COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

January/February 2003 Volume 9 Number 1



THINGS TO WATCH IN 2003

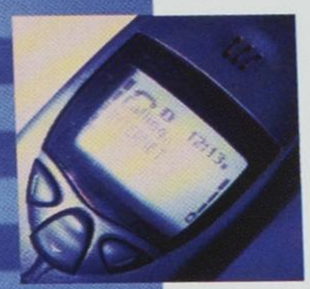
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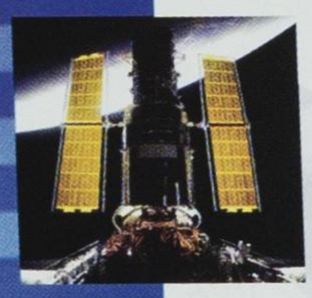
Nichia and Sony in laser alliance	Reports from IEDM and CS-MAX	Cree achieves record LED sales

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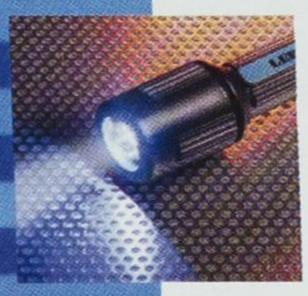
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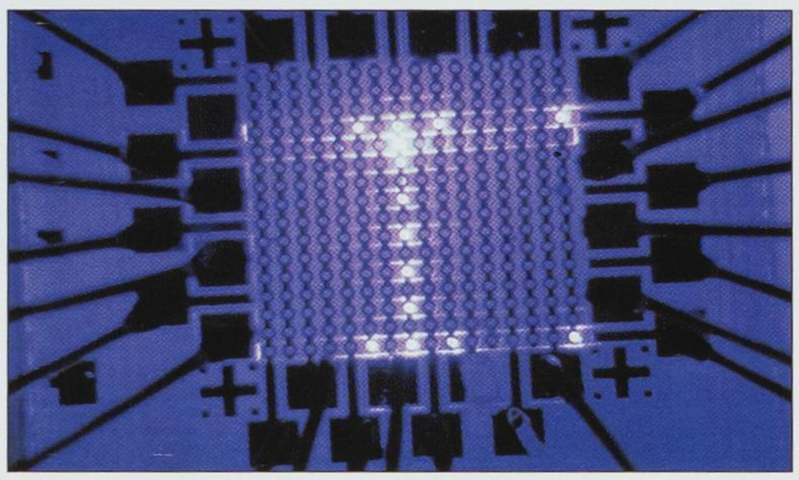
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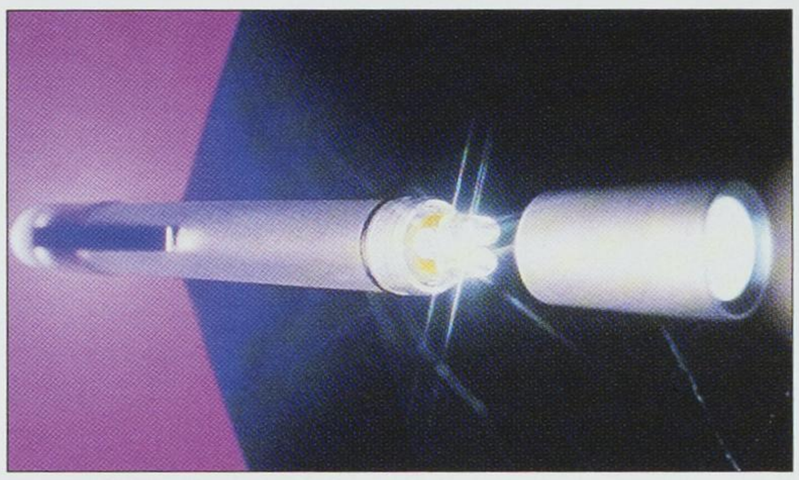
COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

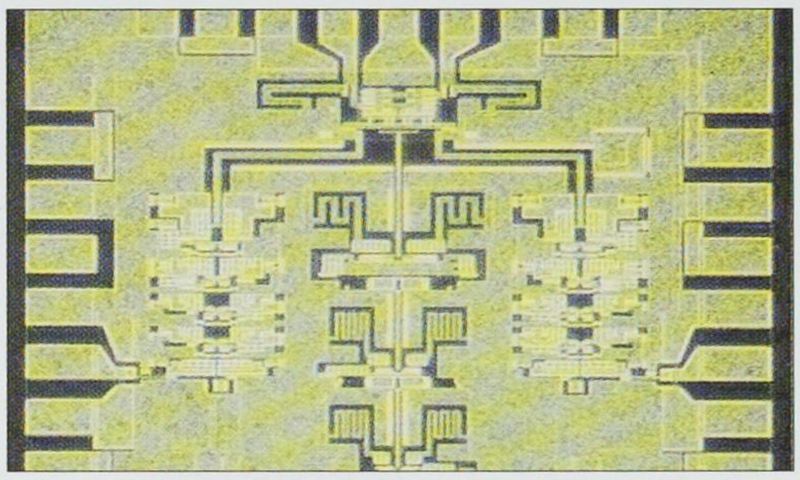
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The largest ever array of GaN micro-LEDs has been fabricated by Strathclyde University **p11**



White LEDs are starting to replace incandescent bulbs in general lighting applications **p22**



A 100 Gbit/s InP logic circuit was one of many new developments discussed at the IEDM **p27**

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Last year was one of consolidation and contraction for the compound semiconductor industry, but also one that brought new opportunities. In our annual look at things to watch, Tim Whitaker and Jon Newey describe some of the likely developments in 2003.

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27 IEDM highlights include SiGe HBTs operating at 350 GHz
Results presented at December's IEDM raised the bar for device performance, writes Tim Whitaker. Key announcements included a 350 GHz HBT, AlGaN/GaN FETs providing 2.3 W at 30 GHz and 100 Gbit/s logic ICs fabricated using InP HEMTs.

31 CS-MAX brings manufacturers together in Silicon Valley
If you want to find out what techniques are used to manufacture all types of state-of-the-art compound semiconductor devices then CS-MAX is a good place to start, writes Jon Newey.

36 Wafer-scale processing leads to low-cost optical integration
A novel epitaxial transfer technology could provide the key to low-cost, wafer-scale integration of optical components, write William Waters and William Clark from Optogration.

On the cover: *cellphones, WLANs, fiber-optic components and LEDs are just some of the things to watch in 2003 (montage by Vic Le Billon) – see p22.*

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Three-Fives and Silicon Heterostructures

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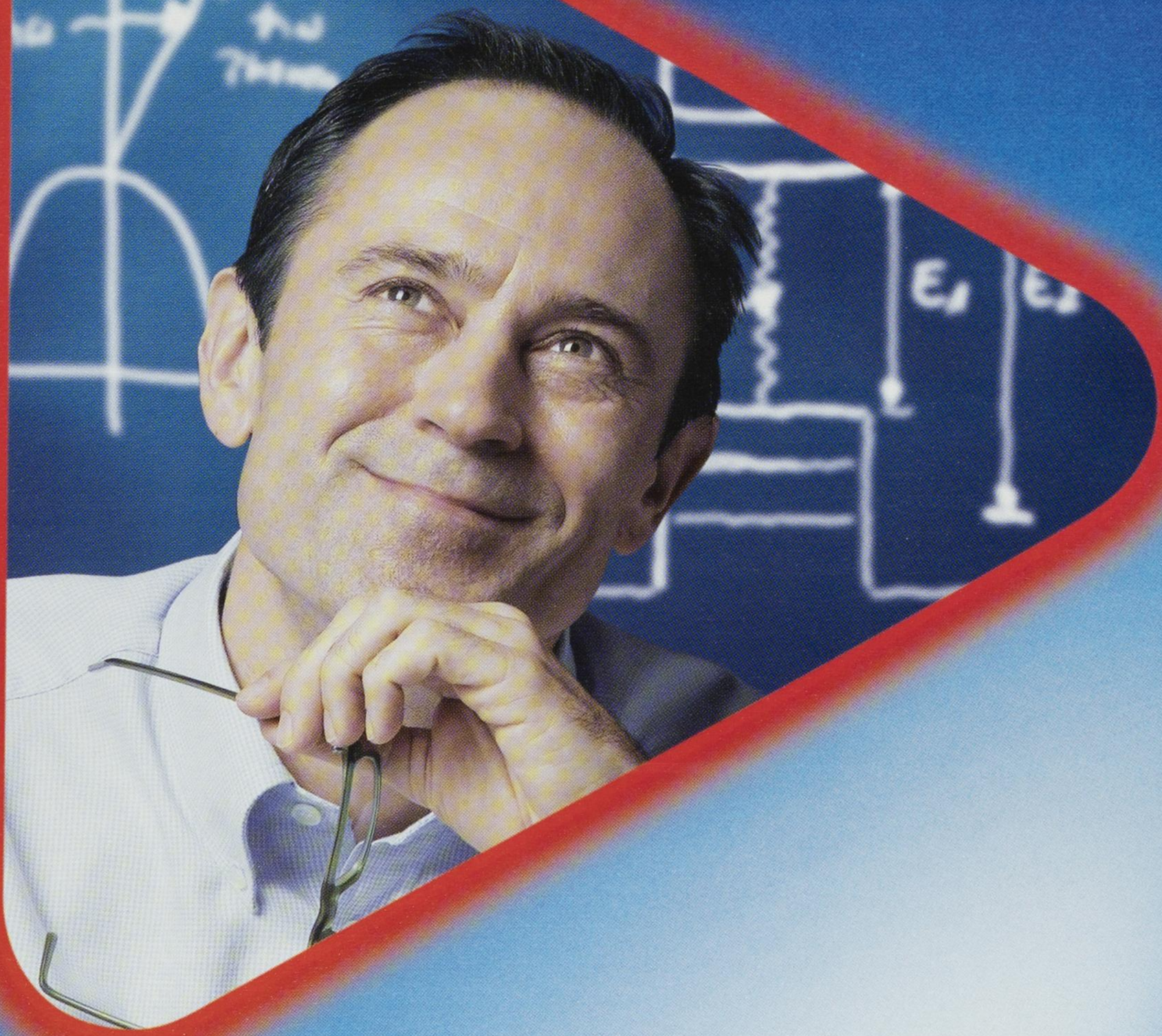
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RUBICON TECHNOLOGY

Nichia and Sony form laser alliance

In the latest of a series of agreements in the nitride optoelectronics field, Nichia and Sony have formed an alliance to develop technologies to mass produce violet laser diodes for use in optical disc recording and playback. The companies will jointly develop 405 nm high-power violet laser diodes for "Blu-ray Disc", one of the competing formats for next-generation large-capacity optical discs. Mass production is expected in spring 2003, and each company will manufacture and sell products resulting from the development program.

Sony has a 5% stake in Nichia, and is also one of the nine companies that jointly proposed the Blu-ray format (see p22). After independently pursuing R&D in violet laser diodes, Sony and Nichia have been involved in a collaboration to develop violet laser diodes since June 2002. The latest agreement extends this by allowing the companies to share their extensive intellectual property portfolios, including process patents and technological know-how.

According to a joint press release, Sony and Nichia reached their agreement "through recognition of the significance of meeting market demands by expediting the joint development of violet laser diodes in the field of optical disc recording and playback." The companies also said they will "pursue the timely creation and expansion of the market for violet laser diodes through active future co-operation."

The agreement with Sony was the culmination of a busy year for Nichia, which also reached agreements with Osram Opto Semiconductors, Toyoda Gosei, Lumileds and Cree during 2002.

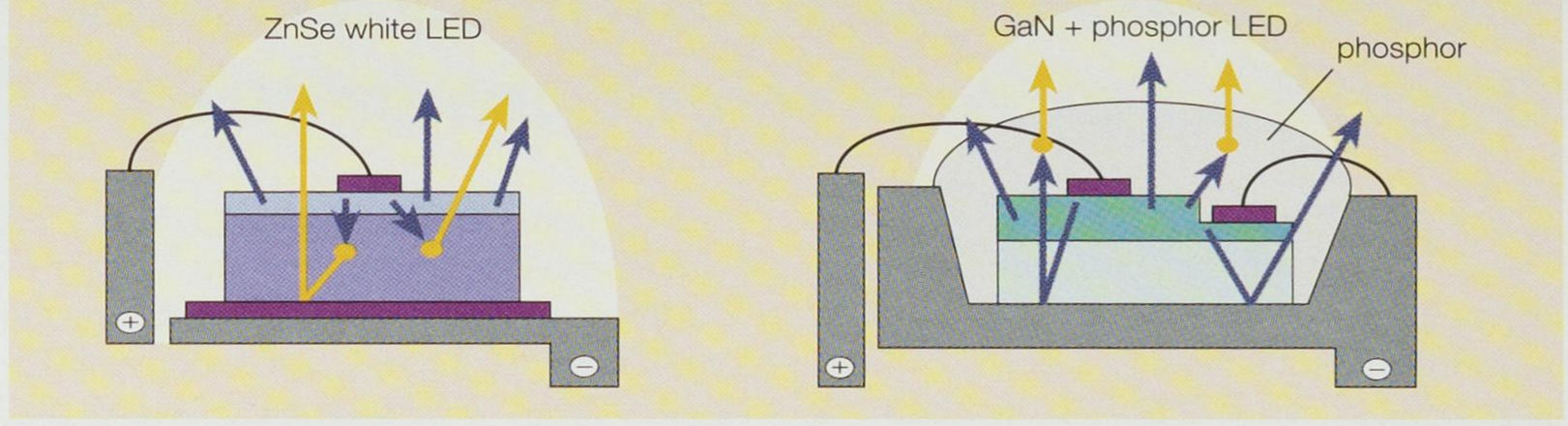
Joint venture to produce ZnSe-based white LEDs

Sumitomo Electric plans to commercialize its ZnSe-based white LEDs by teaming with Taiwanese epiwafer manufacturer Procomp. The companies are to establish a joint venture under the name Supra Opto Inc, with Procomp and Sumitomo holding 60% and 40% ownership, respectively.

Sumitomo developed ZnSe-based white LEDs about four years ago. The company's device is a homoepitaxial ZnSe blue LED grown on a ZnSe substrate, which simultaneously produces blue light from the active region and a broad emission spectrum, centered on yellow, from the substrate. The addition of a dopant to the substrate causes it to absorb blue light emitted by the active region of the device, and to re-emit light at a longer wavelength in the green-to-red spectral region.

This differs from conventional white LEDs, which are made by combining a blue LED chip with a yellow phosphor, or a UV LED with a tricolor or polychromatic phosphor. The phosphor absorbs short-wavelength (blue or UV) light and downconverts it to a longer wavelength. Sumitomo's approach should avoid the patents owned by Nichia, Osram and others in this field.

Comparison of the ZnSe white LED and a conventional device



The ZnSe-based white LED from Sumitomo (shown on the left), and a more conventional GaN-on-sapphire white LED with phosphor downconverter (right).

Sumitomo says the ZnSe LED offers a number of advantages. In conventional white LEDs the use of a phosphor makes packaging more complicated and reduces overall device efficiency. The ZnSe substrate is conducting, allowing the use of top and bottom contacts, unlike GaN-on-sapphire devices. Also, the ZnSe LED operates at a low voltage of 2.7 V, and is highly resistant to static electrical discharge.

The chromaticity of white light produced by any lighting source can be highly important for certain applications, such as indoor retail and office environments. In ZnSe-based LEDs, chromaticity is affected by the wavelength of the blue light produced by the active region and the dopant concentration in the substrate. The latter can be precisely controlled, while the blue LED wavelength shows much less variation with temperature and other parameters than for GaN-based blue LEDs.

Mass production of the ZnSe-based white LEDs is expected to begin in March 2003, with a production volume of 1 million units per month, rising to 3.6 million by the end of the year. Sumitomo will transfer technology and equipment to Procomp, which will carry out epitaxial growth through its Procomp Informatics epiwafer division and chip processing through its Suntek foundry subsidiary.

Picogiga given more time by authorities

On November 25, French epiwafer supplier Picogiga declared bankruptcy under French financial regulations similar to the Chapter 11 rules in the US. Chapter 11 provides a company with a period of respite from creditors while it takes steps to rearrange its financial affairs. Under French regulations, Picogiga has been granted six months from December 2 to seek ways to address its high level of debt. The French financial authorities must have some confidence in Picogiga, as only 3% of applicants are granted a restructuring period.

A deal with Belgian materials company Umicore would have alleviated many of Picogiga's financial problems, but Umicore withdrew at the end of October, leaving Picogiga with an uncertain future (*Compound Semiconductor* December 2002 p7). However, Picogiga reported a surge in orders at the end of last year, and expected revenues of about €1 million for December, giving it a positive cash flow for the month. A large chunk of Picogiga's outgoings have been in interest payments to bondholders, and the company is taking measures to persuade bondholders to convert their bonds to stock.

Emcore expands fiber portfolio by buying Alvesta

Emcore has acquired certain assets of privately held Alvesta Corporation, including product lines, inventory and intellectual property. Alvesta of Sunnyvale, CA, is a developer of VCSEL-based parallel optical transceivers for fiber-optic communication networks. The company pioneered 4-channel parallel optical transceivers for a variety of standards. Each transceiver contains four 850 nm VCSELs and four *pin* detectors, and transmission takes place over a 12-fiber ribbon (four fibers are used in each direction and four are dark). Alvesta's product revenues from sales of its 4-channel products were approximately $5 million in 2001.

The financial terms of the acquisition, which was completed on December 11, 2002, were not disclosed. The purchase price includes the acquisition of intellectual property and inventory, and Emcore has hired Alvesta's key design team.

Alvesta's technology will broaden Emcore's existing 12-channel (15–40 Gbit/s) product line to include 4-channel, 16-channel and 24-channel duplex transceivers. Emcore will continue to support the parallel optical products released by Alvesta, and has already begun production of the 4-channel products in its Albuquerque facility.

These parallel optical modules offer the advantages of high optical port density and low power consumption that are required by next-generation optical networking applications. Emcore now possesses Alvesta's inventory of 4-channel transceivers and can immediately ship Quadlink MSA-compliant parts to customers.

"Alvesta has consistently been a leader in the development of 4-channel parallel optical technology and applications," said Hong Hou, VP of Emcore's fiber-optic division. "We believe that their product technology is a perfect complement to our line of 12-channel parallel optical transceivers and transponders. The acquisition of Alvesta gives us the opportunity to expand our product portfolio to include 4X optics, MSA-compliant pluggable transponders and key product technology."

Growth in LED business drives Cree to record revenue levels

Cree reported revenue of $56.7 million for the December 2002 quarter, the highest quarterly revenue figure in the company's history. This represents a sequential increase of 16% over the previous quarter, and a 38% increase over the $41.1 million for the year-ago period. Net income for the quarter was just under $9 million, or 12 cents per share, compared with a loss of over $17 million in the year-ago period.

"We are extremely pleased with our results in terms of revenue and earnings," said Chuck Swoboda, Cree's president and CEO. "During the quarter, our ability to maximize capacity through productivity improvements and a more favorable product mix provided us with the leverage to grow the business faster than expected and exit the quarter with the highest quarterly revenue in the company's history."

Growth was driven by continued demand for LEDs from handset and automotive applications. Cree's LED revenue increased 18% over the September quarter, while unit shipments increased 15% sequentially and 89% over the year-ago period. Quarterly LED shipment volumes were at the highest level in the company's history. Average selling prices of LED products increased 3% sequentially, while average production costs for LEDs decreased 8% during the quarter, benefiting from productivity gains as the company's production capacity was ramped up.

Cree wrote off $1.4 million in fixed assets associated with a novel epitaxy equipment project that was discontinued, and SG&A costs dropped $1.4 million due to the reduced legal fees associated with the settlement of Cree's litigation with Nichia. According to Swoboda, Cree is targeting revenue in the $59–60 million range for the March 2003 quarter, based on continued growth of LED sales. "We plan to grow the LED business by more than 5% sequentially, once again reaching record levels," he said. "We already have more than 80% of our revenue target booked for the quarter."

Swoboda says that next-generation SiC MESFETs will be released by Cree in the next few months, while first customer samples of GaN devices should be available by the end of calendar 2003. Cree recently demonstrated a 10 kV SiC MOSFET that is more than 100 times smaller than an equivalent silicon device, although commercial introduction is more than a year away.

ADC and Gore Photonics set to auction off their assets

ADC is auctioning the entire contents of its tunable laser fab in Järfälla, Sweden (formerly Altitun), and its pump laser fab in Vadnais Heights, MN (formerly Spectracom). The closures were announced last year after ADC failed to find a buyer for the facilities.

In related news, Gore Photonics is offering at auction the contents of its VCSEL manufacturing fab in Lompoc, CA, and its VCSEL packaging and module assembly facility in Elkton, MD. On the same auction site, Gore is offering intellectual property relating to manufacturing of VCSEL and *pin* detector arrays used in the nLighten parallel module product line. Gore announced that its VCSEL business was for sale at the end of August last year. Questioned about the auction announcements, Russell Shaller, GM of Gore Photonics, said: "We are in the process of selling the [VCSEL] business to another company. The assets that are not purchased as part of the business will be sold via auction."

Veeco and FEI merger is called off

Veeco Instruments and FEI have agreed to terminate their merger agreement of July 2002, citing difficult market and economic conditions, and the uncertain timing of a recovery in the semiconductor equipment industry. Veeco had agreed to acquire FEI in a stock-based deal worth about $1 billion (*Compound Semiconductor* August 2002 p4). However, in December 2002 the companies announced that they would not be able to complete the deal by December 31, meaning that either party had the right to call a halt to the merger.



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  John McInerney, Director of Research and Development, *Novalux Inc.*
- **GaAs and SiGe: a comparison of manufacturing, technology and economic issues**
  Mark Wilson, Director of Technology Strategy, *Motorola Semiconductor Products Sector*
- **Beyond CMOS: an overview of SiGe and other new silicon technologies**
  Trevor Yancey, *IC Insights*
- **Strained silicon and the competitive landscape for communications semiconductors**
  Amberwave Systems (speaker to be confirmed)
- **Status and outlook for gallium nitride optoelectronics and electronics: technology and markets**
  Robert Steele, Director of Optoelectronics, *Strategies Unlimited*
- **The GaN market: a new growth industry; players and market dynamics**
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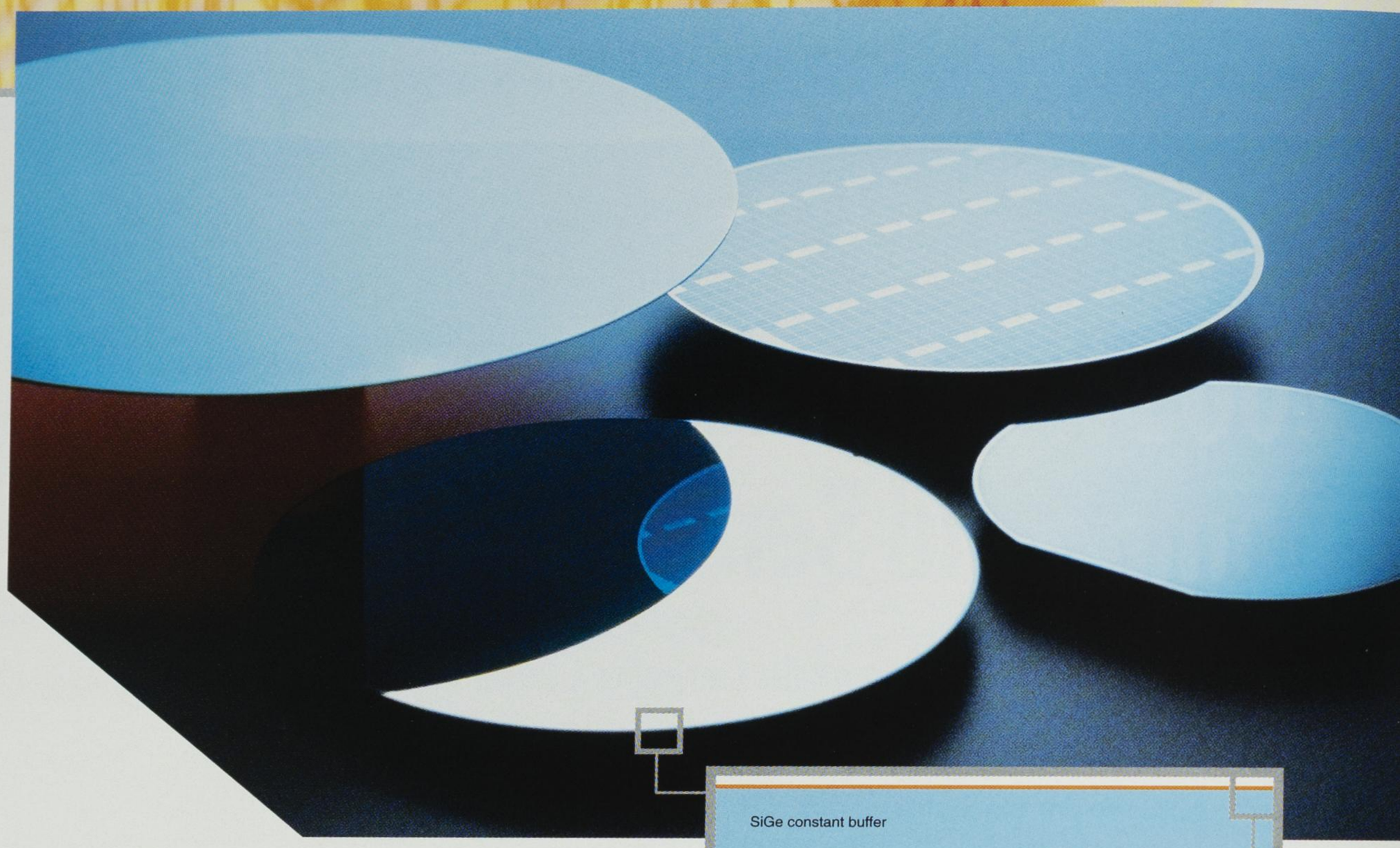
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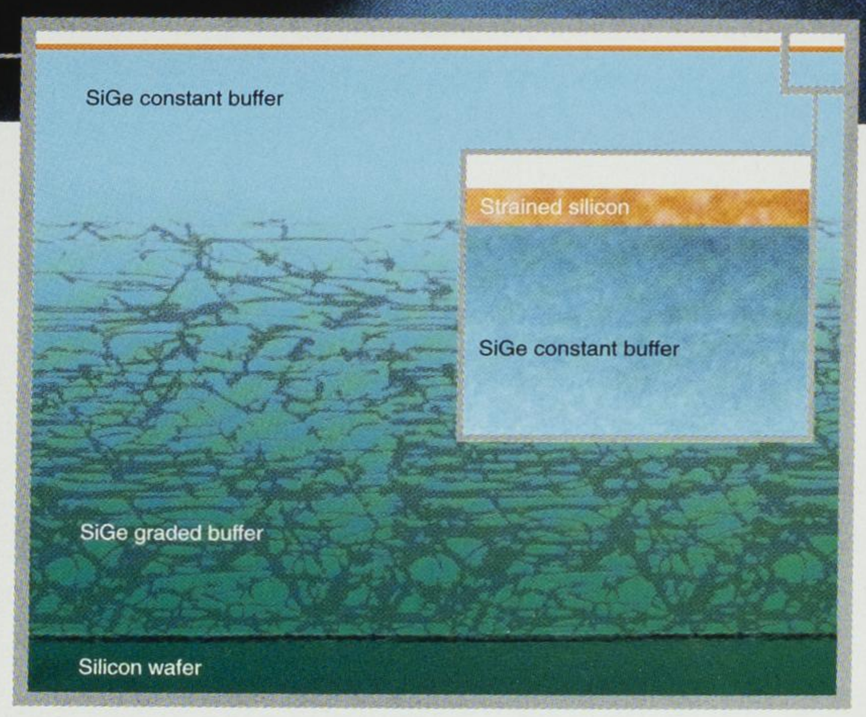
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RSC embarks on sub-micron InP HBT project

Rockwell Scientific Company (RSC) has received a $5.9 million contract from the US Space and Naval Warfare Systems Center under a DARPA program that is entitled Technology for Frequency Agile digitally Synthesized Transmitters (or TFAST). The transmitters are key components in aircraft and satellite communications systems. The work funded at RSC will enable the development of InP ICs that directly synthesize higher frequency signals, thereby eliminating costly and bulky frequency multipliers in the transmission chain.

