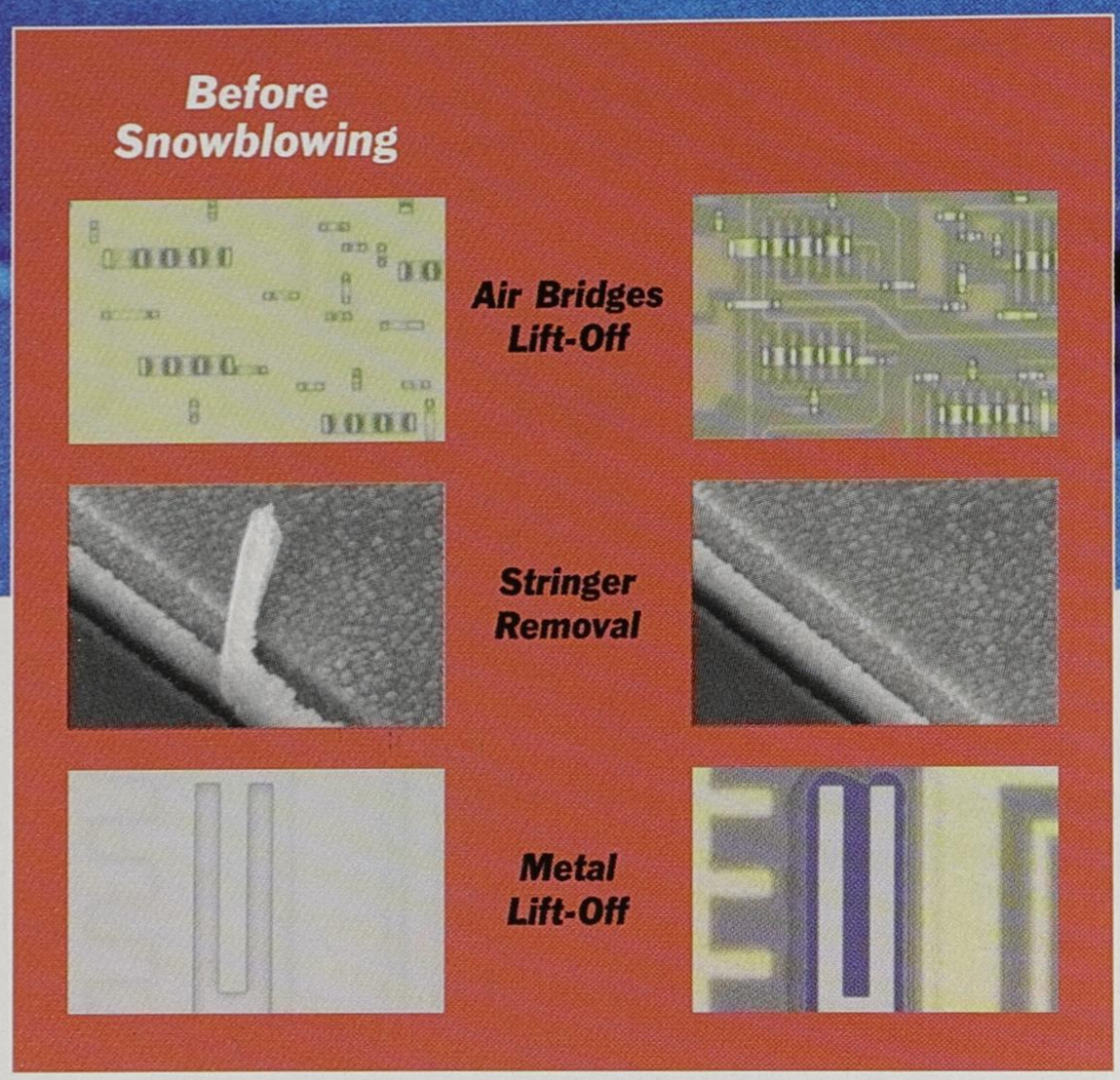
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mushroom gate PHEMT process can operate at speeds in excess of 40 GHz. The MHEMT process in development is targeted at applications up to 100 GHz.

MOC's products feed the parent company's wireless and optical communications business requirements as well as other customers. As the new name suggests, the market on which the company intends to concentrate most effort in the future is components for optical networks. All new processes and products are aimed at this market. As well as InP-based electronic and optoelectronic components (lasers and photodetectors for example), GaAs devices are also needed in the so-called physical layer of optical networks. MOC is also looking to GaAs as the material of choice for optical modulators for 40 Gbit/s applications. This is very much a start-up activity for MOC. Having a product base that is not yet established has shielded the company from the recent downturn in this market that has so affected established operators. Products are now sampling to internal customers at the system level within Marconi, and the company hopes to be in a good position to capitalize when the market upturn comes.

Alenia Marconi Systems

This organization based in Rome, Italy is a joint venture formed by the Italian company Alenia (part of the Finmeccanica group) and GEC-Marconi Systems (the defense electronics unit of GEC, now part of BAE Systems). The role of Alenia Marconi Systems' (AMS's) GaAs activity is one of R&D and small-volume manufacture. AMS's production is almost entirely for internal consumption and feeds the defense and aerospace systems activities further downstream. Its primary products are MMICs for radar transmit/receive modules, but a few niches are also served such as GaAs-based detectors for X-ray and high-energy physics. The two main production processes are for HFETs and ion-implanted MESFETs, backed up by circuit design and packaging capabilities. These processes run on a 3 inch line, with conversion to 4 inch to begin soon.

The next generation of radar will require broadband MMICs, and it is here that much activity is concentrated at the moment. PHEMT and HBT processes are being evaluated for this high-power application and a research program for GaN- and SiC-based devices is under way for future generations of high-power devices. At high powers, packaging becomes a big issue. AMS is working on a proprietary AuSn bump-bonding technology for improved thermal management in high-power, high-temperature environments.



UNITED MONOLITHIC SEMICONDUCTORS

Fig. 3. A low-noise amplifier for 10–16 GHz operation, including UMS's self-biased MMIC technology. The device measures 1.52 × 1.08 mm.

Filtronic

A relative newcomer to GaAs device production, Filtronic Compound Semiconductor signaled its intentions in this area when it purchased the Litton Solid State plant in Santa Clara, CA. This gave it an established design, test and relatively small-scale manufacturing facility. In 2000 the company acquired a former DRAM production facility in Newton Aycliffe, UK, and set about converting this to provide a 6 inch GaAs process line for large-volume manufacturing.

Market conditions and a phased plan for start-up mean the Newton Aycliffe site is by no means fully utilized. The current first phase of operation has seen about one-third of the available area being used. This gives a possible 30 000 wafer starts per year, with market conditions determining if and when the remaining capacity will be used. An increase to 50 000 wafer starts could be made without any significant capital expenditure. MBE is done in house using a 7 × 6 inch wafer reactor. The line produces a range of standard products including PHEMT-based switches and LNAs, with PHEMT FETs and PAs for GSM applications currently under development. A design and foundry service is also available.

The PHEMT technology is aimed at wireless and fiber-optic communications applications. Two depletion mode (D-mode) PHEMT processes have now been released. The first is a single recess process for ultra-low-noise devices, and the second is a double recess process for higher-power devices.

A 0.5 μm E-mode PHEMT process has also been released. Control functions such as switches made with this technology offer performance benefits over MESFET technology that will be needed for next-generation multimode handsets. E-mode PHEMTs are also competing with HBTs for the PA function in handsets.

Being established in the filter and antenna business, Filtronic is well positioned to take advantage of the trend towards integrating components into modules. The company has begun sampling a receiver module that combines the antenna, receiver filter and LNA MMIC. "Filtronic fundamentally believes in the move to higher levels of integration and have taken this approach in many of our product areas," said Christopher Snowden, CEO of FCS.

The recent announcement of alliances with BAE Systems and M/A-COM (see p12) has brought a much needed boost to FCS. This should help ease the plant into profitability next year, and perhaps answer those who have questioned Filtronic's wisdom in remaining in the business of components for handsets, given the market conditions and well established competition.

OMMIC

Based near Paris, France, OMMIC is an independent but wholly owned subsidiary of Philips and was formerly known as Philips Microwave Limeil. The company provides a GaAs MMIC foundry service to Philips and external customers, as well as supplying 4 inch and 6 inch epiwafers from two MOVPE reactors. OMMIC is now converting production to 6 inch, with mid-2003 as the target for completion.

OMMIC has a range of standard products based on MESFET and PHEMT for the wireless and fiber-optic communications markets. These cover the 2.5–40 Gbit/s data rates and include digital ICs, transimpedance amplifiers, laser drivers and modulators, and LNAs and PAs for LMDS, cellular base stations and satellite communications. The MESFET designs are used on older-generation products and are gradually being phased out, with all new work being done on PHEMT processes. The bulk of OMMIC's business is in the standard products and contracts for low- to mid-volume ASICs.

OMMIC was amongst the first to intro-

duce E- and D-mode PHEMT processes. These give gate lengths of 0.18 μm and yield MMICs with f_t values up to 73 GHz. Further HEMT processes are under development, including a 0.18 μm gate length process using a high indium content E/D-mode HEMT structure on both GaAs and InP substrates. This is designed to give an f_t of >150 GHz, thus giving operating frequencies suitable for 40 Gbit/s (OC-768) optical network applications. A GaAs MHEMT process is at an advanced stage of development and is scheduled to be made available later in 2001.

Fraunhofer IAF

This branch of the Fraunhofer Society concentrates on compound semiconductor materials and devices. Predominantly a contract researcher, Fraunhofer IAF also does small-volume manufacturing of MMICs and optoelectronic devices based on GaAs and other compound semiconductors (see *Compound Semiconductor* February 2001, p31). Though processing is done on 4 inch wafers, a custom MBE service is available for 6 inch wafers in small to medium volumes. Designing circuits based around PHEMT processes gives MMIC PAs operating at up to 60 GHz for wireless communications.

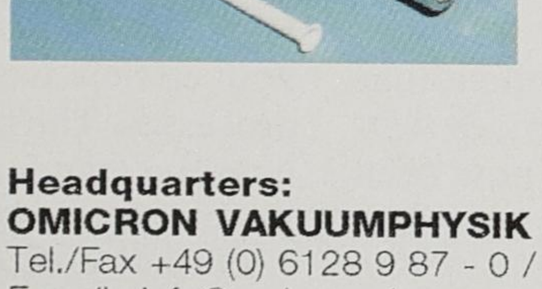
Infineon and UMS are amongst those working with Fraunhofer IAF to develop MHEMT processes. This will avoid the need for expensive, and as yet small-diameter, InP substrates. A metamorphic buffer allows devices to be grown on relatively cheap 6 inch GaAs wafers. Though InP substrates offer better thermal conductivity for high-power applications, the move to flip-chip packaging and bump bonding should offer sufficient thermal management for MHEMTs on GaAs. A number of gate-length MHEMT processes are being developed, with the 0.15 μm process giving a 13.5 dB gain at 94 GHz with an extrapolated F_{max} of 450 GHz. An E-mode MHEMT process is also being developed with the switching elements of fiber-optic communications networks in mind.

Conclusion

Across Europe, the total GaAs activity may look relatively insignificant at first glance. Infineon aside, Europe is a little different to the rest of the world. The GaAs activity often forms a small part of the business in large companies such as Philips. This contrasts with the US where names synonymous with GaAs device manufacture such as RFMD and TriQuint have their origins as stock market-floated spin-offs from big parent companies such as TRW. However, there is strength in the depth and variety of activity, backed by a rolling program of research leading to new processes designed to meet the demands of emerging applications. The European GaAs industry has survived until now because it has been both innovative and competitive. Looking ahead, Europe seems well placed to benefit from the technologies under development as they move into the mainstream. 40 Gbit/s optical networks are a market where European GaAs device manufacturers could do well.

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INSTRUMENTS FOR SURFACE SCIENCE

Tunable lasers offer network flexibility

Equipment manufacturers are actively evaluating tunable laser technologies and are ready to take advantage of these products when they become available, write ***Lisa Huff*** *and* ***Christine Mulrooney*** *of Communications Industry Researchers (CIR).*

To achieve the vision of a programmable network, equipment providers are actively considering the use of tunable components, and, more specifically, tunable lasers. These devices allow a level of flexibility that is unavailable today, and have obvious benefits for optical networking systems. In DWDM networks, for instance, tunable lasers can theoretically reduce the number of lasers required to support 128 different channels from 128 lasers with discrete wavelengths, to 8 lasers with 16 tunable wavelengths. Instead of having to maintain a full inventory of spares for each channel or port, service providers would be able to stock a few tunable transmitters that could be used to replace failed parts.

Sparing is just one potential application of tunable lasers. More exciting is the prospect of remote service provisioning of the network. This would allow service providers to remotely change the wavelengths utilized by a specific customer to provide "bandwidth on demand". The potential cost and performance benefits of such an approach are enormous.

At present, however, the reality is that tunable lasers are still a long way from realizing their full potential. While considerable growth is expected in this marketplace, most of the growth will not materialize for a few years, by which time tunability will have rapidly become a standard feature of many telecommunications lasers.

Today's tunable reality

At this time, there are only two uses for tunable lasers. The main use is in deployed systems, where tunables are used as temporary replacements for lasers that have failed, in order to keep the equipment running. The tunable laser is replaced with a fixed wavelength laser when the correct one is obtained. Tunable lasers are also being used in performance monitoring equipment to monitor several wavelengths at once.

Our research indicates that most equipment manufacturers have been slow to deploy tunable laser technologies. There is general concern about the robustness and long-term reliability of tunable lasers. Today's products have shown good performance but only in the lab environment, leading equipment manufacturers to believe that tunable lasers are not ready for broad implementation. Nonetheless, most are actively evaluating tunable laser technologies and are ready to take advantage of these products when they become available.

Building the perfect laser

For the tunable laser market to reach its full potential there must be some resolution of the numerous technological issues that currently exist. In particular, the market will have to determine the importance of the various trade-offs that are implicit in the tunable laser technologies now being considered. Equipment manufacturers and component suppliers alike are trying to obtain the perfect tunable laser using a variety of technologies, each with its own advantages and disadvantages (see table below). In particular, there is a trade-off between wide tunability and optical output power for most device types.

Many tunable laser manufacturers are arduously working at improving the reliability of their devices, and all are starting to incorporate integrated wavelength lockers in order to improve stability of the device at each wavelength. Improvements in manufacturing process controls are being realized, and most component manufacturers are expecting to be in volume production of qualified products by the

Technology choices for tunable lasers

Laser type	Tuning mechanism	Advantages	Disadvantages	Suppliers
Distributed feedback (DFB) laser	Temperature	Wavelength stability Well developed process	Low output power Limited tuning range Slow switching speed	Nortel, JDS Uniphase, Fujitsu
Distributed Bragg reflector (DBR) laser	Temperature Current	High output power Fast switching speed Wide tuning range	Yield issues Size Low output power Wavelength instability	ADC, Agere, Agility, Alcatel, JDS Uniphase, Marconi, Multiplex
External cavity laser (ECL)	Mechanical Current	Wide tuning range High output power Spectral purity	Higher cost Shock/vibration sensitivity Slow switching speed	New Focus, Iolon, Blue Sky
Vertical cavity surface emitting laser (VCSEL)	Mechanical	Low cost Low power consumption Good mode stability	Low output power Not traditional 1550 nm technology	Bandwidth9, Nortel (CoreTek)

end of 2001. Among these are Nortel High Performance Optical Components, New Focus, Agility, Alcatel Optronics, ADC, JDS Uniphase, Marconi Optical Components, Iolon and Corning. Fujitsu claims it is already in volume production with its devices, and that they are being incorporated into Fujitsu DWDM equipment.

Nortel has addressed the stability issue by designing its tunable transmitters with integrated wavelength lockers and closed feedback for continuous tuning over the life of the device. Many other manufacturers are starting to use similar techniques in order to assure equipment manufacturers that tunable lasers are viable for system deployment in the long term.

Future applications

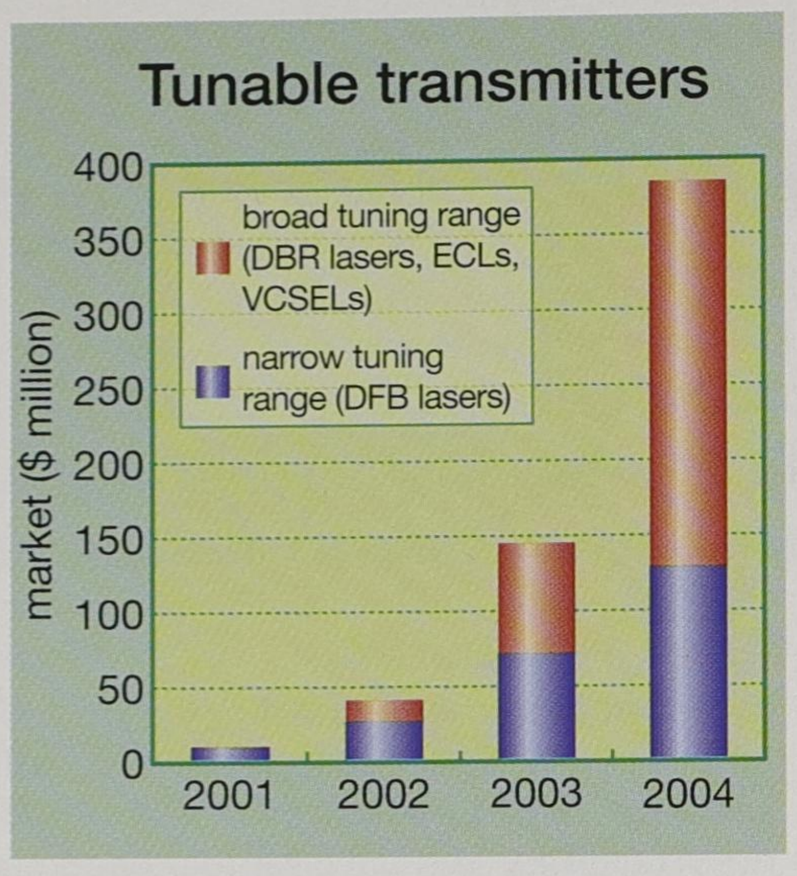
Although the technological issues outlined above will take some time to address completely, this process will eventually open up new applications for tunable lasers. Initially, these devices will be deployed as spares for fixed lasers that fail. But in order to take full advantage of the functionality of these tunable components, the topology and management of the network, including software, must change. Therefore, we see a relatively slow adoption of the devices over the next few years.

Although equipment manufacturers are not currently deploying tunable lasers to their full functionality, they are excited about the prospects that these components hold. Once the reliability issues are resolved (and there is no doubt that this will happen), equipment manufacturers will use them for inventory reduction, performance monitoring and dynamic provisioning.

Long-haul and metro markets

The long-haul market will be the first to adopt tunable lasers. Historically, this market has been the proving ground for most new optical technologies, and is better able to bear the cost of these new technologies. In the short term, long-haul applications will utilize tunable DFB lasers, but will adopt DBR lasers and ECLs in the longer term. These latter device types offer broader tuning and higher optical output power.

Because of its large size, the metro market is one area in which we see particular potential. However, before tunables can be widely used in the metro environment, costs will need to approach those of fixed wavelength lasers. Nonetheless, the metro market has a huge potential for growth and is already the focus of many tunable laser manufacturers. Since metro distances are relatively short, output power does not need to be as high as for the long-haul market. Cost is a huge consideration in this arena, so low cost technology, coupled with automated manufacturing, will be key for supplier success.



The technology winners in the metro space are likely to be DFB lasers and VCSELs. Since DFBs are a proven technology, equipment manufacturers will find them easier to qualify and less costly than any of the other types. The inherently low cost of VCSELs will win them a share of the metro equipment business.

The dynamics of the long-haul and metro markets will also influence the strategy adopted by companies developing tunable lasers. Concentrating on the metro market in the near-term is not a sound strategy unless the company has a revenue stream to sustain it for at least two years until the market develops. Equally, it could be a mistake to concentrate on widely tunable lasers if these do not have sufficient power to address the initial market for long-haul applications.

Device types and markets

Tunable DFB lasers are already starting to be deployed for sparing and replacements for fixed wavelength applications, and some equipment manufacturers, such as Fujitsu, are starting to incorporate them into their OADMs as light sources. Other tunable laser technologies have not reached the price points to be readily incorporated into systems. However, CIR sees a migration in the market over the next five years, from narrowly tuned DFB lasers to more widely tuned DBR lasers, ECLs and VCSELs, as the stability and price issues are resolved.

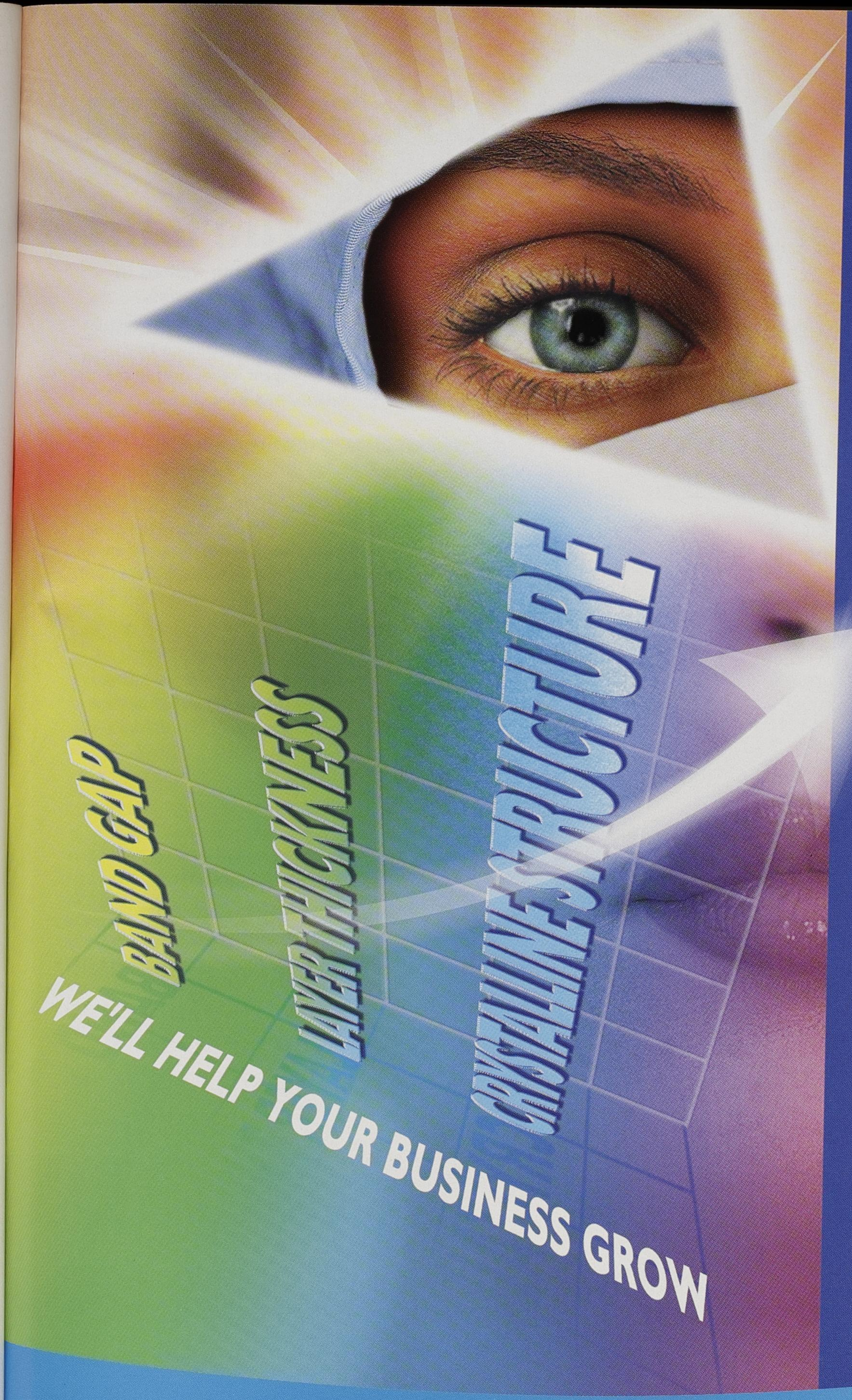
The tunable transmitter market will remain fairly small until at least 2003 (see graph, left). In 2001, the market forecast of $10.8 million consists entirely of narrowly tunable DFB devices. As the market improves, and applications such as wavelength routing and optical add/drop light sources start to develop, a $142 million market will emerge in 2003. Widely tunable lasers will become the majority of the tunable market in 2004.

