COMPOUND SEMICONDUCTOR

March 2002 Volume 8 Number 2

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FIBER-OPTIC COMPONENTS

Automation, modulators and 2D VCSEL arrays

ALSO INSIDE

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Contact
Joanna Hook
Compound Semiconductor
Institute of Physics Publishing
Dirac House
Temple Back
Bristol BS1 6BE, UK
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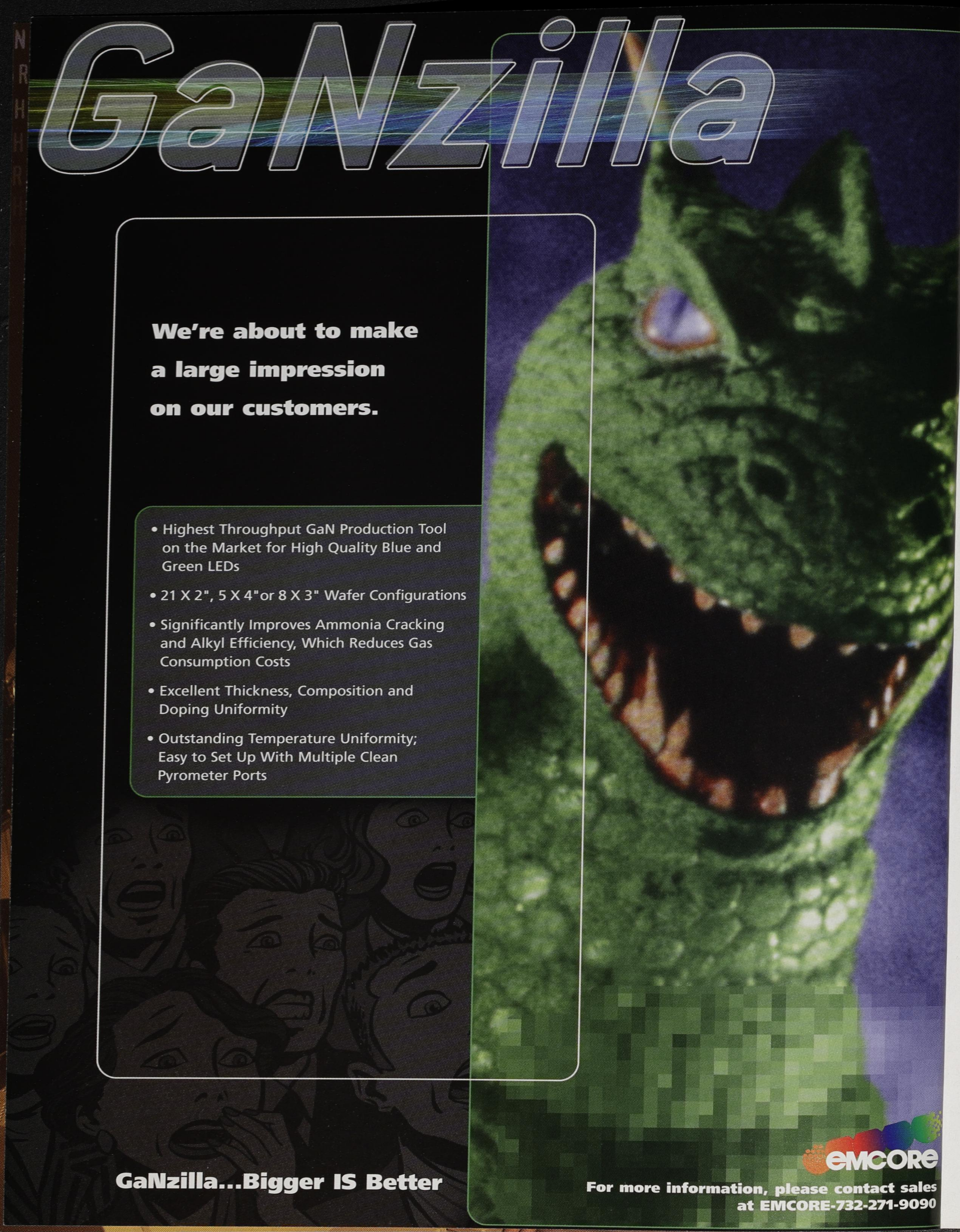