Direct digital synthesizers (DDSs) have a sine-wave output, the frequency of which is controlled by a digital input. A major goal of the program is the development of sub-micron InP HBT technology that will be required to produce high-frequency DDSs with high dynamic range, low phase noise, low DC power and wide bandwidth. Current GaAs DDS technology operates at up to 2 GHz output with 60–70 dB dynamic range. A scaled-down InP HBT technology will enable the production of DDSs with an order of magnitude higher output frequency operating at one tenth of the power.

Current InP HBT processes can achieve emitter stripe widths of about 1 μm and 5000-transistor integration levels. "A DDS needs a very high transistor count," said Bobby Brar, RSC's manager of materials and devices and the program's leader. "Digital-to-analog converters traditionally require tens of thousands of transistors, so we are trying to scale down the device, with the equally important goal of keeping the yield high so that we can get high transistor counts." The four-year goal of the program is to get to a 0.15 μm process with a 20,000-transistor integration level. "The approach will be to show, on a lower integration count, the small device geometry demonstrating the performance required. The task will then be to work on the integration levels while maintaining the speed," said Brar.

Such aggressive scaling will require the development of a self-aligned dielectric sidewall spacer process to replace the metal masks for self-alignment that the compound semiconductor industry has relied on in the past. In this way, the project will emulate Si/SiGe HBT process technologies that produce self-aligned emitter and base regions. Such a process is essential for achieving good isolation and high yield for the high integration levels that are aimed for.

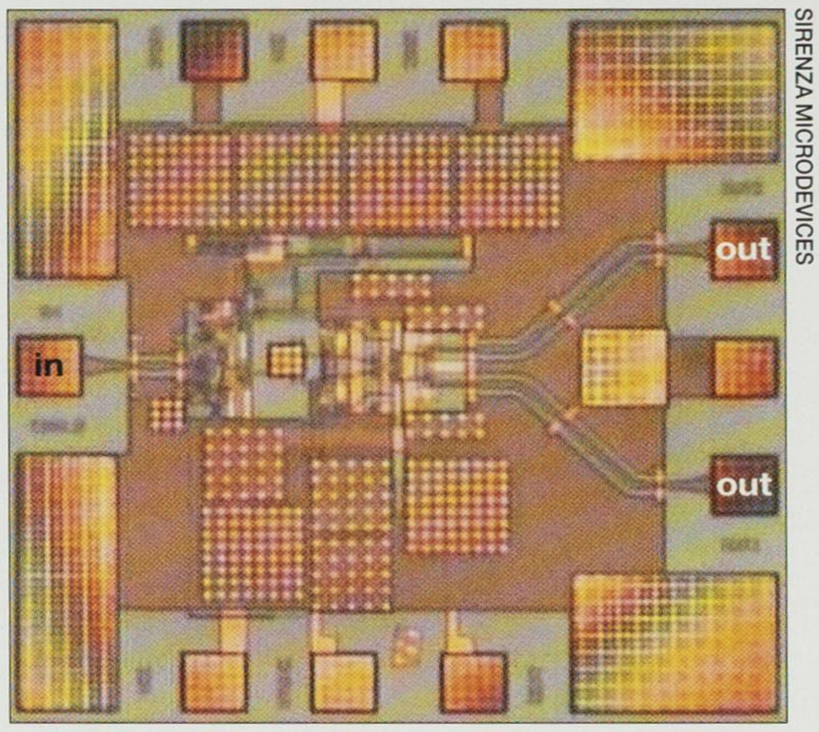
One of the partners in the program is Global Communications Semiconductors (GCS), a foundry service provider with an InP HBT process. GCS will be involved in the development of the sub-micron process, helping to ensure that it can be transferred to a high-volume manufacturing environment. The University of California at Santa Barbara (UCSB) is another partner in the development. Mark Rodwell's team at UCSB is aggressively pursing an emulation of current SiGe HBT processes in InP, including emitter and base regrowth.

Vitesse and MOSIS lead the way in InP HBT foundry services

Vitesse Semiconductor has become the first company to offer InP HBT foundry services through MOSIS, a provider of prototyping and small-volume production services for IC development. MOSIS already offers low-volume and multi-project wafer runs for GaAs ICs through French GaAs foundry Ommic, and for CMOS and SiGe BiCMOS devices through IBM, Austria Microsystems, TSMC, and others. By working directly with MOSIS, customers will now have access to Vitesse's proprietary InP VIP-1 technology at its 4 inch fab in Camarillo, CA. MOSIS will provide access to device models and design rules, as well as reticle composition and overall schedule coordination.

The VIP-1 process offers circuit designers high-speed and high-voltage operation, suitable for digital, analog and RF circuits at 10 GHz or higher. The key active device is an SHBT, with f_t and f_{max} values of 150 GHz and BV_{ceo} in excess of 4.5 V.

Sirenza develops 40 Gbit/s tunable TIA



SIRENZA MICRODEVICES

A micrograph of Sirenza's 40 Gbit/s tunable TIA. The chip measures 1 x 1 mm².

Sirenza Microdevices, a fabless designer and supplier of RF components for communications equipment manufacturers, has announced the development of a 40 Gbit/s common-base transimpedance amplifier (TIA). The new TIA employs electronically tunable transimpedance bandwidth control to compensate for various combinations of photodetector and hybrid interconnect parasitics that may be encountered when manufacturing optical receiver modules. The tuning transimpedance bandwidth range of 10 GHz will simplify the design of such modules.

The TIAs, described by Sirenza at the 2002 GaAs IC Symposium, were fabricated using Global Communications Semiconductors' InP HBT process. The TIA achieves 62.3 dBΩ (1.3 kΩ) differential transimpedance with a bandwidth (BW) of 39.3 GHz, while consuming only 165 mW of DC power. This performance corresponds to a transimpedance-BW product per DC power of 310 ΩGHz/mW, the highest reported to date in the industry for 40 Gbit/s common-gate or common-base TIAs.

Sirenza buys Vari-L

Meanwhile, Sirenza is to acquire the assets of Vari-L Company in Denver, CO, for $13.6 million in common stock and cash loans of $1.4 million. Vari-L designs and manufactures wireless communications components that generate or process RF and microwave frequency signals. The company's customer base includes Agilent, Ericsson, Lockheed Martin, Lucent, Motorola, Nokia and Raytheon.

RFMD, Skyworks unveil next-generation PA modules

RF Micro Devices and Skyworks Solutions have launched new ranges of compact PA modules for use in CDMA wireless handsets. The 4 × 4 mm^2 modules continue the trend for shrinking the sizes of modules, while increasing the number of devices and functions.

RFMD's RF6100 module family offers multiple voltage reference and output power options to accommodate existing and next-generation CDMA baseband chipsets. The RF6100-4 PA module has been optimized to deliver 29 dBm of output power to accommodate additional functions such as GPS. The modules are manufactured using RFMD's upgraded GaAs HBT process, which gives devices with lower current variation with temperature, improved gain per stage, higher breakdown voltages, and enables reductions in component count and package size through higher levels of on-die integration.

Skyworks' new PA modules can be operated at the same voltage as typical CDMA baseband devices, eliminating the cost and complexity of an on-board voltage regulator to connect the two devices. The CX77100 series is manufactured using the company's InGaP HBT process.

Skyworks has improved the linearity of its CX77112 CDMA/PCS device so it can drive 29 dBm of output power in applications such as dual-band handsets with GPS capability.

Skyworks endows new academic chair

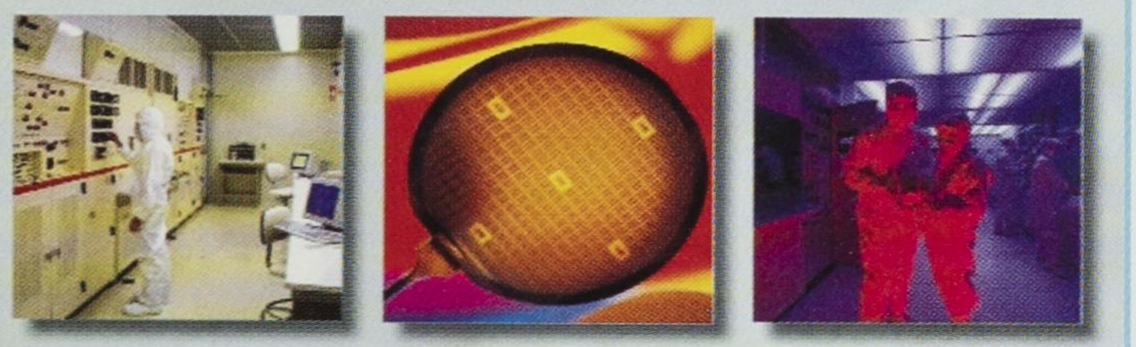
Skyworks Solutions has established its first endowed academic chair at the Jacobs School of Engineering at the University of California, San Diego (UCSD). The endowment creates opportunities for students and faculty to work collaboratively with Skyworks engineers to develop new semiconductor technology.

The inaugural recipient of the Skyworks chair is Peter Asbeck, who is a pioneer in the field of high-speed ICs using advanced materials. Asbeck joined UCSD in 1991 after working at Rockwell Science Center for 13 years. He is recognized as an authority on the design and development of power amplifiers and other ICs using GaAs HBT and other high-speed technologies. In August 2002, Asbeck won the 2003 IEEE David Sarnoff Award, which is awarded each year for outstanding achievement in the field of electronics.

RFMD ships 802.11a WLAN chipsets

RF Micro Devices has made its first shipments of 802.11a WLAN chipsets. The company anticipates that shipments will ramp in the current quarter and accelerate throughout 2003. The higher data rates supported by 802.11a products and the increased channel count at 5 GHz provide a cost-effective medium for applications requiring a large bandwidth.

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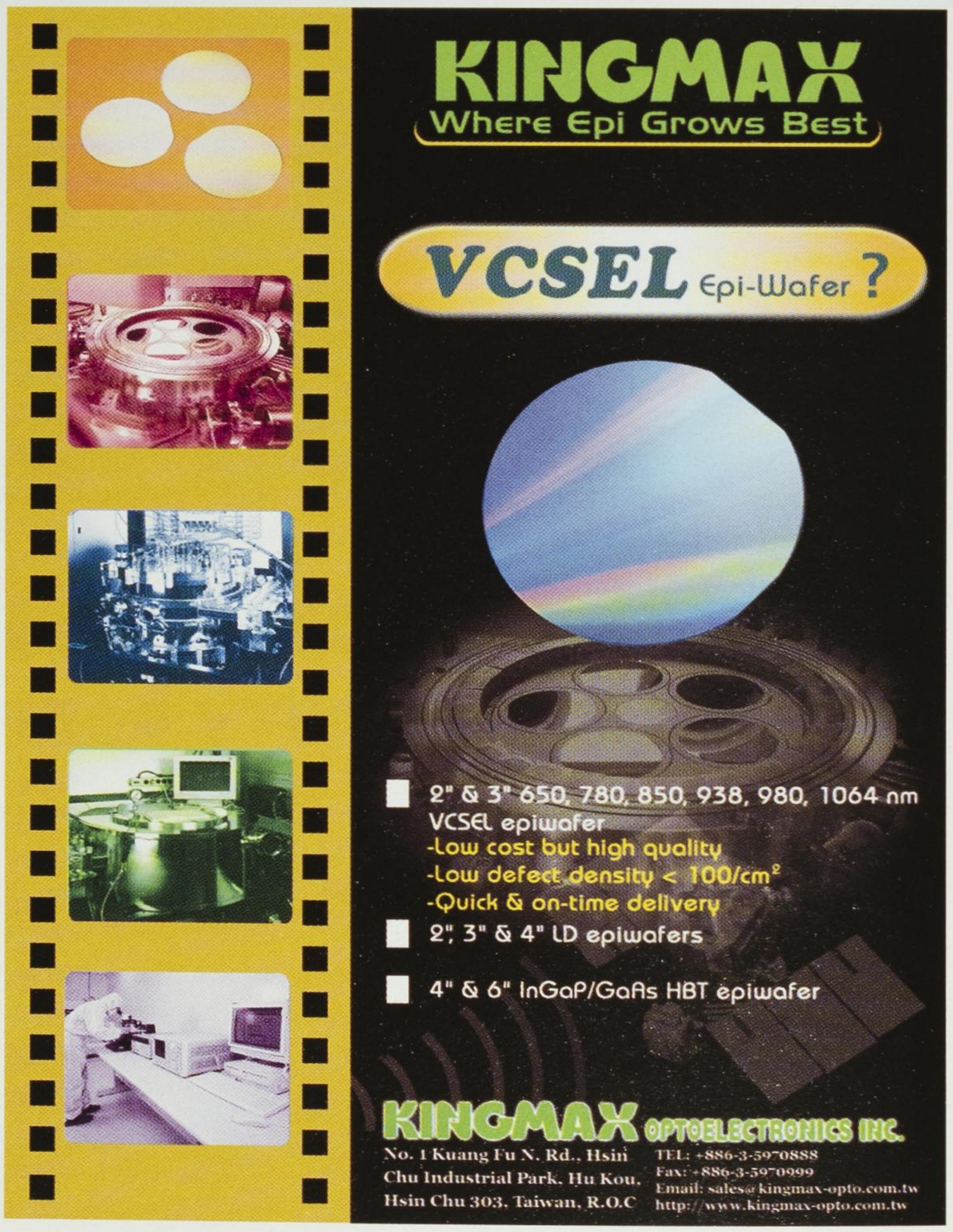
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New phosphors improve white LED performance

Toyoda Gosei and Nichia have both introduced new white LED products with improved color characteristics. Toyoda Gosei has developed a new high-brightness white LED that provides excellent color rendering, especially from colors in the problematic red region of the spectrum. The True White-Hi combines a short-wavelength (374–401 nm) LED chip with red, green and blue (RGB) phosphors and another proprietary phosphor. Samples are available and the company plans to begin production shipments in February 2003.

Toyoda Gosei currently makes several white LEDs, including a multichip RGB product that can produce white light and a full gamut of colors. The company's White-Hi LED combines a blue chip with a proprietary phosphor (not Ce:YAG, which is widely used in the industry and subject to patents owned by Nichia and Osram Opto Semiconductors). The White-MP combines a UV LED and RGB phosphor mixture, developed in collaboration with Toshiba.

In related news, Nichia has developed a "warm white" LED with a color temperature of 2800 K. The white light produced by this device is closer in appearance to the light from an incandescent bulb, while conventional white LEDs produce cold white light reminiscent of fluorescent lighting.

Conventional white LEDs manufactured by Nichia combine a blue LED chip with a YAG phosphor that emits in the yellow region of the spectrum. Nichia's new device incorporates a newly developed red phosphor as well as the YAG phosphor and blue LED chip. In addition to providing light with a color temperature in the 2500–3500 K range, the color shift in the new LEDs caused by forward current change and temperature change will be reduced compared with conventional white LEDs.

The devices have a luminous efficiency of 20–25 lm/W and a directivity of 50°. Nichia released evaluation samples in December 2002, and will ship samples of its high-power variant in January 2003. The company initially expects to produce 100,000 units per month of the lamp-type LED series and 1 million units per month of the Power LED series.

Dentistry boosts blue LED market

A new application in dentistry is emerging for blue LEDs operating at around 460 nm. The devices are used in place of conventional halogen lamps for curing polymers, which are part of the composite material used to fill teeth.

According to Lumileds, several companies are now incorporating its Luxeon V Dental LED-based light source in dental light-curing devices, which provide faster curing times, easier use, and consume less energy than current products. Currently, most blue light sources in dentistry use tungsten filament halogen lamps that incorporate a blue filter to produce light in the 400–500 nm region. This light is directed down a waveguide such as a fused glass bundle. The end of this waveguide is placed adjacent to the soft uncured composite filling material positioned in a tooth cavity.

A typical dental composite contains a mixture of monomers, a photoinitiator, a tertiary amine, and silica particles to provide the required hardness. When excited by the absorption of blue light, the photoinitiator stimulates the production of free radicals from the tertiary amine, which causes polymerization and hardening of the composite.

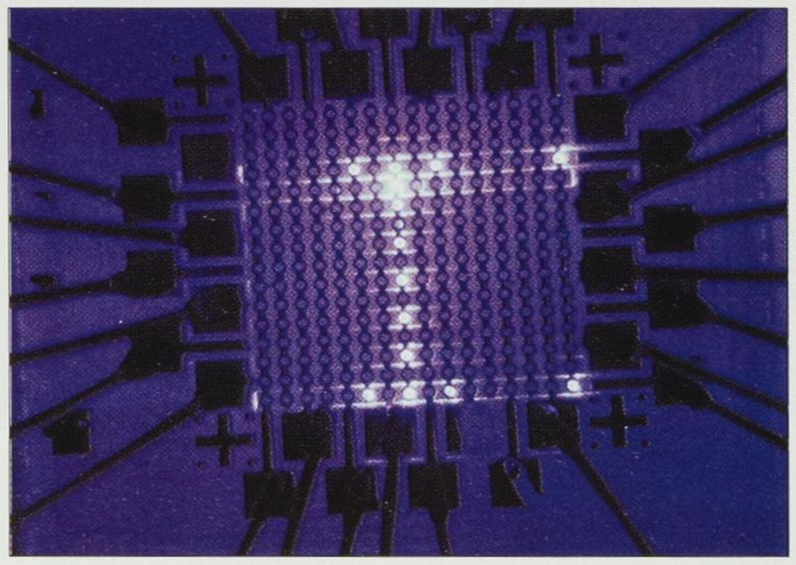
LEDs offer a number of advantages for such applications. The use of a monochromatic light source with typical 460 nm peak wavelength eliminates the need for inefficient color filters, while the low-voltage DC operation allows small handheld and cordless designs. Halogen lamps require intensive fan cooling, and have a short lifetime compared with LED sources. Further benefits include instant illumination, precise beam control, minimum glare, low UV light, mercury-free operation and a cool light beam that is safe to the touch.

Italian company Mectron has launched the Starlight Pro, which incorporates the power and small size of the Luxeon V into a hand piece that weighs just 105 g. The product provides faster curing times for patients, while for dentists it has less weight, a smaller design and is more energy efficient. A division of 3M Company's Health Care Business also recently launched a product based around the Luxeon V Dental.

Tiny GaN LEDs made into 128 x 96 array

Researchers at Strathclyde University's Institute of Photonics in the UK claim to have fabricated the largest array of GaN-based micro-LEDs. The 128 × 96 array measures 3.5 × 2.5 mm and contains 12,288 emitters, each with a diameter of 20 μm. The team says the devices will be useful in microdisplays and optical biochips for efficient DNA analysis.

Current power levels are about 0.1 mW per element with an operating voltage of around 3.5 V. To date the researchers have made arrays that emit blue light at 470 nm and have constructed a prototype alphanumeric monochrome microdisplay. According to project leader Martin Dawson, there is potential to extend this to full-color operation by adding a polymer or phosphor material on top of selected elements to shift their emission wavelength.



UNIVERSITY OF STRATHCLYDE

A prototype display comprising a 16 x 16 array of 470 nm GaN-based micro-LEDs.

As well as being some 25 times smaller than conventional LEDs, micro-LEDs offer several benefits over their larger counterparts. "They are more efficient and have operating speeds of a few hundred picoseconds," said Dawson. "The array is also a multi-element device where the emitters can be controlled independently. Conventional LEDs are a single-element emitter technology."

The researchers are also using their technology to excite organic materials with fluorescent markings. "This is potentially a very compact and quick way to analyze multiple DNA samples," said Dawson. "Instead of scanning one laser source over the samples, you can use a 2D multi-element emitter source to read the information simultaneously."

Dawson and colleagues are now developing 370 nm (violet) and 540 nm (green) devices, and hope to commercialize the technology in two to three years.

SiGe Semiconductor wins $42.8 million in funding

SiGe Semiconductor, a fabless supplier of analog SiGe-based ICs located in Ottawa, Canada, has raised $42.8 million in Series B funding. The investment, which was led by Boston-based TD Capital Technology Ventures, is the third-highest round of financing closed by a fabless semiconductor company during the last year, and the funds will be used to support new product developments and ongoing operations. SiGe Semiconductor's ICs are targeted at Bluetooth-enabled portable devices, WLAN access points, high-speed optical interfaces, GPS systems, cordless telephones, and 2G, 2.5G and 3G cellular handsets.

"We are proud of our continued successes in light of the current market conditions," said Jim Derbyshire, president and CEO of SiGe Semiconductor. "We've followed the right strategy in diversifying our product lines into markets where our core technology, SiGe, provides significant advantages. This has both protected our company from the downturn, and fueled our growth."

Oki and Peregrine in UTSiR deal

Oki Electric Industry is to combine its expertise in LSI circuits with Peregrine Semiconductor's UTSiR CMOS-on-sapphire technology, to make low-power communication products. UTSiR, or ultra-thin silicon, is a technology used to form very thin silicon layers on sapphire substrates with fewer crystal defects than conventional methods. CMOS-on-sapphire is an SOI technology used to manufacture transistors on a completely insulated substrate that has less impact to parasitic capacity, resulting in transistors with ultra-low power consumption and excellent high-frequency characteristics.

Under the partnership agreement, Oki will license Peregrine's UTSiR technology, the companies will jointly develop UTSiR products, and Oki will act as a second source/foundry for Peregrine's UTSiR products. In addition, the companies will market and sell Peregrine's products together with chipsets provided by Oki, and they will also share intellectual property.

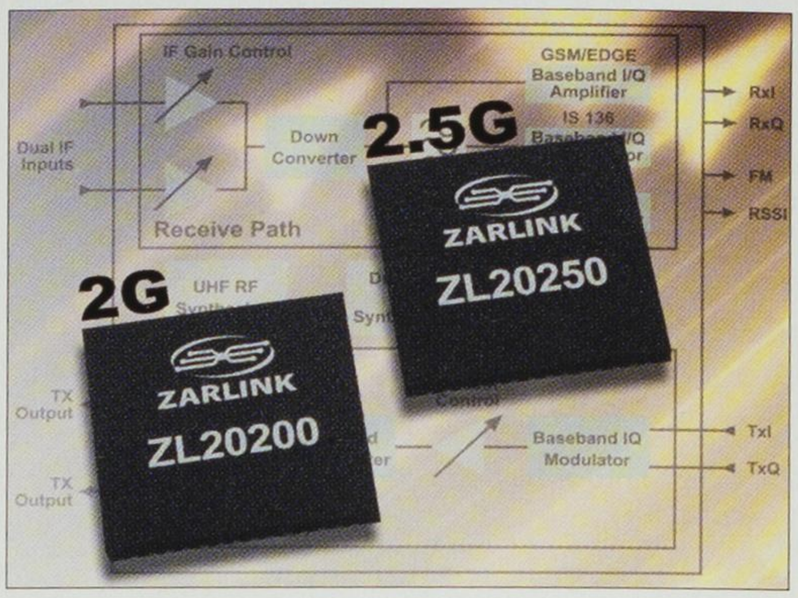
UTSiR technology enables the development of high-quality RF semiconductors with ultra-low power consumption. Oki offers expertise in volume production with fully depleted SOI LSI technology, which is well-suited to low power-consumption LSIs. Initially, Oki will market the chipsets that combine LSI with Peregrine's UTSiR products, such as RF switches and high-performance mixer and phase locked loop components. Oki and Peregrine will also jointly develop wireless communications LSIs, such as RF front-ends for mobile phones and GPS receivers, for introduction in late 2003.

Equipment sales

- **Chartered Semiconductor Manufacturing** (CSM), the leading semiconductor manufacturing company in Singapore, has installed a **Bede** D1 X-ray metrology tool. CSM will use the Bede D1 for a range of materials characterization applications relating to the manufacturing of advanced semiconductor devices, and particularly for its advanced SiGe processes. The D1 will be used in both CSM's research and development program and for routine production quality control.

- **DCA Instruments** has received an order for an 8 inch MBE system from the **University of Stuttgart, Germany**, for the growth and fabrication of SiGe heterostructure devices. The system features a UHV robotic cluster tool handler for wafer transfer and a customized growth reactor for Si/SiGe. DCA has also received an order for an E450 UHV reactor for electron beam deposition from the **University of Hannover, Germany**.

Zarlink unveils new transceiver chip



ZARLINK

Zarlink's single-chip SiGe BiCMOS transceivers are for 2G and 2.5G handsets.

Zarlink Semiconductor has launched what it describes as the world's most compact and cost-effective radio chip for 2G handsets. The ZL20200, a SiGe BiCMOS IC, integrates call, receive and transmit circuitry on the same piece of silicon. The transmitter portion drives an external two-stage power amplifier.

Two of the world's leading cellphone manufacturers are currently evaluating the transceiver chip, which eliminates at least 35 separate components, shrinking the radio "footprint" by up to 40% and reducing the bill-of-material cost by up to 20%. Zarlink has also launched the ZL20250, a single-chip radio transceiver for multimode 2.5G networks.