Sub-systems

CIR believes that the future of tunable lasers will also include a transition of vendor focus from component level products to sub-systems. Eventually, most tunable laser manufacturers will sell transmitters, i.e. products at the sub-system or module level. This makes sense since the laser manufacturers are most familiar with controlling the tunability of their lasers, and have in most cases already developed transmitter sub-systems. The only problem with this is that if component suppliers have different tunable transmitters, equipment manufacturers would have to accommodate at least two different designs in order to have a second source.

ADC and Agility recently proposed the obvious solution for the second sourcing issue, namely a multi-source agreement (MSA). This would allow component suppliers to develop tunable lasers using any technology but within a certain footprint and with standard control parameters. Such an MSA is likely to do more to enable the market than anything else. The success of this MSA is not only important for tunable transmitters and lasers, but also for the future of standardization of optical components. If this agreement is successful, CIR predicts that most other new optical sub-systems will be designed under similar agreements.

Lisa Huff and Christine Mulrooney are both senior optical components analysts at Communications Industry Researchers (CIR) of Charlottesville, VA. A report entitled "Tunable Optical Components: A Technologies & Market Assessment" was released by CIR in July 2001. For further information, contact Robert Nolan, tel. + 1 804 984 0245 ext. 15, or e-mail: robert.nolan@CIR-inc.com.



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Intermixing drives photonic integration

Quantum well intermixing could become a key process in developing next-generation monolithically integrated optical components, writes ***John Marsh*** *of Intense Photonics.*

In the field of optical communications, the transition from point-to-point systems to networks is demanding components with much higher performance. The improvements needed span a wide range of parameters, from more dynamic and flexible operation to better mechanical and thermal stability.

The technology platform required to realize these advances successfully and cost-effectively needs to be extremely versatile. It must be capable of replacing a wide range of passive components with active elements, and of easy integration of both active and passive functions.

Integration of discrete devices brings numerous benefits to the optical communications system designer. Losses associated with coupling to fibers are eliminated, and the number of packaging stages is reduced. Also, mechanical and thermal stability are greatly enhanced – these are attributes which are particularly beneficial to functions required for the all-optical network, such as wavelength conversion and switching. Integration of different optical elements within a single device also supports advances in terms of functionality; this enables, for example, the realization of novel semiconductor lasers with high output power or ultra-short pulses.

In developing monolithic photonic integrated circuits (PICs) for future generations of optical communications networks, Intense Photonics has chosen quantum well intermixing (QWI) as its fabrication platform, following many years of development and experimentation with different optoelectronic materials and device structures. This article introduces the technology, contrasting it with traditional bulk material and quantum well approaches to monolithic integration.

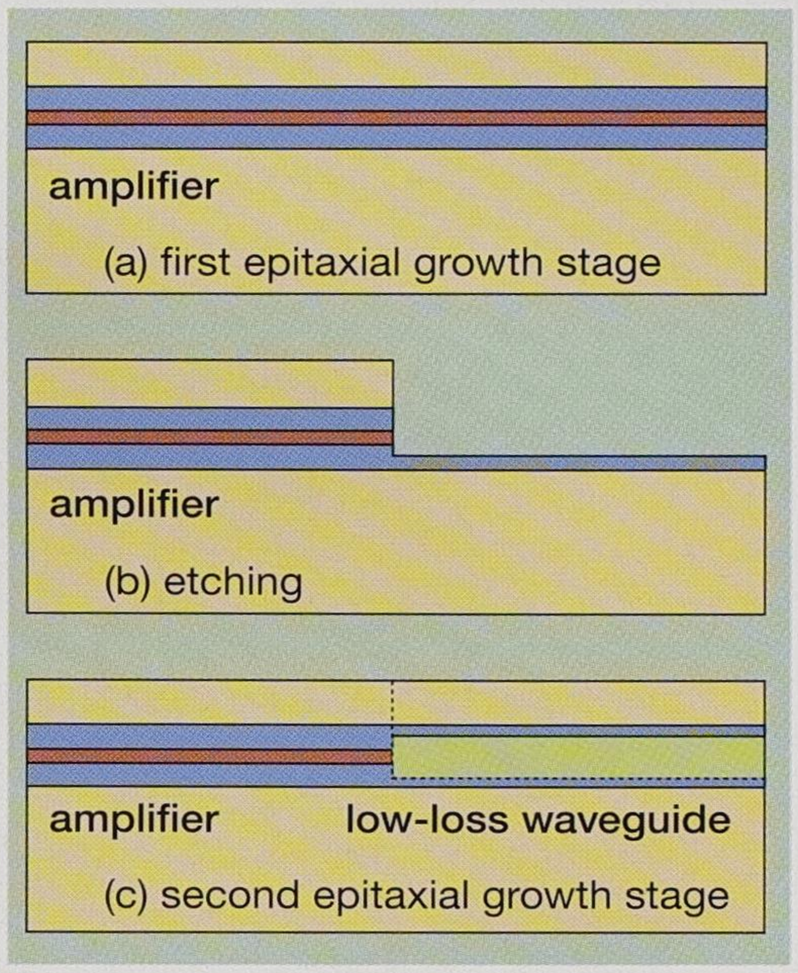


Fig. 1. The principal steps required to fabricate an active/passive waveguide butt joint in bulk semiconductors.

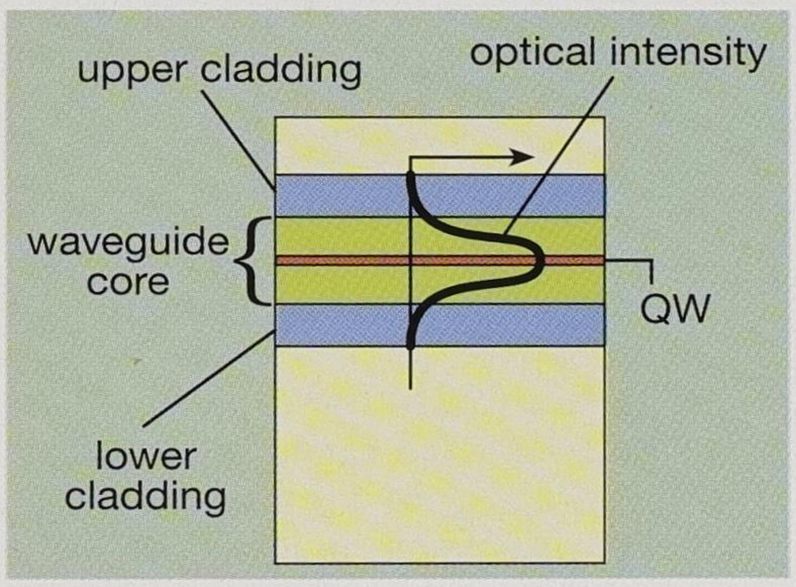


Fig. 2. Cross-section of an SCH device, showing the waveguide core containing a single QW at its center. The intensity variation with depth of the guided mode is also illustrated.

Monolithic integration technologies

Monolithic photonic integrated circuits are fabricated in either GaAs- or InP-based heterostructure material systems, depending on the application wavelength. Traditional approaches to monolithic integration, using bulk materials, make use of etch and regrowth fabrication techniques.

The main steps to integrate a fundamental optoelectronic building block – a gain region with a passive waveguide – are illustrated in figure 1. An epitaxial structure, usually that of the gain region, is first grown across an entire GaAs or InP substrate. The gain region of the final device is masked using photolithography, and the device is then etched to create a slot for the passive waveguide. In a second stage of epitaxy, the passive waveguide is then grown into the slot.

This process typically has low yield, due to the difficulty both of regrowing on a vertically etched surface, and of regrowing with high precision. A further problem is that the material selection necessitates a compromise between the bandgap, refractive index and layer thickness of the passive waveguide. There is inevitably a mode mismatch at the butt joint, resulting in losses due to scattering and back-reflection.

There are significant advantages in moving to quantum well (QW) active layers. A QW is a very thin semiconductor layer, typically ≤ 10 nm, sandwiched between "barriers" of larger bandgap material. Because of the bandgap difference, electrons and holes are trapped in the QW. The small size of the well causes the electron and hole energy levels to become quantized, and so the bandgap energy of a QW is larger than that of an equivalent bulk layer.

Although a QW confines carriers (electrons and holes) efficiently, because it is thin it does not confine light effectively, the wavelength of light being much larger than the well thickness. QW waveguide devices are therefore grown with separate waveguide layers, which comprise the waveguide core. Because the carriers are confined in the QW and the light is confined in the waveguide core, this type of structure is called a separate confinement heterostructure (SCH).

An SCH is illustrated in figure 2. The optical overlap between the waveguide mode and a QW is much smaller than that

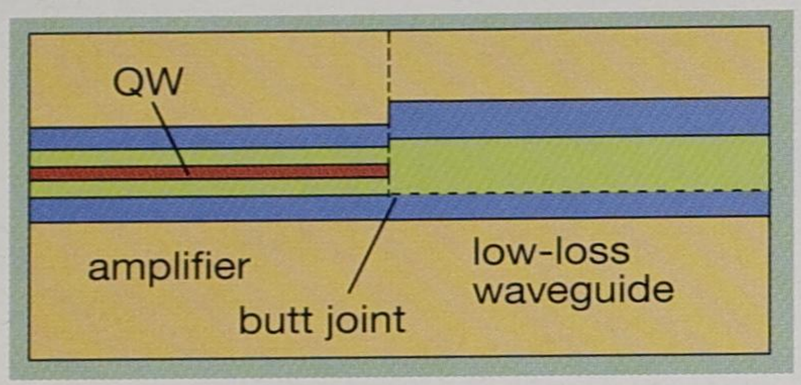


Fig. 3. An active/passive waveguide butt joint in a QW structure. The passive section has the same structure as the amplifier, except for the absence of QWs. The precision of regrowth, in terms of thickness and composition, determines the quality of the butt joint.

between the waveguide mode and the waveguide core. This makes it possible to remove the QWs from the waveguide core, leaving a passive waveguide with identical dimensions and virtually the same refractive index. Scattering and reflection losses at the butt joint are, in principle, extremely small. However, if regrowth is used, the precision to which the layers can be grown in terms of thickness and composition determines the quality of the butt joint (figure 3).

A different solution is to vary the width of the QWs across the wafer during a single stage of epitaxy. In this approach, which is achieved using selective area epitaxy, the substrate is coated with a dielectric mask in which slots are opened using photolithography and etching. No growth takes place on top of the mask, but surface migration of the growth species can take place for some distance across the mask to the nearest opening. The growth rate – and hence the QW width – in the opened areas therefore depends on the width of the opening and the patterning of the mask. The technique is quite limited with regard to the bandgap changes that can be achieved, and it cannot be used to pattern the bandgap across a wafer in two dimensions.

A further integration approach, which is being used by Intense Photonics, is based on QWI. QWI is a technique that allows the properties of a semiconductor QW structure to be modified, typically allowing its energy bandgap to be increased. Multiple optical communications functions can therefore be integrated monolithically on a chip.

Quantum well intermixing

A variety of QWI techniques have been developed, including impurity induced, impurity free (dielectric cap), implantation induced and laser induced. Impurity-free techniques are highly preferable, since the introduction of electrically active dopants into a semiconductor waveguide results in optical absorption. The impurity-free vacancy disordering (IFVD) technique makes use of dielectric caps on the surface of the semiconductor to create vacancies on the group III lattice site. The vacancies diffuse through the semiconductor and, as a result, individual atoms hop from one lattice site to another. As a result of this process the QW intermixes with the adjacent barrier material.

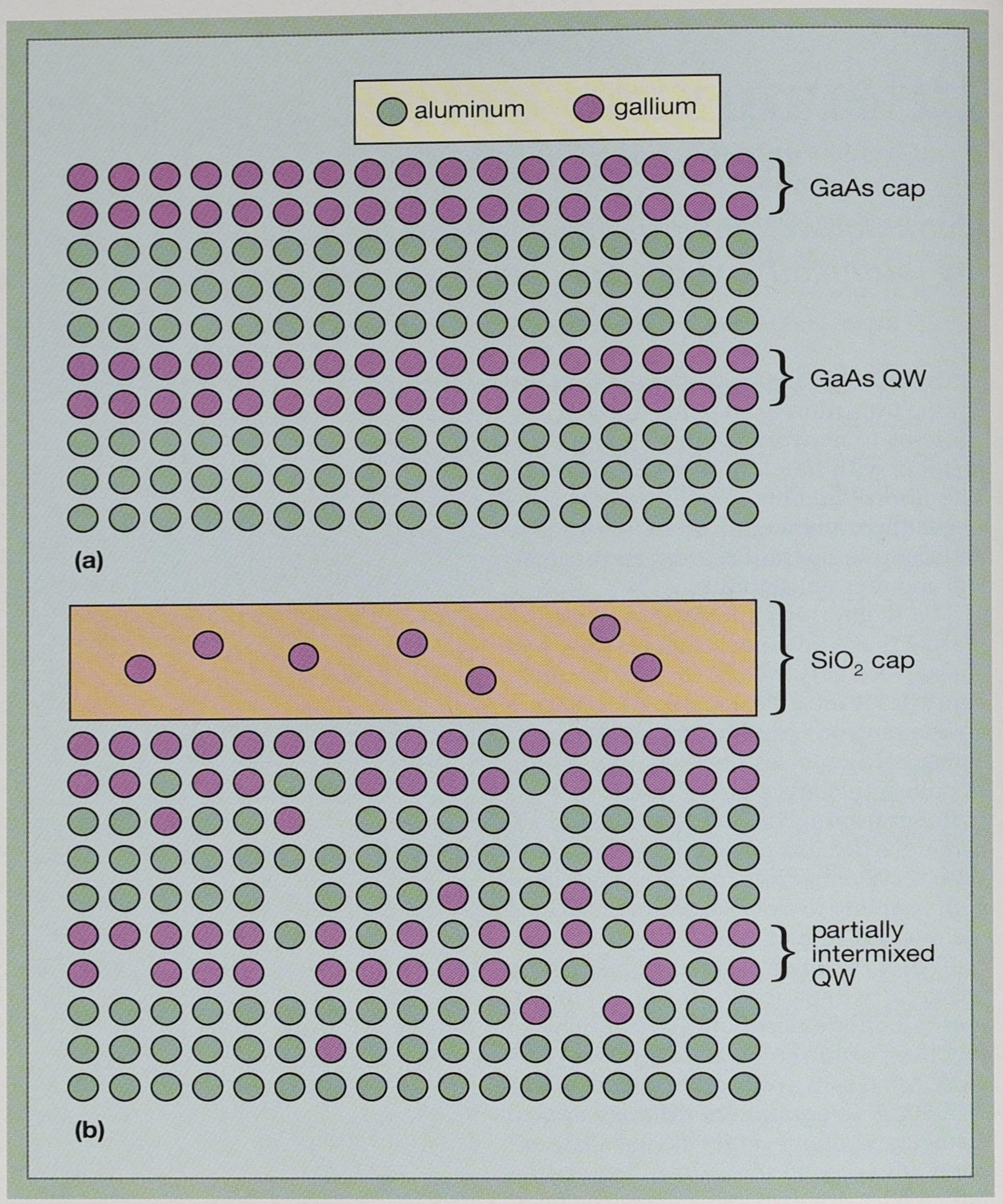
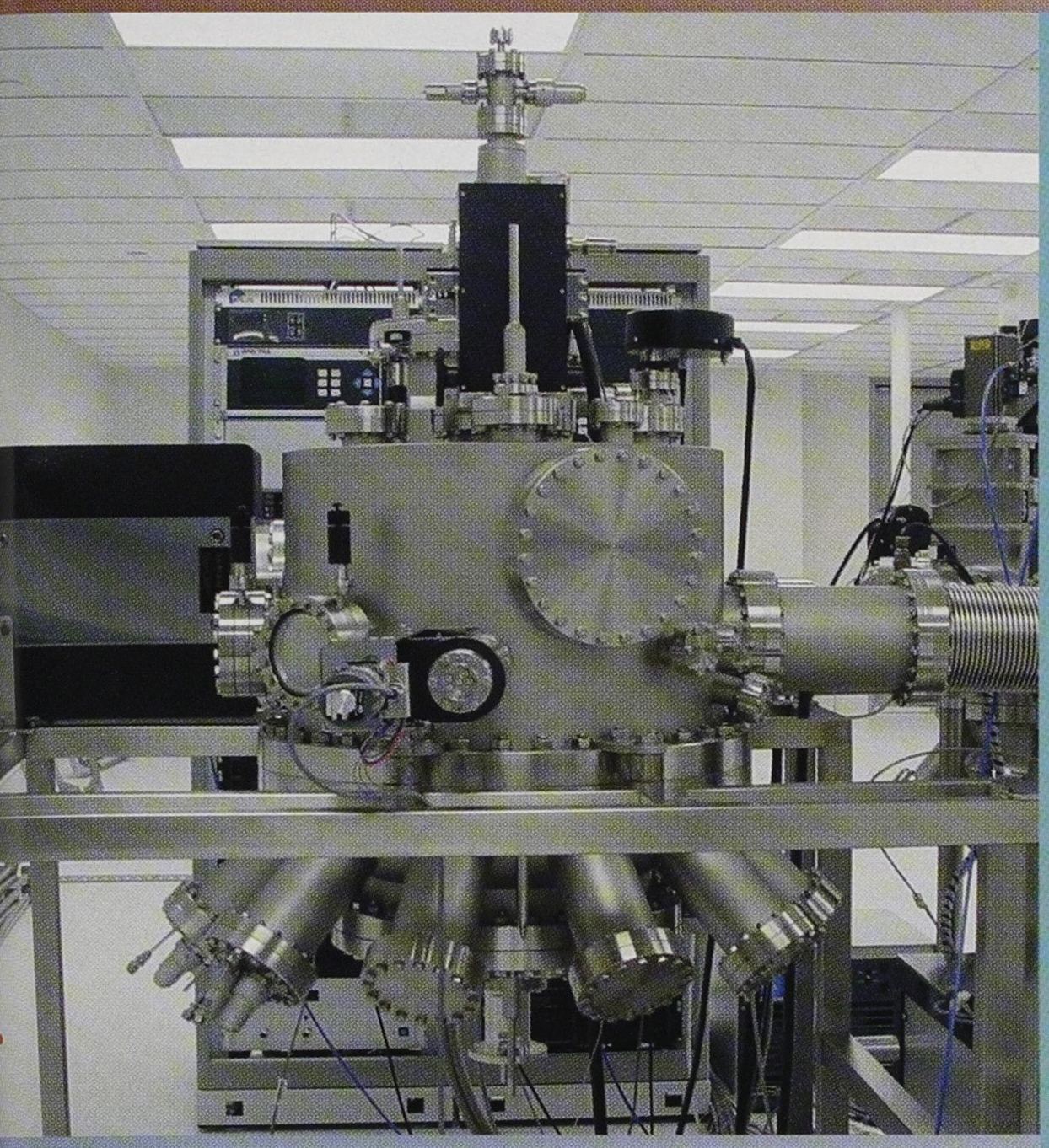
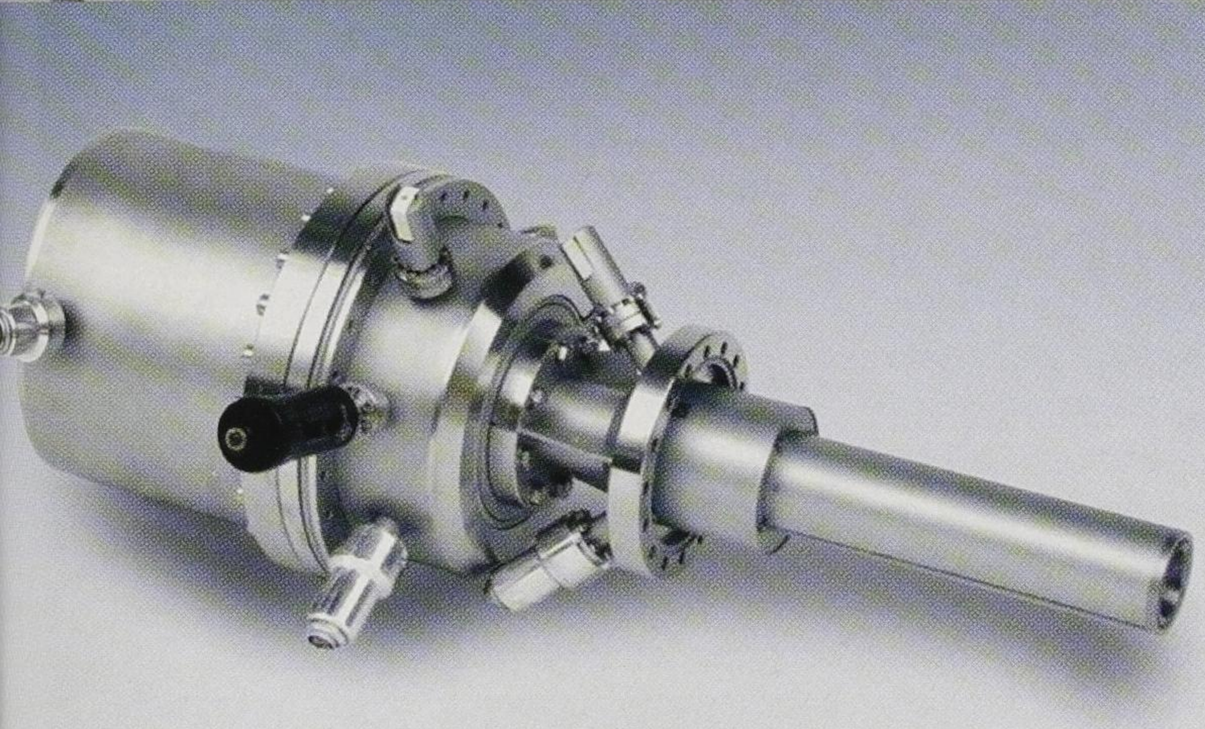


Fig. 4. (a) An as-grown GaAs/AlAs QW structure, and (b) the same structure after quantum well intermixing using impurity-free vacancy disordering.

The IFVD process is illustrated in figure 4, which shows the atomic structure of an as-grown GaAs/AlAs QW structure, with a GaAs cap and a GaAs QW (figure 4a). The sample is coated with a layer of SiO_2 and then annealed. At elevated temperatures Ga is soluble and has a high diffusion coefficient in SiO_2, so during the annealing stage some Ga atoms dissolve in the SiO_2 cap. Vacancies are created as a result of Ga atoms leaving the semiconductor, and these vacancies have a high diffusion coefficient in the semiconductor. The vacancies diffuse from their high concentration region at the surface to low concentration regions (the remainder

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DCA INSTRUMENTS

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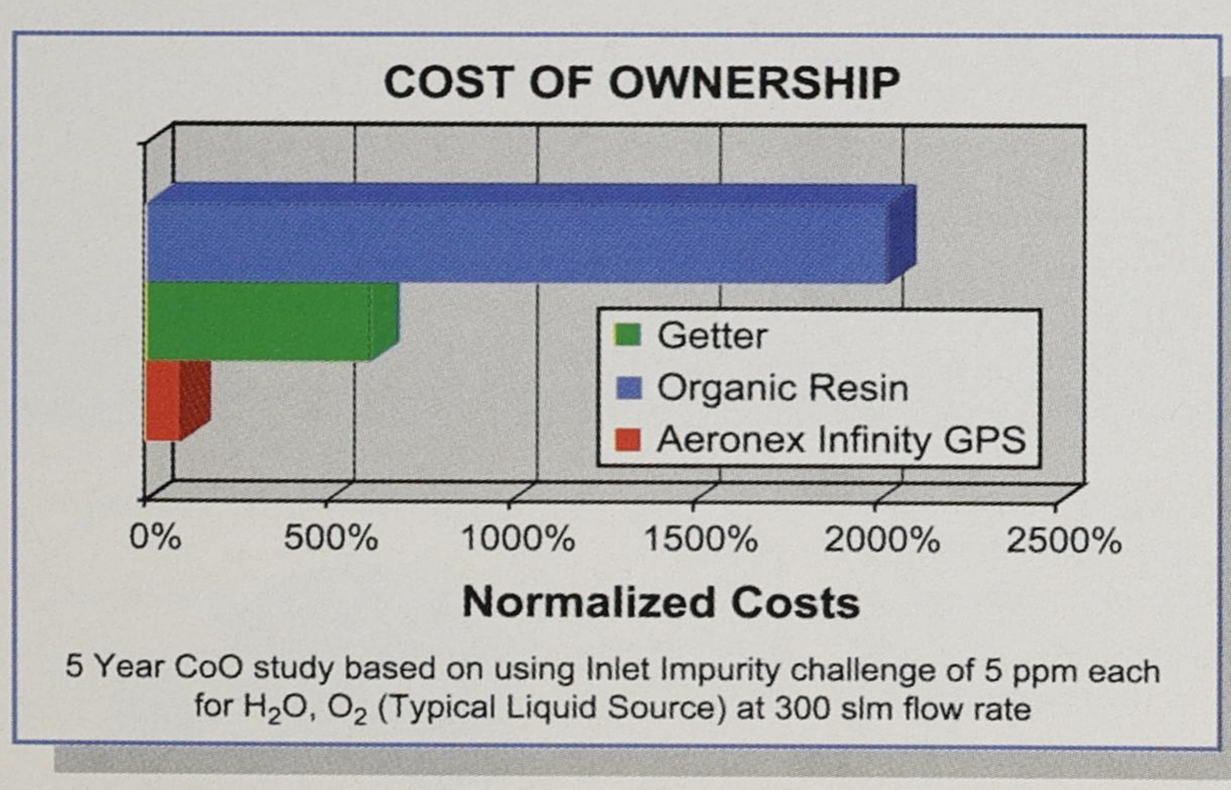
To provide a continuous supply of pure gas, the Infinity is designed with two purifier beds in parallel. While one bed is on-line, the second is automatically regenerating. Preconditioning time is eliminated, as is running on a spent or cracked purifier. No special gas blends are needed for start-up and hydrocarbons are never outgassed.



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of the semiconductor), with individual vacancies following a "random walk". The effect of the random walks of a large number of vacancies is to intermix the regular layered structure of the as-grown structure (figure 4b).

The effect of intermixing on the band structure of the quantum well is illustrated in figure 5. The red lines show the conduction and valence bands of the as-grown structure. Because the central GaAs layer is a QW, the electron and hole levels are quantized, so the effective bandgap is wider than that of bulk GaAs. Intermixing causes Al to diffuse into the well, and Ga to diffuse out. This widens the well and increases its average bandgap (shown in blue). The bandgap of the intermixed QW is wider than that of the original well, allowing the intermixed structure to be used as a passive waveguide.

An active/passive waveguide butt joint fabricated using QWI is illustrated in figure 6. It can be seen that a key advantage of the QWI process is that the active waveguide is in perfect alignment with its passive counterpart. Furthermore, the refractive index step at the butt joint can be designed to be negligible. The average composition of the waveguide core is identical in the active and passive regions. However, the bandgap of the QW has been changed by QWI, so the refractive index of the QW region is also modified, and this change in index can be significant – as high as 5%. It has already been noted that the optical overlap between the waveguide mode and a QW is small, typically around 1%, so the change in index of the guided mode is around 10^{-3}, a value that would be very difficult to achieve routinely using regrowth. The corresponding reflection coefficient at the butt joint is around 10^{-5}.

Applications of QWI

Because QWI is highly suited for the realization of active/passive butt joints, it could become a key process in the manufacture of monolithic devices and PICs. Examples of component sections that have already been demonstrated using QWI technology include:

Active Bandgap-tuned laser active regions, semiconductor optical amplifier gain blocks, semiconductor optical amplifier non-linear blocks, bandgap-tuned electro-absorption modulators, bandgap-tuned phase modulators, tunable gratings, saturable absorbers.

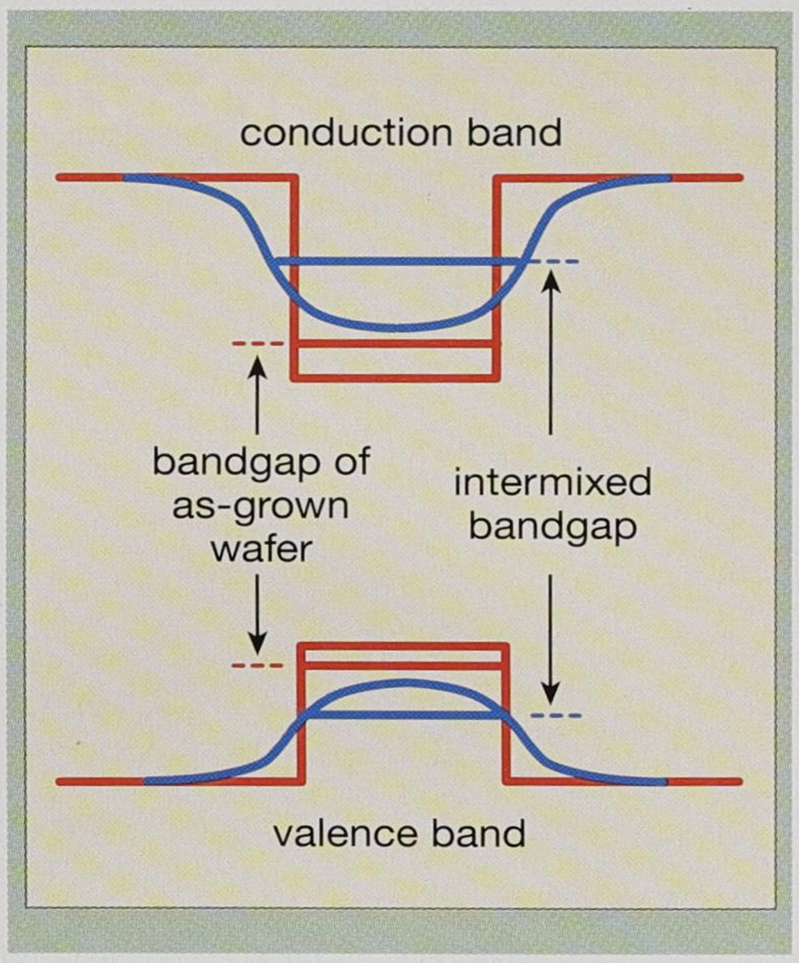


Fig. 5. Conduction and valence band structure of a GaAs QW with AlAs barriers before intermixing (red) and after QWI (blue).

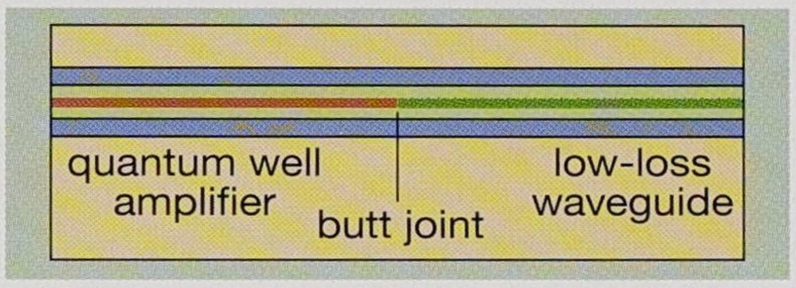


Fig. 6. Butt joint realized using QWI: the active and passive sections are in perfect optical alignment.

Passive Low-loss waveguide interconnects, splitters and couplers, array waveguide multiplexers and demultiplexers, grating components, non-absorbing mirrors.

QWI-based integrated components have already been fabricated by Intense Photonics. A simple example of the use of QWI is to make the mirror facets of a 980 nm laser non-absorbing to improve performance and yield. More sophisticated multi-function components combining a passive waveguide, gain section and saturable absorber have also been fabricated. The latter device implements a mode-locked laser producing picosecond pulses at a repetition frequency determined by the cavity length, and might be used as a source in an optical time division multiplexed system, or for all-optical clock recovery. The number of ways in which the sections can be combined is essentially unlimited, allowing completely new functions to be realized, including those required by all-optical network and future ultra-high-speed networks.

Integration technology

Intense Photonics has developed proprietary technology that allows QWI to be used to fabricate complex photonic integrated circuits in a production environment. This technology base includes:

Thermally matched dielectric caps For IFVD to be an effective integration technology, separate dielectric caps are required to enhance and suppress intermixing. However, IFVD takes place during a high temperature anneal, and there will be large thermal stresses if the dielectric caps have different coefficients of expansion. These stresses can be sufficiently large to cause mechanical damage to the device. The process used by Intense Photonics effectively eliminates this problem.

Scalable process The QWI process uses standard semiconductor processing equipment to deposit the dielectric caps. The process can be scaled in terms of both throughput and wafer diameter.

Impurity-free process The IFVD process is impurity free, so no electrical dopants are introduced into the passive waveguide. Introducing electrical dopants would result in free carriers (electrons or holes) that absorb light, which means that the passive waveguides would have high attenuation. The IFVD process circumvents this limitation, and makes it possible to include long lengths of passive waveguide in photonic integrated circuits.

Wide range of materials The same basic process has been used in both GaAs- and InP-based material systems, allowing it to be used in devices and PICs operating at important wavelengths such as 980, 1310 and 1550 nm.

Intermediate bandgaps Varying the process parameters allows intermediate bandgaps to be realized. A chip with as many as 20 different bandgaps has been demonstrated using a single annealing stage.

John Marsh is professor of optoelectronic systems at Glasgow University, Scotland. He is also a co-founder and the chief research officer of Intense Photonics, a company using QWI to develop next-generation photonic integrated circuits for the optical communications market. Web: www.intensephotonics.com.

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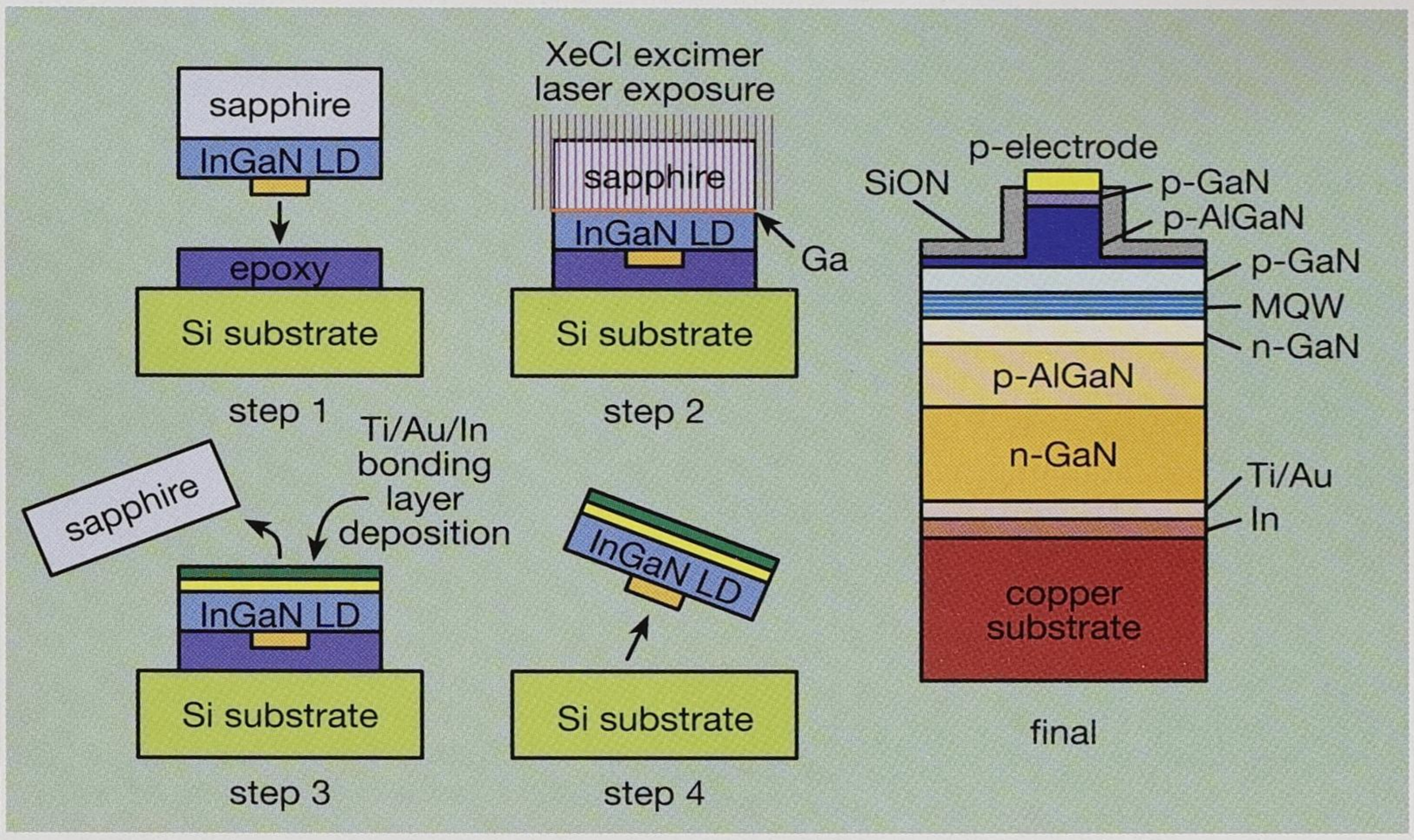
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Nitrides scale new heights in the Rockies

The major advances in progress reported by delegates at ICNS-4 point to exciting times ahead for nitride semiconductors. ***Richard Campion*** *and* ***Nicola Stanton*** *report.*

The fourth International Conference on Nitride Semiconductors (ICNS-4) was held on 16–20 July in Denver, Colorado. With twice the number of delegates (600) than the previous conference in Montpellier, and over 20 invited speakers, ICNS-4 demonstrated that GaN and its alloys have come of age as commercially viable materials. There was strong representation from Europe and Asia, as well as the US, showing the worldwide interest in this topic. Significant progress was reported in the fundamental understanding of growth and defect mechanisms, bulk material growth, and device fabrication and performance. Amongst the applications discussed were high-power LEDs and transistors, blue lasers and exciting flip-chip designs. Whilst AlGaInN dominated the proceedings, there was also work presented on mixed arsenic-nitrides such as AlGaAsN and InGaAsN.



XEROX

Fig. 1. The Xerox excimer laser lift-off and transfer process. This enables the laser to be flipped and bonded to a high thermal conductivity copper substrate. The process would be suitable for applications including face to face emitter/detector designs for lab-on-a-chip fluid spectrometers.

FETs, 2DEGs and HBTs

Micovic *et al.* of HRL Laboratories, CA, described significant advances in the growth of AlGaN Schottky HFETs grown by plasma-assisted MBE. They reported a power density of 6.6 W/mm at 20 GHz for devices grown on SiC. Good reproducibility of sheet resistance and effective Schottky barrier thickness was achieved, with low noise operation comparable to state of the art GaAs devices. A device with a short gate design operated up to 140 GHz.

HFETs fabricated by MBE on SiC substrates were also described by Webb *et al.* from the Institute for Microstructural Science in Ottawa. After overcoming the difficulties in SiC surface preparation, low temperature (77 K) mobilities of ~11 000 cm^2/Vs were recorded, with HFET characteristics showing no current slump. Interestingly both sets of devices showed no light sensitivity and did not require surface passivation.

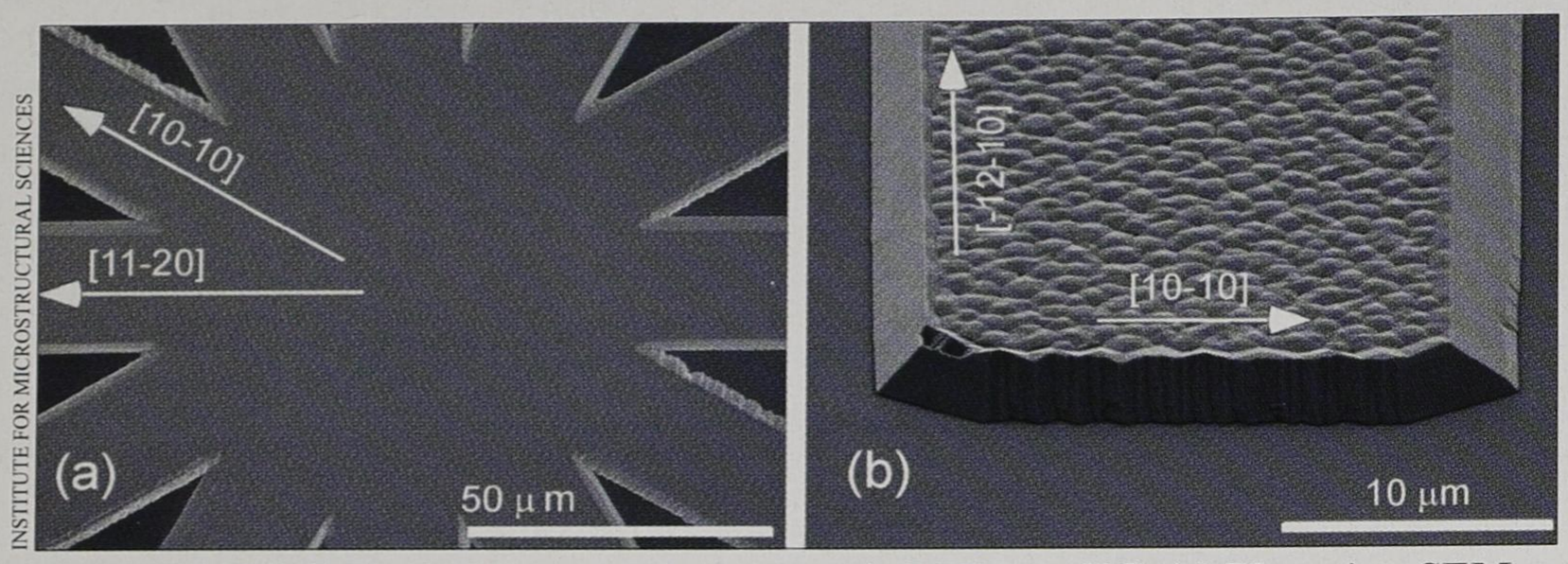
Manfra *et al.* from a collaborative group including Lucent Technologies, MIT and the University of Columbia reported on the growth of AlGaN/GaN two-dimensional electron gases (2DEGs) by MBE. Low temperature (4 K) electron mobilities of 75 000 cm^2/Vs at sheet carrier densities of ~$1.5 \times 10^{12}/cm^2$ were measured, and the fractional quantum Hall effect was observed at high fields. This performance demonstrates the vast improvement in growth techniques which have been made over the last couple of years, when state of the art mobilities of such structures were ~10 000 cm^2/Vs.

Makimoto *et al.* from NTT Basic Research Laboratories described HBT devices based on InGaN/GaN. The transistors showed a current gain (β) of 20 at a collector current of 3 mA, higher than similar devices based on the AlGaN/GaN system ($\beta \sim 11$). The p-type density in the InGaN base was reported to be 10^{19} cm^{-3} leading to the good device performance.

The first reporting of AlN/GaN double barrier resonant tunneling diodes was made by Kikuchi *et al.* from Sophia University, Tokyo. The devices had a peak to valley ratio of 3:1 at room temperature and were grown by MBE on MOVPE-grown substrates. The characteristics of both double barrier and superlattice (SL) barrier (four monolayers thickness) AlN/GaN devices were discussed, with negative differential resistance observed at 2.4 V and 1.6 V, respectively.

UV photodetectors

Campbell *et al.* of the University of Texas discussed two designs for a back illuminated solar-blind photodetector. The first, a PIN type, had a UV to visible light rejection of over three decades and exhibited low noise and low dark current performance. The second, an MSM type that obviates the need for p-doping, exhibited



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Fig. 2. ELOG GaN nitride grown by ammonia MBE on SiC. (a) Plan-view SEM image of a GaN pinwheel pattern and (b) morphology of the facets on the edges of lateral growth fronts is strongly dependent on crystallographic orientation.

similarly good characteristics and had an external quantum efficiency of 48% at 12 V bias for a wavelength of 262 nm, and a dark current determined to be <20 fA.

LEDs and lasers

Koike *et al.* from Toyoda Gosei, Japan, highlighted the large improvement in the optical efficiency of nitride-based LEDs and lasers that has been achieved since such devices first became commercially available some six years ago. Improving the lifetime of laser diodes for use in consumer electronics such as DVD systems is an obvious goal. The presentation detailed some of the advances in material quality, including a reduction in dislocation density of two orders of magnitude. Since dislocations are known to significantly reduce the lifetime of laser diodes, limiting them is necessary to realize the full commercial potential of nitride-based lasers.

Götz *et al.* from LumiLeds gave an impressive visual demonstration of high-brightness LEDs. Developments include increasing the conductivity of the n and p layers, engineering the strain in the layers and improving contacting and packaging strategies. The result was a demonstration of a traffic light assembly requiring 12 LEDs, compared to the 200 or so conventional LEDs required in current assemblies. A wall-plug efficiency of ~26% was achieved for a wavelength of 428 nm.

The fabrication of a deep UV LED was described by Shatalov *et al.* from the University of South Carolina. They discussed the problems associated with current crowding and the high Al content in the quaternary AlGaInN layers. In an attempt to control the defects in the layer, a pulsed epitaxy technique was developed for layers on sapphire substrates. The total power was determined to be three times higher than similar devices on conventional MOCVD epilayers, the difference being ascribed to a lower defect density in the layer and high quality quaternary barriers.

Quaternary InAlGaN UV LEDs emitting at ~320 nm were also described by Hirayama *et al.* of the Institute of Physical and Chemical Research, Japan. The improved UV performance over the traditional AlGaN QW structures was attributed to indium segregation (observed in cathodoluminescence measurements) in the InAlGaN MQWs.

These developments are helping to improve the performance of the limited range of commercialized nitride-based devices, and open the way for new classes of device to begin emerging onto the market.