AmberWave to use Mitsubishi in Japan

AmberWave Systems has appointed Mitsubishi as its sales agent in Japan to help establish a presence in the Japanese market for AmberWave's strained silicon technology. Mitsubishi will work with AmberWave to license the technology to Japanese IC manufacturers, and will provide strained-silicon test wafers from AmberWave to companies that are looking to integrate strained silicon into their manufacturing processes.

Several Japanese companies including Toshiba and Hitachi have already started to develop strained silicon processes, while in the US both IBM and Intel have announced plans to incorporate their own strained silicon technologies into future production processes. So far, two major chipmakers – AMD in the US and UMC in Taiwan – have endorsed AmberWave's strained silicon approach.

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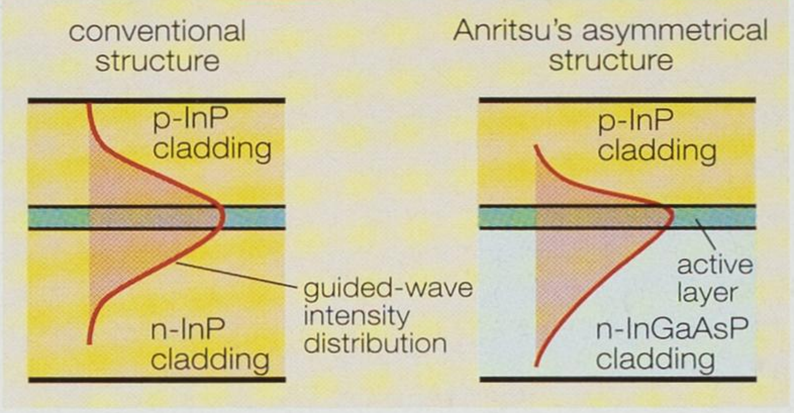
Anritsu develops 1 W, 14xx nm lasers

Japanese laser manufacturer Anritsu has developed a 14xx nm band high-power laser diode with an asymmetric cladding layer structure that provides an output power exceeding 1 W. The devices are designed for pumping Raman fiber amplifiers.

Longer laser cavities are very effective in increasing the output power of laser diodes, due to better heat dissipation and lower resistance. However, since the internal loss in conventional diodes is relatively high, power efficiency is reduced when the cavity length increases. Consequently, an excessively high current is necessary to obtain a high output power.

Anritsu's new high-power laser employs an asymmetric cladding layer structure with InGaAsP, which has a high refractive index, as the n-cladding layer. The p-cladding layer is InP. This new structure minimizes absorption loss in the p-side cladding layer, which is the main cause of internal loss, by shifting the guided-wave field distribution in the laser cavity towards the n-cladding layer (see figure).

Anritsu's high-power laser



ANRITSU

The new laser has an InGaAsP n-type cladding layer, which reduces internal losses by shifting the guided-wave intensity away from the p-cladding layer.

The structure also allows the use of a thicker active layer, resulting in a decrease in the diode resistance. Consequently, both increased efficiency and reduced drive voltage can be achieved at the same time. Moreover, the device has a narrower emission beam divergence angle than conventional lasers and an almost circular beam shape, which facilitates high-efficiency coupling to the single-mode fiber.

Anritsu says that the internal loss is two-thirds that of a conventional diode, while power consumption is reduced from 5.1 W (for 500 mW output power) to only 3.3 W for a record-breaking output power level of 1 W for a 3 mm long chip.

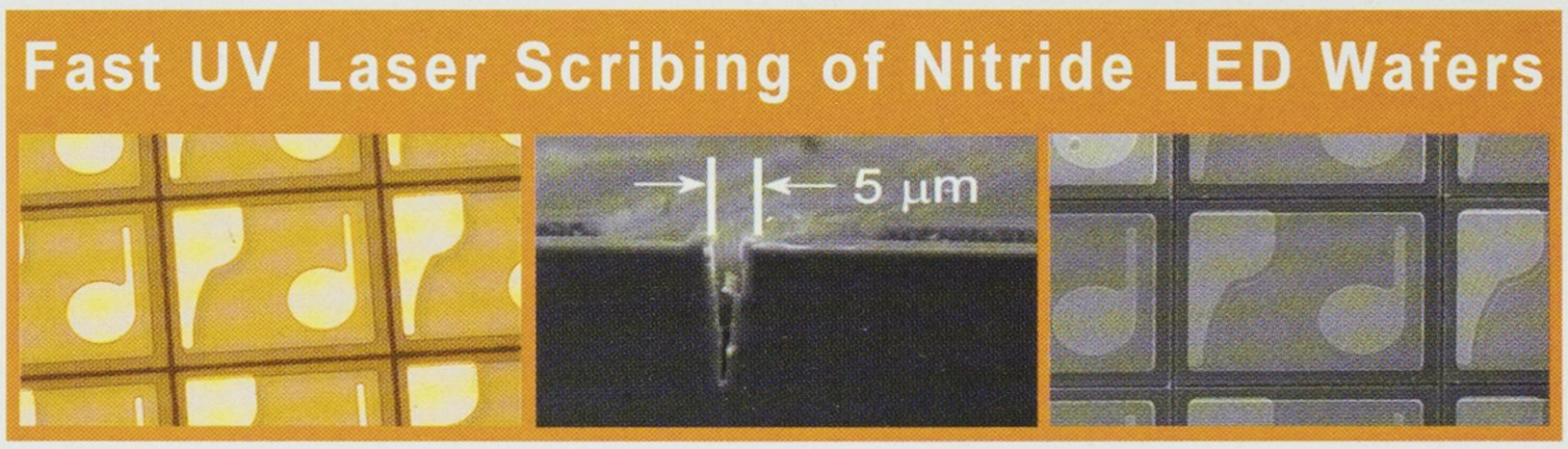
High-responsivity photodetectors

Anritsu has also developed photodetectors with a responsivity of 1 A/W, which compares with 0.55–0.6 A/W for conventional devices. The improved efficiency results from changes to the epitaxial structure; layers of InGaAsP and InP that have high and low refractive indices, respectively, ensure that any light not initially absorbed in the InGaAs absorbing layer is reflected back into the layer rather than out of the device. Anritsu says that the detectors function adequately with about half the optical input power of other devices, reducing the need for optical amplification to boost signals. The company plans to begin manufacturing devices with the new structure in February.

Sharp increases red DVD laser production

During the coming year, Sharp is to boost the production of red semiconductor lasers for DVD players by as much as 100%. The growing popularity of DVD players, particularly in China, is causing a shift in the semiconductor laser market. Japanese companies such as Sharp, which together with rivals Sony and Sanyo dominate the production of lasers for CD and DVD applications, are moving away from infrared (780 nm) devices and towards red (650–660 nm) lasers.

Sharp now produces about 3 million red lasers per month, and its plans call for an increase to between 4.5 and 6 million units a month. Production of high-quality lasers suitable for DVD recorders will total more than 1 million per month. However, as infrared laser production declines, Sharp's total production of semiconductor lasers will remain at around 11–12 million units a month during the coming year. Sharp plans to shift all production of red semiconductor lasers to its Mihara plant in Hiroshima Prefecture, which opened in May 2002. Its Nara plant will stop making red lasers, but will continue to perform finishing and packaging, along with a plant in Indonesia.



JPSA Introduces the IX-300 ChromaDice UV laser wafer scribing system.

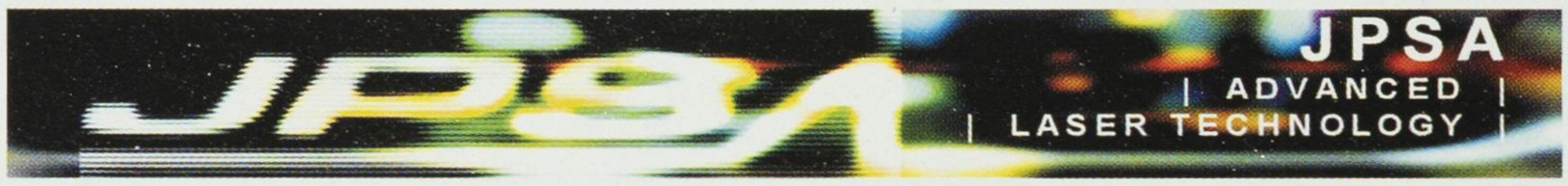
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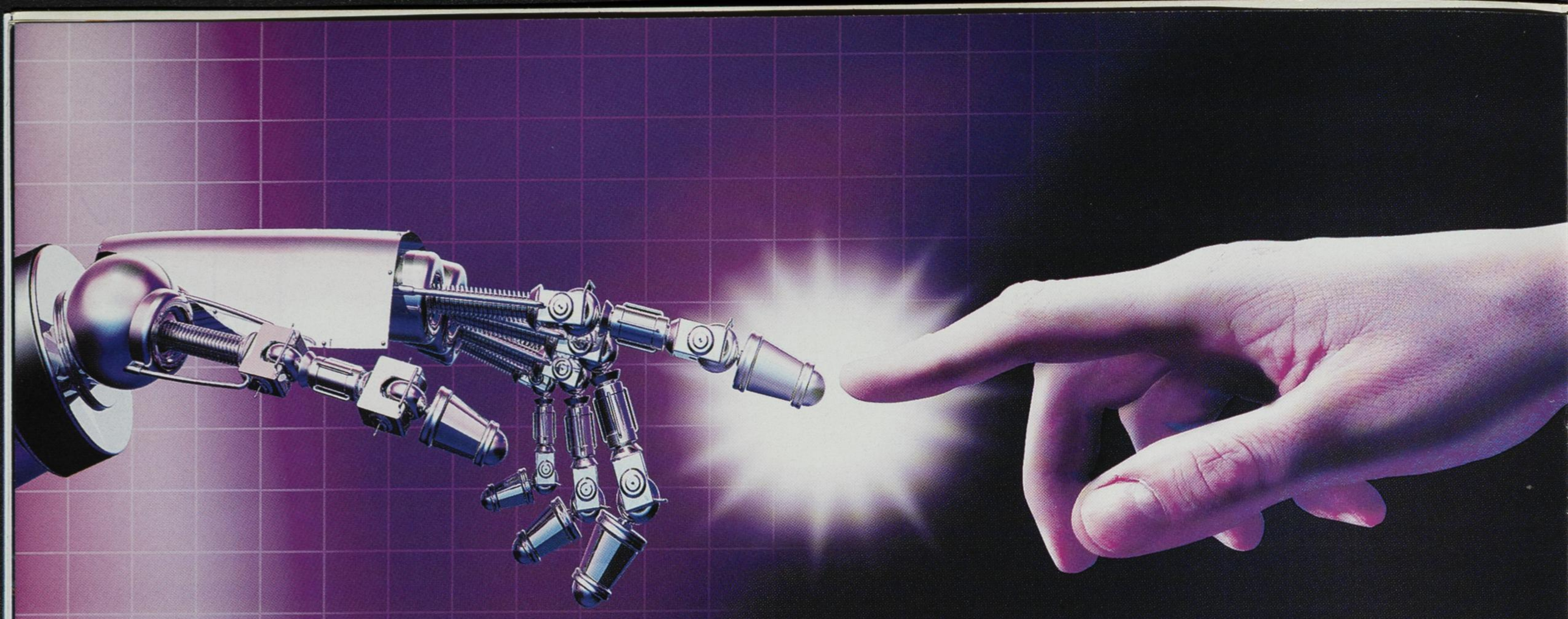
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Tyntek and Opto Tech set to expand blue LED capacity

Two Taiwanese chip makers are to increase their output of blue LEDs this year. Tyntek plans to raise its production capacity for blue LEDs in 2003 to a level of around 20 million chips per month. The company will sell its own brand products to packaging companies that need SMD LEDs in order to manufacture white LED backlights for mobile phones. Tyntek will also maintain its OEM business of grinding, cutting, classifying and testing LED chips fabricated by other companies.

Opto Tech also expects to increase its output of blue LEDs in 2003 to 3 million units per month. The LED maker has invested in Highlink Technology, which supplies Opto Tech with LED epiwafers at a rate of around 2000 per month. Opto Tech says that the epitaxial material supplied by Highlink enables the fabrication of LEDs with a luminance as high as devices manufactured by Nichia, and that high luminance is a particular advantage for the white LED market.

Japanese firms gear up for LED production

Several Japanese companies are preparing to begin the production of new types of LEDs. In the spring of 2003, Sanken Electric plans to release samples of its blue GaN-on-silicon LED (see *Compound Semiconductor* January/February 2002 p12). The company had previously planned to outsource epitaxial growth of the device structures, but has now acquired its own crystal growth equipment.

Meanwhile, Seiwa Electric, which began offering blue LEDs in April 2002, is planning to begin sampling a white LED product in early 2003 that incorporates a proprietary color-converting phosphor. Seiwa says that its phosphor color converter has a higher conversion rate than the YAG phosphors used by some other white LED manufacturers. As a result, a thinner phosphor can be used, allowing surface-mount white LEDs just 0.4 mm thick to be manufactured. The luminance of standard 5 mm white LEDs supplied by Seiwa is 5000 mcd at 20 mA, and the company plans to produce chips at a rate of 1 million units per month.

Meanwhile, Omron has begun marketing a high-brightness double reflection (DR) LED that boosts the efficiency of light utilization by more than two times compared with conventional LEDs. The DR-LED features Omron's proprietary double reflection structure, in which the LED package has a convex mirror in the rear (see *Compound Semiconductor* October 2001 p15). Any light that suffers total internal reflection at the package/air interface is reflected backwards towards the mirror and then re-reflected out of the package. Omron is aiming to sell about 30 million units of the DR-LED in the 2005 fiscal year, which will generate around ¥4–5 billion ($33–42 million).

Nichia to offer YAG phosphor patents

News from Taiwan suggests that Nichia intends to offer licenses for its patents relating to YAG phosphor, which is used in the manufacture of white LEDs. This should be of interest to the large number of LED packaging companies, such as Everlight and Unity Opto, that manufacture white LEDs. Due to intellectual property restrictions, Taiwanese companies cannot sell white LEDs in Japan and Europe and are forced to concentrate on the second-string markets in China and Korea. Patent licenses from Nichia would be good news for packaging companies and blue LED chip makers such as UEC, Epistar and Tyntek.

LEDEX reveals lower current chips

LED Expert Corporation (LEDEX) of Kaoshiung, Taiwan, a supplier of GaN-based UV, blue and green LED epiwafers and chips, has announced the availability of 100% probed and sorted chips for low-current applications. Commercially available UV, blue and green LED chips are typically specified at a forward drive current of 20 mA, but many devices, particularly for use in mobile phone backlights, work at lower currents. The dominant luminescence wavelength of InGaN/GaN quantum wells typically increases by 1–2 nm when the forward current is reduced from 20 to 5 mA.

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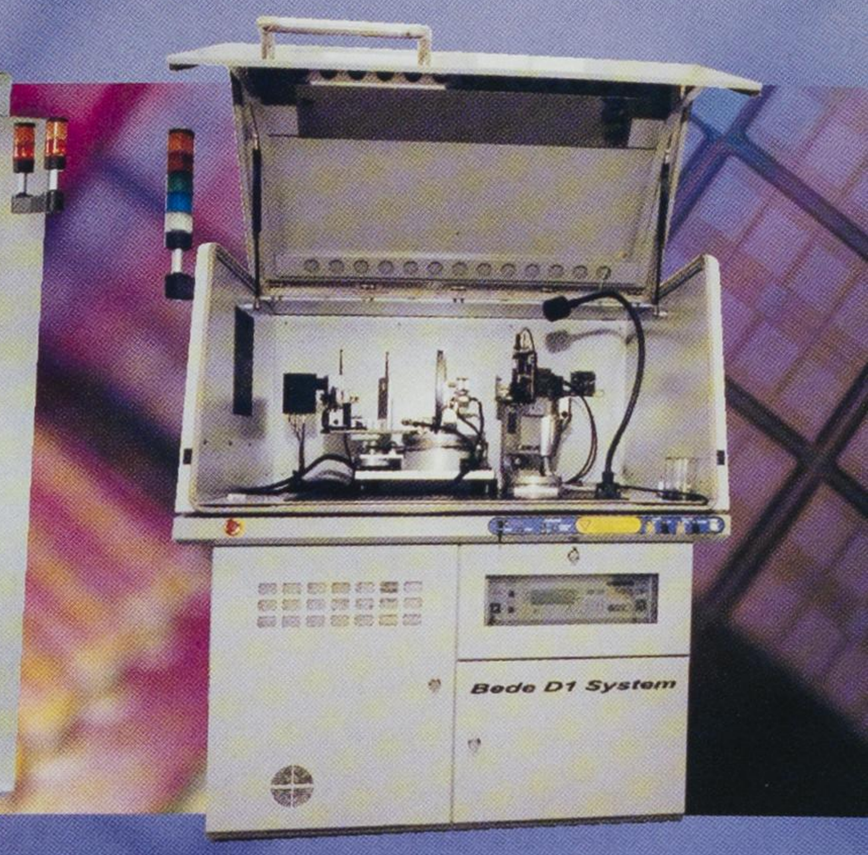
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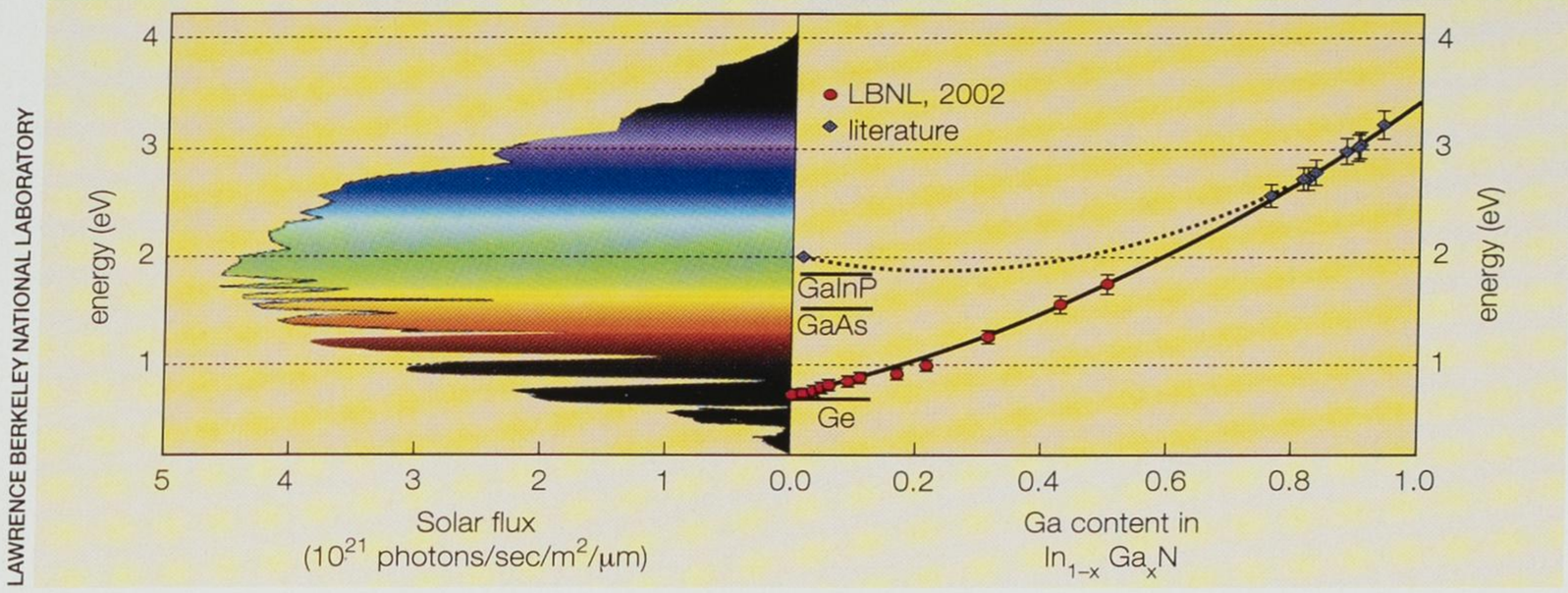
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Indium nitride bandgap is measured at 0.7 eV

The bandgap range of InGaN compared to the solar spectrum



The bandgap range of $In_{1-x}Ga_xN$, as shown on the right, varies from 0.7 eV (x = 0) to 3.4 eV (x = 1), which provides a very close match to the solar spectrum.

A press release from Lawrence Berkeley National Laboratory (LBNL) announced that the bandgap of indium nitride had been measured at 0.7 eV, rather than around 2.0 eV as previously thought. Using MBE-grown samples from Cornell University and Ritsumeikan University, Japan, the LBNL team measured the optical properties of a wide range of InN and InGaN films. It was found that the bandgap of InGaN decreased with increasing In content, from 3.4 eV for pure GaN to 0.7 eV for InN (see figure). According to LBNL, the value of 2.0 eV was derived from InN samples fabricated by sputtering, where the possible introduction of impurities such as oxygen could displace the bandgap of the material.

However, LBNL's press release was not without controversy. Days later, *Compound Semiconductor* received a letter from a group of scientists from Russia, Germany, Belarus and Japan, indicating that they had measured similar values for the bandgap of InN, and that their work predated the journal papers submitted by LNBL (for full details, see the December 20, 2002 story on *compoundsemiconductor.net*).

LBNL is interested in the applications of InGaN as a solar-cell material. The bandgap range of InGaN from 0.7 to 3.4 eV provides a very close match to the solar spectrum (see figure). The most efficient solar cells combine several materials with different bandgaps to utilize the different portions of the solar spectrum. Each cell absorbs light with an energy just above the material's bandgap, while light below the bandgap energy passes through to the next cell. Triple-junction solar cells manufactured by Spectrolab combine GaInP (bandgap = 1.85 eV), GaAs (1.43 eV) and Ge (0.66 eV), and have an efficiency of about 28%.

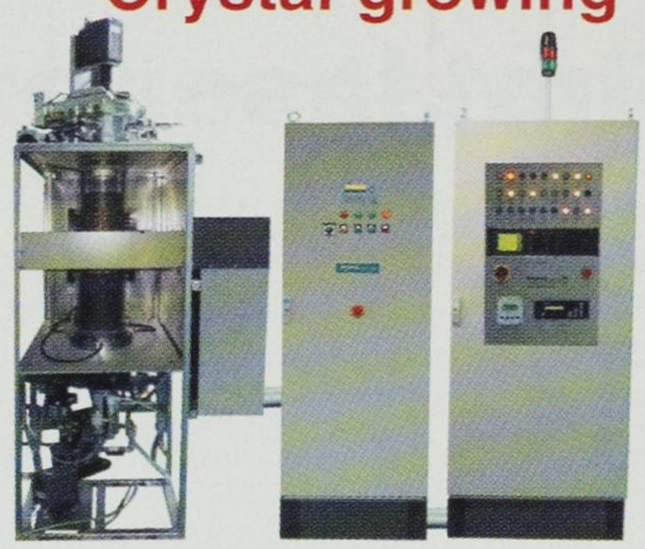
According to Wladek Walukiewicz from LBNL, two layers of InGaN, one tuned to a bandgap of 1.7 eV (around 52% In) and the other to 1.1 eV (about 80% In), could attain the maximum theoretical efficiency for a double-junction cell of 50%. Lattice mismatches will cause problems when attempting to grow monolithic structures; however, it has proved possible to get efficient emission from highly defective material to make InGaN-based LEDs. Other issues, such as growing p-type material, will also need to be addressed.

SiC MEMS devices emerge from MUSiC

The multi-user SiC (MUSiC) scheme for low-cost prototyping of SiC MEMS devices has produced its first wafers. The first run involved different designs from 13 organizations and was completed by FLX Micro, a provider of MEMS designs and processes based in Solon, OH. MUSiC is the only surface micromachining process that utilizes SiC structural layers. The mechanical, chemical and thermal properties of SiC allow MEMS technology to be extended to a wider range of applications and operating environments.

linn High Therm

Crystal growing



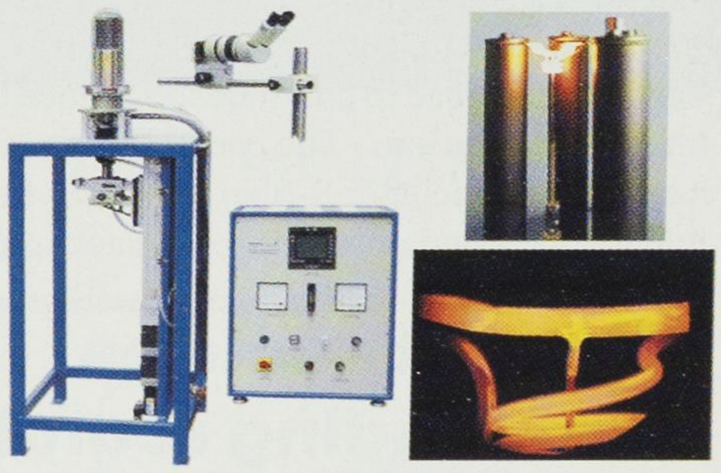
Production system for sublimation growth of 2 inch 4H- and 6H SiC single crystals for optoelectronics, power- and high temperature electronics. Allows the precise control of process conditions (temperature field, gas pressure, gas composition). Tmax 2400 °C.

SiC



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GaAs



Micro-Crystal growth system for pulling of single crystalline fibers from the melt in the atmosphere of inert gas or air. Fiber dimensions: Ø = 0,2-2,0 mm, lmax = 250 mm. Up to 2000 mg of starting material is melted in a platinum crucible (for high-melting compounds also Ir-, W-, Mo- crucibles) and a fiber crystal is pulled down through a capillary nozzle in the crucible bottom. Power unit: primary heater 80 W (max. 500 W), secondary heater 30 W (max. 200 W).

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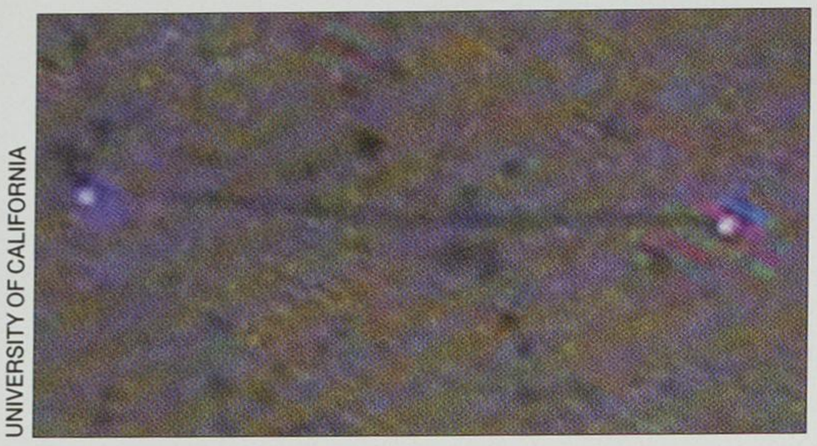
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First laser emission from GaN nanowires

Researchers at Lawrence Berkeley National Laboratory and the University of California at Berkeley have made the first observation of UV laser emission from GaN nanowires (*Nature Materials* 2002 **1(2)** 106). The research into GaN nanowires is an extension of the work by the same team, led by Peidong Yang, that last year reported UV laser emission from ZnO nanowires (*Compound Semiconductor* August 2001 p24).