By studying the behavior of dislocations in the wings of non-contact laterally overgrown material, Tomiya *et al.* of Sony have observed a low dislocation density region in the central portion of the wing. They related short laser lifetimes to high dislocation densities and high device power consumption. By carefully positioning the lasers on the low dislocation density regions they have extended the lifetimes to 6000 hours and have T_o values of ~160K.

Mukai *et al.* from Nichia presented a comparison of laser diode characteristics grown by epitaxial layer overgrowth (ELOG) on freestanding GaN substrates and thick GaN templates. It was reported that the application of the ELOG technique was indeed beneficial to device performance, with estimated lifetimes in excess of 15 000 hours achieved under CW, 30 mW operation.

New applications

Field emission from heavily Si-doped AlN was described by Kobayashi *et al.* of NTT Basic Research Laboratories. They reported a field emission current density of 0.22 A/cm^2 for a 0.4 μm, highly Si-doped (~1×10^{21} cm^{-3}) AlN layer. This current density is seven times greater than that seen for diamond field emission cathodes and this novel material clearly has potential applications in cold cathodes for displays.

Novel applications for FETs based on wurtzite GaN as polar liquid/gas detectors or pressure sensors were reported by Eickhoff *et al.* of Walter Schottky Institute, Munich. The surface-charge state of the gate region is modified by contact with a polar liquid (e.g. water or acetone) and a suitably biased device can be made to give large voltage swings dependent upon the liquid present. The talk concentrated on the wetting behavior of nitrogen and gallium polarity surfaces.

Kneissl *et al.* from Xerox, Palo Alto, reported a simple ambient excimer laser lift-off process (figure 1) that gives freestanding devices with ultra smooth back surfaces that can be bonded to another material of choice (e.g. copper/diamond). They reported InGaN MQW lasers with enhanced thermal and optical performance, and proposed face to face emitter/detector designs for lab-on-a-chip fluid spectrometers, as well as the possibility of other applications using laser lift-off, flip-chip technology.

Epitaxy and materials

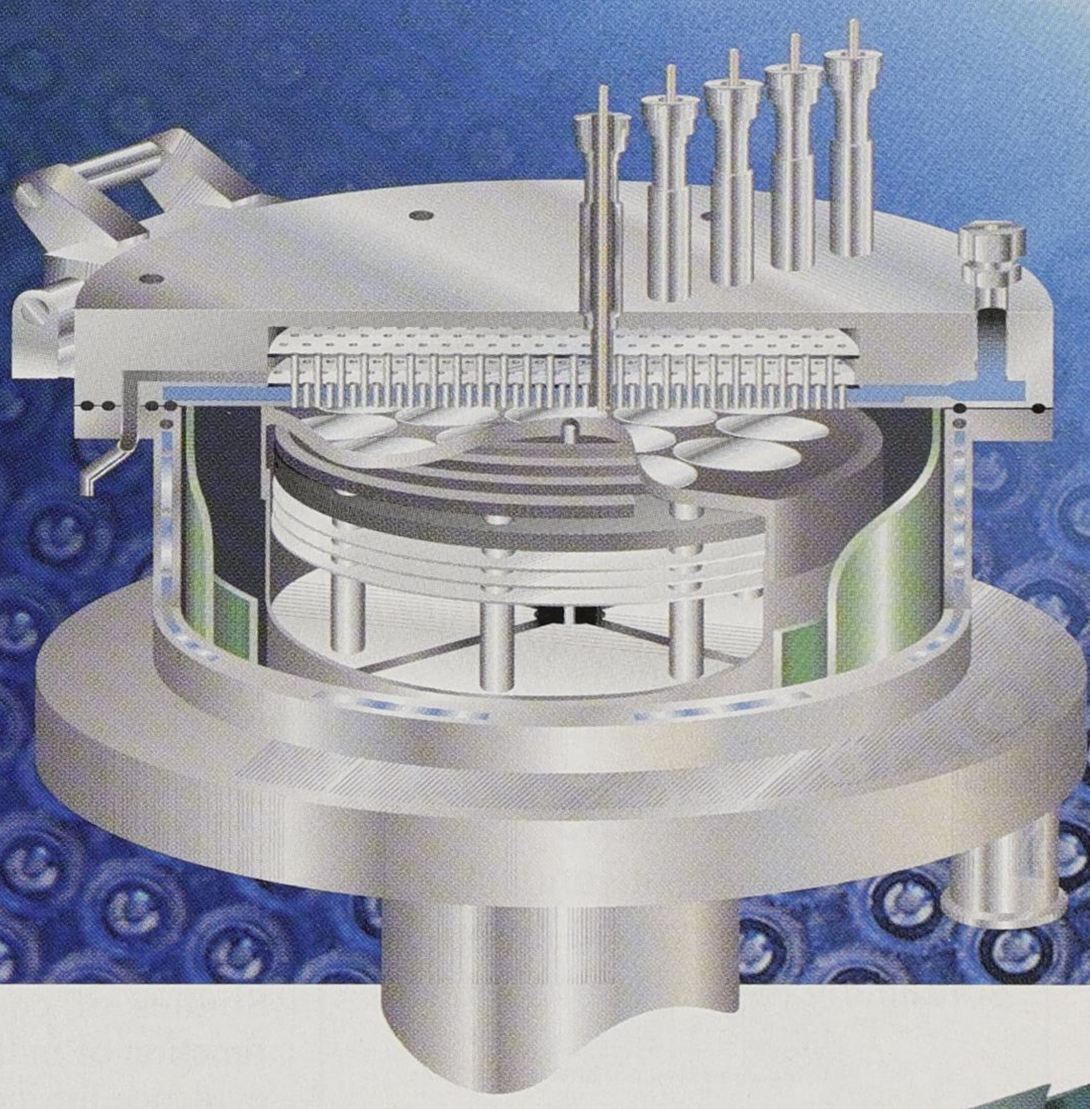
Chowdhury *et al.* of the University of Texas reported on the electrical properties of p-doped AlGaN/GaN SLs with variations in well width, layer numbers and composition grown by low pressure MOCVD. They considered the strain state and coherence of the SLs and made comparisons with similar structures where the SL was replaced by a layer of pure AlGaN of the same composition. They showed that some SLs have higher conductivity than the equivalent thickness of bulk material.

By using growth interruption, Sugahara *et al.* of Oklahoma State University showed that the structural and optical properties of InGaN/GaN MQWs grown on sapphire by MOCVD can be signifi-

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cantly improved. The degree and nature of the improvement is dependent on interruption time and whether the interrupts are before, after, or before and after each InGaN layer.

Tanka *et al.* showed that pre-growth etching of SiC substrates could improve the crystalline and surface quality of AlN films by creating regular stepped terraces on the substrate surface. This allows AlN nucleating on a given step to coalesce with material on adjacent steps in a crystallographically coherent manner.

Tang *et al.* from the Institute for Microstructural Science in Ottawa showed that selective area growth and ELOG are possible with ammonia MBE. This was not previously thought to be feasible. They showed that the morphology of facets at the edges of the lateral growth fronts is strongly dependent upon the crystallographic orientation (figure 2). Christen *et al.* of Otto-von-Guericke University, Magdeburg, presented a beautiful set of images showing a comprehensive scanning cathodoluminescence and micro Raman study of the lateral growth fronts of ELOG GaN grown by MOVPE. They showed that the growth rate and thus the impurity incorporation rate, as well as local strain, are factors which are strongly influenced by the lateral growth direction. By such optimization they have demonstrated very high quality overgrowth coalescence.

Stutzmann *et al.* from the Walter Schottky Institute in Munich described a method for controlled growth of epilayers of mixed polarity separated by inversion domains. This was achieved by growth of a thin buffer layer followed by patterning and subsequent selective etching of the buffer layer. Regrowth over the patterned layer causes controllable growth of epilayers of mixed type. The possibility of fabricating devices exploiting the differing electronic properties of the two types may now be realized.

EXAFS studies of InGaN films were reported by Miyajima *et al.* from Sony. Studies of co-ordination number as a function of indium content revealed good evidence for indium segregation behavior in this alloy. They observed that the co-ordination number of an indium atom's second nearest neighboring indium atom was higher than those estimated from a random GaInN alloy, in which the indium atoms should randomly occupy the cation sublattice.

Screw dislocations

Using a first-principles total energy approach, Northrop *et al.* of Xerox, Palo Alto, showed that the likely nature of screw dislocations in GaN is a small hollow core decorated internally with Ga atoms, such cores being strong non-radiative recombination centers. Under very nitrogen-rich growth conditions the core would be depleted of Ga. However, under Ga-rich conditions the core would contain a pair of helices of Ga atoms. Between these two growth conditions, varying degrees of Ga vacancy would appear in the helices.

Timely support for this work came from the next presentation by Manfra *et al.* of Bell Labs, Murray Hill, who have devised a method of scanning current-voltage microscopy based on a biased AFM tip. This beautifully demonstrated that the cores of the hillocks on the surface of GaN grown in Ga-rich MBE are dislocations that are conducting at low bias. Those grown in nitrogen-rich conditions require a high bias before conducting. They also presented structural evidence that the presence of excess gallium leads to structural changes in the dislocation cores and even a nano-droplet of gallium at the top of the dislocation.

Conclusions

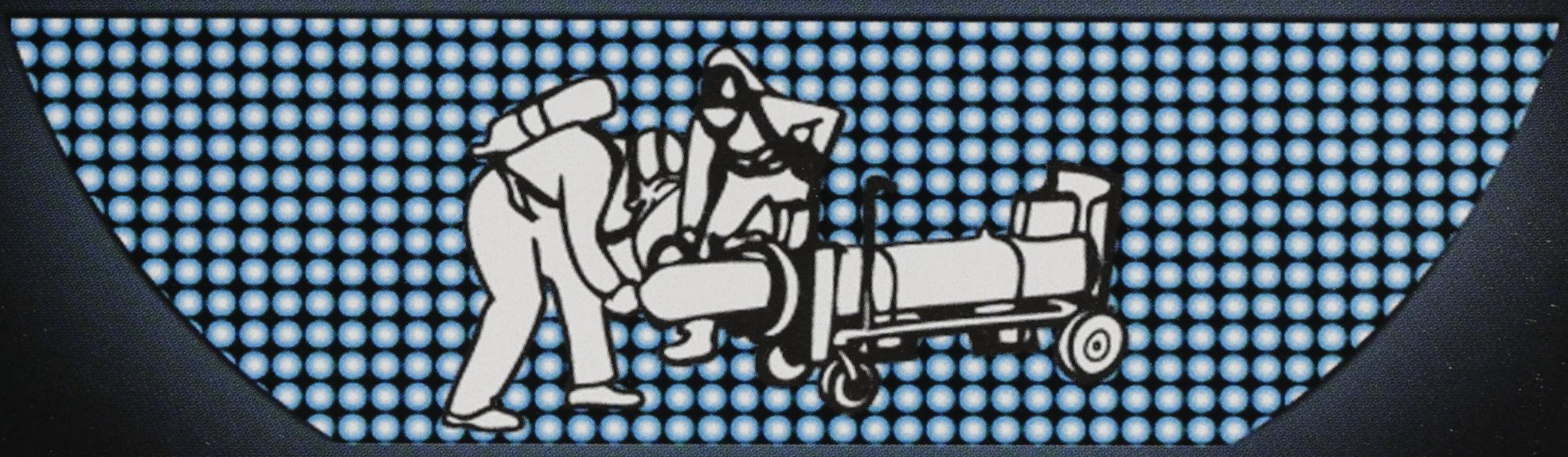
Adding to the oral presentations were a multitude of poster presentations over the course of the conference, making it clear to all who attended that the field is moving forward at a rapid pace. Indeed, what was most apparent in all areas of nitride semiconductor research was an incremental improvement in experimental achievement, and the theoretical background that supports it. These developments are helping to improve the performance of the limited range of commercialized nitride-based devices, and open the way for new classes of device to begin emerging onto the market.

The proceedings from ICNS-4 are to be published in two special editions of *Physica Status Solidi* (Wiley) towards the end of this year. The full technical program of ICNS-4 can be found at: www.mrs.org/meetings/icns-4.

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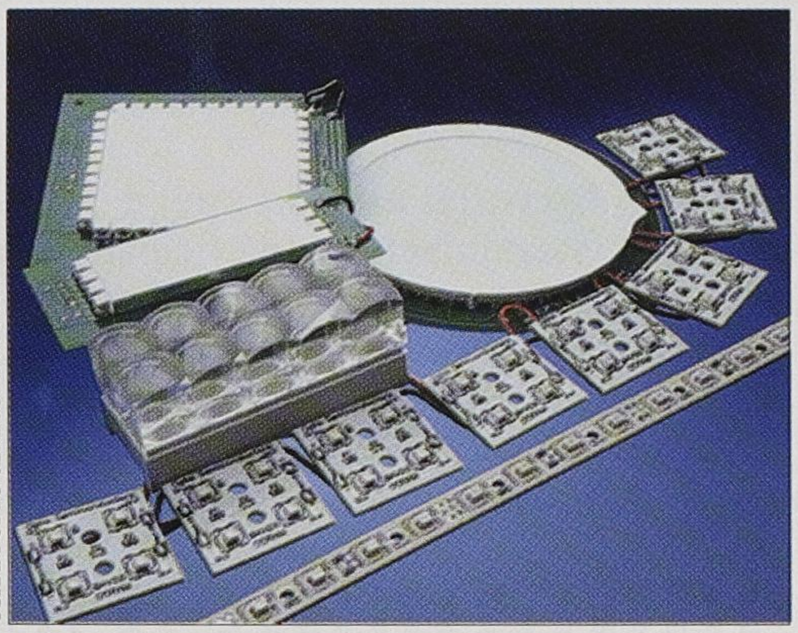
NEMA forms Solid State Lighting Section

The solid-state lighting industry is in flux: the National Electrical Manufacturers Association has embraced new lighting solutions using LEDs, while the US Congress is being asked to fund further development, writes ***Kathryn Conway*** *of LED Consulting.*

The recent formation of a Solid State Lighting Section signals the start of a dynamic era for the Lighting Division of the National Electrical Manufacturers Association (NEMA). The launch of this industry group is timely because the United States Congress will soon deliberate whether or not to include support for solid-state lighting research in its pending energy bill and appropriations.

The need for a new NEMA section was first discussed in April, when 24 manufacturers and an additional 10 participants from government, academia and consulting firms convened at NEMA's headquarters in Rosslyn, Virginia. Although LEDs are a relatively new light source, and as yet undefined as a lighting product category, all present easily came to a consensus on the benefits of working together to advocate advances in technology, applications and standards through a well-established entity.

Participants enthusiastically expressed their belief that semiconductor products "introduce a whole new level of flexibility in lighting solutions, such as control of intensity, color and other technical parameters." So, rather than limiting the new section to LEDs, they decided that the term "solid-state lighting" would better describe the many emerging technologies that their companies are exploring and manufacturing. As a follow-up, four manufacturers volunteered to draft a product scope and statement of activity and operation.



OSRAM OPTO SEMICONDUCTORS

A family of LED products manufactured by Osram Sylvania.

Scope of work and action plan

In June the group reconvened to refine its product scope that was in turn approved by NEMA's Board of Governors in July. The Solid State Lighting Section encompasses two product and technology types, the first being "Semiconductor light sources including LEDs, laser diodes, organic LEDs and any other semiconductor light source." The second is "Fixtures, luminaires, and associated hardware, power supplies, mechanical or electronic control devices, and software written to operate, facilitate, and control the light produced by a solid-state light device." Cognizant of the creativity and rapid evolution of solid-state lighting, the authors of the product scope have specifically left the door open for as yet unknown technologies that could be categorized as solid-state lighting.

The new Section's primary tasks are to integrate solid-state light sources in existing lighting practices and to create new practices to fully exploit the technologies' potential. Additional tasks include developing a center of expertise and creating definitions of terms.

Beyond standard fare

Manufacturers clearly do not relish the thought of having their new products governed by outmoded or misapplied standards. Few standards exist today that adequately address the needs of the solid-state lighting market. The Section will proactively seek to collaborate with recognized policy- and standards-setting organizations. This is an area in which NEMA offers a distinct advantage. NEMA has significant expertise in code and standard development. For example, NEMA industry director Kyle Pitsor explained to the new Section that the International Electrotechnical Commission (IEC) lighting committee (TC34) has recently revised its scope to incorporate LED lighting standards. NEMA administers the US technical advisory group for TC34, and is responsible for gathering widespread input. Measurement standards for LEDs will remain under the purview of the Commission International de L'Eclairage/International Commission on Illumination (CIE). Some of the members of the Solid State Section are also very active in CIE.

Matrix of technical themes

Eager to move on many fronts, the industry leaders represented in the new Section compiled a list of technical themes they would like to tackle together. Nearly everyone agreed that providing information to the public and to practicing lighting professionals would both fill a void and help to create a stronger demand for solid-state lighting. The themes are:

- Definitions, measurement and color.
- Life testing and lumen maintenance.
- Human factors, safety, emissions and susceptibility.
- Signs and signals.
- LED-based lighting fixtures (including low voltage, stage and studio, track, lamps/bulbs, and underwater fixtures) and consumer products such as toys and nightlights.
- Interchangeability and connectors, power supplies and system efficiency.
- Environmental issues such as disposal and energy efficiency.

For each of the above themes, section members are assembling information about relevant codes, standards, ongoing research projects, publications and organizations. This data is arranged in a matrix for easy reference; NEMA staff maintain the document for the section members' use.

Next-Generation Lighting Initiative

In an exciting outgrowth of a paper authored by Roland Haitz *et al.* (see *Compound Semiconductor* March 2000, p34), the US government is considering support for solid-state lighting research, specifically for "white light" semiconductor devices. The call for government backing was advanced through both the efforts of the Optoelectronics Industry Development Association (OIDA) and the US Department of Energy's recent roadmapping activities. The Next-Generation Lighting Initiative was introduced in two separate bills in July, first in the House "SAFE Act of 2001" by W Tauzin of Louisiana, chair of the Senate Energy and Commerce Committee and then in the Senate by Jeff Bingaman of New Mexico, chair of the Energy and Natural Resources Committee, and Michael DeWine of Ohio.

Advocates expect the texts to converge in a compromise that could include the following provisions:

- Establishing an industry/academia/government initiative to be administered by US DOE.
- A call for a strategic research plan.
- A request for millions of dollars of funding for a grant program.
- Specific technology, efficiency and market goals to be achieved during the next decade.
- Inclusion of both LEDs and OLEDs.

Members of the NEMA Solid State Lighting Section are hopeful that language that would encompass the entire white light emitting solid-state lighting system would be adopted in the final version.

Moving forward at light speed

Among the manufacturers participating in the Solid State Lighting Section discussions are Color Kinetics, Cree, Gelcore, Ledtronics, Lumileds, Norlux, Osram, Permlight, Philips Lighting and Uniroyal Optoelectronics. Firms with solid-state lighting manufacturing facilities in North America may apply to join the Section. Members pay an annual fee to NEMA and an additional sum to support the budget and activities of the Section. The next meeting will be held on the evening of October 18, 2001, at the Hyatt Islandia Hotel in San Diego, California, convenient for those manufacturers attending Intertech's "LEDs 2001" conference. With an ambitious agenda ahead, the Solid State Lighting Section promises to be one of NEMA's most active sections.

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LED products illuminate LightFair 2001

In the second of two reports from the recent LightFair trade show, ***Kathryn Conway*** *describes more lighting products that take advantage of the unique properties of LEDs.*

New LED products illuminated the path to the future of lighting at LightFair 2001, held May 29 to June 1 in Las Vegas. This premier lighting industry trade show attracted an international audience of more than 16 000 designers and buyers to view more than 1200 exhibit booths. HB-LEDs continue their rapid move into the world of lighting, progressing from previous years' market niches such as exit signs and traffic signals toward illumination for architectural applications. As at last year's LightFair (see *Compound Semiconductor* July 2000, p46), LED products captured ample awards from sponsors and from the Illuminating Engineering Society of North America.

Emerging from emergency-only

The lighting community has come to accept and expect LEDs in emergency and egress lighting applications. Most emergency egress signage exhibitors, including Lightguard and MaxLite, featured new products evenly illuminated with only a few HB-LEDs. Not surprisingly, the electricity crisis in the West seems to have prompted more manufacturers to display the US EPA/US DOE ENERGY STAR logo for qualifying LED exit sign products. Manufacturers are also offering directional signs that take advantage of the trend of increasingly high-brightness LEDs. For example, Exitronix introduced the "LC Series" of dynamic signs for traffic lane control.



LOUIS POULSEN LIGHTING

Fig. 1. LED products featured at Louis Poulsen's award-winning booth included Pharo LEDs, the circular wall-mounted units containing blue LEDs, and DEX, the small "brick light" fixture shown in a row of six across the front of the low floor module.

Using fewer LEDs but those with much higher light output than available in past, means that LED lighting products now have sleeker, more attractive shapes. For example, Targetti North America introduced the ADA-compliant Usher Seat Light to fit neatly and safely under the armrests of theater chairs, adding to its existing lines of edge and path-lighting products.

Several manufacturers brought LEDs more into the mainstream of their architectural offerings. Winner of a Best Booth Award, ERCO Leuchten GmbH introduced its Orientation Luminaires to highlight passageways and to accent architectural forms, taking a Best of Show in Emergency Lighting. Their stainless steel surface and safety glass are designed for specification grade installations. Lucifer Lighting Company won Best of Show in the Landscape Lighting category for the Stealth Steplight, which has a slim profile and miniature size, also thanks to LEDs. Not all manufacturers trended smaller though. Louis Poulsen Lighting Inc, after

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p-type : Zn or undoped

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winning a Best Booth Award (see figure 1), promoted the merits of the Pharo LED, "the largest, brightest, in-grade LED lamp source product available," meant for façade and accent illumination.

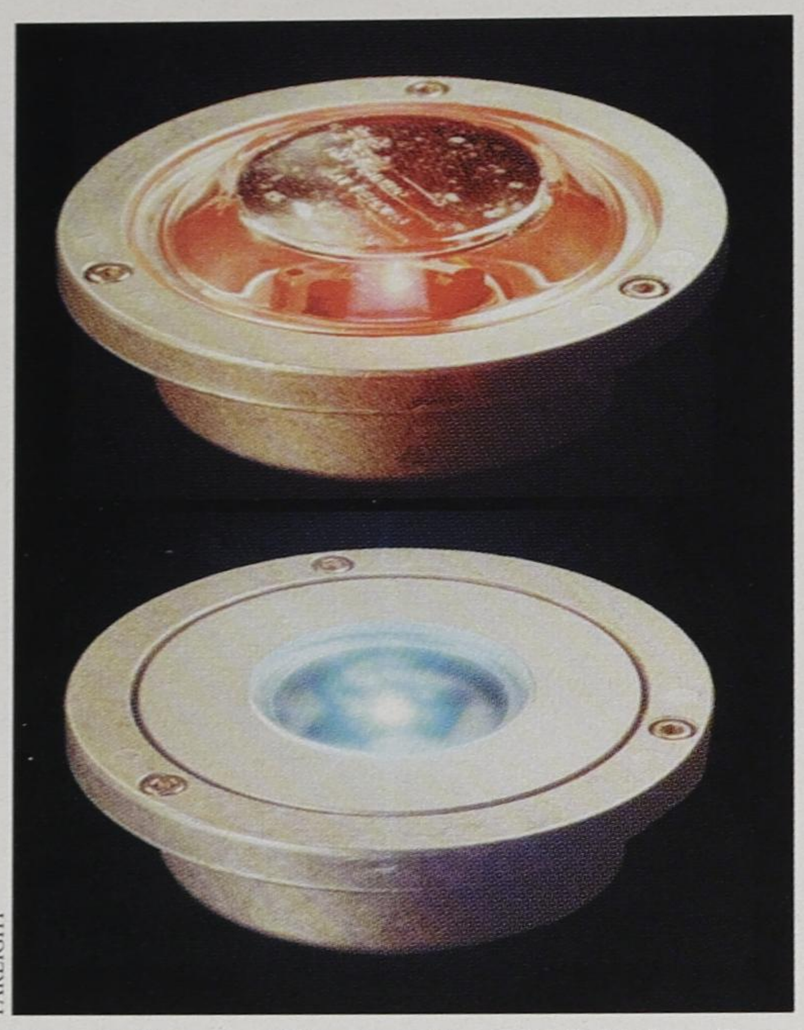
Farlight introduced the uniLED luminaire family of rugged pathmarking lights, with several beam pattern variations. The family of single-LED luminaires is designed to serve in various applications from roadways and airfields to architectural and landscape lighting. The products (see figure 2) are completely sealed, can be driven over, and have power consumption less than 2 W, with an estimated maintenance-free life span of over ten years.

Nudging out neon

The next market niche likely to be conquered by LEDs is linear decorative, conventionally done with fluorescent, neon or miniature incandescent lamps. These older sources can be hazardous due to excess heat and electrical system problems, they require higher input wattage than LEDs do, and may not last as long as LEDs, thus requiring more maintenance and replacement. As more architects and facility managers become familiar with the long service life of LEDs, they will seek products that they can recommend to clients as "maintenance-free." Nowhere is this more important than in facade, landscape, and fountain lighting, where light bulb changes are inconvenient, costly and sometimes hazardous for facility personnel. Solid-state devices are especially well-suited for any application where vibration is an issue. So LEDs may well become the favorite light source of installers, lighting designers and luminaire manufacturers, who are the first to hear complaints and who ultimately bear the expense of call-backs and returns from customers.

Playing the trend toward colorful outlines, Candylites showed eight colors of low voltage Litesicles, designed for trim and accent lighting. Their LEDs are in 3/4 inch diameter sealed acrylic tubes of various lengths that can connect end-to-end. Tokistar Lighting Inc showed its frosted LED System 180 products including LS Series Exterior-Grade Flexible Tapelight, Linear Extrusion Systems, and Flexible Lightstring with Panel Fasteners. These systems operate at 12V AC, and individual LEDs can be replaced if necessary.

Color Kinetics, well-known for its LED innovations, announced its foray into the world of computer and video game players with the LED Surround Light Entertainment Systems, "a complete design/playback system for creating immersive environments." Last (but certainly not least) Color Kinetics recently showcased its digital LED products in what is claimed to be the largest chandelier in the world, in the Hollywood Casino in Shreveport, LA.



FARLIGHT

Fig. 2. Two of Farlight's uniLED family of luminaires. (top) Semiflush luminaires project only 11 mm above the surrounding surface and have 360° omnidirectional output; they are designed to be seen with equal brightness from distances ranging from 0.5 miles to 10 feet. (bottom) Flush luminaires are visible from very low viewing angles and have numerous uses, including pedestrian walkways where snowplows are used. Web: www.farlight.com.

TIR Systems introduced two distinctive LED products in the Destiny Series (see figure 3). The Vertical ColorBar can be wall-mounted indoors or outdoors for wall-washing in corporate or retail settings. The Illuminated Pole combines LEDs with high-tech light guides for decorative way-marking in plazas, parks and other landscapes, and is available in heights of 6, 8 and 10 feet. For areas where independence from the electric grid is desirable, Light Projects London featured Tsola, a product line of outdoor recessed LED indicator lights powered by integral solar panels.

Prominent in announcing the names of retail stores, "channel letters" and other luminous cues are another big target for LED manufacturers. Hollow, translucent letters typically contain small fluorescent or miniature incandescent lamps, while opaque letters are outlined with neon. Numerous exhibitors showed channel letter products, including Act One Communications, LumiLeds Lighting and Osram.

Modulating the market

To beat the odds in the illumination world, LEDs will fare best in groups or modules. LEDs may be bright when viewed directly, but individually they are no match for the light output of even the least efficient incandescent lamp. LightFair attendees saw a dizzying variety of LEDs this year. Diversity rules: no trend is apparent as manufacturers play the numbers game with arrays ranging from a few LEDs to hundreds of LEDs, in a myriad of colors and packages, and in just as many geometric combinations. For example, Kingbright USA Corp, LEDtronics and Sun LED Corp each offered hundreds of modules. Perhaps this is life as usual in the speedy semiconductor industry, but it perplexes luminaire manufacturers in the slower-paced lighting community! Creating the winning modules – the ones that will become the standard "light bulb" for the future generation of lighting fixtures – is clearly one of the biggest challenges facing LED manufacturers.

In the category of Specialty Lamps, LumiLeds Lighting won Best of Show for their Luxeon line of power light sources. Promising a 25 000 hour service life with less than 20% decline in light output for these sources, the Philips/Agilent joint venture has responded to the market's concerns about reliability and performance. These high-brightness sources, coupled with controllers, come in Star, Ring and Flood configurations (see *Compound Semiconductor* July 2001, p11).

NorLux, a subsidiary of Uniroyal Technology, attracted designers by showcasing its new Hex LED package in several types of luminaires, including a polished aluminum task light (see *Compound Semiconductor* June 2001, p9). Mounted on a hexagonal aluminum plate, these monocolor, binary complementary and RGB sources are being marketed as easy to assemble and to position for secondary optics.

OptoTechnology's Shark Series offers

designers a high light output module using 50 LEDs (in any of 5 colors) die-mounted to a beryllium substrate.

Osram Opto Semiconductors, a joint venture between Osram and Infineon, groups its modules into three "families" (see photo, page 75). Modules without lens systems include LINEARlight, LINEARlight Flex (TapeLED), BACKlight, and COINlight. Modules with a lens system are named EFFECTlight and modules with light guides come in three shapes as MARKERlights. All of these products are designed for use with Optotronic power supplies and simple-to-use connectors.

Longing to be light bulbs

The big lamp manufacturers may not yet be ready to aggressively cannibalize their established incandescent lamp lines, but many companies showed LED lamp systems that are compatible with conventional screw-base and snap-base sockets. Monochromatic LEDs dominate this niche because white LEDs are expensive, not yet bright enough to compete with traditional white sources, and they fall far short of most lighting designers' expectations for color rendering and color temperature. However, the fast-growing and highly lucrative retail lighting sector needs light sources that are colorful, reliable, and energy efficient.



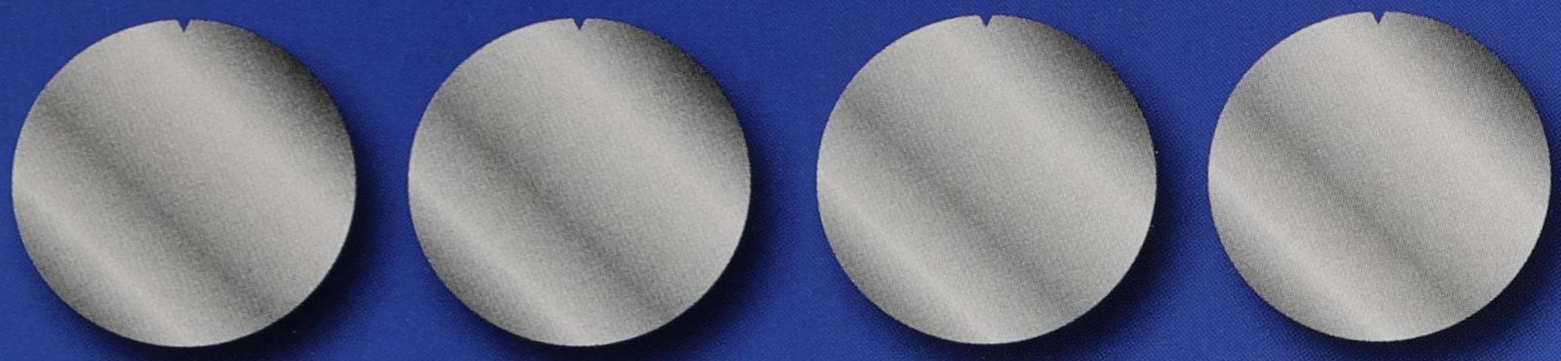
TIR SYSTEMS

Fig. 3. The Destiny ColorBar (left) from TIR Systems is designed for wall-mounted lighting applications, while the Destiny Illuminated Pole (right) is available in heights of 6, 8 and 10 feet.

One of the most widely used lamps for retail lighting is the MR-16: a multi-faceted reflector lamp usually incorporating a low-voltage halogen light source. Designers use the MR-16 to enhance the sparkle of retail sale items. Several manufacturers, including Bruck Lighting Systems, introduced LED MR-16 products. Boca Flasher displayed LED MR-16s, in addition to an array of standard size base LED lamps, in both bare-lamp and globe-encased options. Some Boca Flasher products can be used in dynamic displays run by the 3-color Analog Color Wash Controller. COLOR LED, marketing for two Chinese companies, offered several types of LED lamps with screw bases for both indoor and outdoor applications.

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The challenges of running a dual-use foundry for military and commercial users

In a GaAs wafer fab, the vastly different requirements of military and commercial customers can be managed using a flexible approach and adherence to fundamental manufacturing basics, write ***Lisa Aucoin and colleagues*** *from Raytheon RF Components.*

Most GaAs wafer fabrication facilities in existence today focus their product offerings on the commercial marketplace for applications ranging from discrete FETs to cellular telephone amplifiers. As the demand for volume increases along with market-driven price pressures, most GaAs manufacturers have followed the trend of high-volume silicon fabrication facilities; a dedicated fab for each process. For foundries producing modest volumes and serving multiple customers, including military users, a dedicated facility for each process is not feasible. Through the application and adaptation of some basic operational principles, there exists a business model that effectively allows multiple processes without sacrificing the introduction of crucial technology innovations.

The first GaAs wafer fabrication facilities were built mainly to provide the GaAs MMICs required to meet performance specifications for radar applications. Out of this military heritage grew a host of commercial applications needing the frequency response and bandwidth provided by GaAs. These applications included satellite telecommunications and cellular telephones and base stations. The rapid rise in the mobile handset industry drove the demand for GaAs MMICs to the highest levels in history, thus changing the paradigm for GaAs from engineering to full-scale manufacturing. Following the trend of the silicon industry, GaAs manufacturers were dedicating fabrication facilities to one or two major processes and adopting the operational principles of the silicon manufacturers in order to maximize productivity and reduce operational costs. The military customer's need for highly engineered components at a competitive cost appears to be diametrically opposed to the requirements of a high-volume commercial wafer fab. This paper addresses a business model and an operational philosophy that balances the military and commercial product require-

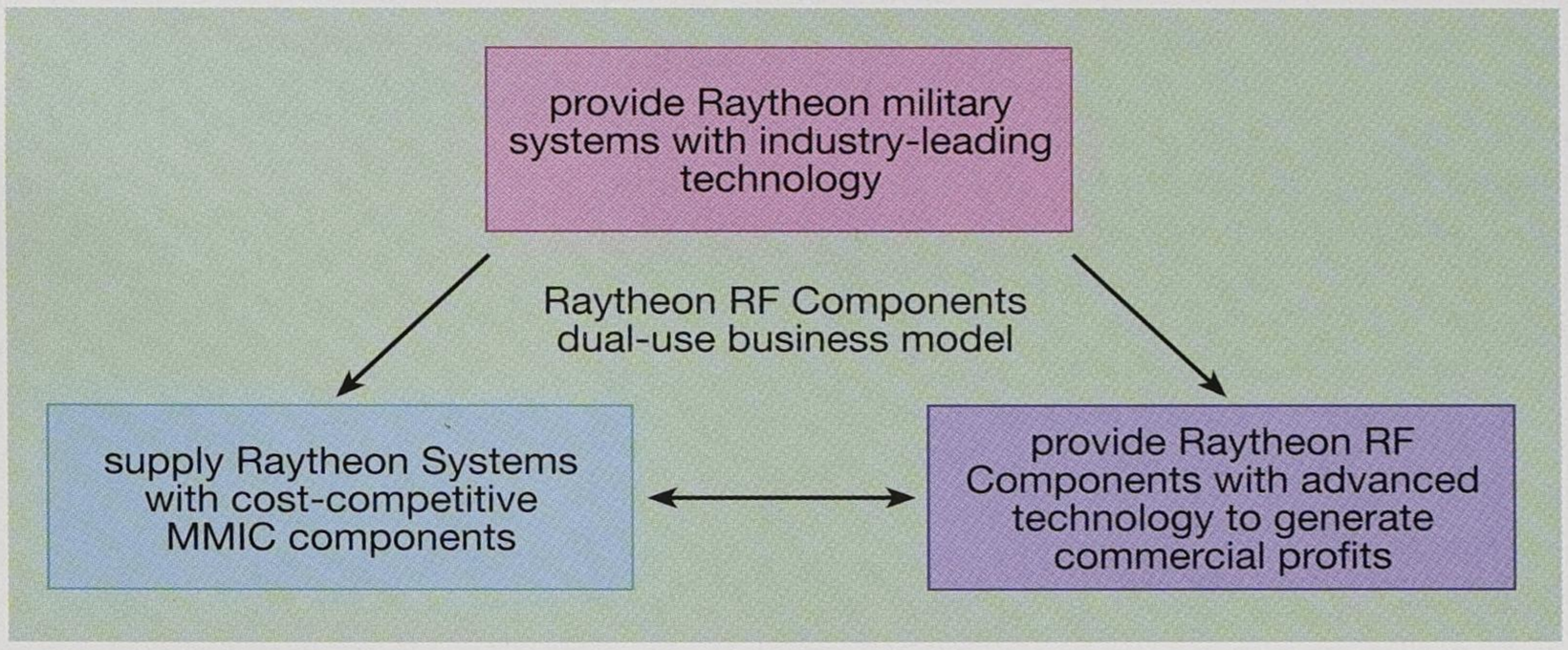


Fig. 1. Raytheon RF Components' dual-use business model balances the continuous need for technology products with the reduction to practice of highly engineered components.

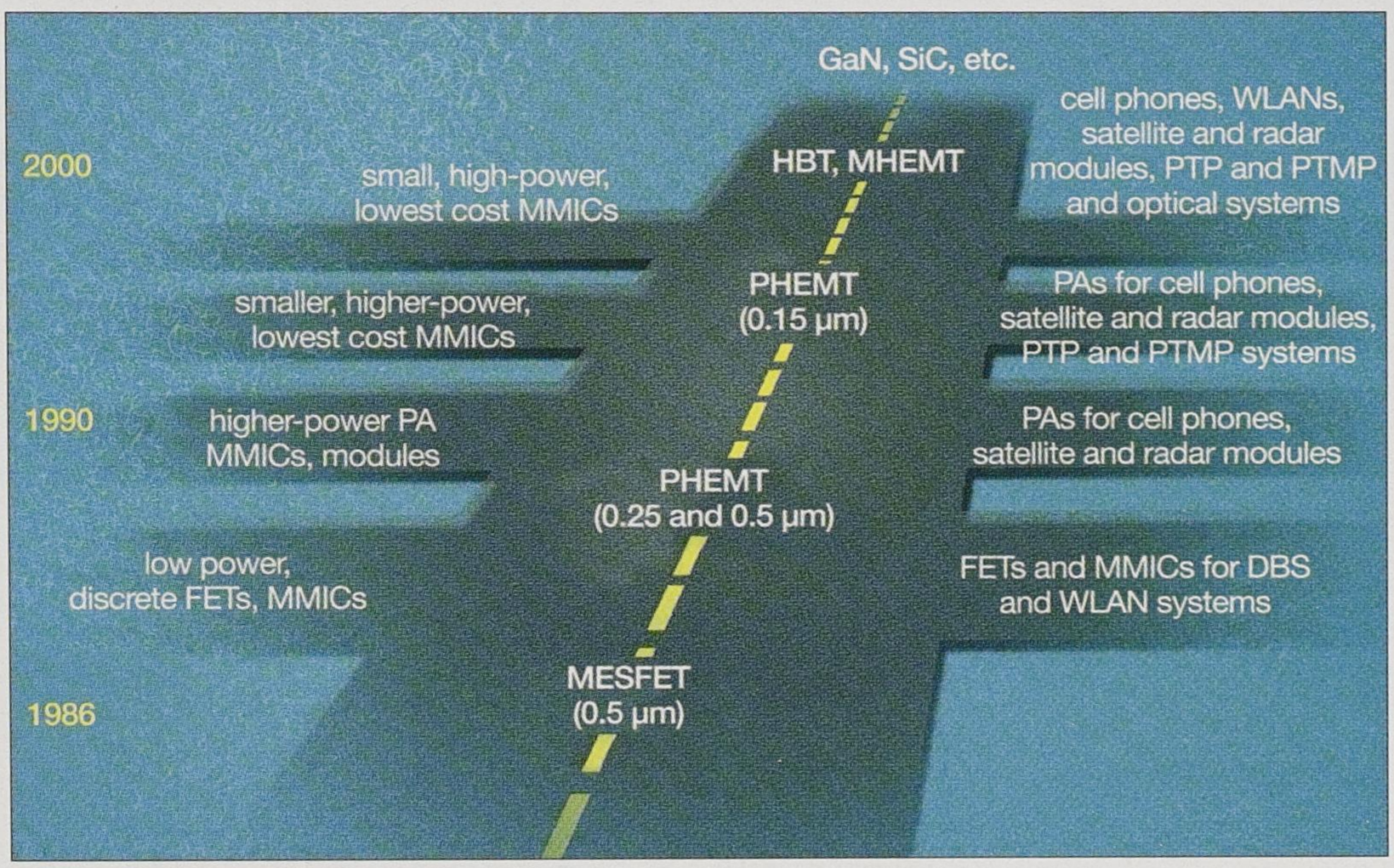


Fig. 2. The technology roadmap shows that the primary discriminator for Raytheon RF Components is material and process technology investments.

ments with the manufacturing tools required to run a cost-effective semiconductor fabrication facility.

Dual-use business model

The methodology of running an operation requires an understanding of the underlying business model. Raytheon RF Components' business model, shown in figure 1, is implemented with the requirement to provide Raytheon's defense segments with leading-edge technology to enable orders to be won for next-generation systems. The technologies pursued by Raytheon RF Components are intended to provide the next "order of magnitude" improvements in either power density, gain, efficiency, linearity, noise figure or bandwidth, as shown by the technology roadmap in figure 2. It is not sufficient to merely prove that a technology is achievable but rather it is necessary to make the technology manufacturable. Due to the capital-intensive nature of semiconductor processing, asset utilization is critical to reducing overall cost. The business model is realized by utilizing commercial high-volume production to reduce MMIC costs to military system customers.

Understanding demand

Executing the business model is where the dual-use challenge begins. Figure 3 outlines some of the major differences that cause disparity between the high-volume operations and military requirements. The key focus of any fabrication facility is to maximize productivity. In high-volume facilities, manufacturing controls all variables that could potentially affect productivity. Strict adherence to design rules is an absolute must and the number of process variations is kept to a minimum. With this approach, statistics and sample probing can be used to eliminate defective product. Further, in the commercial world, product life cycles are short and old products are continuously being replaced with higher performance products or products with more functionality. In the mobile handset market, for example, the market has moved from single-mode handsets to dual-mode phones with Internet capability in less than 18 months.

Contrast this with the high performance, high reliability requirements for military components. Due to the nature of the business, it is necessary to show traceability to the component level. The

Military vs commercial requirements

Military component requirements	Typical wafer fab operational principles
Inspection/data recording	Statistical process control
Known good die	Sample probe (DC/RF)
Small wafer runs	Minimum lots sizes or minimum numbers of runs
Maintain many processes	Focus on a few core processes
Tweak process or design rules for RF performance	Strict adherence to design rules and process rules
Military inspection	Commercial inspection

Fig. 3. Differences between typical military component requirements and high-volume wafer fabrication operation.

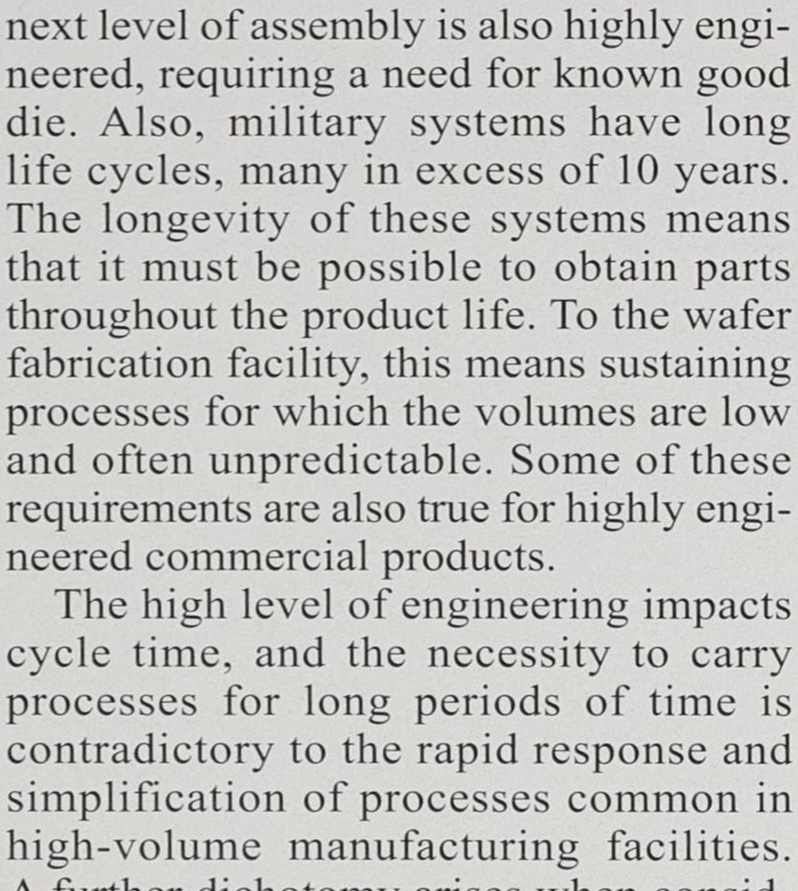


Fig. 4. Weekly process demand variation for GaAs die, by process for year 2000. Each symbol represents a process. The yellow circles represent research wafers.

next level of assembly is also highly engineered, requiring a need for known good die. Also, military systems have long life cycles, many in excess of 10 years. The longevity of these systems means that it must be possible to obtain parts throughout the product life. To the wafer fabrication facility, this means sustaining processes for which the volumes are low and often unpredictable. Some of these requirements are also true for highly engineered commercial products.

The high level of engineering impacts cycle time, and the necessity to carry processes for long periods of time is contradictory to the rapid response and simplification of processes common in high-volume manufacturing facilities. A further dichotomy arises when considering the number of wafers; this ranges from only a few per month to several thousand per month.

A quantitative view of processes or product types within a manufacturing plant can be obtained using a process called demand variability analysis. In this analysis, the variation of occurrence is measured over a fixed time period. Figure 4 shows such an analysis by process type, which is carried out on a weekly basis at Raytheon RF Components.