The GaN wires are formed using nickel particles that act as a catalyst and are distributed on a sapphire substrate. The reaction of Ga and ammonia at 900 °C results in the formation of GaN nanowires with nickel particles at the ends. The nanowires typically have a 100 nm diameter, small enough to act as a laser cavity and optical gain medium. The ends of the nanowires act as laser mirrors, and optical pumping of the nanowires induces an electron-hole plasma in the wire. The electrons and holes recombine to produce UV photons with wavelengths between 360 and 400 nm, and as the pump power increases, the emission shifts to longer wavelengths.



UNIVERSITY OF CALIFORNIA

Optical image of a GaN nanowire laser. The color indicates lasing from the wire ends.

Yang and his colleagues are now working towards electrically pumped lasing from the nanowires, effectively creating nanowire laser diodes. Possible applications include optical data storage and on-chip chemical analysis.

Yang is also a co-founder of Nanosys, a company based in Palo Alto, CA. Nanosys specializes in the development of systems that exploit the electronic, optical, magnetic and chemical properties of low-dimensional structures such as nanowires and quantum dots. The company has an exclusive license from the University of California to exploit the nanowire technology. "The GaN nanolasers have great potential to compete with GaN blue lasers in terms of ease of manufacture, brightness and much smaller dimensions," said Yang.

Lehigh optical center wins funding

Lehigh University has received $15 million from the Pennsylvania Department of Community and Economic Development for its Center for Optical Technologies. The university is matching the contribution to the center, which was set up in January 2001, with a $1 million state grant, and has also received $1 million from the US Army.

The center is an industry-led organization that was set up to advance the research into and commercialization of optical technologies. Its mission is to "collaborate with industry leaders on research and technology transfers designed to continue to advance the Internet revolution." The center's proposed major thrusts include all-fiber networks, flexible displays and optoelectronic packaging, and may extend to research into GaN, MEMS and quantum dots and wires.

Daniel Smith, who is president and CEO of Sycamore Networks, a provider of data switching products for optical networks, has established the Smith Chair of the Center of Optical Technologies at Lehigh, in honor of his parents. The endowment will fund the director position at the center.

James Hwang, a professor in Lehigh's Compound Semiconductor Technology Laboratory, has been appointed interim director of the center. Hwang co-founded Quantum Epitaxial Designs, which later became part of IQE. Hwang's aims in the first year are to sign up 10 companies as paying members of the center, and to secure further funding.

Alfalight secures third funding round

Alfalight, a manufacturer of high-powered laser diodes from Madison, WI, has announced a third venture funding round of $15 million. This brings the total investment since the company was founded to $49.1 million.

Alfalight was founded in 1998 by a team from the Reed Center of Photonics at the University of Wisconsin to commercialize high-power diode lasers with aluminum-free active regions. The company is developing several high-power laser products in the 700–1600 nm region, targeting optical communications, military and industrial applications.

"Given the current economic environment and the reduced investments in start-up technology companies, our ability to close such a significant round validates the strength of our defined market opportunities, the company's technology and the team bringing it to market," said Eric Apfelbach, Alfalight's president and CEO. "This funding will assist Alfalight to commercialize laser diode modules that are significantly more powerful and less costly per Watt than those available today, and also to achieve its goal to further automate the diode laser and packaging production process."

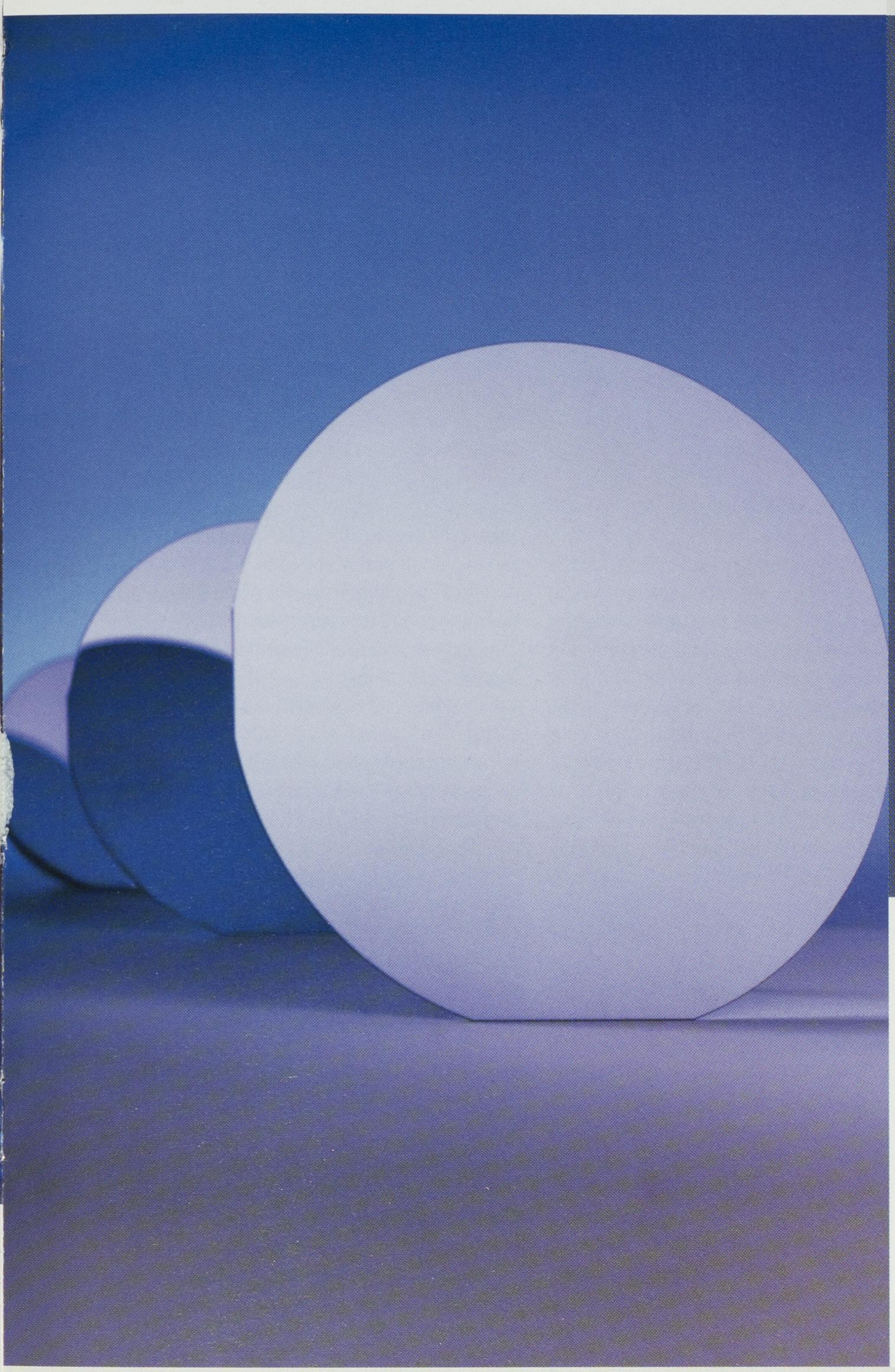
CdSe quantum dots boost organic LEDs

Researchers at the Massachusetts Institute of Technology (MIT) have produced an OLED containing CdSe quantum dots (QDs) that is about 25 times more efficient than the best QD-containing organic LEDs made to date (*Nature* 2002 **420** 800). Seth Coe and colleagues at MIT used a structure containing a single layer of CdSe nanocrystals sandwiched between two organic thin films. The nanocrystals act as QDs evenly distributed across the device, with each QD being about 3 nm in diameter. The organic layers above and below the QD layer supply charge to the dots. The CdSe QDs are deposited using a solution method rather than MBE or MOCVD, which are used for making all-semiconductor QD devices. The solution technique gives dot sizes with less than 6% standard deviation, resulting in a PL curve with an FWHM of 30 nm, compared with 50–100 nm for standard OLEDs.

The spectrum of emitted wavelengths has a Gaussian profile that is determined by the size uniformity of the QDs, and so the emission spectrum can be tuned to particular wavelengths by varying the size of the dots. For CdSe QDs, emission between 470 and 630 nm is possible. So far, the demonstrated efficiencies of QD-containing OLEDs is far below that of standard OLEDs, but the MIT team believe that the quantum efficiency and luminous power can be considerably improved.

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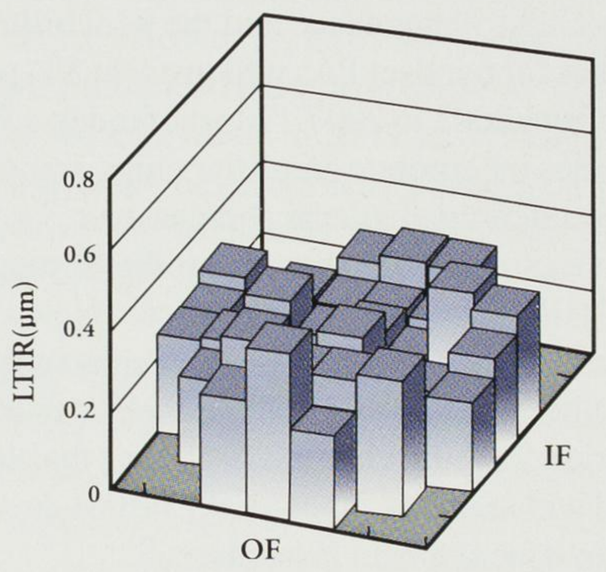


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4-inch InP LTIR Map



Site size: 12mm (37sites), LTIRmax=0.40μm, TTV=1.52μm

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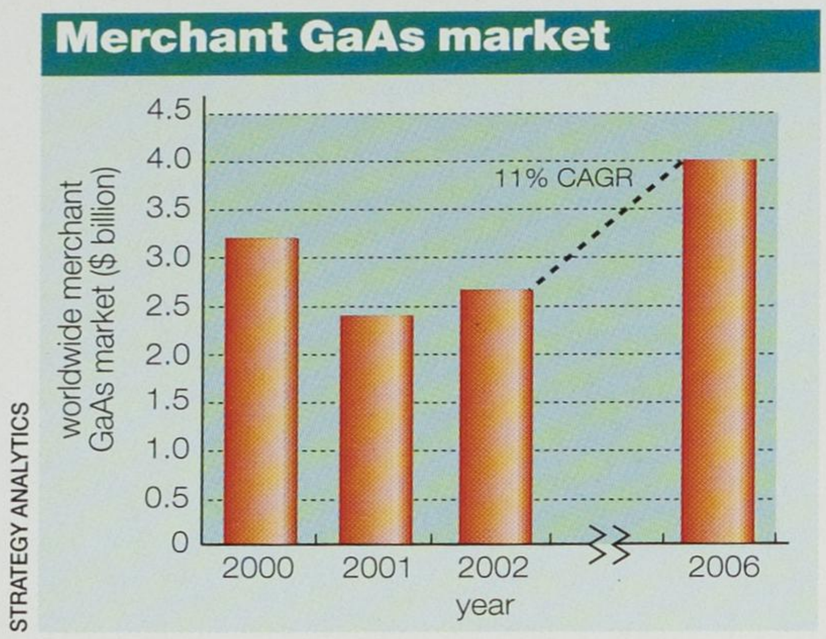
Things to watch in 2003

Last year was one of consolidation and contraction for the compound semiconductor industry, but also one that brought new opportunities. In our annual look at things to watch, **Tim Whitaker** and **Jon Newey** describe some of the likely developments in 2003.

The GaAs industry went through considerable upheaval in 2002; Alpha merged with Conexant's wireless business to form Skyworks, TriQuint bought Infineon's GaAs business and Raytheon teamed with WIN Semiconductors in Taiwan. Agilent, Filtronic and Skyworks all closed fabs in California, while Vitesse, the first company to build a 6 inch GaAs fab, announced that it plans to exit the GaAs manufacturing business in 2003.

According to Strategy Analytics, GaAs is expected to take an increasing slice of the cellphone PA market, while automotive radar will move towards mass production. The company estimates that the worldwide merchant market for GaAs microelectronics devices (discretes, digital ICs and MMICs) was $2.4 billion in 2001, a decline of 33% compared with $3.2 billion in 2000, and is forecast to grow at a CAGR of 11% through to 2006 (see graph, right).

While the GaAs MMIC market has already started to recover, silicon has taken over from GaAs in many digital IC sockets in telecom and datacom equipment. The digital GaAs IC merchant market declined by 54% in 2001, and is not expected to recover. Strategy Analytics predicts that the handset market will continue to dominate the consumption of GaAs MMICs, driven by an increase in the penetration of GaAs for the PA function. By 2007, PAs will account for nearly 100% of the revenue from GaAs in handsets, and the $1.2 billion market for handset PAs will grow at 8% per year from 2002 to 2007. "Most of today's PA modules incorporate amplifier chips, impedance matching elements and passives," said Christopher Taylor, director of the Strategy Analytics RF component service. "New PA modules have started to include antenna switch and other functions, and this has helped to offset price declines. Our forecast shows that this trend will make PA modules the fastest growing revenue segment in handsets."



After a 33% decline in 2001, the GaAs market should see ongoing modest growth.

Mobile handsets

According to Gartner Dataquest, 104.3 million mobile handsets were shipped in the third quarter of 2002, a 7.8% increase over the same period in 2001. Strategy Analytics put the figure for the same period slightly lower at 101 million units. New features including color displays, cameras and information content were heralded as the drivers that would boost handset sales even higher in the December quarter last year. Dataquest estimated that more than 40% of all phones sold in Japan in the third quarter of 2002 featured cameras. Figures from Allied Business Intelligence (ABI) suggest that in 2002 just over half of all handset sales were to existing users upgrading to new models. ABI predicts that by 2008, 85% of handset sales will be replacements.

However, in mid-December Nokia warned that its fourth-quarter revenues would fall at the low end of previous guidance due to disappointing sales of new model phones. Retailers reported that handsets with cameras and color screens proved to be a little too expensive as Christmas gifts, and the biggest sellers were models offered with prepaid subscriber plans.

A seasonal dip in the market is expected in the March 2003 quarter, but the overall market is expected to grow by 6–10%, according to Samsung and Nokia. Samsung put the figure for units shipped in 2002 at 410 million and predicts a rise to 435 million units in 2003. Nokia's figure for 2002 is 400 million with 440 million expected in 2003.

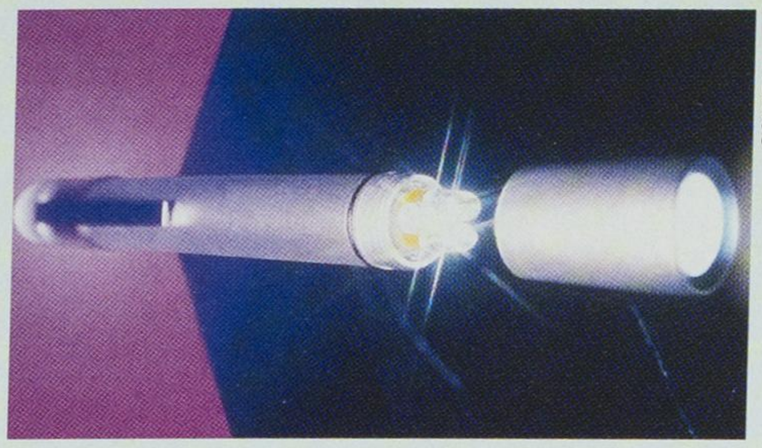
Wireless LANs

The number of WLANs deployed in 2002 mushroomed, resulting in an ever-larger number of PCs, especially portable ones, being shipped with WLAN cards. According to Forward Concepts, the value of the WLAN chip market grew by 43% to $364 million in 2002. WLANs represent a volume market for chip manufacturers, but it might not be the cash cow that the figures suggest. Plenty of manufacturers are willing to meet the rocketing demand for WLAN chips, which is resulting in plunging average selling prices (ASPs). Forward Concepts says that in 2002 ASPs dropped 31% and that pricing pressure looks set to continue in 2003. GaAs represents a relatively small part of the total WLAN market, as it is used mainly in the PA portion, and even here many manufacturers are using SiGe.

However, GaAs IC manufacturer RFMD intends to be a big player in the WLAN market. It has a high-volume GaAs IC manufacturing facility and so can offer GaAs PAs to complement its BiCMOS WLAN components at a competitive price. "The WLAN chip market might experience 20–30% ASP erosion for some time, but RFMD has experience of living in this type of market," said RFMD's Doug DeLieto. "We've seen 15–20% ASP erosion for years in handset PAs, which accounted for 89% of our December 2002 quarter revenues." In 2002, its first year of WLAN shipments, RFMD achieved the number two spot in the WLAN transceiver market with $25 million in revenues, and is aiming to grow that to $150–200 million.

LEDs and solid-state lighting

The nitride LED industry went through massive changes in 2002, as a number of companies reached agreements relating to the use of each other's intellectual property. Most of the deals involved Nichia, which is rumored to be considering offering licenses to its white LED technology to Taiwanese companies (see p17). Japanese chip makers besides Nichia and Toyoda Gosei are now starting to enter the nitride LED market using technologies that



LEDTRONICS



NOKIA



SAMSUNG

White LEDs, wireless LAN cards and mobile handsets will all be important applications for compound semiconductors in 2003.

circumvent patents owned by other companies; these include Sanken and Seiwa Electric, which are making GaN-on-silicon and white LEDs, respectively (see p17). Meanwhile, Supra Opto, the joint venture between Sumitomo Electric and Procomp, looks set to challenge the GaN-based LED industry by manufacturing white LEDs based on ZnSe (see p5). Will 2003 finally see a real commercial market for ZnSe-based devices?

Chip manufacturing and epiwafer production capacity for blue LEDs continues to grow in Taiwan, which already dominates the AlInGaP LED industry. Blue LEDs made in Taiwan are currently at the lower end of the brightness scale, which is the most price-competitive segment of the market, but are expected to improve rapidly. Elsewhere in Asia, Samsung, the Korean giant that currently orders about 30 million LED chips per month from Taiwanese manufacturers, is reportedly close to completing a large facility to meet some of its internal requirements.

The highest profile market for high-brightness LEDs is in cellphones, particularly blue LEDs for keypads and white LEDs for backlighting color screens. Samsung has predicted that 40% of all new handsets will have color screens by the end of 2003. The dark cloud on the horizon for white LEDs in handsets is the emergence of organic LEDs (OLEDs). Cambridge Display Technology (CDT) expects OLEDs to be deployed in handsets later this year. "We expect OLED displays to displace LCDs as the preferred technology in mobile handsets over the medium term," said Stewart Hough, VP of Business Development at CDT. "OLEDs offer improved performance over LCDs in terms of brightness, viewing angle and lower power capability."

Solid-state lighting has emerged as one of the most exciting new growth areas in the compound semiconductor industry. Strategies Unlimited predicts that the market for high-brightness LEDs in lighting applications will grow from $85 million in 2002 to more than $500 million in 2007. Applications such as architectural lighting, machine vision, illumination for signage, flashlights, and decorative, accent and marker lights form the foundation for lighting market growth, and have mostly used colored light. However, white LEDs are poised to enter the $12 billion market for general illumination thanks to tremendous progress in lumen output, with higher efficiencies than incandescent lamps. As well as improving LED chip technology, manufacturers are working to build white LEDs that provide more user-acceptable lighting with the correct color rendering index and color temperature for different applications. A particular effort is the focus on new phosphors and near-UV emitters (see p11).

Because solid-state lighting offers the potential for significant energy savings, various national governments have targeted LED technology for accelerated R&D funding. A national solid-state lighting effort is underway in Japan, and proposals for a US program have received broad-based support in Congress.

DVD and laser diodes

DVD continues to be a growth market for companies, mainly in Japan, that fabricate red laser diodes operating at 650–660 nm. Sharp is reducing its output of 780 nm CD lasers while ramping up its capacity for 650–660 nm devices to the 4.5–6 million units per month range (p15). Sony is also building a new factory to double its output of 655 nm red DVD lasers to 10 million units per month.

A more exciting but longer-term market is for next-generation high-definition DVD players. Several rival formats have been launched by manufacturers keen to grab their share of royalty payments. A consortium of nine leading consumer electronics companies led by Sony announced Blu-ray Disc, while Toshiba and NEC weighed in with their Advanced Optical Disc (AOD) alternative. Further clouding the waters, Warner Bros suggested using new compression methods to increase the capacity of existing 650 nm DVD technology. After several manufacturers exhibited prototype Blu-ray systems at a show in Japan late last year, it seems that high-end professional players could be available by the end of 2003, but it will be 2004 at least before commercial models reach the market.

Both Blu-ray and AOD will use 405 nm violet lasers. Sony has gained a strong position in this market by allying with Nichia, still the only commercial supplier of violet lasers (see p5). However, both Sanyo and Sharp have announced plans to commence production of violet lasers in 2003, and Cree, which has a laser development agreement with Rohm, plans to launch a 30 mW product in the first half of 2003.

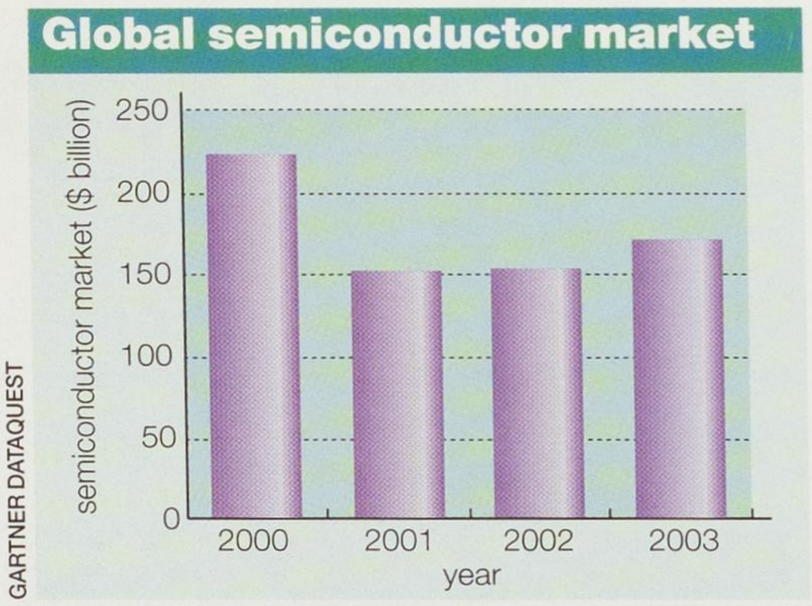
Fiber-optic components

During 2002, the optical communications industry got to grips with its dire situation, with companies embarking on huge cost-cutting measures. This saw some of the largest players, such as Agere, Nortel, ADC and Marconi, divest themselves of their optical components businesses, and the disappearance of many smaller component manufacturers, either through closure (e.g. Qusion, Siros) or purchase

by another company (e.g. Cielo, Sparkolor). Such measures are continuing in 2003 as component manufacturers shape up for a year when limited growth is expected to return.

According to a new report from Strategies Unlimited, the global market for optical components will grow by 30% in value in 2003 as inventories are finally depleted and the market begins to see new system orders. Even with 30% growth, component vendors' revenues in 2003 will total $2.1 billion, far below the $9.1 billion peak seen in 2000. ElectroniCast is predicting that the market for OEICs will grow rapidly from $320 million in 2002 to $572 million in 2003, and will reach $1.9 billion in 2006.

One of the drivers for industry consolidation is the demand placed upon component vendors for a new generation of components that exhibit higher levels of integration at lower prices. A good recent example was Bookham Technology's acquisitions of the optical components divisions of Nortel and Marconi. This gave Bookham access to components such as lasers and modulators that it required to augment and ultimately integrate with its passive components. The acquisitions also gave Bookham the critical mass and market share that may well prove crucial to any component vendor with an eye on long-term survival.



After two lean years for semiconductors, double-digit growth is expected in 2003.

VCSELs and QD lasers

VCSEL technology at 850 nm has found a niche for itself in short-reach optical communications, but VCSELs operating at 1310 nm are required for longer-reach applications. There have been many issues to grapple with surrounding the integration of the long-wavelength-emitting active region and the mirror stacks. Jim Tatum, Honeywell's strategic marketing manager for VCSEL products thinks that 2003 will be a transition year for 1310 nm VCSELs. "I don't believe that there will be significant commercialization of long-wavelength VCSELs in 2003," said Tatum. "This should be the first year of technology feasibility in field applications, and deployment should begin in earnest in 2004."

Another laser technology that promises high performance at a lower cost is the quantum dot (QD) laser. Recent years have seen an exponential increase in the number of QD-related journal papers being published, but to date Zia Laser of Albuquerque, NM, is the only commercial venture attempting to make a living out of QD lasers (*Compound Semiconductor* June 2002 p14). Manufacturers are looking ahead to small form-factor multisource agreements for the next generation of transmitter modules. Because QD lasers have lower threshold currents and higher slope efficiencies than QW lasers, they dissipate less power, an important consideration when reducing the footprint of modules.

Funding for new optical component start-ups such as Zia Laser is now much harder to come by as venture capitalists tighten up their requirements for product and business plans. "The basic value proposition of producing a higher performance laser that can transmit further and reduces the cost of the component is a very solid one," said Luke Lester, Zia's CTO. "If Zia had spun out of the University of New Mexico two years earlier it would have got 10 times the funding and had a number of companies copying it immediately. In the current climate, VCs want to see that there is a need for the technology. However, given the value proposition of QD lasers, other start-ups will be along soon, and established laser manufacturers will release QD products."

Indium phosphide

The big commercial driver for InP-based microelectronics was high-speed optical communications networks. Just as InP devices seemed to be reaching the required performance levels, the bottom fell out of this market. Most of the companies with InP products and development programs are also working in other materials, and so are still around and reshaping their businesses to deal with the present situation. InPhi, which began as an InP start-up in 2000, now offers CMOS products in association with Broadcom to complement its InP range. Vitesse, a long-time compound semiconductor player, is now predominantly a CMOS company. However, it is retaining an InP development activity and also offers InP foundry services.

In 2003, Vitesse will continue to develop its next-generation process called VIP-2, a dual HBT InP process with an f_t of 300 GHz and BV_{ceo} in excess of 10 V. State-of-the-art transistor integration levels in InP are at the 5000 mark, with Vitesse and others looking to push this up in the coming year. The integration level issue is a crucial one if InP is to fulfill its promise and find new applications. This is being addressed in a new DARPA-funded four-year program at Rockwell Scientific, the first results of which should begin to appear in 2003.

SiGe and strained silicon

SiGe really took off in 2002, with SiGe HBT and BiCMOS devices achieving widespread design-ins, especially in the area of wireless communications. This will accelerate in 2003 as communication IC manufacturers either continue the development of their own SiGe manufacturing processes or work with foundries. At the IEDM in late 2002, IBM once again set the high-speed SiGe standard for others to follow; its SiGe HBT process yielded an f_t of 350 GHz, higher even than any III-V HBTs yet reported (see p27). This year will undoubtedly see an increase in not only headline speeds, but also the speeds and power handling ability for commercially available SiGe ICs.

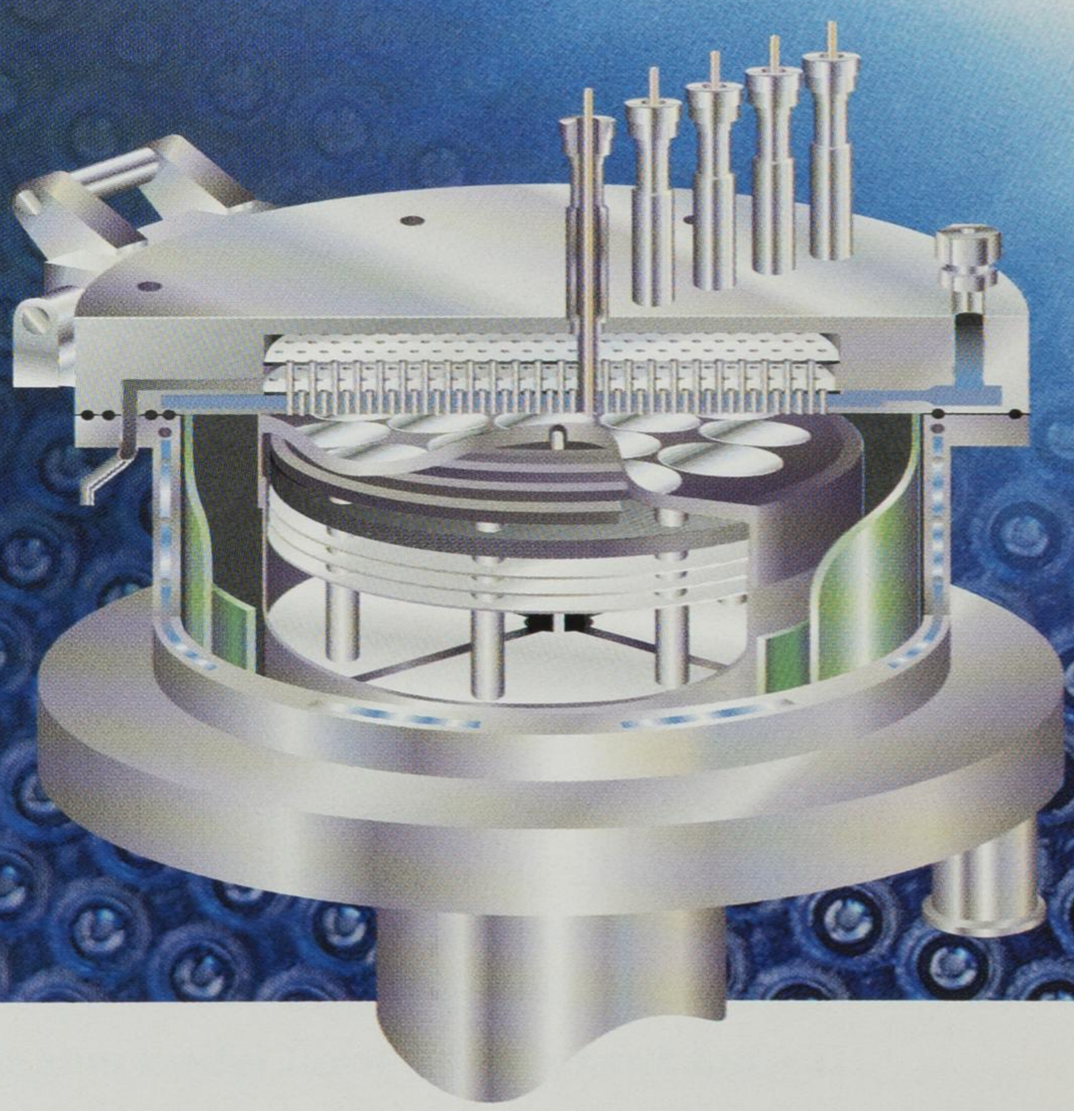
For CMOS to continue its inexorable march, the development and integration of new materials into CMOS processes is required. One of these is strained silicon, the implementation of which relies on some of the expertise and technology developed in the III-V industry. The biggest players in CMOS have strained silicon on their technology roadmaps, and the first prototype strained silicon CMOS circuits are expected this year. One of the prime movers in this field is AmberWave Systems, which is involved in development partnerships with IQE and Aixtron, companies traditionally associated with compound semiconductors, and is also mounting a drive to get its technology adopted in Japan through a collaboration with Mitsubishi.

Other new technologies being investigated by the silicon industry are continuing to provide welcome opportunities for compound semiconductor equipment manufacturers as the depression in their traditional markets continues. MBE may prove to be a key technology for the production of single crystal oxide high-k gate dielectrics. This year should see further announcements of orders for epitaxial growth equipment for this application, and more developments by MOCVD equipment manufacturers as they modify their tools for the deposition of oxides, SiGe and strained silicon.

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IEDM highlights include SiGe HBTs operating at 350 GHz

Results presented at last December's IEDM raised the bar for device performance, writes **Tim Whitaker**. Key announcements included a 350 GHz SiGe HBT, AlGaN/GaN FETs providing 2.3 W at 30 GHz and 100 Gbit/s logic ICs fabricated in InP-based HEMT technology.

As usual, the International Electron Devices Meeting (IEDM), held December 8–11 in San Francisco, gave a snapshot of the state of the art in advanced semiconductor technology. Most of the papers were related to mainstream silicon CMOS, although technologies such as strained silicon and SOI are becoming increasingly prevalent. A small number of compound semiconductor papers were also presented, notably in the field of nitride electronics.

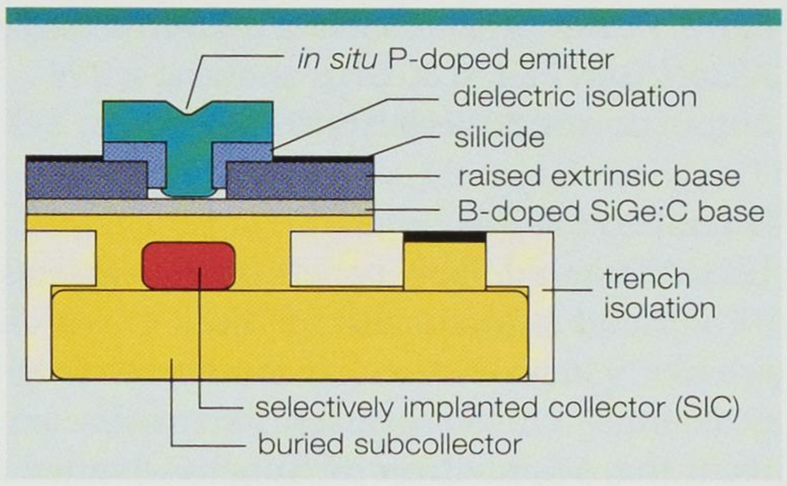
SiGe HBTs reach 350 GHz

IBM Microelectronics continued to increase the performance of its SiGe HBT process, reporting an f_t of 350 GHz. This is the highest reported f_t value for any silicon-based transistor and the highest for any bipolar transistor, including those fabricated using III-V materials. At last year's IEDM, Ida *et al.* from Fujitsu reported an InP/InGaAs DHBT with an f_t of 341 GHz.

IBM's device had an f_{max} of 170 GHz and BV_{CEO} and BV_{CBO} values of 1.4 and 5 V, respectively. The structure (see figure 1) features shallow and deep-trench isolation, while a buried subcollector layer and an n-epitaxial layer form the collector region, along with a selectively implanted collector pedestal. A SiGe base layer doped with boron and carbon was grown by non-selective UHV CVD, and a B-doped raised extrinsic base was formed self-aligned to an *in situ* P-doped emitter. Simultaneous optimization of f_t and f_{max} resulted in values of 270 and 260 GHz, respectively.

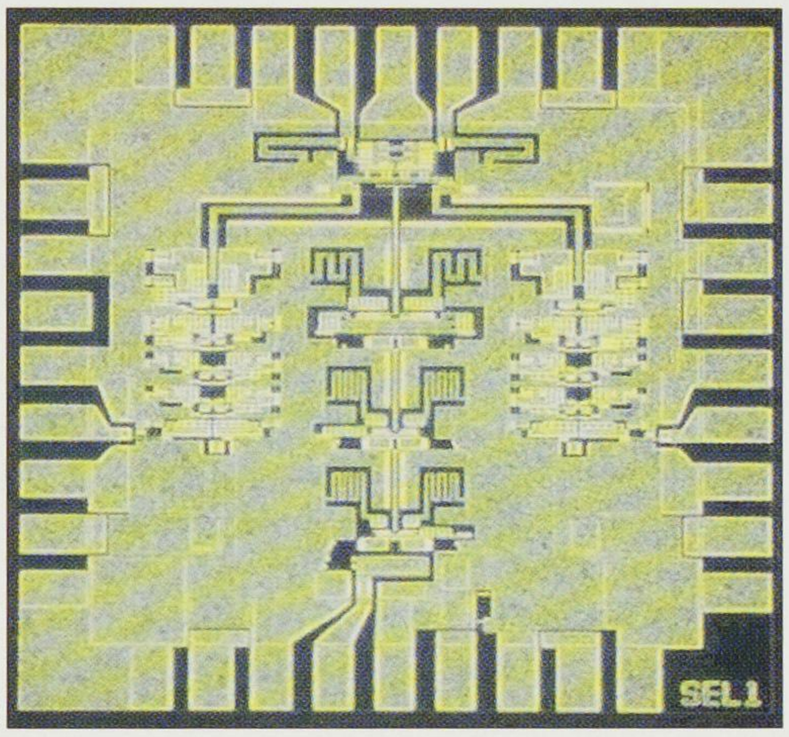
Infineon has also made great strides with SiGe. This year, Böck *et al.* reported a dynamic 1:2 frequency divider operating at 99 GHz, which the authors claimed to be the highest reported divider operating frequency for any transistor technology. The total power consumption of the circuit was just 290 mW. The SiGe transistors have a double-polysilicon self-aligned emitter base configuration with a SiGe base (doped with B and C), which is integrated by selective epitaxial growth. The devices had an f_t of 155 GHz at $BV_{CEO} = 1.9$ V, an f_{max} value of 167 GHz and a 4.7 ps gate delay. The analog performance of the technology was also investigated by fabricating a 19 GHz LNA, which had a 50 Ω noise figure of 2.2 dB and a gain of 26 dB; these are record values for silicon LNAs at this frequency.

IHP of Germany reported a novel SiGe HBT structure without deep-trench isolation and with low-resistance collectors formed by high-dose ion implantation after shallow trench formation. The technology yielded an f_t value of 190 GHz at $BV_{CEO} = 2.0$ V, as well as HBTs with $f_t \times BV_{CEO}$ products above 360 GHz. Ring oscillator delays of 4.3 ps and a high yield of 4000-transistor arrays were also demonstrated. The high-speed HBT module was integrated into a 0.25 μm CMOS platform, leaving CMOS device characteristics unchanged.



IBM

Fig. 1. A cross-section of IBM's SiGe HBT structure, which was used to obtain a record-breaking f_t value of 350 GHz.



NTT

Fig. 2. A 100 Gbit/s selector IC fabricated using InP-based HEMT technology.

100 Gbit/s logic ICs using InP

Researchers at NTT Photonics Laboratories described what they believe to be the fastest logic operation of a transistor-based IC. The group reported error-free multiplexing and demultiplexing functionality at 100 Gbit/s using InAlAs/InGaAs/InP HEMT technology (see figure 2). NTT fabricated two ICs using a 0.1 μm gate length InAlAs/InGaAs/InP HEMT process, which provided f_t and f_{max} values of 175 and 350 GHz, respectively. A 100 Gbit/s selector IC contained two data buffers, a clock buffer and a 2:1 selector core circuit that was designed to directly drive the external 50 Ω load without the need for output buffers.

In order to confirm the error-free operation of the 100 Gbit/s selector IC, it was necessary to build a second IC capable of demultiplexing the 100 Gbit/s signal to 50 Gbit/s. This allowed the output waveform to be recorded using a 50 GHz bandwidth digitizing sampling oscilloscope. Error-free operation with a bit error rate of less than 10^{-10} was confirmed for both the 100 Gbit/s multiplexing function of the selector IC and the 100 Gbit/s demultiplexing function of the second IC. Power dissipation was 3.2 and 4.7 W, respectively.

Nitrides provide power and linearity

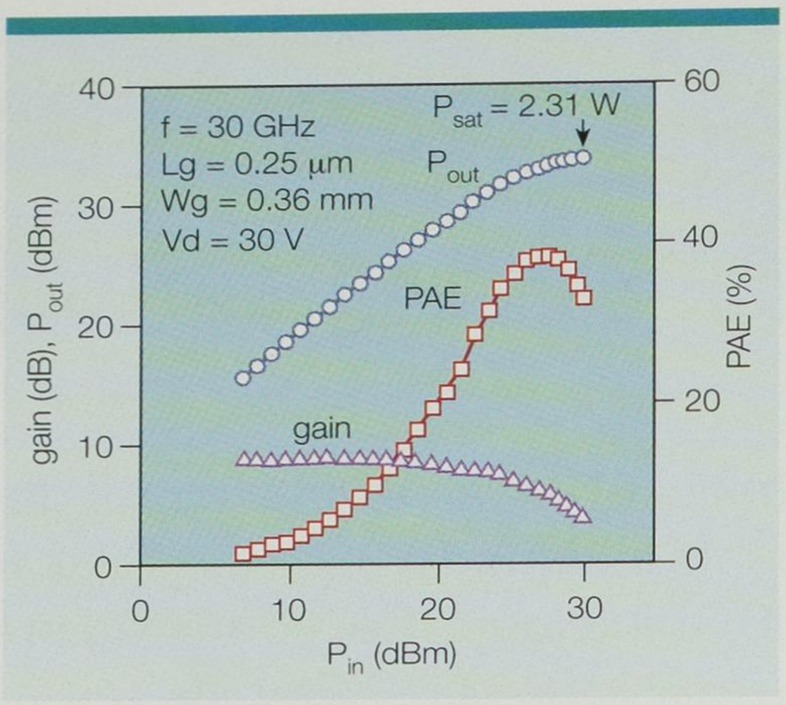
A number of papers described record performance for AlGaN/GaN HEMTs, which are attractive for high-power and high-frequency applications. Kasahara *et al.* from

NEC described the first successful watt-level Ka-band power operation of an AlGaN/GaN HFET on SiC. A device with a gate length of 0.25 μm and a gate width of 0.36 mm had a maximum CW output power of 2.3 W at 30 GHz, together with a PAE of 38% and a linear gain of 8.8 dB at Vds = 30 V (see figure 3). The authors believe that the output power of 2.3 W and the power density of 6.4 W/mm are the highest values reported to date for GaN-based devices at Ka-band frequencies. The device had an f_{max} of 120 GHz and a drain current density of 1 A/mm. The electrode layout and surface passivation layer were optimized to enable operation at a bias voltage of 30 V. GaAs transistors operating at a bias voltage of 5–8 V require passive circuitry to combine the output power of multiple transistors, resulting in larger chip and package sizes, increased power loss and narrower frequency bandwidths. NEC believes that the nitride-based power amplifier will be suitable for operation in all the main millimeter-wave communication bands at 22, 26 and 38 GHz.

Meanwhile, R Quay and colleagues from the Fraunhofer Institute of Applied Solid-State Physics reported AlGaN/GaN-on-SiC HEMTs operating at up to 40 GHz. The devices had a gain in excess of 6 dB and a maximum output power of 0.3 W, equating to a power density of 1.23 W/mm for a gate width of 8 × 30 μm (0.24 mm). The CW PAE was 10% at a Vds of 26 V, while the peak PAE was 16% at Vds = 15 V.

Linearity is also an important characteristic of AlGaN/GaN HEMTs targeted at applications such as wireless base stations. Nagahara *et al.* from Fujitsu reported excellent linearity characteristics of AlGaN/GaN HEMTs at Vds = 30 V, and class AB operation at 1.9 GHz. The devices, grown on SiC, exhibited a third-order intermodulation distortion (IM3) of –34.7 dBc for an output power level of 26 dBm (backed-off 8 dBm from the saturation power). The RF performance is attributed to suppressing current collapse under a high applied voltage, using an optimum n-AlGaN donor layer thickness and SiN passivation.

Yi-Feng Wu and colleagues from Cree Lighting also reported on the excellent linearity of AlGaN/GaN HEMTs at 4 GHz, including an IM3 of –30 dBc and a PAE of 40% with only –2.6 dB back-off. The results can be compared with the –30 dBc IM3 and 45% PAE achieved by InP-based HBTs at 10 GHz.



NEC

Fig. 3. Power performance of a 0.36 mm wide AlGaN/GaN FET at 30 GHz, showing 2.3 W output power, 38% PAE and 8.8 dB gain.

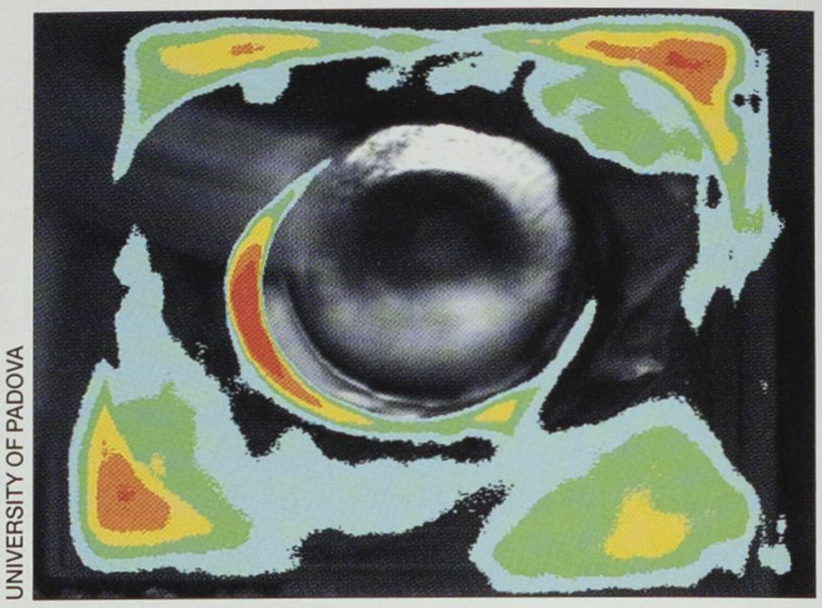

UNIVERSITY OF PADOVA

Fig. 4. Emission micrograph of a GaN-on-SiC LED after aging at 100 mA DC; high-temperature and short-wavelength irradiation result in the formation of a partially opaque damaged layer.

Strained silicon

IEDM featured many papers on the subjects of SOI and strained silicon, both of which are likely to provide enhancements to next-generation CMOS processes. Two papers, one from the Association of Super-Advanced Electronics Technology in Japan, and the other from IBM, described efforts to combine SOI and strained silicon. IBM provided the first clear evidence of performance enhancement in n-FETs on strained silicon/SiGe-on-insulator substrates. The structure of the substrate consisted of a 15 nm strained silicon layer and a 40 nm SiGe layer (50–70% relaxed) above a buried oxide layer. For devices with a 60 nm gate length and a raised source and drain structure, the overall performance enhancement was 20–25% compared with SOI control n-FETs. It is expected that p-FET enhancement can also be achieved with high Ge-concentration substrates.

Degradation in GaN LEDs

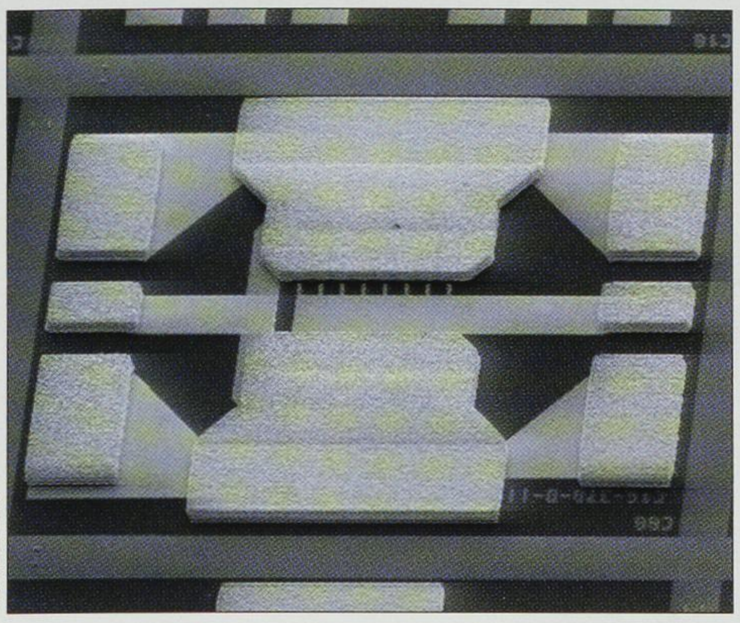
Although long lifetime is generally quoted as a major advantage of LEDs compared with traditional light sources, lumen maintenance remains a critical issue. Previous studies of LEDs have revealed a rapid loss of light output, severe degradation of the encapsulating packaging material, problems with thermal management and other issues. As packaging improves, more focus is being placed on failure modes and mechanisms related to the die and the materials.

High-current accelerated aging tests carried out by the Italian universities of Padova, Bologna and Bari, together with Gelcore, revealed five distinct failure modes for GaN-on-SiC LEDs. For encapsulated devices, testing at high current levels and therefore high junction temperatures causes degradation of the epoxy material, which then causes the formation of an opaque layer on the device surface (see figure 4). High current and temperature affect the semi-transparent top ohmic contact, leading to an increase in series resistance and current crowding effects, and a reduction in optical power. Also, an increase in Mg doping takes place, possibly due to decomposition of Mg complexes and Mg reactivation. Changes take place in the distribution of deep levels already present in untreated devices, and shallow traps are also generated. Finally, extended defects are created in devices treated at high current density.

Ge MOSFETs

Devices fabricated from strained silicon layers on relaxed SiGe virtual substrates have shown enhanced device performance compared with bulk silicon. Since high hole-mobility enhancement is achieved in p-MOSFETs fabricated in strained silicon on a high (83%) Ge-content SiGe channel, it is attractive to consider the potential of pure Ge channels. Compared with silicon, pure Ge offers 2× higher mobility for electrons and 4× higher mobility for holes.

Chui *et al.* from Stanford University described the fabrication of p-type surface channel Ge MOSFETs with a ZrO_2 (high-k dielectric) gate oxide and a platinum gate electrode. The peak temperature of the entire process was 400 °C, significantly lower than for comparable silicon processes. For a gate length of 2 μm, the devices demonstrated a low-field mobility twice that of silicon MOSFETs. The use of thicker gate dielectrics and sub-micron gate lengths should improve the performance of this technology.



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Fig. 5. A HBT power cell, which is used for basestation applications and delivers 10 W of output power at 2 GHz with a PAE of 50% and a gain of 8 dB.

Meanwhile, Shang *et al.* from IBM's Semiconductor R&D Center reported the first demonstration of Ge p-MOSFETs with a gate dielectric (GeON) thickness of less than 10 nm and a sub-threshold slope of 82 mV/dec. The Ge p-FETs showed more than 2× higher drive current and transconductance than silicon control devices, as well as a mobility enhancement of about 40%.

Gate oxides

In order to continue to aggressively scale-down CMOS technology, high-k gate dielectrics with low gate leakage and thin equivalent oxide thickness are required. Many alternative materials to SiO_2 have been suggested, including HfO_2, ZrO_2, $Zr_xSi_{1-x}O$ and HfO_xN_{1-x}. One of the problems with HfO_2 is selective etching. A team from France Telecom, ST Microelectronics, CEA-LETI and Philips avoided the etching issue by using a damascene process to fabricate a 40 nm transistor with a HfO_2 dielectric and a poly-silicon gate. The leakage current was more than two decades lower than comparable devices using SiO_2.

In a late news paper, Jeon *et al.* of the Kwangju Institute of Science & Technology in Korea and the Oak Ridge National Lab, US, reported the growth of epitaxial $SrTiO_3$ by MBE for MOS gate dielectric applications. The material showed an equivalent oxide thickness of 5.4 Å and a leakage current density of only 7×10^{-4} A/cm^2.

GaInP/GaAs power HBTs

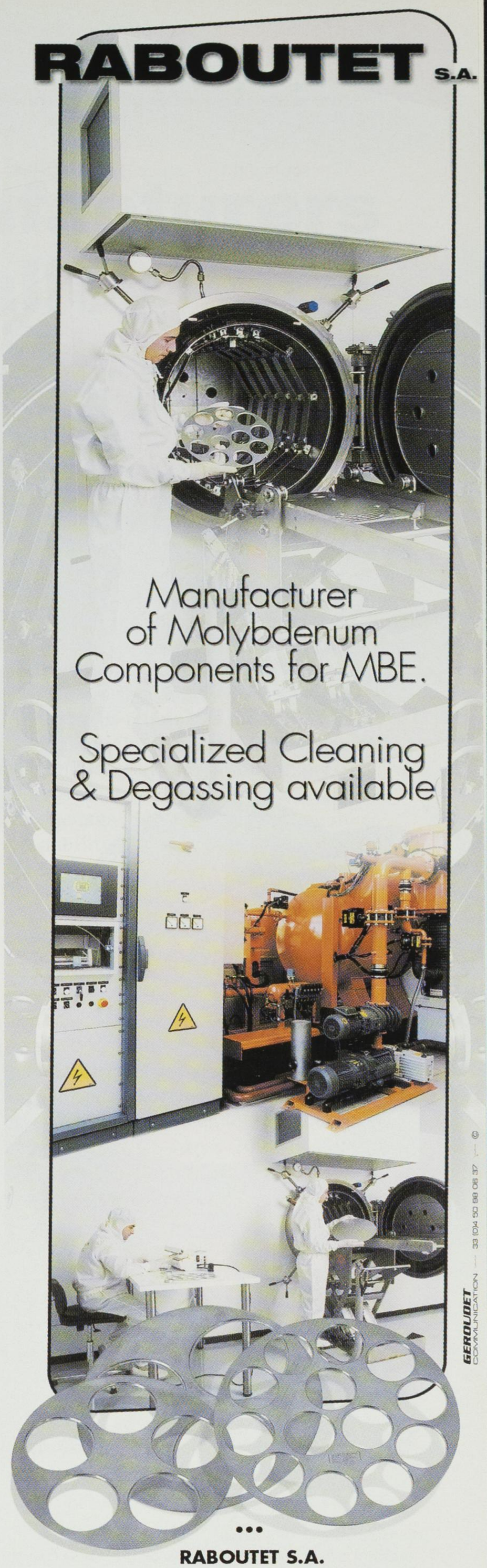
GaInP/GaAs HBTs are suitable for use in base-station amplifiers, where high supply voltage operation is required. A group from FBH Berlin, Germany, and United Monolithic Semiconductors in France and Germany reported GaInP/GaAs HBT power cells operating at bias voltages up to 32 V delivering 10 W of output power at 2 GHz. The high voltage requirement was fulfilled using a thick and weakly doped collector layer; by using a 3.5 μm thick collector layer, record breakdown voltages of $BV_{CBO} = 80$ V and $BV_{CEO} = 47$ V were achieved. Power cells with a total emitter area of 5000 μm^2 delivered 10 W of output power with a PAE of 50% and a gain of 8 dB (see figure 5). The performance of the devices is limited by heat removal, and flip-chip mounting of power HBTs on AlN carriers is now under development.