Using this technique, the operations management can understand what processes and products are being run and with what consistency they can be predicted. Referring back to figure 4, Raytheon typically runs and optimizes its yield improvement, tool SPC (statistical process control) and shop floor control system to those products which are located in "B" cell on the diagram. Those products in the "C" cell are research processes or candidates for obsolescence. As volume and predictability for a given process increases towards the "A" cell, a mixed-mode wafer fabrication facility would be forced to either dedicate a set of resources (equipment and personnel) to that process or alternatively, outsource the excess volume.

Operational challenges

Operating an effective dual-use semiconductor manufacturing facility requires strict adherence to fundamental manufacturing basics with some optimization around the differences described in the previous section. The basics include yield improvement, work-flow optimization (kanban) and SPC. While these criteria appear obvious, there is temptation to disregard the basics or to sub-optimize around a single process as the number of processes or complexity of a process increases. This section focuses on three approaches to meeting the operational challenges of a high-mix semiconductor wafer manufacturing facility: composite yield, a Web-based pull (kanban) system and the appropriate implementation of SPC.

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Composite yield

Composite yield consists of measuring all yield points relative to a process or product (sometimes referred to as end-to-end). The composite yield consists of the following four yield points: line yield, dc yield, RF yield (where applicable) and die visual yield. The main difference between the dc and RF yield points in this model compared to most foundries is that they are product specific. The dc and RF test coupon data are part of the line yield and are reflective of the overall health of the process as it runs on the manufacturing floor. The line yield is process-specific and includes both mechanical and electrical criteria. Likewise, die visual is typically a measure of the process pertaining to cleanliness and mechanical robustness. The dc yield monitors the process stability and can also be specification driven to some extent. In the case of RF yield, most foundries consider this an MMIC design issue. Keeping in mind that "good die delivered to the customer" is the only thing that counts, all functions need to be held responsible for yield improvements, be it the design engineer or the manufacturing engineer.

The composite yield charts drive design for manufacturability and promote a dialogue between processing, design and applications engineers. All personnel understand the yearly yield requirements and the facility's position against them. These charts drill down into the yield drivers with pareto charts and action plans to improve. Attention is immediately drawn to the drivers with the biggest impact.

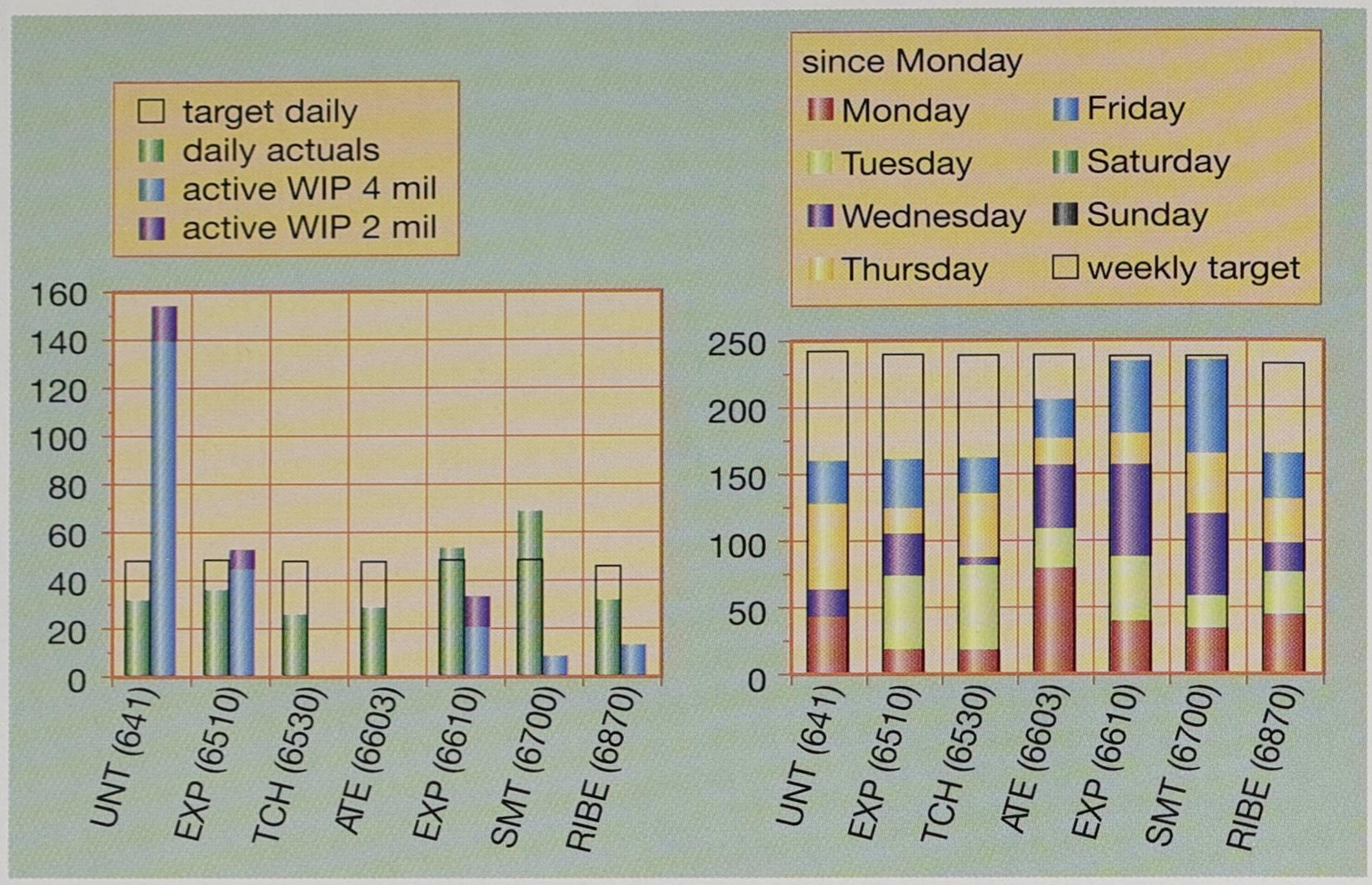


Fig. 5. Web-based pull system for the backside operation. The left picture shows targets and actual for the current day. The right picture shows progress by major operation for the week.

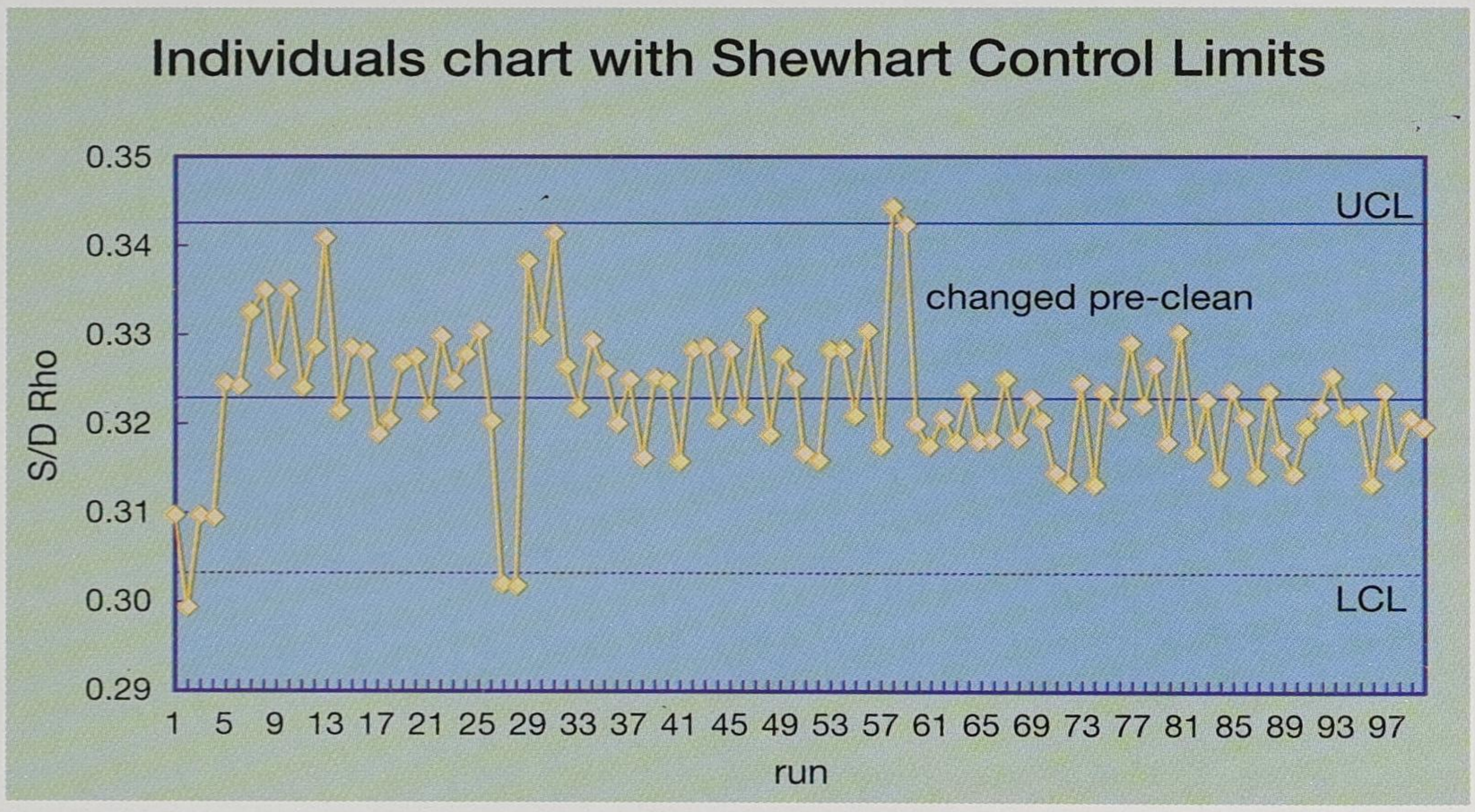


Fig. 6. Shewhart control charts are used to monitor daily operation and long-term variability in a given process.

Web-based pull system

A significant challenge in a high-mix semiconductor facility is ensuring that all wafers move and that they move according to a predetermined time and route. In setting the Takt time for the facility, the wafers must be at the right place at the right time. In a mixed-mode configuration, this challenge is exacerbated by the requirement to continuously change or calibrate tools or processes. Our Workstream shop floor control system gives real time process instructions for each wafer lot. To ensure that the right wafers are being pulled, we have supplemented Workstream with a simple Web-based tracking system by critical work cell. The six work cells are photolithography, etch, metal deposition, nitride deposition, inspection and backside.

Figure 5 shows an example of the actual screen that is shown in the wafer fab. There are large wall mounted screens in every bay which scroll through each work cell and are updated every hour. Using this system, the operator works to the daily target for each of the major steps, and the chart is updated as a wafer is completed. The active work in process (WIP) is also shown so that all personnel can assess what work needs to be completed to feed the remaining steps down the line.

The system also keeps track of the weekly progress by major operation. Using this system, all wafer lots are treated the same, and provisions can be made at the manufacturing management level to process the occasional "hot" lot. The pass-down of information during shift changes has become a real-time procedure, rather than dedicating supervisory time on the floor to update

lot status. Further, the daily floor meetings are focused on why targets were not met. The operators now understand that exceeding a target is just as bad as under performing to the target.

Statistical process control

Running multiple processes requires strict adherence to SPC, particularly as it pertains to tool performance. With large numbers of tool set-ups, a tool set and its associated qualification must be optimized for throughput and simplicity of change-over. The tool set is one of the few constants that can be relied upon in diagnosing root cause and corrective action for any scrap generated on the manufacturing floor.

Measurement tools must be kept at their peak performance. Driving the tool set to a process capability index (Cpk) greater than 2.0 significantly reduces the qualification time required to run low-volume and low-demand wafer lots, allowing personnel resources to solve fab-wide yield issues or bring on new processes, rather than attempt to steer a process.

In a high-mix facility, manufacturing often has the requirement to run lots sporadically and not with optimal balance. The key to doing this successfully is to drive variation to its lowest level and to monitor the ongoing effect of that change long term, as shown by the example in figure 6.

Conclusion

By definition, the dual-use foundry is a low-volume, high-mix wafer manufacturing facility. However, the dual-use foundry is further defined by the continuous investment in leading-edge semiconductor technology. The combination of high technology requirements with the necessity of reducing these technologies to practice is the discriminator that separates the dual-use foundry from a conventional job shop or a development laboratory.

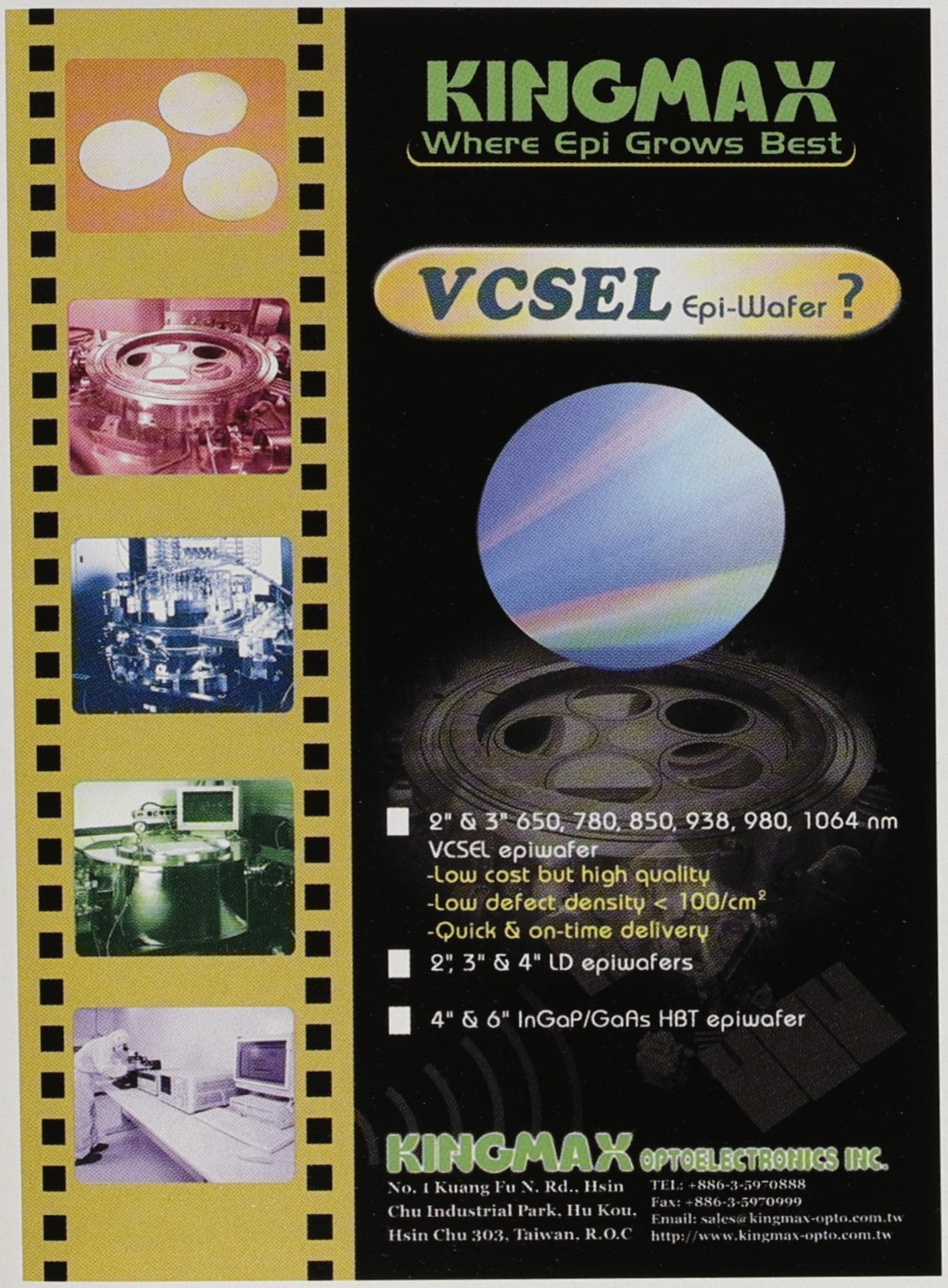
The ability to provide high-performance MMICs for military applications at reasonable costs, requires a focus of fundamental manufacturing basics including SPC, yield improvement, preventative maintenance and efficient WIP flow management. Upon this foundation, the dual-use foundry requires flexibility, an extension of the yield improvement initiatives to include composite yield, and the application of the kanban across all products and processes regardless of volume.

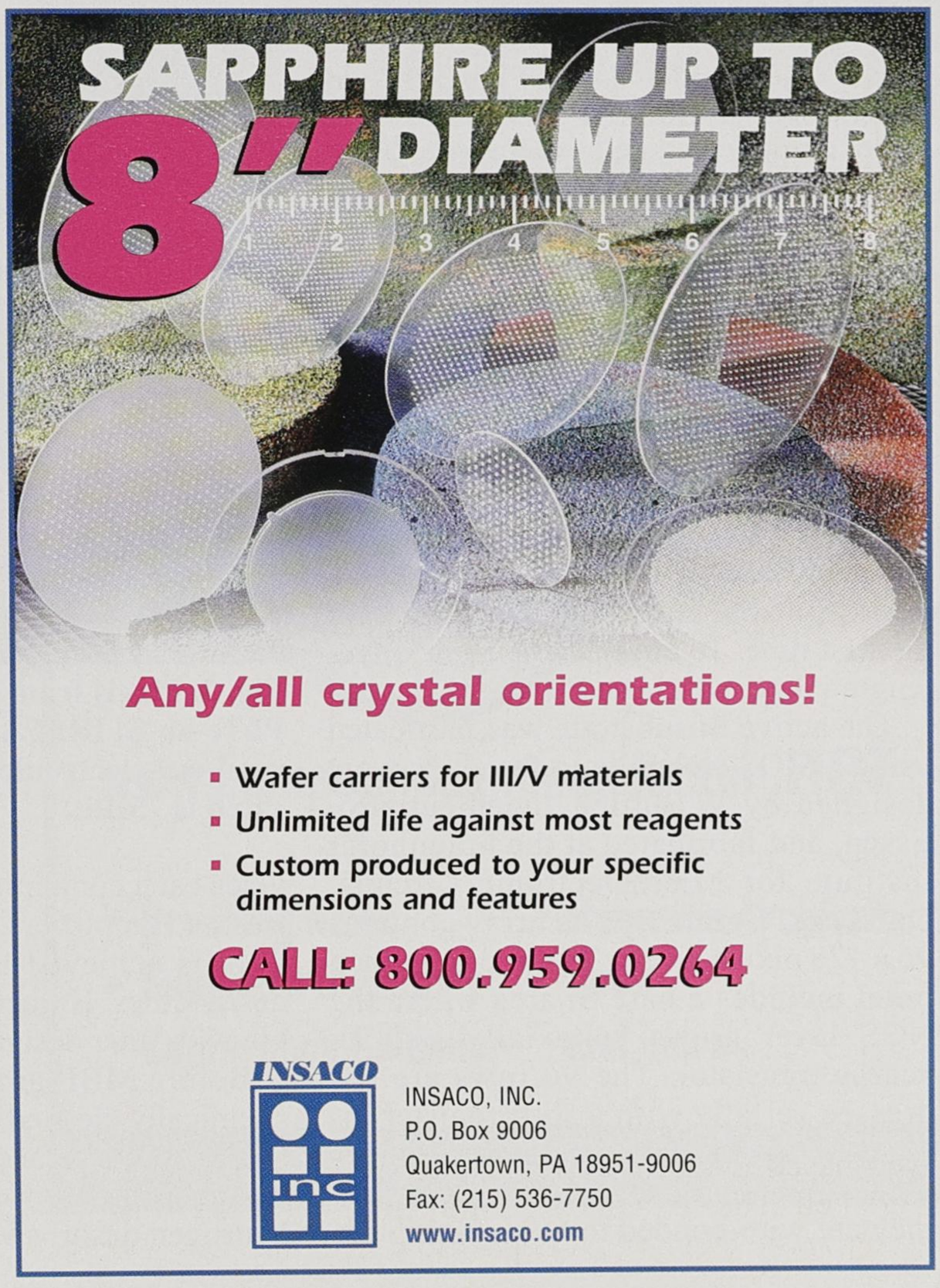
Acknowledgments

The authors would like to acknowledge the invaluable help of R Beaudoin, R Cantuloupo, B Lauterwasser, E Newton and J Scott.

L Aucoin, M Durschlag, D Janeczek, R Novo and R O'Shea are with Raytheon RF Components, based in Andover, MA. Web: www.raytheon.com/micro.

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PbTe IRFPAs for low-cost thermal imaging

Lead chalcogenides offer a low-cost alternative to II-VI and III-V materials for the fabrication of infrared focal plane arrays. ***Karim Alchalabi, Dmitri Zimin*** *and* ***Hans Zogg*** *report on how they have monolithically integrated these with silicon read-out circuitry.*

Up to now, the most sensitive infrared focal plane arrays (or IRFPAs) for thermal imaging were fabricated in a hybrid manner. A chip fabricated with the infrared sensitive material, in most cases a narrow-gap semiconductor (NGS) such as InSb or HgCdTe, or a quantum-well infrared photodetector (QWIP), contains the individual sensor pixels. This sensor chip is connected to a silicon read-out chip with integrated signal processing and multiplexing electronics. Typical arrays comprise 128 × 128 or more pixels, and electrical connections for each of the individual sensors are made with extremely small indium bumps. This bump bonding technique is now well established, but rather complicated and expensive; see for example Capper and Elliot.

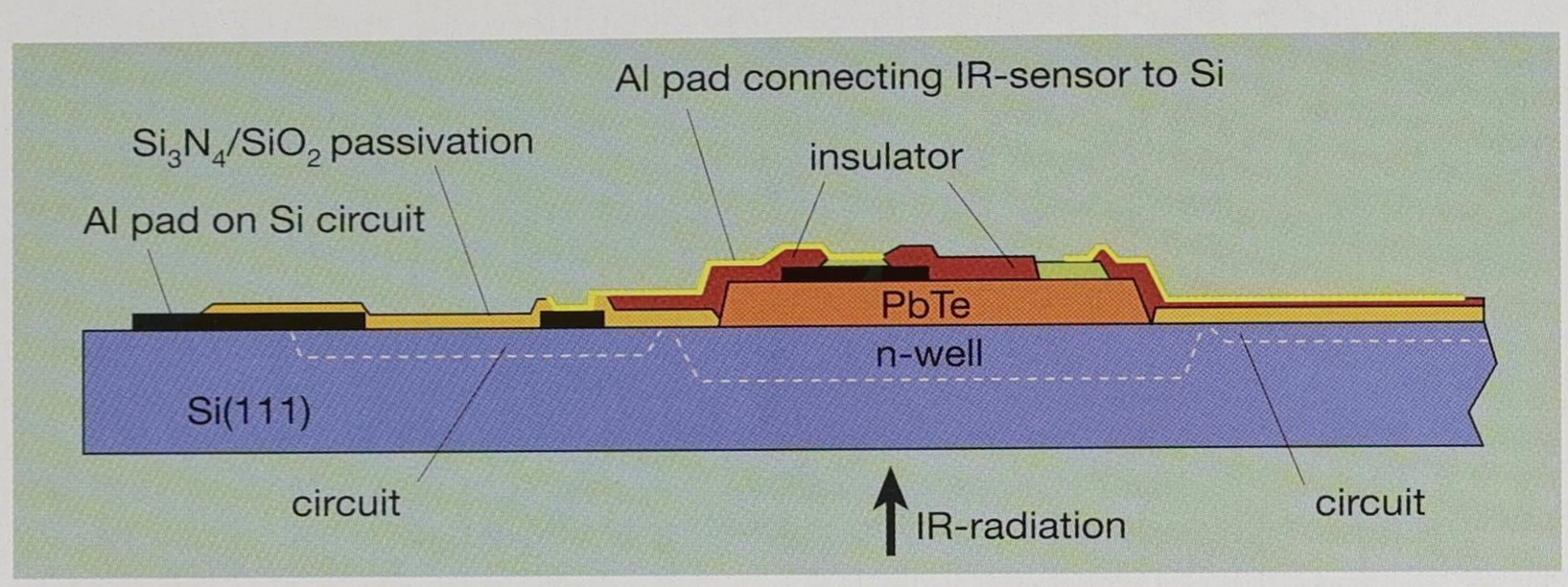


Fig. 1. Cross-section of one pixel with the epitaxial PbTe IR sensor grown on the silicon CMOS read-out circuitry.

Monolithic integration with silicon

A considerable cost saving would be possible if the narrow-gap infrared sensitive material could be grown epitaxially directly on the Si read-out chip on areas which are not occupied by the signal-processing circuits. Using a lead chalcogenide (IV-VI) NGS as the sensor material, we were able to demonstrate such a heteroepitaxial but monolithic IRFPA for the first time. To cover the 3–5 μm wavelength range, we chose PbTe.

The active Si substrate was fabricated using CMOS technology; the chips were designed by W Buttler, Ingenieurbüro, Essen, and fabricated at the Fraunhofer Institute for Microelectronic Circuits, Duisburg, Germany. The array contains 96 × 128 pixels with a 75 μm pitch. Each pixel includes a bare Si area where the NGS layer grows epitaxially, and an access transistor. The 96 rows are addressed serially with a shift register integrated into the chip, while the 128 lines are fed out in parallel to both sides where they are wire-bonded to two off-chip devices each containing 64 current integrators and amplifiers. A fill factor of about 40% is achieved by employing robust design rules. Higher fill factors are possible with finer design rules.

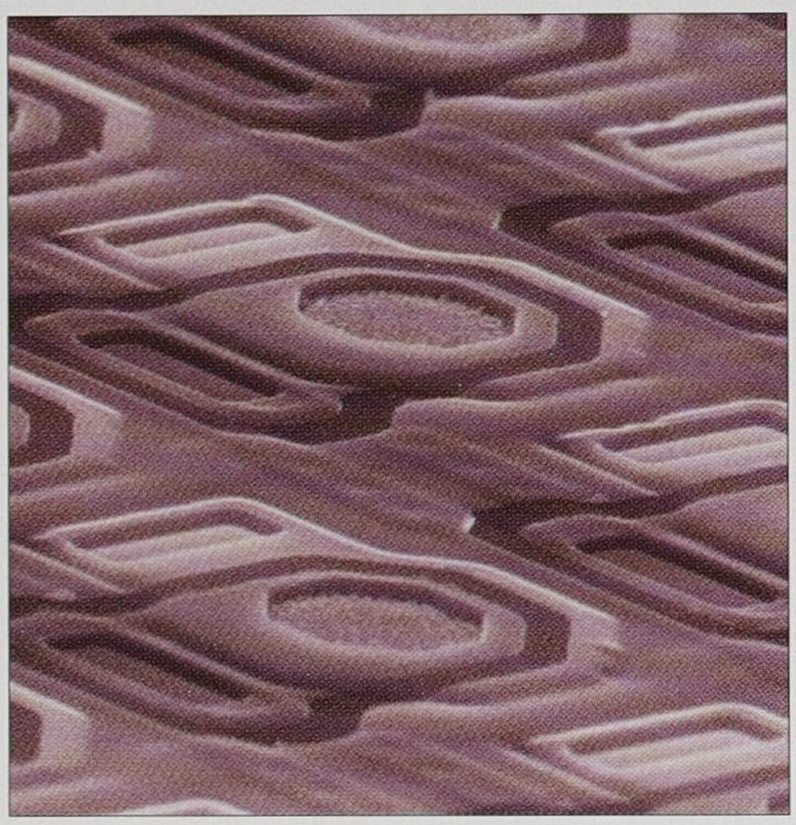


Fig. 2. Pixels from a processed epitaxial PbTe-on-Si IRFPA integrated with the read-out electronics in the Si substrate. Pitch is 75 μm.

Before MBE growth, the substrate is chemically cleaned to obtain a hydrogen-terminated surface in the pixel areas where epitaxial growth has to occur. The hydrogen desorbs when heating the substrate to the growth temperature. A 3 nm CaF_2 buffer layer is grown first at 450 °C, followed by a 3–4 μm thick lead-chalcogenide layer at <400 °C. The standard Al metallization of the active Si substrate withstands these growth temperatures without problems.

Photovoltaic sensors are then delineated in the IV-VI layers by wet- and dry-etch processes, and electrical connections between the IR-pixels and the read-out defined. Figure 1 shows a schematic cross-section of one pixel, and figure 2 a micrograph of a part of the completed array.

High pixel yield

Up to 98% of the pixels were operative in our first, not yet optimized processes. As a result of using a direct bandgap semiconductor, quantum efficiencies are high (typically > 50%). The distribution of the sensitivities (differential resistances at zero bias Ro) of an arbitrarily chosen line had a mean value of about 4 MΩ at 95 K, corresponding to a RoA product of 90 Ωcm^2. This sensitivity is considerably higher compared with our first results (K Alchalabi *et al.*) and much above the ambient temperature IR background fluctuation noise limit, thus allowing sensitive thermal imaging.

We assembled a simple demonstration

IR camera by connecting the 64 output lines at one side of the array to a 64-channel amplifier chip. An infrared image obtained in this way (figure 3) demonstrates the functionality of the design. The integration time is 100 µs/line and the noise equivalent temperature difference (NETD) resulting from the individual sensor and amplifier parameters is estimated to be below 100 mK.

Low cost, high performance

Fabrication costs of such IRFPAs are low since large standard prefabricated and tested active Si substrates containing many devices can be used. Also, the MBE growth is simple, and the final IR-pixel delineation can be performed with standard processes. While the bandgap of PbTe is fixed, ternary lead chalcogenides such as $Pb_{1-x}Eu_xTe$ or $Pb_{1-x}Sn_xTe$ allow tuning the bandgap to obtain cut-off wavelengths covering the full 3–5 and 8–12 µm wavelength range of the atmospheric infrared windows. Lead chalcogenides are much easier to handle than

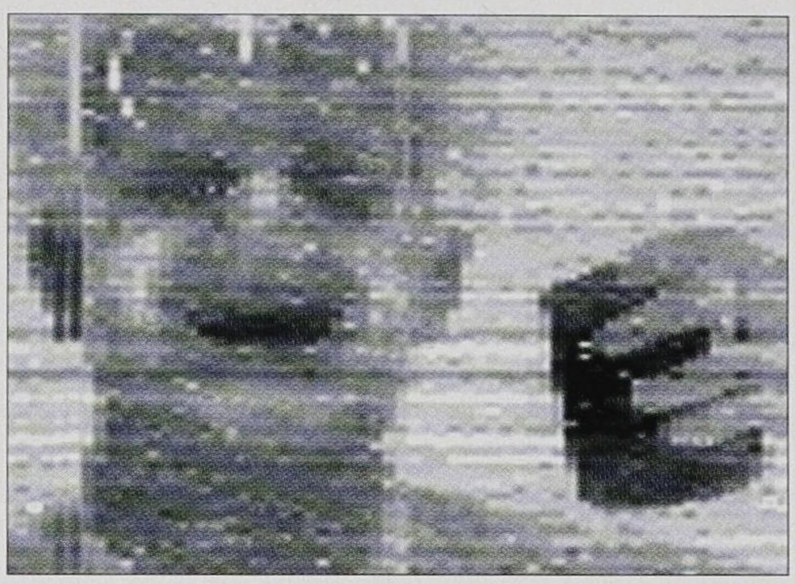


Fig. 3. Infrared image obtained with a rudimentary demonstration IR camera set-up using the monolithic PbTe-on-Si array. Operating temperature is about 95 K, and line integration time 100 µs. The left part of the array was bonded to a 64-channel read-out amplifier device.

II-VI compounds, while their theoretical performances are comparable. In addition, lead chalcogenides are "forgiving" materials, i.e. a rather high number of defects is tolerable. This allows us to grow layers of sufficient quality on Si substrates, despite the large lattice and thermal expansion mismatch.

The dislocation densities (as high as 10^7 cm^{-2}) limit device performance, but performance is still high enough for most applications with ambient background temperatures. Such applications include fast imaging if the sensitivity of highest-quality hybrid IRFPAs is not required, or if the recording speed of uncooled microbolometer IRFPAs is not sufficient.

Further reading

K Alchalabi, D Zimin and H Zogg *Electron. Dev. Lett.* 2001 **22(3)** 110; *Proc. SPIE* 2001 4369–41.
P Capper and C T Elliott eds 2001 *Infrared Detectors and Emitters: Materials and Devices* (Kluwer Academic).

H Zogg, K Alchalabi and D Zimin are in the Thin Film Physics Group at the Swiss Federal Institute of Technology, Zurich, Switzerland. E-mail: zogg@phys.ethz.ch; Web www.tfp.ethz.ch.

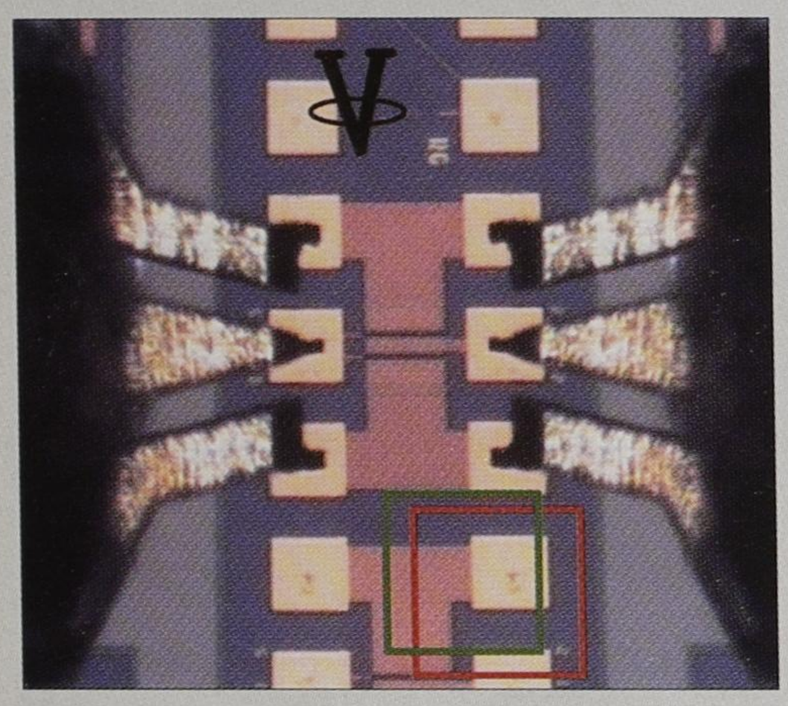
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Software offers automatic alignment

Cascade Microtech has introduced Nucleus Vision 1.0 Software, an advanced pattern recognition software package for Cascade Microtech semi-automatic probe stations. Vision 1.0 Software offers automatic module alignment for blue-tape probing, automatic X/Y die stepping correction, and one-step automatic microscope objective calibration.

Utilizing state-of-the-art pattern recognition technology ensures fast and accurate pattern matches. The software integrates seamlessly with Nucleus 2.1 Prober Control Software so that existing customer test programs controlling



Nucleus need no modification to add Vision's capabilities.

Contact Ellen Payne, Cascade Microtech, 2430 NW 206th Avenue, Beaverton, OR 97006, USA
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Fax +1 503 601 1002
E-mail ellen_payne@cmicro.com

System for 2- and 3-D bump inspection

Robotic Vision Systems has released its next generation WS-2500 bumped wafer inspection system. The new model provides full capability for 2-D surface defect detection at high-speed production rates. Improvements in laser technology have increased system throughput for 100% 3-D inspection



of bumped wafers.

Applications include flip chip, MEMS and optoelectronics. Both bump metrology and defect detection are accomplished through a combination of 2-D and 3-D inspection technologies. The versatile design allows users to select different inspection strategies to optimize process and production requirements.

The system allows measurement of bump features such as size and position, and detects defects such as missing bumps, bridging and foreign material. An air-bearing x-y stage moves the wafers beneath the inspection module with a resolution of 0.1 μm.

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Tel. +1 781 302 2439

New PA test system offers cost reduction

Agilent Technologies has introduced the A22pa power amplifier (PA) test system that enables RFIC manufacturers to reduce cost of test by up to 50% on cellular handset PAs.

Agilent has achieved a significant cost-of-test reduction by lowering its entry-level price by 32% from the previous model and increasing throughput by up to 50%. Throughput improvements can be attributed to several new enhancements, including a redesigned receiver to provide fast power servo control to test power amplifier devices at specified power output, a modulated source providing faster frequency and power setup, and power supplies that enable faster DC measurements.

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X-ray diffractometer for process control

Philips Analytical's DCD Pro X-ray Diffraction Analyzer performs ultra-fast rocking curve wafer mapping for semiconductor process development and high-volume production control. Typical applications include SiGe HBT structures, III-V, II-VI, GaN and HEMT devices. The dynamic range of the system is more than 5 orders of magnitude, enabling the accurate measurement of intense substrate peaks, and peaks from very thin, weakly diffracting layers.

A cassette of 25 wafers can be measured and analyzed within one hour, and epitaxial layers thinner than 20 nm in less than a minute.

Philips' Auto-fit dynamical scattering simulation and fitting software is Windows-based for easy use, with data acquisition and interpretation fully automated. There are options for ternary and quaternary analyses, and facilities for measuring offcut angles in substrate wafers.

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Karl Suss/Labsphere VCSEL tester

Karl Suss and Labsphere have released a new automated VCSEL test system designed for high-speed wafer level device characterization. It uses a patented system called the Spectralon Integrating Sphere to minimize reflections and eliminate damage to the device under test. The core of the test system is the Suss PA200 semi-automatic probe system, which is combined with

LabSphere's control system.

The tool is configured to provide L-I-V curves, optical power measurements, peak wavelength, full width half max, kink voltage/current curves and spectral analysis. The sphere's insensitivity to beam alignment and divergence allows accurate total flux measurements to be obtained. The accuracy of all measurements is assured with NIST traceability.

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Praxair 6.5 grade ammonia for GaN

Praxair has released new semiconductor grade ammonia (NH_3) with a minimum purity of 99.99995% (6.5), the highest specification in the industry. The 6.5 grade ammonia has impurity levels of less than 50 ppb of oxygen and less than 200 ppb of water.

Contact Lisalynne Quinn, Praxair Inc.
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E-mail lisalynne_quinn@praxair.com

PCB inspection system from Viscom

Viscom's S6055 family of AOI inspection systems offers high speed, inspection efficiency, and a user-friendly interface for production-speed inspection of solder connections on PCB assemblies, as well as solder paste print inspection and assembly check. A new cast aluminum foundation gives the system complete stability to operate at high speed, and a performance-proven propulsion system based on synchronized linear motors that now deliver five times better definition of the position sensor.

The use of Viscom's megapixel technology gives the S6055 high inspection speeds without compromising depth of inspection. Additionally, the system uses Fire-Wire technology, which permits a digital transfer of the picture data to the computer without distortions of the analog picture signal, further reducing false failure indices.



The S6055 also operates with dual track transport and processing, for optimum performance. Maximum board size is 457 × 508 mm for single-track systems and 457 × 350 mm for double-track systems.

Contact Paul J Handler, Viscom USA, 3290 Green Pointe Parkway, Suite 400, Norcross, GA 30092, USA
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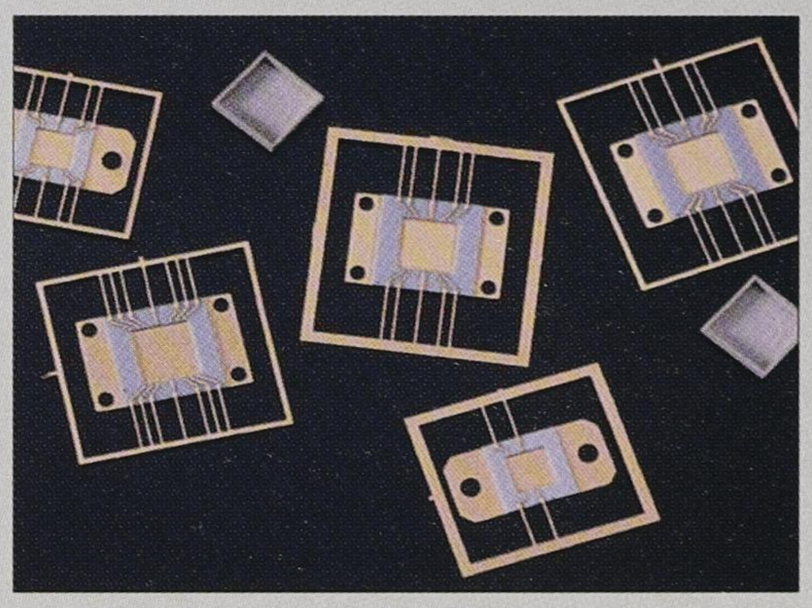
Fast ramp hotplate from MRSI

MRSI has introduced a new hotplate system capable of ultra-fast temperature ramping for laser diode *in situ* eutectic bonding on the MRSI-5005 OPTO. Temperature ramp rates are programmable up to 40°C/s heating or cooling. This is accomplished by using a hotplate with a high ratio of electrical power to thermal mass inertia. Fast cool down is accomplished by controlled pulsed inert gas flow around the heated element. A thermocouple is available for attachment directly to the work piece, while the software displays the actual temperature in real time. This enables direct process feedback and monitoring during product assembly.

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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

CALENDAR

24–28 September
Gallium Arsenide Applications Symposium (GAAS 2001) (part of European Microwave Week)
London, UK
Web: www.eumw.com

30 September – 4 October
European Conference on Optical Communication (ECOC)
Amsterdam, The Netherlands
Web: www.ecoc-exhibition.com

1–3 October
North American MBE Conference (NAMBE 2001)
Providence, RI, US
Web: www.engin_brown.edu/faculty/beresford/nambe

1–4 October
28th International Symposium on Compound Semiconductors (ISCS 2001)
Tokyo, Japan
Web: www.iscs.iis.u-tokyo.ac.jp

3–5 October
US Workshop on the Physics and Chemistry of II-VI Materials
Orlando, FL, US
Web: www.ii-viworkshop.org

9–11 October
International Symposium on Microelectronics (IMAPS 2001)
Baltimore, MD, US
Web: www.imaps.org/imaps2001

11–14 October
IMAPS Advanced Technology Workshop on Optoelectronics Packaging
Bethlehem, PA, US
Web: www.imaps.org

17–19 October
LEDs 2001 (organized by Intertech)
San Diego, CA, US
Web: www.intertechusa.com/division_electronics/index.htm

21–24 October
GaAs IC Symposium
Baltimore, MD, US
Web: www.gaasic.org

29–31 October
10th Topical Meeting on Electrical Performance of Electronic Packaging (EPEP 2001)
Cambridge, MA, US
Web: www.epep.org

28 October – 2 November
International Conference on Silicon Carbide and Related Materials
Tsukuba, Japan
Web: www.icscrm2001.gr.jp

12–15 November
Laser and Electro-Optics Society Annual Meeting (LEOS 2001)
San Diego, CA, US
Web: www.i-leos.org

26–30 November
MRS Fall Meeting
Boston, MA, US
Web: www.mrs.org/meetings

2–5 December
International Electron Devices Meeting (IEDM)
Washington, DC, US
Web: www.his.com/~iedm

For links to event Web sites, visit the Calendar section of our Web site at www.compoundsemiconductor.*net*.

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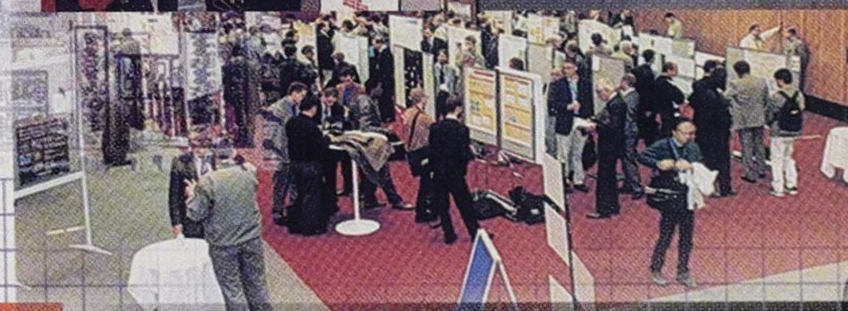
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JDS Uniphase takes a big bath

*Can JDSU shrug off a $50 billion loss? Meanwhile, semiconductor equipment and materials suppliers are living through the Chinese curse of "interesting times". **Marie Meyer** reports.*

"May you live in interesting times" says an old Chinese curse. "Interesting" seems like the most polite thing that one can say about today's financial markets.

Case in point: JDS Uniphase can now lay claim to the dubious distinction of generating the largest corporate loss in history – $50 billion. Yet Wall Street has, for the most part, taken the news in its stride, and refrained from punishing the stock even further.

JDSU appears to be engaging in a classic accounting practice that has recently acquired the nickname "big bath". It consists of gathering up lots of bad news and delivering it all in one batch as a massive one-time hit to the balance sheet. Nortel and Corning have already done the same. A maneuver best used when times are bad and expectations are low, it helps to make earnings reports for future quarters look better. Moreover, there isn't a lot of downside to the company taking the bath. While $50 billion is a huge number, most of the loss that JDSU reported was a "paper loss" that has no impact on the company's cash position or other important aspects of operations.

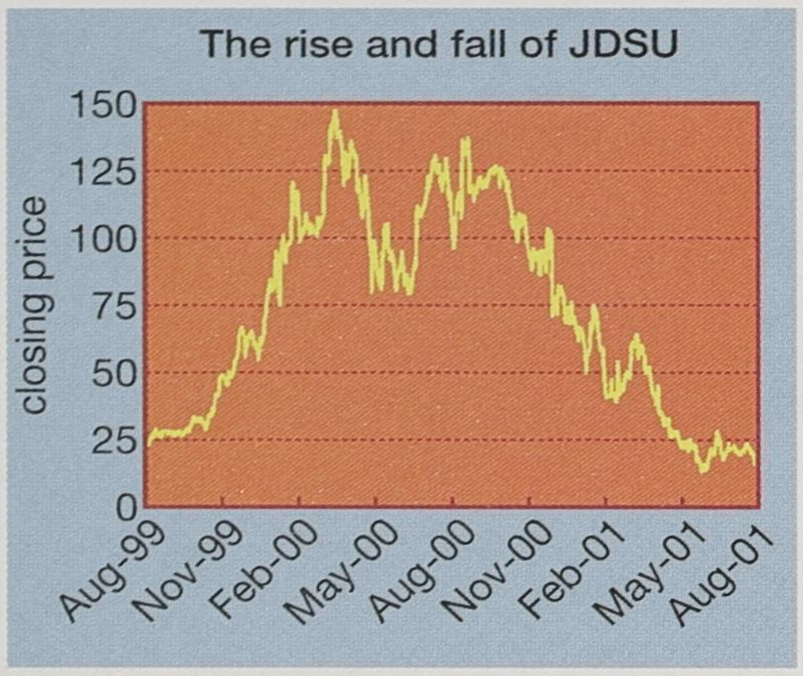
$44.8 billion of the loss stemmed from write-downs of goodwill relating to corporate acquisitions. "Goodwill" represents the difference between the asset value of an acquired company and the total purchase price. For example, JDSU paid $41.5 billion to acquire SDL, which had tangible assets valued at $2 billion. The difference between the two numbers is "goodwill". It is a depreciating asset, appearing on the earnings statement as goodwill amortization, an item that counts against earnings.