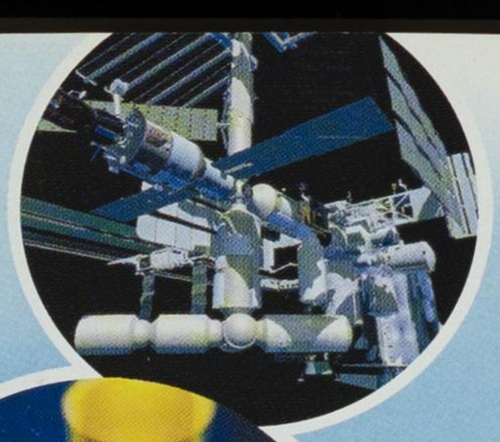
Ge and SiGe photodetectors

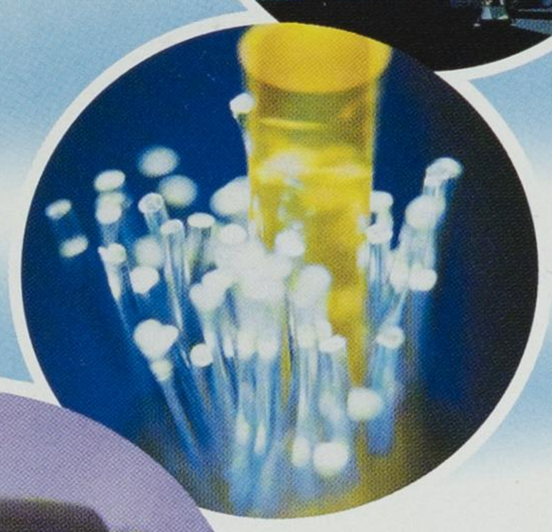
A group from Motorola, Unaxis Balzers, ETH Zurich and the University of Texas described 1.3 μm epitaxial Ge-on-silicon photodetectors with a 3 dB bandwidth of 3.5 GHz at –3 V, believed to be the highest frequency response measurements for such a device. The devices consisted of a 10 μm graded SiGe buffer and a 1 μm Ge layer deposited on a silicon substrate by low-energy plasma-enhanced CVD in less than 40 minutes. This is an order of magnitude faster than UHV CVD techniques can achieve, although the threading dislocation density of 1.5×10^5/cm^2 was an order of magnitude better than previously reported values. The devices showed a responsivity of 0.51 A/W and a quantum efficiency of 49%.

Z Pei *et al.* from ITRI in Taiwan fabricated SiGe/Si MQW heterojunction phototransistors (HPTs) with a record responsivity of 1.47 A/W and a bandwidth of 1.25 GHz at 850 nm. The devices also operated at 1310 nm with 0.15 A/W responsivity. In the HPT, multiple $Si_{0.5}Ge_{0.5}$/Si quantum wells act as light-absorbing layers between the base and collector regions of a Si/SiGe HBT structure. Electrons generated in the MQWs are swept to the collector while holes diffuse to the base region and are injected into the emitter by virtue of a decrease in the base-emitter energy barrier. In turn, this allows a large number of electrons to diffuse across the base to the collector, amplifying the initial current.

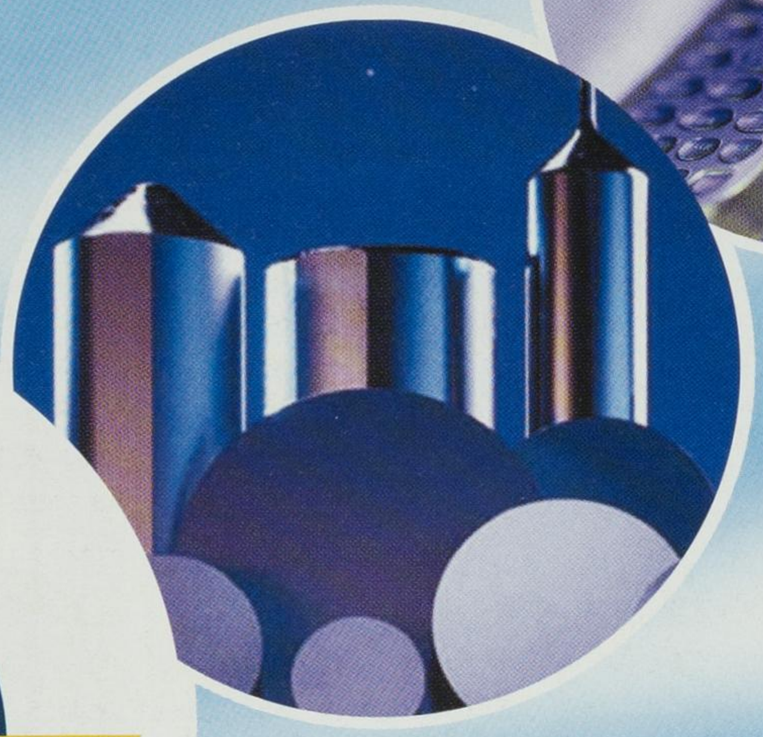
Ge quantum dots (QDs) can also be used to extend the operation of photodetectors to 1550 nm. A group from the National Taiwan University reported a Ge QD device capable of detecting at 820, 1300 and 1550 nm with responsivities of 130, 0.16 and 0.08 mA/W, respectively. The structure consisted of five layers of Ge QDs with 2 nm wetting layers and silicon spacer layers.











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CS-MAX 2002

CS-MAX brings manufacturers together in Silicon Valley

If you want to find out what techniques are used to manufacture all types of state-of-the-art compound semiconductor devices then CS-MAX is a good place to start, writes **Jon Newey**.

The second running of CS-MAX took place in San Jose, CA, on November 11–13, and pulled together 98 companies representing all of the steps in electronic and optoelectronic device manufacture into one exhibit. Many more companies contributed to the technical program that was running in parallel with the exhibit, giving manufacturers of processing tools and those that use them the chance to discuss the latest developments and how these are being brought to bear on the issues of manufacturing efficiency and enhanced device performance. As well as sessions covering generic processes such as etching, epitaxy and die separation, there were also sessions covering the manufacturing processes for specific device types including LEDs, lasers and HBTs.

Newly added to CS-MAX were sessions on silicon heterostructures, heterointegration and environmental health and safety. The health and safety session included discussions on new technologies for handling hazardous waste, and a presentation from Thales Research and Technology in France on the characterization of hazards in emerging technologies using GaN epitaxy as an example. Health and safety issues are an important consideration in overall fab management, which was another area covered at the meeting (see articles in *Compound Semiconductor* November 2002).

Silicon heterostructures

The session on silicon heterostructures reflected the push of technologies developed in the compound semiconductor industry into silicon device manufacturing. Mayank Bulsara of Amberwave Systems (Salem, NH) gave an overview of strained silicon technology and its commercialization status (*Compound Semiconductor* September 2002 p39). Since its first demonstration in 1991, strained silicon has come to be recognized as a key to extending the silicon roadmap. It is therefore now in development at most of the major CMOS IC manufacturers and prototype circuits are emerging. The beauty of strained silicon CMOS is that it uses much of the process technology that already exists in mainstream CMOS manufacturing. However, Bulsara pointed out that the implementation of strained silicon is forcing the industry to learn about many of the techniques perfected by the compound semiconductor community for measuring and monitoring complex epilayers.

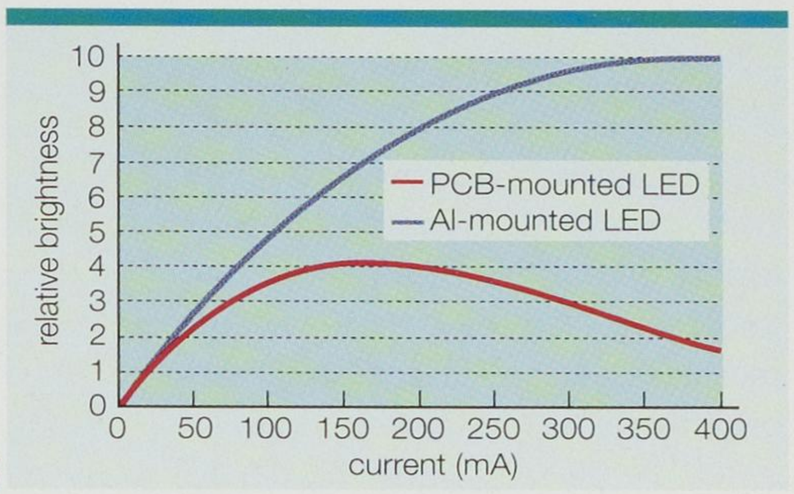


Fig. 1. The performance of two LEDs of the same type on different mountings. The LED on an aluminum mounting can be driven at higher currents to give higher light output because the aluminum conducts heat away from the LED junction much more effectively than the PCB-mounted device.

Dieter Knoll of IHP in Frankfurt, Germany, presented details of a low-cost BiCMOS process incorporating SiGe:C HBTs that has recently yielded record-breaking devices (*Compound Semiconductor* October 2002 p22). The process, developed jointly with Communicant Semiconductor, is relatively simple in that it dispenses with epitaxially buried sub-collectors and deep trench isolation. The BiCMOS process uses 25 lithography steps and has four metal layers to give two standard HBT variants, one optimized for speed ($f_t = 85$ GHz, $BV_{CEO} = 2.4$ V) and the other one for breakdown voltage ($f_t = 60$ GHz, $BV_{CEO} = 3.2$ V).

To enhance the RF performance of the low-cost process, the lateral dimensions of the devices can be reduced along with the emitter width, giving values for f_t and f_{max} of 120 and 180 GHz, respectively. The BV_{CEO} value can also be improved within the same process flow to give up to 9 V while maintaining a $BV_{CEO} \times f_t$ product of 220 GHz.

An important part of the process is the HBT-before-CMOS integration scheme. In BiCMOS processes the HBTs are inserted part way through the CMOS flow. The IHP approach of forming the HBTs before the CMOS steps eliminates the effects of the HBT thermal budget on the CMOS devices and allows easy migration of the HBT process as CMOS generations change. The scheme takes full advantage of the inherent stability of the SiGe:C HBTs and their ability to withstand the thermal impact of the CMOS processing steps.

LEDs

The two sessions on LEDs included presentations from Emcore and JPSA on the laser scribing techniques that are helping to improve yields in GaN-on-sapphire LED manufacturing. Pai Hsiang Wang of UEC in Taiwan updated delegates on the company's wafer bonded LED technology, which was announced at CS-MAX 2001 and is now being used to manufacture LEDs with 10 W power output (*Compound Semiconductor* December 2002 p25). The laser scribing and wafer bonding developments are helping to push up the all-important lumens per dollar figure by increasing LED output power and decreasing production costs.

Kelvin Shih of Lawrence Technological University, MI, described a system that he has developed for the direct measurement of the junction temperature in an LED. Previous methods of temperature measurement have been approximate, making it difficult to accurately determine the effect of junction temperature on luminous flux. Junction temperature is an important parameter as the dominant wavelength will increase by 1 nm for every 10 °C rise in junction temperature.

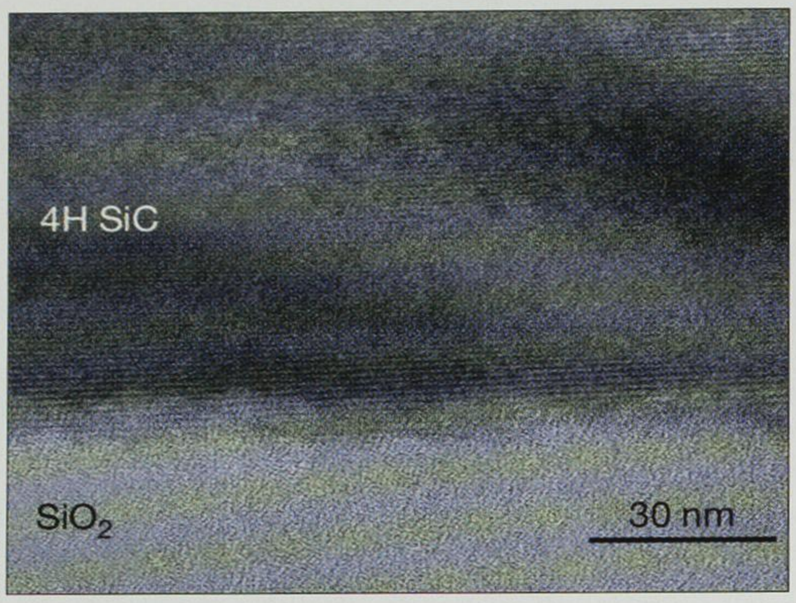
Shih's device helps LED users and manufacturers to determine the best current at which to operate a particular model of LED in order to gain the best light power output. LED brightness increases with drive current up to a peak before tailing off as the junction temperature continues to rise. With careful LED chip and packaging design the heat can be better dissipated and the brightness at a given current can be increased.

The junction temperature measurement device uses two LEDs of the same type; the first is used as an ambient temperature reference driven at a small constant current to prevent self-heating, while the second is driven at an elevated current. The reference LED allows the measurement of the actual rather than approximate relationship between junction temperature and ambient thermal resistance in the test LED. The output of the tester can be plotted in a number of ways, including relative brightness versus current. Shih gave an example of the measurement on two Lumileds Snap 150 LEDs, the first mounted on a PCB and the second on an aluminum substrate (figure 1). For the PCB-mounted LED, the maximum brightness was obtained at 170 mA and was 4.09× that at 20 mA. The junction temperature at maximum brightness was 73 °C above ambient. For the aluminum-mounted LED, the current could be increased to 370 mA before the maximum brightness was reached. At this point the output was 9.94× that at 20 mA, yet the junction temperature was only 61 °C above ambient. Adding a good thermal conductor as a mounting reduced the thermal resistance and lowered the junction temperature for a given operating current, thus prolonging the life of the LED.

From his experiences with the tester, Shih had observed that not only do different color LEDs (AlInGaP-red and InGaN-blue, for example) behave differently, as might be expected, but those operating at the same wavelengths but manufactured by different companies also behave differently.

Heterointegration

The integration of dissimilar materials and device types through hybrid or monolithic technologies is desirable for a number of reasons, and each method has its strengths and weaknesses. Heterogeneous integration, or heterointegration, can be thought of as sitting in between monolithic and hybrid approaches to integration. It generally involves wafer-scale processing and testing of the separate components, but also has many of the advantages of hybrid integration, including the ability to independently optimize the components before integration.



SOITEC

Fig. 2. Soitec is now extending its Smart Cut process originally developed for SOI manufacturing to other semiconductors. In this case bonding a SiC wafer to an oxidized silicon wafer, enabling the original SiC wafer to be reused.

Laser scribing and wafer bonding developments are helping to push up the all-important lumens per dollar figure.

William Waters of Optogration, Newburyport, MA, discussed an epilayer transfer technique that allows the integration of an entire unprocessed epitaxial structure, such as a laser or photodiode, with a circuit or array of circuits (see page 36).

Compound semiconductors on silicon (CSOS) was the subject of a talk by Fabrice Letertre of Soitec in France. Soitec's Smart Cut process for wafer bonding is used for the high-volume production of its SOI wafers. Letertre and colleagues are now extending the process to produce CSOS wafers. The Smart Cut process avoids many of the disadvantages of other techniques for producing CSOS wafers, such as complex buffer layers for epitaxial growth of GaAs-on-silicon and the expensive etch back and thus loss of the compound semiconductor wafer in thin-film transfer techniques.

The Smart Cut process involves ion implantation of the compound semiconductor wafer before it is bonded to the silicon. The bonded structure is then split along the implant peak, leaving a thin compound semiconductor layer on the silicon wafer. After polishing, the original compound semiconductor wafer can then be reused.

The process has been used to demonstrate SiC, InP, GaAs and SiGe on silicon. Letertre mainly discussed the application of Smart Cut to SiC as part of a collaborative project with CEA and LMGP labs in Grenoble, France. The group has successfully bonded 4H and 6H SiC layers to silicon using conducting and insulating bonding layers that are required for different device types (figure 2). One of the aims of the project is to provide a way of making SiC application engineered structures for GaN epitaxy, while reusing the expensive SiC wafer many times. The group has demonstrated GaN growth by MBE onto the bonded SiC layer and is currently investigating MOCVD growth.

The growth of GaAs epitaxial structures on Ge wafers is nothing new and is used in the production of very high efficiency double- and triple-junction solar cells. However, other device types manufactured using GaAs on Ge are not commercially available. Ge substrate manufacturer Umicore hopes to change attitudes and has demonstrated 6 and 8 inch Ge wafers for GaAs epitaxy. Bendix Meulemeester from Umicore discussed the production techniques for large-area Ge wafers and how the wafers could support the development of Ge-based electronics. Meulemeester reminded his audience that the first transistors were made from Ge in the 1940s. Ge channels show up to an 800% increase in carrier mobility over silicon channels, and excellent compatibility of Ge with new high-k dielectrics has been reported. However, Ge is not a common element and there is certainly not enough of it to replace silicon as a base material for microelectronics. If Ge-based devices do emerge, then they are likely to be reserved for high-end applications where cost is of less importance than performance.

Optoelectronics

Susan Lindsay of JDS Uniphase described the design, fabrication and characterization of lenses monolithically integrated with photodiode receivers. After epitaxial growth of the photodiode structure, the InP substrate is thinned and spin-coated on the backside with photoresist. The resist is then patterned into disc shapes and reflowed so that the discs form into spheroids as the molten resist minimizes its surface energy. A reactive ion etch with 1:1 selectivity to resist is used to etch back the InP and resist surface, leaving spheroid lenses of InP topped with resist (figure 3).

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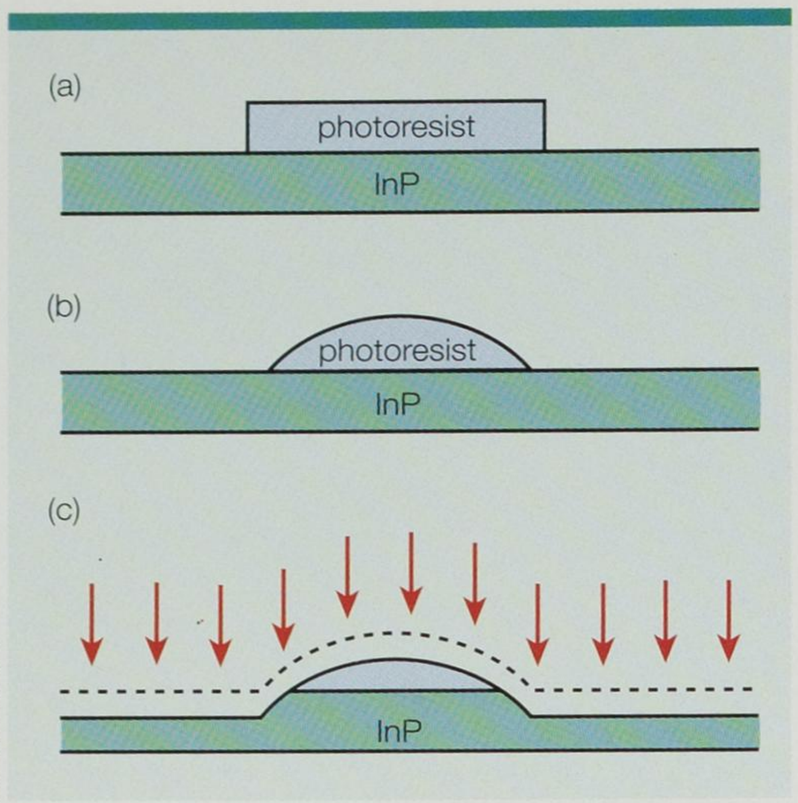
Using the lenses on the illuminated backside of photodiode chips increases the effective area for coupling to other components by 14.9× that of an unlensed chip. Tests have shown that the lens allows a large tolerance in the placement of the chip relative to other optical components so that a more relaxed, cheaper and quicker passive rather than active alignment scheme can be used. This reduces the assembly and packaging costs for fiber-optic receivers.

David Forbes of Alfalight, a manufacturer of aluminum-free lasers, gave an interesting presentation on his experiences of the variation in quality of GaAs wafers from different manufacturers and the impact on laser reliability. The results were surprising given the maturity of GaAs substrate manufacturing technology. The work focused on epi-ready 2 inch GaAs wafers from three different manufacturers, referred to as A, B and C. Vendor C had the worst morphology problems, with epilayers showing a high density of surface defects and haze compared with A or B.

The most remarkable feature observed when growing on wafers supplied by C was the appearance after epitaxial growth of a pattern on the backside of the wafer (figure 4). The pattern was the same shape as the retaining spider in the fluoroware packaging in which the wafers are supplied. Mostly this pattern had no effect on the epilayers, however, in a couple of cases the epilayer showed a PL intensity distribution that matched the spider shape, with the most intense PL coming from within the spider pattern. PL from the backside of the wafer also gave greater intensity inside the pattern. Surface analysis techniques showed that outside of the pattern there was a higher concentration of F, Si, Na and hydrocarbons compared to within the pattern. Forbes suggested this indicated that the containers used by vendor C were outgassing and that the spider was shielding parts of the wafer from contamination. Wafers from A and B showed no backside patterning after epitaxy.

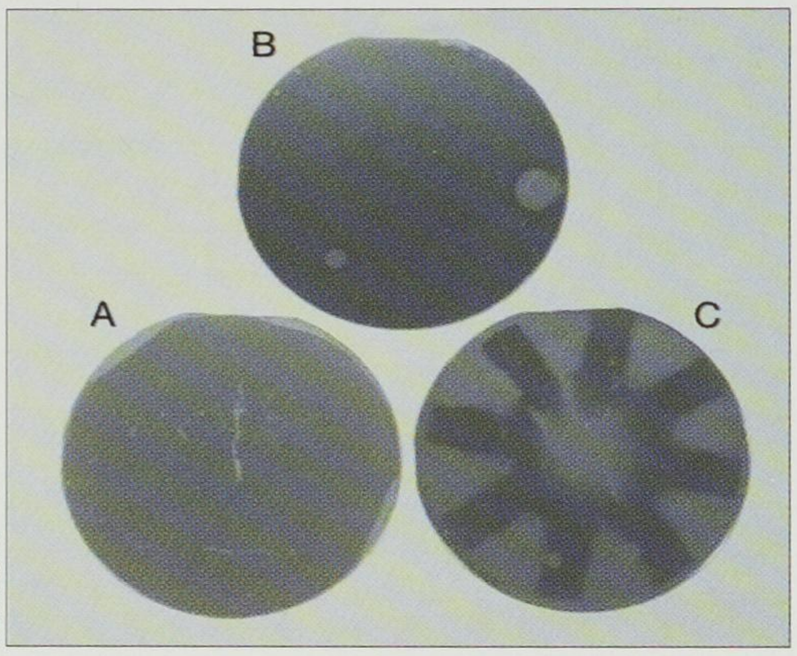
High-stress lifetime testing of 980 nm lasers grown on the three different vendors' substrates was carried out. Lasers on supplier C's wafers failed within 1000 hours, with those fabricated on wafers from A and B showing lifetimes in excess of 1000 hours. With further device development using the substrates from suppliers A and B, high-stress lifetimes of more than 3000 hours have been achieved.

GaAs substrates were also the subject of a presentation by Russ Kremer of wafer manufacturer Freiberger. After discussing the two dominant growth techniques, liquid encapsulated Czochralski (LEC) and vertical gradient freeze (VGF), Kremer talked about the different needs of optoelectronic and microelectronic devices and how these mapped to the properties of the two wafer types. For unipolar devices such as HEMTs and MESFETs, high-resistivity substrates are crucial to reducing parasitic losses during RF operation and also help to lower the turn-on voltage. LEC wafers are the substrate of choice for unipolar devices because of the superior cross-wafer uniformity of the EL2 defect, which is responsible for the resistivity of the material.



JDS UNIPHASE

Fig. 3. The low-cost process for fabricating lenses to give a high effective coupling area. A photoresist layer is patterned into discs on the backside of the InP substrate (a). The resist is heated and the discs form spheroids (b). An etch removes both InP and the photoresist to leave a spherical lens of InP topped with resist (c).



ALFALIGHT

Fig. 4. Backside patterns on wafers from vendors B, C and A after P-containing epitaxy. Wafers from vendor C often show the fluoroware spider pattern after epitaxy.

Bipolar devices such as HBTs and LEDs have been successfully manufactured using both types of substrate, although there is some evidence that VGF substrates are better for HBTs that experience high injection currents. Lasers have a very low tolerance of crystalline defects and are grown onto VGF substrates, where the slow bulk crystal growth results in about an order of magnitude lower dislocations compared with LEC wafers.

Epitaxy

In the last five years the number of specialist epiwafer suppliers has grown considerably, driven by the rapid rise in demand from manufacturers of optoelectronic devices for fiber-optic networks and ICs for wireless communications. Many of these epiwafer vendors are now suffering in the current downturn, but such times also bring opportunity as device manufacturers delay plans to start up or expand their own epitaxy facilities and outsource the work.

Michael Yang of Visual Photonics Epitaxy in Taiwan described how Taiwan has become an important center for high-volume epiwafer production. According to Yang, there are now 134 MOCVD reactors distributed amongst 14 epiwafer vendors, and the number is growing as capacity is expanded to meet the demand for blue LEDs.