By taking advantage of this opportunity to slash its goodwill figure, JDSU has put itself in a position to deliver better reported earnings in the future, without a material alteration in its "real-world" financial position. However, the reduction in goodwill should also be seen as a tacit admission by the company that it overpaid for the companies it acquired. But again, the damage done to the company is difficult to quantify, because it paid for these companies with its own stock, which was also overvalued.

The three biggest acquisitions JDSU made in the last two years were OCLI, E-TEK and SDL. At the time these deals were announced they were valued at $2.6 billion, $15 billion and $41.5 billion respectively. However, each was an all-stock deal, and these "value" figures reflect the price of JDSU's stock on the day the deal was announced. If they were valued at today's share price, they would drop to $460 million, $1.2 billion and $3 billion, respectively.

Company	Symbol	Closing price August 20	52 week low–high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha Industries	AHAA	29.12	13.0625–55.3750	1.281B	67.06
Anadigics	ANAD	13.76	10.5000–37.5000	417.2M	N/A
Celeritek	CLTK	14.96	9.8125–50.0625	179.8M	N/A
Conexant	CNXT	9.63	6.9000–54.9375	2.429B	N/A
Endwave	ENWV	1.24	0.9000–20.6250	42.4M	N/A
RF Microdevices	RFMD	23.54	8.7500–47.5000	3.881B	N/A
Stanford Microdevices	SMDI	7.17	4.2188–60.2500	209.7M	23.12
TriQuint	TQNT	19.40	10.2500–61.5625	2.516B	32.20
Vitesse	VTSS	13.23	13.0700–95.1875	2.520B	N/A
Opto companies					
Agilent	A	26.45	24.3000–68.0000	12.090B	27.46
Agere	AGRA	4.60	4.1000–9.5000	7.521B	N/A
Alcatel Optronics	ALAO	7.45	7.4500–71.7500	122.9M	6.54
Coherent	COHR	35.35	25.0000–82.0000	1.000B	12.51
Cree	CREE	20.81	12.2100–73.7500	1.513B	56.24
JDS Uniphase	JDSU	7.07	7.0700–128.0000	9.306B	N/A
Uniroyal Technology	UTCI	5.69	5.2000–18.8750	148.7M	N/A
Semiconductor materials & equipment companies					
ATMI	ATMI	23.18	14.3750–32.7300	701.3M	29.18
AXT	AXTI	16.35	13.2500–46.4375	365.0M	12.94
Emcore	EMKR	14.10	14.0500–60.4688	486.7M	N/A
Kopin	KOPN	12.31	4.0000–38.5625	799.3M	N/A
Tegal	TGAL	2.25	1.3125–5.2500	28.3M	28.75
Trikon	TRKN	12.00	7.1250–26.2500	153.80M	6.14

**Market capitalization = # shares × current share price.*
***Price/Earnings ratio = current share price ÷ (income for the last 4 quarters ÷ # shares).*



JDSU shares have dropped from $150 to their lowest point in two years.

Obviously, write-downs of this sort would be excruciating if the company had paid in cash. And they may still be painful for any former OCLI, E-TEK or SDL shareholders who received an exchange of JDSU shares and did not cash them in. But, for JDSU itself, these write-downs can be seen as simply the cost of eliminating 90% of its competition in the fiber-optic components market – leading to who-knows-what level of opportunity when recovery kicks in.

Aixtron and Emcore

In a topsy-turvy world where a $50 billion loss can be shrugged off, it probably shouldn't be surprising that reporting good news can spark a sell-off. This appears to be what has happened to Aixtron and Emcore, as both companies tested new 52-week lows after announcing good results for the June quarter.

Aixtron reported second-quarter sales of €58.9 million (€1 = $0.90), roughly even with the previous quarter and 36% higher than the year-ago period. Operating income was €14.4 million, up 39% over the comparable quarter in 2000 and roughly flat sequentially. Aixtron's revenues for the first six months of the year were 79% higher than last year. For the year, Aixtron is forecasting total revenues of €239 million and net income of €30 million, up 51% and 62% respectively over the results from 2000.

For the June quarter Emcore reported record revenues of $53 million, up 10% over the previous quarter and up 76% compared with the year-ago quarter. Income, excluding goodwill amortization, was $915 000, compared with $31 000 for the March quarter.

Investors are not responding – on either side of the Atlantic. Shares in Aixtron have slid 46% since June; Emcore shares are down 35%. The timing of these declines is difficult to understand. Admittedly, Aixtron's sales forecast for the year indicates that the next two quarters will be flat compared to the previous two, but in the current climate that would seem to be no small achievement. There have been reports in the European press that some traders are selling because they doubt whether the MOCVD market can continue to grow at 75% per year. However, this would seem to be such an overstatement of the obvious that it is difficult to believe that this news was not factored into the share price long ago. Aixtron's management recently reiterated their estimate of "growth of an average 30% p.a. for the next few years", which would ordinarily seem like more than enough to satisfy investors.

Aixtron and Emcore – the last six quarters

	Q4 '99	Q1 '00	Q2 '00	Q3 '00	Q4 '00	Q1 '01	Q2 '01
Aixtron (€ '000s)							
Revenues	25 400	22 900	43 400	28 900	62 700	59 800	58 900
Operating income	3900	5100	10 200	4000	13 600	14 300	14 200
Emcore ($ '000s)							
Revenues	16 501	23 925	30 023	34 057	40 064	47 907	52 890
Operating income*	–2709	–258	583	–27 871	–3634	31	915

**Excludes goodwill amortization and losses from UOE and Gelcore joint ventures.*

The case for Emcore's decline is even more difficult to understand, as the company would seem to be doing everything right. Aixtron has always been consistently profitable, but Emcore has not. However, this year they have, for the first time in recent memory, reported profits in two back-to-back quarters (see table above). ("Profits" here being defined as operational profit, before allowances for goodwill amortization.) Moreover, the company appears to be making genuine progress in its efforts to enter the fiber-optic component market. While it is true that this sector is seriously out of favor with investors right now, at least Emcore is targeting the short-haul segment, which is showing more signs of life than the long-haul market. Other encouraging signs: the company raised $175 million via a debt offering, giving it plenty of cash to plow into R&D for that nascent opto product line. Revenues have grown sequentially over the last six quarters (averaging 10% per quarter). And Emcore also sold off its interest in the loss-making LED joint venture with Uniroyal, which had put over $4 million in red ink on Emcore's balance sheet in just the past two quarters.

So why isn't Wall Street responding? Traders have indicated concern that the VCSEL product line will take off slowly, due to order push-outs from some customers. But more to the point, Emcore may be pulled to earth by its MOCVD equipment business. The centerpiece of Emcore's corporate strategy for the past four years has been to diversify beyond equipment manufacturing into potentially more lucrative areas, such as epiwafers and devices. But the pronounced weakness in the HBT and HEMT epiwafer market in the first half of the year resulted in Emcore's shipments of materials declining 10% in the June quarter, while equipment shipments rose 20%. As a result, equipment sales now constitute more than 75% of Emcore's revenues for the first time since December 1999. Thus the same forces that are depressing Aixtron's shares may also be working upon Emcore

To this commentator, in both cases the timing seems very odd indeed – why sell off now, when things are looking reasonably good, rather than four or five months ago when things were looking truly awful? Perhaps the fact that these companies are hitting new lows is another sign that the bottom has been reached.

Epiwafer vendors report

As Emcore's results demonstrate, the market for electronic epiwafers has been pretty horrendous in the first half of this year. HBT-specialist Kopin has seen its market cap reduced by two-thirds. But recently its share price has begun to rebound from the depths that it reached in April.

For the June quarter, Kopin reported revenues of $9.2 million – down sharply from the $24.4 million reported in the year-ago quarter. Most of the decline came from the epiwafer business – down from $19.5 million to $3.8 million. In contrast, the company's display business was up 8%.

Kopin has been hit hard by the turmoil at Conexant, historically its largest customer. Purchases have dropped from $10 million per quarter in 2000 to $3.5 million in the June quarter, according to analysts at C E Unterberg Towbin. But Kopin is having some success attracting new customers, who accounted for 50% of revenue in the June quarter. The company landed contracts to supply InGaP HBT wafers to Alpha and Anadigics, and is sampling at Motorola and TriQuint. Kopin should also be able to begin delivering improved gross margins in the epiwafer business, as 6" wafers now account

for 50% of shipments (up from just 10% in the first quarter). However, the company says that its capacity utilization will, at best, reach just 40–50% by the end of the year.

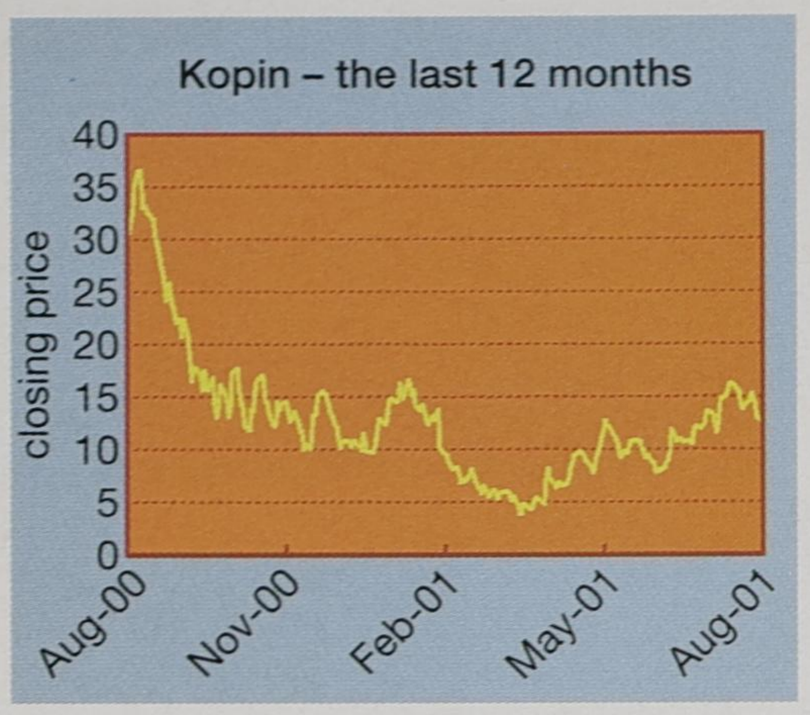
Revenues at fellow epiwafer vendor IQE have held up better, largely due to its more diversified product range. Revenues for the June quarter were GBP 13.16 million ($18.97 million), a record for the company. This was double the revenues reported in the year-ago quarter, but flat compared to the previous quarter. Operating profit before goodwill and one-time charges was GBP 1.29 million ($1.86 million). Again, this was a major improvement over the year-ago period (by 3×), but flat compared to the March quarter.

Commenting on the results, IQE CEO Drew Nelson said that the III-V epiwafer operations performed well in the first half despite a rapidly deteriorating optoelectronics market and continued softness in the wireless market. "The UK facility generated an exceptional performance, partly due to focusing on advanced product areas such as VCSELs where demand has remained relatively robust, and partly as a result of winning significant development work, which has helped to offset declining production volumes."

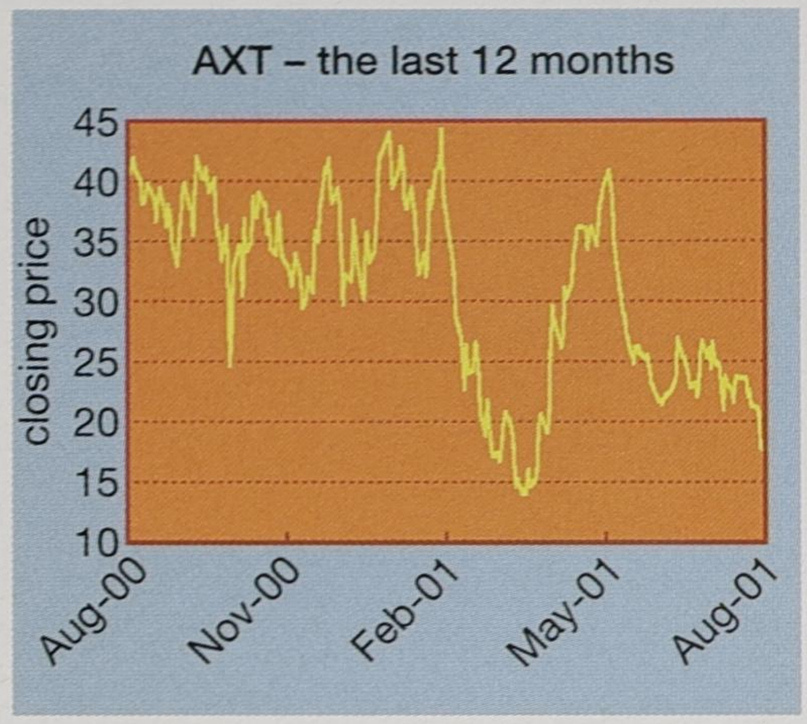
However, Nelson also noted that capacity utilization was weak at the company's US operation (the former QED), which has much larger exposure to the wireless market.

Picogiga has yet to announce its full results for the June quarter. However, the company has announced that its sales were €4.57 million during the quarter, which is a sequential increase of 10% over the first quarter of 2001. This welcome news would seem to be yet one more indicator that the worst of the slump in the wireless sector is now over.

The company also reported that its backlog at the end of June was valued at €10 million, €2 million higher than it was at the end of last year. Linh Nuyen, chairman and CEO of Picogiga, noted that the company has €18 million in cash available, some of which will be spent on "intensified" R&D programs that will allow the company to diversify out of its traditional reliance on the HEMT market. Modulight, the company's Finnish optoelectronic start-up, will begin operating in September. The company is also branching out into phosphide and nitride compound semiconductors.



Kopin has been boosted by displays and hopes the worst is over in wireless.



Volatility continues for AXT shares.

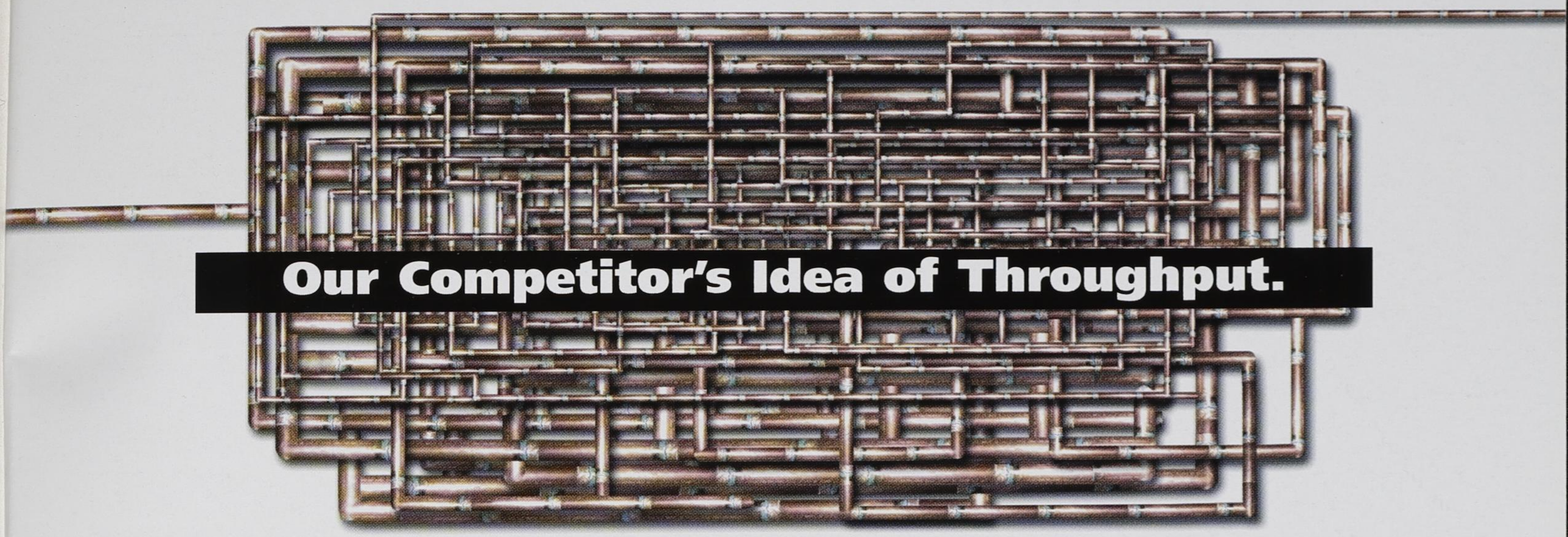
AXT's roller-coaster ride continues

Shares in AXT continue their up-and-down odyssey. Having dipped as low as $13.25 in April, the company rocketed up to $40 in May, close to its 52-week high. Since then, however, there has been a steady trend downward into the $15–17 range. As suggested earlier, this author does not have any great insights into investor behavior, but here is one plausible interpretation of what has happened.

The share-price rise began in mid-April in anticipation of the company's first-quarter earnings announcement. And indeed, when it came out on 25 April, it showed that AXT had recorded record revenue for the quarter, up 8% sequentially over the previous quarter. Given that most semiconductor companies were reporting declining revenues at that time, investors were thrilled. The company got a further boost by announcing the availability of new telecom laser and 850 nm oxide VCSEL products. And on 1 May TRW announced its plans to spin off its InP operation into a new company (Velocium). This created the prospect of more demand for AXT InP products. (AXT's InP revenues have been growing ~25% per quarter and now represent a quarter of AXT's total substrate sales.)

On 21 May AXT shares closed at $40.67, but have declined steadily since then. Presumably, investors slowly grasped the possibility that the strength of AXT's first-quarter results may have been skewed somewhat by the company's "supply guarantee program". Last fall, when GaAs substrate prices were rising and supplies were running thin, AXT entered into long-term fixed-price supplier agreements with several of its largest customers. Participating customers were assured that they would receive an agreed supply of wafers at predetermined delivery dates and prices. In return they made partial, non-refundable advance payments to AXT and agreed to give 90 days' notice before changing any orders. AXT reported that nine customers agreed to purchase $91.6 million-worth of GaAs and InP substrates under the program in 2001 – more than 50% of AXT's production, if current trends hold up.

While this program was intended to protect customers from potential shortages, the 90 days' notice provision became a liability for them in the first quarter in the face of the unexpected and severe recession in the GaAs industry. Dale Pfau of CIBC World Markets believes that the supply guarantee program "artificially" insulated AXT from the overall weakness in the GaAs semiconductor market during the first half of 2001, as some customers were required to accept shipments of GaAs wafers that they really didn't want or need. Now, he warns, "this situation may accelerate the downturn in revenues for AXT during the second half of 2001, as orders are pushed out and canceled". Despite the fact that AXT's results for the June quarter were in line with estimates (revenue of $41.3 million, income of $5.2 million), the company's share price has failed to rebound. Pfau has warned that AXT may now lag behind the recovery of the GaAs semiconductor market, and indeed AXT executives themselves have also advised of sequentially lower GaAs substrate revenues in the second half of the year – partially offset by higher InP revenues in the fourth quarter. This is certainly an "interesting" – and unexpected – side effect of a sales program that seemed like a good idea at the time.





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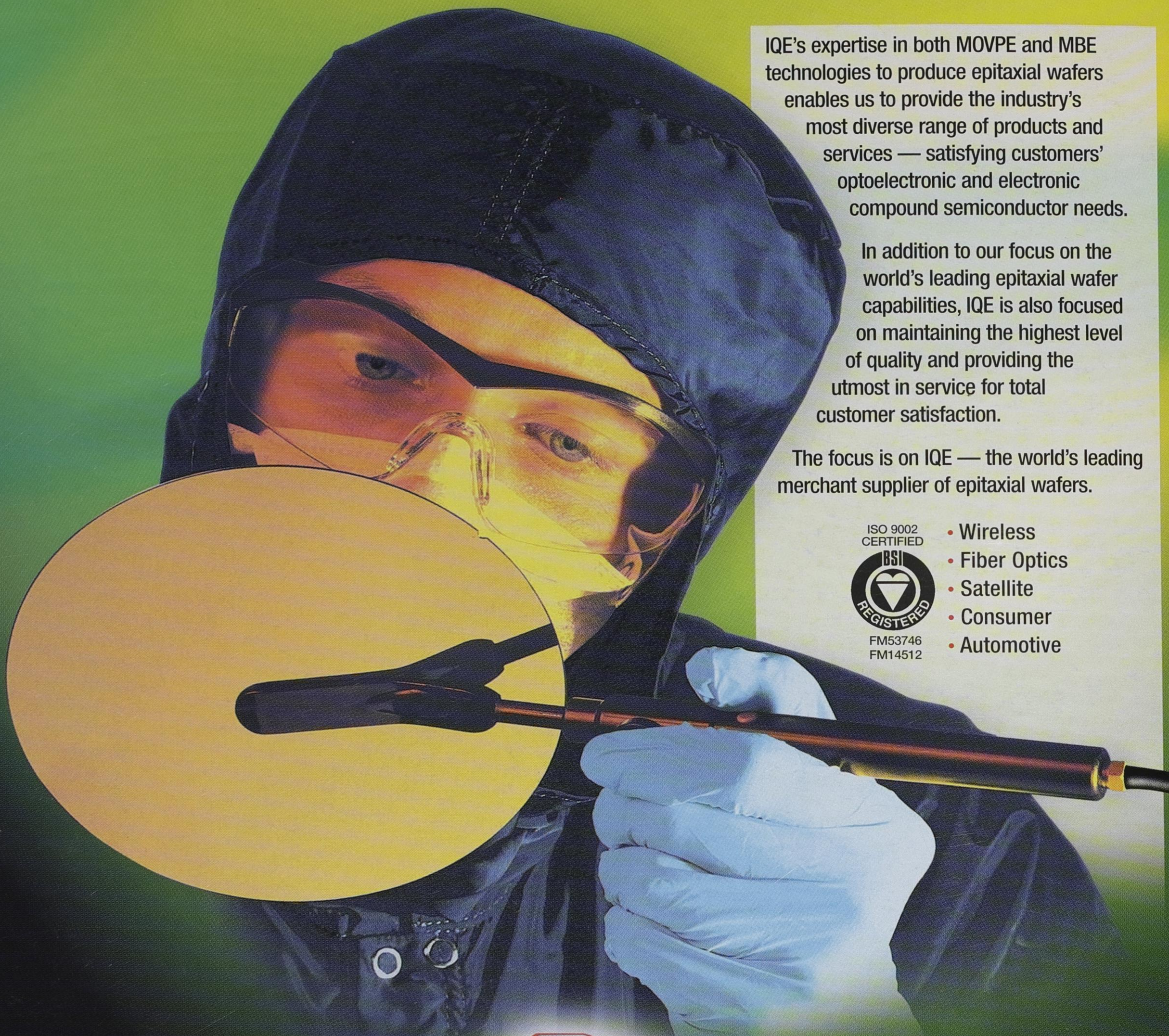
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