The MBE versus MOVCD debate still rages and the main manufacturers of the two types of system were represented at CS-MAX. Bernd Schulte of Aixtron gave a talk describing the various MOCVD options available for the manufacture of just about any device requiring compound semiconductor epiwafers as a starting material. Tom Bird of Veeco argued the case for production MBE systems using the experience gained by laser manufacturer Lasertel of Tucson, AZ, when setting up its MBE facility. Bird presented figures for the operating costs of MBE and MOCVD systems of $12.08 and $19.90 per wafer, respectively. He argued that the less stringent health and safety requirements, coupled with the lower consumption of source materials, could make MBE systems 40% less costly to operate than MOCVD systems. However, Bird's comparison was made between a 7 × 6 inch MBE and a 5 × 6 inch MOCVD tool for electronic applications. The figures may be narrower if a 7 × 6 inch MOCVD reactor was used for the comparison.

The 260 page CS-MAX 2002 Technical Digest is now available to buy. See ad on page 13 or visit compoundsemiconductor.net/csmax.

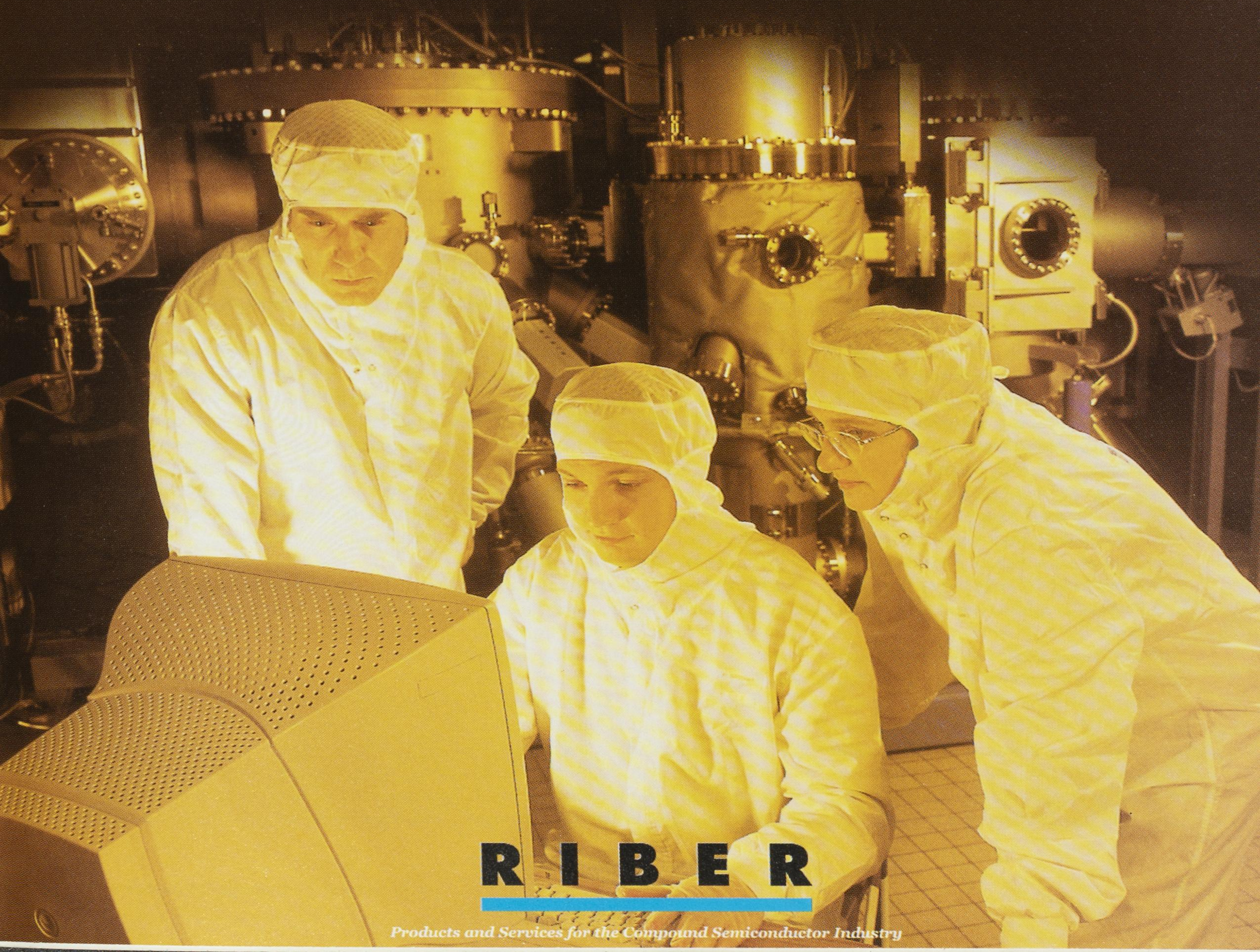
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Products and Services for the Compound Semiconductor Industry

Wafer-scale processing leads to low-cost optical integration

A novel epitaxial layer transfer technology could provide the key to low-cost, wafer-scale integration of optical components, write **William Waters** and **William Clark** from Optogration.

For decades silicon technology has provided a fertile landscape for highly efficient semiconductor manufacturing. In the current high-tech sandstorm, new markets are shouting out for the advantage offered by photonics, but this advantage has so far proved to be elusive. The success of the silicon industry lies in the economies of scale and high functionality achieved through complex circuitry and high-precision, high-yield processes.

Clearly, too few similarities exist between the silicon semiconductor industry and emergent photonics. While silicon manufacturers build systems-on-a-chip, photonics manufacturing is bogged down at the breadboard stage of assembly and functionality. The billion-dollar question is how can the photonics industry achieve a silicon-like economy of scale and a level of automation that will provide the dense, functional modules necessary to propel it forward technically and financially?

For photonics the fundamental problem is that non-silicon-based compound semiconductor material systems must be used to perform the required optical functions. An example is a 1R receiver; this device requires a photodiode to detect the appropriate wavelength and a transimpedance amplifier (TIA) to amplify and convert the photo-generated current to a usable voltage for the system. The photodiode for C- and L-band networks is comprised of an InP-based *pin* photodiode, while the TIA can be silicon, GaAs or even SiGe. Receiver module manufacturers purchase and/or manufacture photodiodes and TIA chips separately, and then practice hybrid assembly techniques to complete the module (see figure 1a).

These sub-assemblies add large parasitics that limit the bandwidth of the components to less than 15 GHz, and make them very costly to produce. Moving forward, photonic devices are expected to operate at up to 40 Gbit/s and it is obvious that the current form of photonic component manufacturing is inadequate. Some photonic component companies are scrambling for a solution to combine optical functions with electronic components as efficiently and cost-effectively as possible. Others are simply stepping away from the business.

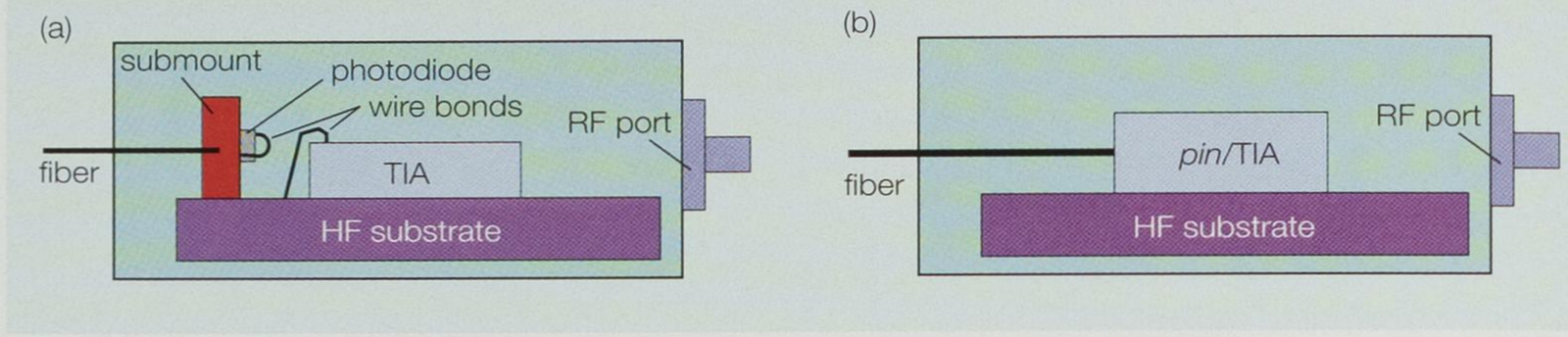


Fig. 1. Photoreceivers fabricated using hybrid manufacturing (a) and ELT integration (b).

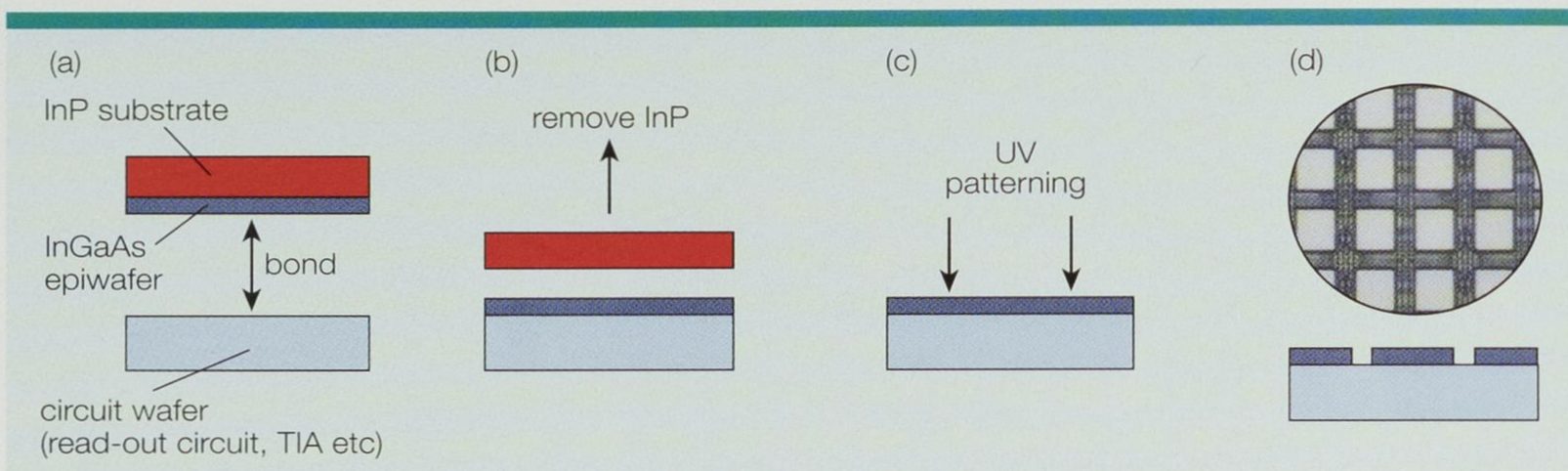


Fig. 2. The basic concept of the ELT process. An InGaAs epiwafer and a circuit wafer are bonded together (a) and the InP substrate handle wafer is removed, leaving only the InGaAs epilayer on the circuit wafer (b). The InGaAs layer is patterned using conventional photolithography (c), leaving optically isolated photodetectors fully integrated with the ASIC (d).

Wafer-level integration

Efficient integration of components offers a way to increase network system functionality and reduce the manufacturing costs of these highly integrated components. To achieve component integration, manufacturers are implementing two main methodologies: monolithic and hybrid. The monolithic approach uses a single material system to fabricate several components together on a common substrate, hence it has limited flexibility. The material system chosen must be able to support electronic circuitry and also emit, detect and guide light of the proper wavelength. Each element or subcomponent must be designed and optimized as a collective unit in a material system that may not be the best choice for that component, leading to inevitable design compromises.

The hybrid approach relies on the assembly of sub-components that have been optimized independently in their own material system; however, current hybridization techniques impose limits on physical size and on electrical performance, and suffer from high manufacturing costs.

Wafer-level heterogeneous integration technology is essential to fully harness the potential of high-performance optoelectronic components and the manufacture of cost-effective sub-modules for next-generation communication networks. However, although the advantages are obvious, the methodology has so far been elusive.

Optogration, a start-up company based in Newburyport, MA, has developed a proprietary, wafer-scale integration technique that enables the direct fabrication of optical devices

on foundry-processed semiconductor wafers. The technique is called epitaxial layer transfer (ELT), and allows the integration of an entire unprocessed epitaxial wafer containing optoelectronic structures such as LEDs, lasers or photodiodes with any application-specific circuit or array of circuits. Subsequently, devices or circuits are fabricated directly on the host wafer using standard photolithography.

Figure 2 illustrates the basic concept of the ELT process. In this example, an InGaAs-based photodiode epiwafer on an InP substrate is bonded to a circuit wafer using a proprietary bonding layer. The InP substrate is then removed, and the epilayer patterned and processed, creating photodiodes in precisely defined areas of the underlying circuit wafer. Unwanted epitaxial material between the photodiodes is removed. The photodiode structures are individually isolated, thereby reducing all resistive, capacitive and inductive parasitics between the devices (passive or active) and the circuit.

The transferred epilayer is thin and semi-transparent, allowing precise alignment of the optical device to the host circuit. The size and alignment of the optical devices is limited only by lithographic constraints. This approach varies significantly from other wafer-bonding techniques, such as those used to manufacture CdHgTe detector arrays, where detectors must be fabricated on the host wafer prior to bump-bonding to a silicon read-out (RO) IC. Therefore precise alignment of the two wafers becomes problematic as dimensions decrease.

Commercial devices

To demonstrate the advantages of our technology, a fully functional 320 × 256 passive imaging receiver was fabricated with 25 μm square pixels on a 30 μm pitch (see figure 3). This receiver was fabricated with the ELT process by integrating high-speed InGaAs

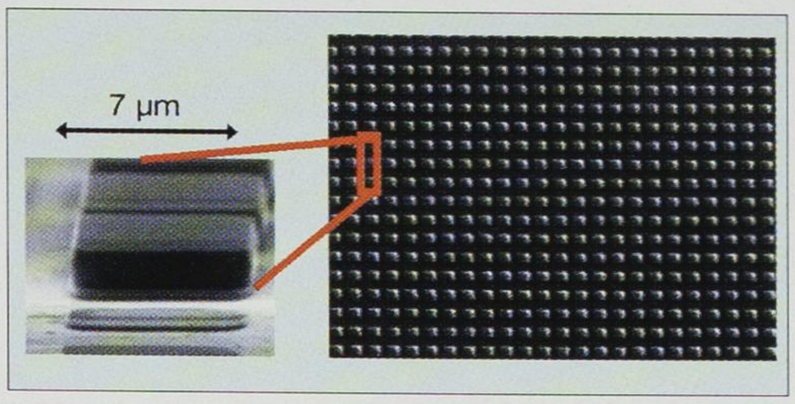


Fig. 3. SEM micrograph of 7 μm diameter *pin* photodiodes with 10 μm spacing.



Fig. 4. Image of a model F-16 demonstrating the functional pixel yield (> 99%) of an InGaAs detector array integrated with an off-the-shelf ROIC using the ELT process.

MSM photodiodes with an off-the-shelf silicon ROIC manufactured by Indigo Systems (part #ISC9705). Figure 4 shows an image from a first-generation receiver, illustrating the successful integration to a commercial ROIC. It demonstrates that the technology is adaptable to commercial circuits and that costly circuit redesigns are not necessary for circuit manufacturers to utilize the process.

Optogration has also integrated InGaAs *pin* photodiodes and avalanche photodiodes with arrays of silicon- and GaAs-based TIAs for optical networking systems. A 10 Gbit/s TIA with a transimpedance of 1000 Ω is currently in manufacturing, with beta testing scheduled for the first quarter of 2003. The design utilizes a fully depleted 0.18 μm SOI process for the TIA, chosen for its high-frequency operation, high yield and low cost. A discrete design, and 4 × 4, 2 × 16 and 2 × 32 arrays, will be delivered from manufacturing in early 2003.

Figure 1b shows a photoreceiver utilizing ELT integration. Compared with the hybrid assembly in figure 1a, this integrated device does not contain a submount or wire bonds, which add to manufacturing costs. To our knowledge this will be the first fully integrated *pin*-TIA receiver array made with fully depleted SOI technology capable of 10 Gbit/s per channel operating in the C and L bands.

Future integration

We view compound semiconductor integration as a packaging problem at the sub-wafer level. Heterogeneous integration technology is essential to fully harness the potential of high-performance optoelectronic components and the cost-effective manufacture of sub-modules for next-generation communication networks. The ELT process and the current implementations illustrate the vitality of this technique as an effective manufacturing tool across the compound semiconductor technology spectrum. We have demonstrated that the technique is capable of integrating devices as small as 7 μm per side and as large as 100 μm per side with silicon and GaAs ICs. Our demonstrations have initially focused on integrating optical detectors and electrical circuits, however, ELT has the potential to affect a much broader range of optoelectronic components. Going forward, we envision ELT as an enabling technology that offers the photonics industry a truly cost-effective and manufacturable method of delivering highly integrated OEICs with system-on-a-chip functionality.

William Waters and William Clark are with Optogration of Newburyport, MA. Tel. + 1 978 394 4167. Email william@optogration.com.

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New MSA for tunable lasers

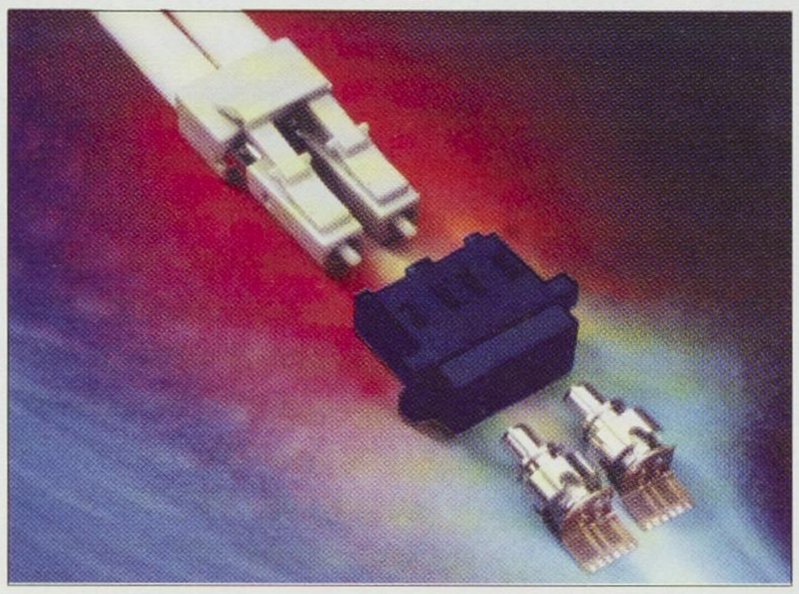
Agility, Alcatel Optronics and Bookham have launched a multi-source agreement (MSA) for tunable laser sources. The MSA defines a small-form-factor plug-in subsystem, including a tunable CW laser with embedded electronics that allows automatic wavelength setting and locking. Covering the C- and L-bands, these standardized products include 10 and 20 mW CW tunable lasers with 25 and 50 GHz wavelength spacing for core DWDM applications. They have a compact footprint with maximum dimensions of 76.2 × 50.8 × 12.7 mm and a dense 40-pin connector for electrical interface.

By standardizing the tunable function through a subsystem, the MSA members allow the use of different, mature technologies for the tunable laser, while guaranteeing the best optical performance at optimized costs. This MSA is a significant step towards the adoption of the tunable function by system manufacturers, which require better flexibility, easier inventory management and reduced costs.

OEpic reveals 850 nm OFE chipset

OEpic of Sunnyvale, CA, has introduced an 850 nm optical front-end (OFE) chipset, incorporating flex board interconnection technology, known as TO-Flex, for low-cost 10 Gbit/s transceivers. The OFE chipset comprises a receiver containing a *pin* photodetector and InGaP HBT TIA, together with an 850 nm VCSEL transmitter, and is priced at $149.

"Our intent is to enable transceiver manufacturers to achieve full 10 Gbit/s performance at a 1 Gbit/s cost target," said Yi-Ching Pao, CEO of OEpic. "With TO-Flex technology, OEpic has extended the low-cost TO platform into the 10 Gbit/s market for the first time."



OEPIC

The TO-Flex platform permits the use of OEpic's optical front-end chipset in all current 10 Gbit/s transceiver MSAs.

Axcel Photonics' 300 mW pump laser obtains qualification

Axcel Photonics, a developer of semiconductor laser diodes based in Marlborough, MA, has received qualification of its 980 nm pump laser diode for 300 mW operation. The lasers have been tested according to Telcordia document GR-468 at 300 mW and at a heatsink temperature of 85 °C for more than 7000 hours without measurable degradation. A failure rate below 300 FIT is predicted for room-temperature operation over a period of 25 years.

"This level of reliability and performance has not been achieved at any recent start-up company," said Wei Gao, CEO, president and founder of Axcel. "This validates the capabilities of the [laser] facet and our patented device design."

Bandwidth9 to use CyOptics modulator

CyOptics is to supply Bandwidth9, a manufacturer of VCSEL-based tunable laser transmission products, with its EAM2010 amplified electroabsorption modulator. The EAM2010 is a monolithic InP-based device with built-in amplification, enabling its use with low-power light sources. The EAM2010 also has integrated power monitoring and allows dynamic control of transmitter output power. It is being used in Bandwidth9's MetroFlex G2 tunable transmitter product, which provides uncompensated reach beyond 600 km at 2.5 Gbit/s.

"Wide tunability of a VCSEL, combined with the extended reach of an amplified EAM, enable a universal transmitter module that can support any ITU channel and any reach," said Vladimir Kozlov, senior analyst at RHK Optical Components. "That is exactly what system vendors are looking for."

Opto Speed teams up with Infomax

Opto Speed (Zurich, Switzerland) and Infomax Optical Technologies (Taoyuan, Taiwan) have agreed to collaborate on the manufacturing and sales of their products. Opto Speed manufactures SOAs, InGaAs photodetectors and Fabry–Perot and DFB lasers, while Infomax offers complementary products including *pin*/TIA modules, transceivers and laser modules. Opto Speed will benefit from Infomax's packaging expertise, enabling it to offer lasers and *pin* detectors in TO cans, and also receiver and transmitter optical sub-assemblies. Infomax will also be able to expand its product portfolio under the agreement.

In brief

- **DenseLight Semiconductors**, a manufacturer of InP-based optoelectronic devices and ICs based in Singapore, has appointed **William Diamond** as its new CEO. Diamond was most recently CEO and president of Wavesplitter Technologies.

- **Ken Jones**, former GM of the Advanced Transmission Division and VP at Vitesse, has been appointed president and CEO of **Essient Photonics**, a supplier of integrated III-V optoelectronic components.

- **Multiplex** has been awarded ISO 9001 certification for the design, manufacture and support processes for its optoelectronic devices, modules and subsystems. The ISO certificate covers all of Multiplex's three facilities in South Plainfield, NJ.

- **Opto Speed**, a manufacturer of InP-based optoelectronic components, has signed a distribution agreement with Unistand Technology to sell and support Opto Speed's suite of products in the Taiwan market.

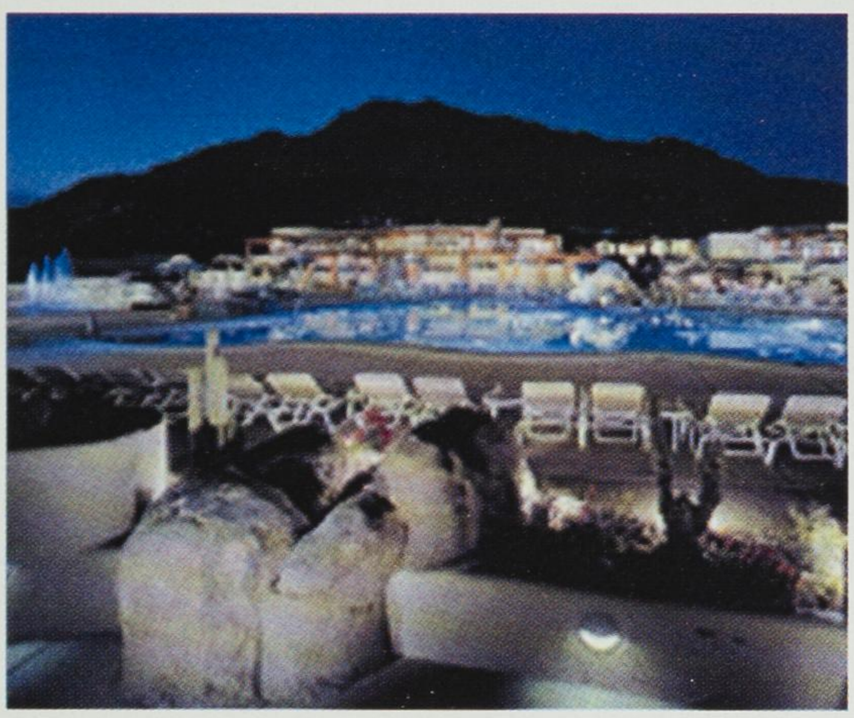
- **Modulight** has signed a distribution agreement with High-Tech Corporation to sell and promote Modulight's products, including optoelectronic (OE) epiwafers, OE chips and packaged components, in the Japanese market.

2003 International Conference on Compound Semiconductor Manufacturing Technology
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During recent years, market forces have produced a slowdown in the industries served by the compound semiconductor community. Looking forward to the coming turnaround, we must redouble our efforts to develop techniques and processes to drive our cost lower and reliability higher to meet the competitive challenge.





In our 18th year, the 2003 MANTECH conference will present:

❑ **Technical Sessions:** Over 80 papers addressing manufacturing, processing, reliability, device technologies, optical devices, materials (GaAs, InP, GaN, SiC, SiGe) and packaging. The plenary session includes talks by internationally-recognized technologists. Invited talks will also be presented on subjects including a review of the technology in Asia, the outlook for military technology, and a variety of other important topics.

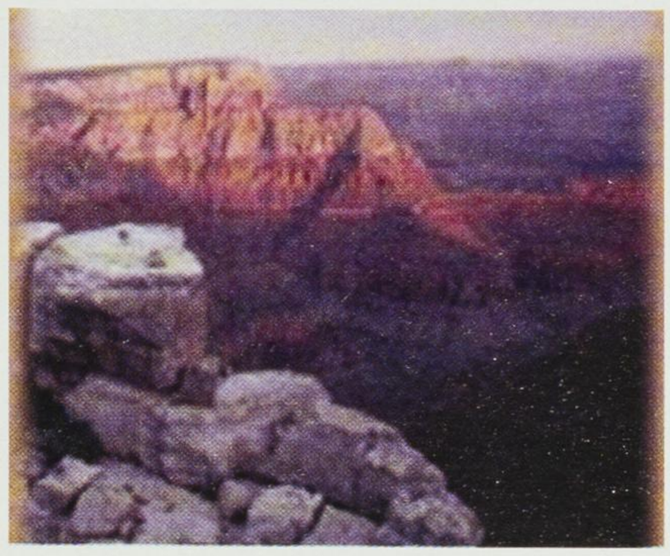
❑ **Workshop:** GaAs MANTECH will again sponsor an intensive one-day workshop led by industry experts on May 19th. Subjects covered will be:

- Integrated Circuits Processing Tutorial
- Wireless Principles (for Dummies)
- Power Amps for Wireless Applications
- GaN
- SiGe
- MEMS
- Advanced Interconnect for Compound Semiconductors

❑ **Interactive Forum:** This popular session provides an opportunity for all conference attendees to engage in personal discussion and information exchange with the authors/presenters in an open and informal environment.

❑ **Rump Sessions:** Following on last year's success, a series of rump sessions are again planned as an opportunity for free-wheeling discussion of important issues.

❑ **Exhibits:** MANTECH is the premier venue bringing the world's leading compound semiconductor manufacturers together with their suppliers. In this one location you will get to see the latest equipment and manufacturing solutions. Over 100 equipment and materials exhibitors are expected to participate.



❑ **Ugly Picture Contest:** This is a very entertaining and informative contest. It gives everyone a chance to benefit from their problems by winning a prize for the most photogenic example of a manufacturing problem and its solution.

❑ **Social events:** The Exhibits Reception, the International Reception, and the Awards Luncheon provide opportunities for attendees to communicate with international colleagues and develop business contacts.

****For registration and Advance Program, please visit us at www.GaAsMANTECH.org**

SAES claims that Aeronex's patent infringement challenge is frivolous

While the arguments over the intellectual property surrounding GaN-based optoelectronics have largely been resolved, in another area of the compound semiconductor world such disputes are ongoing. Rival gas purifier manufacturers SAES Getters and Aeronex are continuing to argue over the ammonia purification products that they manufacture.

SAES Getters of Italy and its US subsidiary SAES Pure Gas have informed their rival, San Diego-based Aeronex, that they believe that patent infringement claims made by Aeronex are frivolous. SAES originally filed suit against Aeronex charging that Aeronex's line of ammonia purifiers infringed its US patent no. 5,716,588 (*Compound Semiconductor* June 2002 p25). In August 2002, Aeronex filed a countersuit claiming that SAES' ammonia purification products infringe on Aeronex's US patent no. 6,241,955 (*Compound Semiconductor* September 2002 p29).

"We were quite astounded by Aeronex's claim of patent infringement," remarked Tim Johnson, business area manager for purification systems at SAES Pure Gas. "First Aeronex copied our product, then they asserted that our product infringed their 'improvement' patent. We pointed out to Aeronex that our product was on sale over one year before the filing of their patent and thus it was logically impossible that our product was infringing that patent." Aeronex, however, is continuing to assert that its patent is both valid and infringed by the SAES product.

SAES has succeeded in obtaining a greatly accelerated schedule from the court and says that it expects to resolve these issues quickly, although no time scale has been publicly announced yet.

BOC Edwards starts up ammonia plant

BOC Edwards has begun high-purity ammonia production through its BOC Lienhwa joint venture at its electronic materials plant in Taiwan. The facility is designed to produce high-purity ammonia for the semiconductor, liquid-crystal and flat-panel display industries in Taiwan, Singapore, Malaysia and China. The plant has a production capacity of over 200 metric tons per year and is presently producing qualification cylinders for customers.

RSoft acquires Artis

RSoft Design Group, which supplies design and business analysis software to the telecommunications and photonics industries, has acquired Artis, a software company with products including tools for the simulation of optical communication systems and the design of optical networks. The acquisition includes the transfer to RSoft of Artis's intellectual property and key employees in sales, technical support and development.

Luxtron moves HQ

Luxtron, a provider of *in situ* fiber-optic temperature sensors to the semiconductor and optoelectronics industries, has relocated its corporate headquarters. The new 33,000 sq. ft facility at 3033 Scott Blvd, Santa Clara, CA, features newly renovated manufacturing facilities, including 4600 sq. ft of R&D and applications engineering space.

Equipment sales

● A **Thomas Swan Scientific Equipment** 7 × 2 inch close-coupled showerhead MOCVD system has been successfully commissioned at **Kansas State University**. The reactor will be used for the R&D of high-efficiency GaN-based UV, blue and green LEDs, and also single-chip arrays of LEDs for display applications.

● The COBRA Inter-University Research Institute on Communication Technologies based at **Eindhoven University of Technology** in the Netherlands has installed an **Aixtron** AIX 200/4. The reactor will be used for the development and production of GaInAsP and GaInAsN lasers emitting in the 1.3 to 1.5 μm region, and also for the development of monolithically integrated active and passive devices produced by epitaxial regrowth.

● **The National Cheng Kung University** in Taiwan has ordered an **Aixtron** AIX 200 for the development of GaInAsN-based optical and electronic communications devices, such as long-wavelength VCSELs and HBTs.

● A number of Taiwanese companies and laboratories have purchased processing tools from Oxford Instruments Plasma Technology (OIPT). **Epitech** has taken delivery of a Plasmalab System100 etching tool for etching features in GaN-based devices and SiO_2 and Si_3N_4 masks in its LED manufacturing facility in Tainan.

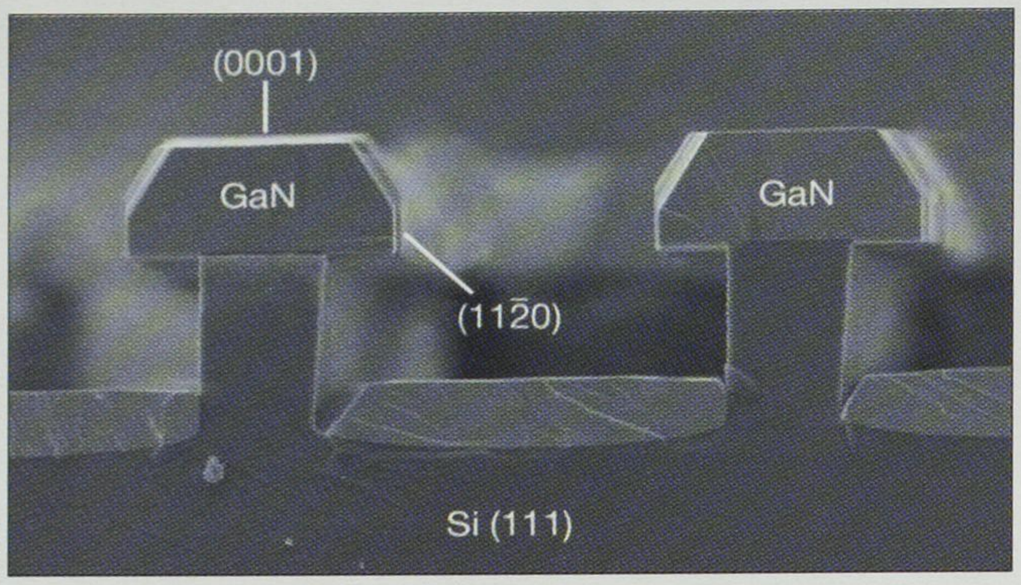
ITE Compound Semiconductor has received a Plasmalab 80plus PECVD tool from OIPT for use in its LED manufacturing facility located in Hsinchu. The equipment is used for the deposition of SiO_2 and Si_3N_4 masks and device passivation on small batches of 2 and 3 inch wafers.

OIPT is to supply a Plasmalab System100 to the **National Nano Device Laboratory** in Tainan for deep reactive ion etching of Si, Si_3N_4 and SiO_2. A second chamber on the system allows the PECVD of Si_3N_4 and SiO_2. The tools will be used for the development of products such as photonic crystals for waveguides and sensor switches using MEMS technologies.

● **Emcore** has recently sold an E300 GaNzilla MOCVD production tool to **Seiwa Electric** of Japan. Seiwa will use the large-scale GaN deposition platform in its high-brightness LED production program. **South Epitaxy Corporation** has announced the successful installation and start-up of a GaNzilla MOCVD reactor at its blue and green LED chip production facility in Tainan, Taiwan.

Tilt eliminated in GaN cantilever epitaxy

Cantilever epitaxy (CE) is a single run selective-area growth technique that is used for dislocation reduction in GaN. Periodic parallel mesas are formed by etching the silicon substrate. Growth occurs vertically and laterally from the silicon mesas to span the trenches, creating a coalesced film (see figure). The GaN spanning the trenches has a dislocation density several orders of magnitude lower than the GaN directly above the silicon mesa.



UCSB

The lateral/vertical growth rate ratio during CE can be controlled by the V/III ratio. The cantilever sidewalls grow in the (11$\bar{2}$0) direction and have inclines caused by the presence of silicon in the reactor from the substrate.

CE extends the early work done on dislocation reduction in GaN via lateral epitaxial overgrowth (LEO). The crystallographic tilt in the GaN wings observed in LEO has been attributed to interactions between the wing region and the dielectric mask. CE became an attractive alternative to LEO as a regrowth is not required and wing/mask interactions are eliminated because the wing region in CE hangs freely over the etched trench. A group of researchers from the University of California, Santa Barbara (UCSB) have shown that despite the absence of a wing/mask interface, there can be up to 1° of crystallographic tilt in the GaN wings during CE. If tilt exists, threading dislocations are created at the coalescence front, reducing the usable area for the growth of device structures. However, further work at UCSB has shown that the tilt can be eliminated by initiating lateral growth with a low lateral/vertical growth rate ratio (*Appl. Phys. Lett.* 2002 **81(19)** 3558).

The ratio of growth rates can be controlled by adjusting several growth variables including V/III ratio, temperature and pressure. By starting lateral growth with a low V/III ratio of 646, tilt was reduced to within the mosaic of the crystal as observed by X-ray diffraction. The relationship between the degree of tilt and the width/height ratio of the cantilever was also studied for constant and variable V/III ratios. It was found that once tilt had been eliminated using the initial low V/III ratio, the V/III ratio could be raised in later stages of growth to enhance the lateral growth rate for rapid film coalescence while keeping the tilt below 0.2°.

New approach to 1300 nm dilute nitride DFB lasers

Single-mode lasers emitting at 1.3 and 1.55 μm are the light sources of choice for fiber-optic transmission systems, and are almost exclusively InP-based. GaInNAs is being investigated for this application because it can be grown on lower cost GaAs substrates and promises improved high-temperature performance due to better electron confinement.

The conventional approach for distributed feedback of etching a grating into the laser waveguide raises some fundamental problems, such as low single-mode yield, longitudinal spatial hole burning and the need for an epitaxial overgrowth process. All these limitations are eliminated by a new process that uses metal gratings applied laterally to the laser ridge. Furthermore, this process can easily be applied to any material system.

A research team from Nanoplus and the University of Wurzburg in Germany, has made the first demonstration of 1.3 μm GaInNAs DFB laser diodes under CW operation employing this new approach (*Appl. Phys. Lett.* 2002 **81(23)** 4330). The uncoated and unmounted 800 × 2 μm^2 SQW devices showed threshold currents as low as 28 mA, efficiencies as high as 0.32 W/A and side-mode suppression ratios greater than 44 dB. DFB lasers with different metal grating periods fabricated from the same wafer emitted in the 1271–1304 nm range. These results clearly show the potential of GaInNAs as an active layer material for single-mode edge emitters in the 1.3 μm optical fiber window.

The researchers are now working to further increase performance in the 1.3 μm range, as well as extending this GaAs-based approach into the 1.55 μm region. New quantum-well designs and laser structures are currently being investigated.

Ni/ITO contacts improve light output from GaN LEDs

Conventional nitride-based LEDs use semi-transparent Ni/Au on Mg-doped GaN as the p-contact material. However, the transmittance of such contacts is only around 60–75%. Although the transmittance can be increased by reducing the Ni/Au layer thickness, the contact reliability becomes an issue when the contact layer is too thin. A research team from the National Cheng Kung University and South Epitaxy in Taiwan has studied the use of Ni/ITO instead of Ni/Au as an ohmic contact on p-GaN (*Phot. Tech. Lett.* 2002 **14(12)** 1668).

The Ni/ITO films were deposited onto p-GaN films and/or glass substrates by electron beam evaporation at 250 °C in an O_2 atmosphere. It was found that the normalized transmittance of Ni/ITO film reached 87% at 470 nm, which was much larger than that of a Ni/Au film. It was also found that the specific contact resistance was 5×10^{-4} and 10^{-3} Ωcm^2 for Ni/Au and Ni/ITO on p-GaN, respectively. Nitride-based LEDs with the two different contact types were also fabricated. It was found that the forward voltage at 20 mA of LEDs with Ni/Au and Ni/ITO p-contacts was almost the same, but the output power at 20 mA was 5.26 mW and 6.59 mW for LEDs with Ni/Au and Ni/ITO contacts, respectively.

During room-temperature lifetime testing, it was found that after 1100 hours at 20 mA drive current, the luminous intensity decayed by 24% and 19% for the LEDs with Ni/Au and Ni/ITO contacts, respectively.

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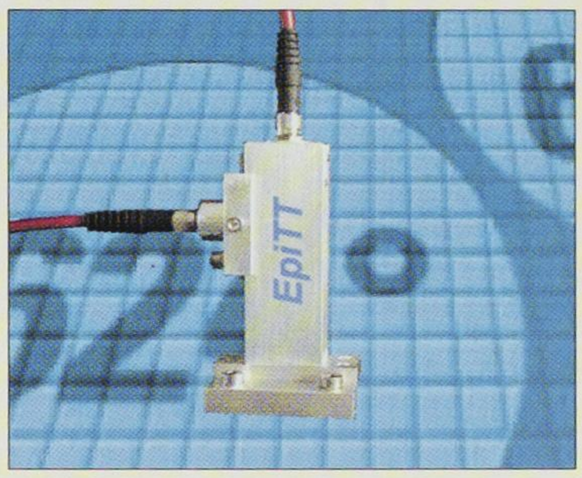


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New *In Situ* Sensor

LayTec GmbH

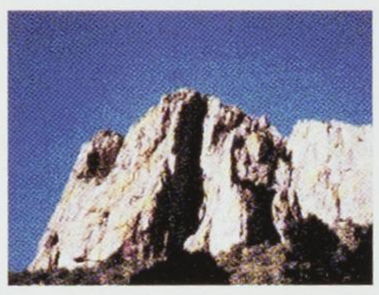
To compliment its unique series of *in situ* sensors, LayTec now offers a double-wavelength reflectometer including true temperature measurement. The **EpiTT** system is specially designed for production-type MOCVD and MBE applications, offering accurate surface temperature measurements (better than ±1 K) and precise growth rate analysis – all in real-time and wafer-selective! Currently two versions are available: one for InP- and GaAs-based materials and one specially optimized for GaN applications. The **EpiTT** comes in a complete set with an easy-to-adjust optical head, a 19" electronic rack and a control computer.



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Invited Speakers	Topics
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Mark Bohr, Intel,	**SiGe technology for 90nm Strained CMOS**
Paul Kempf, Jazz Semi,	**Manufacturable 200GHz SiGe BiCMOS**
Holger Juergensen, AIXTRON,	**Si-based HeteroWafer® Technology**
Gene Fitzgerald, AmberwaveSystems,	**Ultra low defect SiGe relaxed buffers**
Nelson Rowell, NRC Canada,	**Optical Characterisation of SiGe/Si**
Klara Lyutovich, U of Stuttgart,	**Ultrathin SiGe Virual substrates**
Naoharu Sugiyama, Toshiba & MIRAI,	**SiGe on SOI for CMOS**
Doug Paul, Cambridge University,	**SiGe Quantum Cascade Terahertz**
Wei Xin Ni, University of Linkoping,	**Optoelectronics on Silicon**
Didier Dutartre, ST Microelectronics,	**Advanced SIGe BiCMOS**
Larry Larson, UC San Diego,	**SiGe vs CMOS vs GaAs for RF & wireless**
Ken Rim, IBM,	**Strained Si for sub 100nm CMOS**
Tony Peaker, UMIST,	**Defects, Diffusion and Dislocations in SiGe/Si**
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Cree results lift January gloom

In the December 2002 quarter, Cree set company records for revenue and for the quantity of LEDs shipped, while Agere's opto business is expected to boost TriQuint's revenue in the current quarter.



As this issue went to press, the first company earnings for the December 2002 quarter were being released. On January 17, Cree was the only compound semiconductor-related stock to rise in a market depressed by bad news from Microsoft, AMD, IBM and GE. The previous day, Cree had reported a 16% sequential increase in revenue over the September 2002 quarter, setting a company record of $56.7 million in quarterly revenues. The results were based on a 15% sequential rise in unit shipments of LEDs, due to continued demand from handset and automotive applications. Going forward, Cree is targeting a further 5% revenue growth in its LED business for the current quarter.

Market overview

Company	*Symbol*	*Closing price on Jan 17*	*52-week low–high*	*Market cap**
GaAs IC companies				
Anadigics	ANAD	2.41	1.59–14.22	73.7 m
Celeritek	CLTK	6.50	5.01–11.31	80.0 m
Endwave	ENWV	1.24	0.32–5.60	11.1 m
RF Micro Devices	RFMD	6.85	5.16–22.19	1.159 bn
Sirenza Microdevices	SMDI	1.89	1.10–7.62	56.3 m
Skyworks Solutions	SWKS	8.16	2.89–22.00	1.125 bn
TriQuint	TQNT	3.82	2.55–13.09	506.1 m
Vitesse	VTSS	2.165	0.62–13.42	438.8 m
Opto companies				
Agilent	A	18.05	10.50–37.99	8.430 bn
Alcatel Optronics	ALAO	4.25	1.50–7.49	70.1 m
Cree	CREE	18.66	8.99–25.42	1.358 bn
JDS Uniphase	JDSU	2.75	1.58–8.41	3.890 bn
Semiconductor materials and equipment companies				
ATMI	ATMI	19.60	11.75–37.10	600.6 m
AXT	AXTI	1.44	0.94–12.20	32.4 m
Emcore	EMKR	1.77	0.98–11.15	65.2 m
Kopin	KOPN	3.999	1.93–11.73	277.5 m
Tegal	TGAL	0.60	0.13–1.71	9.2 m
Trikon	TRKN	5.67	3.25–15.90	79.5 m
Veeco	VECO	14.82	9.14–38.80	431.9 m
European companies (currency data in €)				
Aixtron	AIXG.F	4.65	4.03–28.20	289.2 m
Bede	BED.L	0.39	0.23–3.21	10.95 m
Bookham	BHM.L	1.16	0.60–2.78	240.0 m
Filtronic	FTC.L	1.38	0.39–6.77	101.4 m
IQE	IQE.L	0.08	0.05–2.96	14.7 m
Picogiga	PGIG.LN	0.42	0.33–5.62	2.7 m
Riber	RIBE.LN	0.93	0.55–5.66	17.5 m
STS	SRTS.L	0.12	0.08–2.60	4.47 m

**Market capitalization = # shares × current share price.*

TriQuint completes Agere purchase

In the first quarter of 2003, TriQuint will begin to see the effects of the acquisition of Agere's optoelectronics business, which was completed on January 2. Excluding the Agere business, TriQuint estimated that its revenue for the first quarter of 2003 would be down by approximately 10% compared with the fourth quarter of 2002, reflecting seasonal trends in the wireless handset market. Including the Agere business, TriQuint's revenue is expected to be up by approximately 5% compared with the December 2002 quarter, and up by around 20% over the March 2002 quarter. However, TriQuint will incur losses due to the Agere acquisition; the company is projecting an EPS loss of approximately 8 cents for the first quarter of 2003. This excludes any charges for the write-off of acquired in-process R&D.

Materials and equipment

X-ray equipment supplier Bede reported revenues of £4.95 million ($7.68 million) for the nine months ended September 30, 2002, representing a 9% increase over the year-ago period. Sixty-three per cent of total revenues came from Bede's successful entry into the high-volume silicon manufacturing market, while revenues from non-semiconductor markets grew to 22% of total sales. The company recorded a pre-tax loss of £2.5 million for the period, and a loss per share of 8.5 pence.

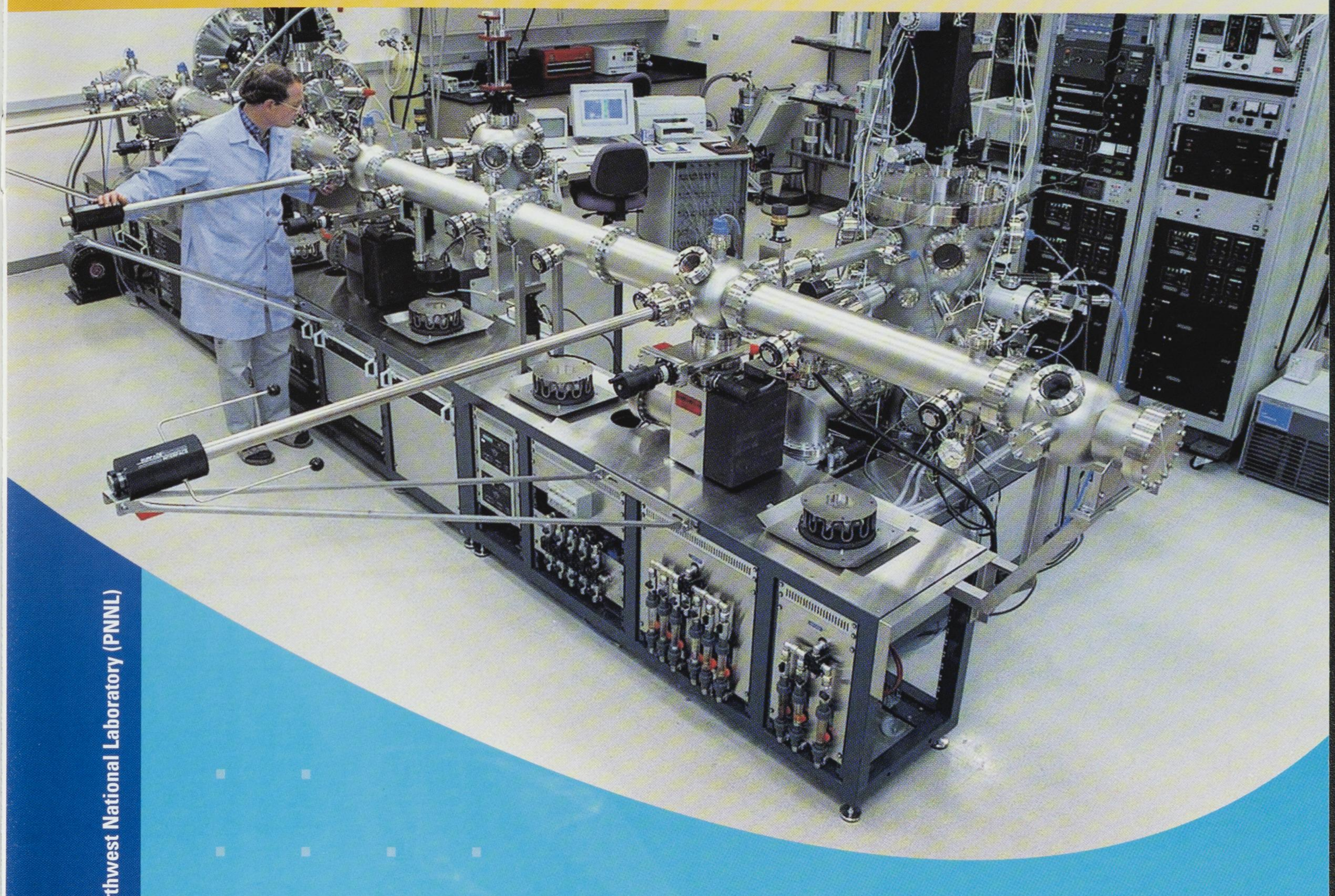
Updating its forecast for the December 2002 quarter, AXT slashed its revenue guidance to $11.8 million – $12.2 million, down from the previous range of $13.5 million – $14.2 million. This is largely as a result of continued price reductions and lower order volumes in AXT's substrate business.

Emcore's annual report for the year ended September 30, 2002, revealed some interesting facts. Systems-related revenues were $35.9 million, or 41% of total revenue, down 73% compared with fiscal 2001. The number of MOCVD production systems shipped decreased 81% from 89 systems in fiscal 2001 to 17 systems in fiscal 2002, at an average selling price of $1.4 million.

During fiscal 2002, Emcore invested approximately $0.4 million in Qusion Technologies, a Princeton, NJ, start-up specializing in the monolithic integration of optical components. In September 2002, Emcore and its other investment partners determined that they would no longer provide additional funding to continue the development of Qusion's products, and consequently Qusion decided to close the business. Emcore purchased all of Qusion's intellectual property and wrote off its entire investment.

Spintronics Research

Proven Technology for Demanding Materials



Courtesy: Dr. Scott Chambers, Pacific Northwest National Laboratory (PNNL)

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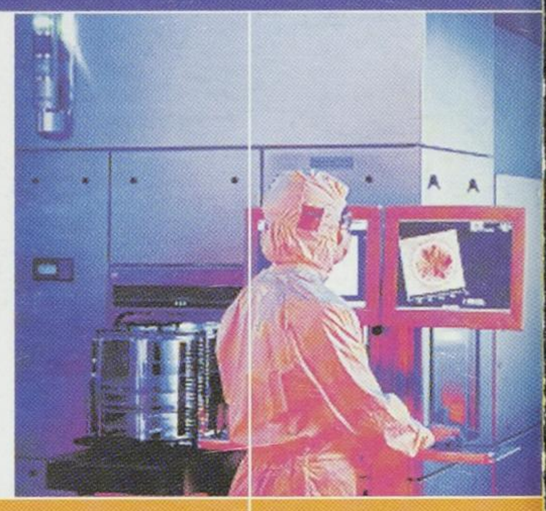
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INSTRUMENTS

2000 Expanded lead in R&D/components
2001 Redefined production MBE
2002 Established MBE leadership
2003 Applied Epi is now Veeco

21st century MBE has arrived.



Veeco



1986 1990 1994 1998 2000 2002 2004

Applied Epi has long been the leader in molecular beam epitaxy (MBE) components. The rapid adoption of our R&D and "silicon-style" production tools has now made us the world's largest MBE equipment supplier.

Now, as Veeco, we're more rapidly advancing MBE from a lab to fab technology for today's emerging devices. With 2X the investment in our MBE product R&D. The launch of our Process Integration Center. And an unmatched global service organization.

Plus we're championing the convergence of MBE with the broader semiconductor world. By aligning MBE with our other process and metrology solutions. And by working with you to develop next generation processes. It's the 21st century, and 21st century MBE is here: Veeco MBE.

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