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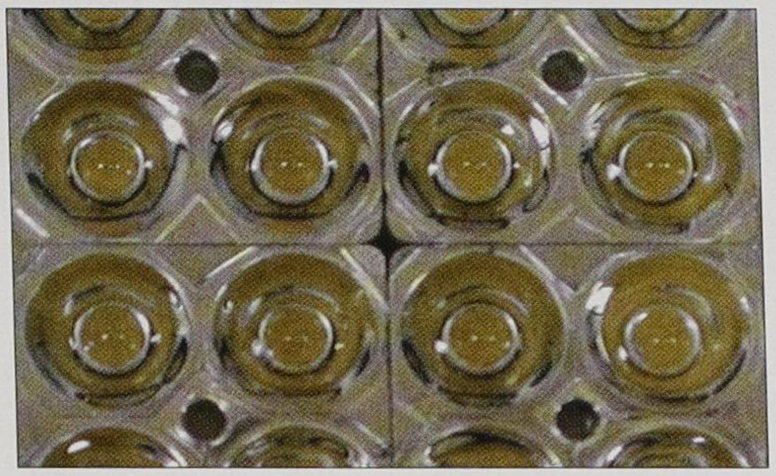
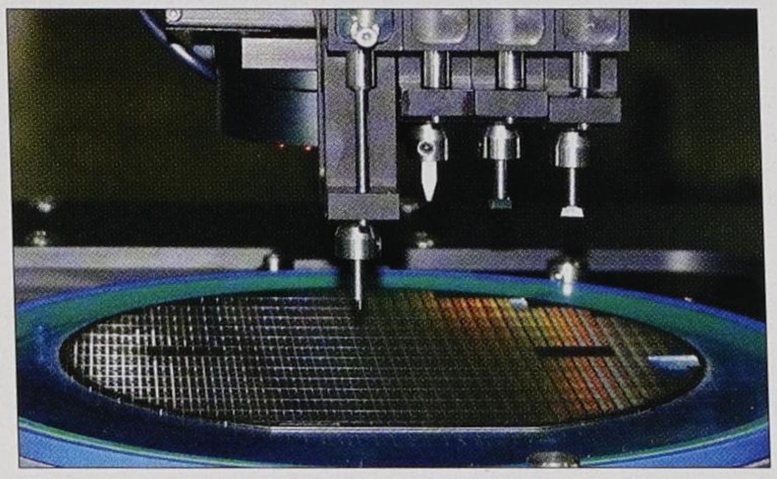


Taiwan's ITRI has successfully developed LEDs, VCSELs and GaN lasers **p9**



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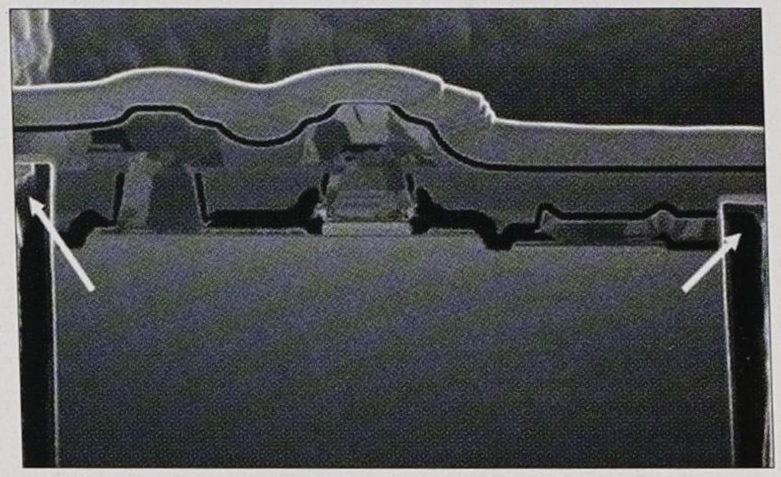

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On the cover: *TeraConnect's transmit and receive modules contain 4 × 12 arrays of oxide-confined VCSELs and GaAs-based photodetectors – see page 57.*

COMPOUND SEMICONDUCTOR

Editor Tim Whitaker
tim.whitaker@iop.org
Tel. +44 117 930 1233
Fax +44 117 925 1942

News editor Richard Dixon
rdixon@compsem.com
Tel. +1 617 666 1720

Technology editor Jon Newey
jon.newey@iop.org
Tel. +44 117 930 1192

Contributing editor Robert Metzger

Managing editor Marie Meyer
marie.meyer@iop.org
Tel. +44 117 930 1034

Publisher Geraldine Pounsford
geraldine.pounsford@iop.org
Tel. +44 117 930 1022

Production Ruth Aspinall/Esther Woodman
Ad production Joanne Scriven
Circulation Laura Serratrice
Art director Andrew Giaquinto
Technical illustrator Alison Tovey
Publishing director Richard Roe

Advertising Nicola Newey/Joanna Hook
nicola.newey@iop.org/joanna.hook@iop.org
Tel. +44 117 930 1032/1033
Fax +44 117 930 1178

Subscriptions
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RFMD opens second GaAs HBT fab

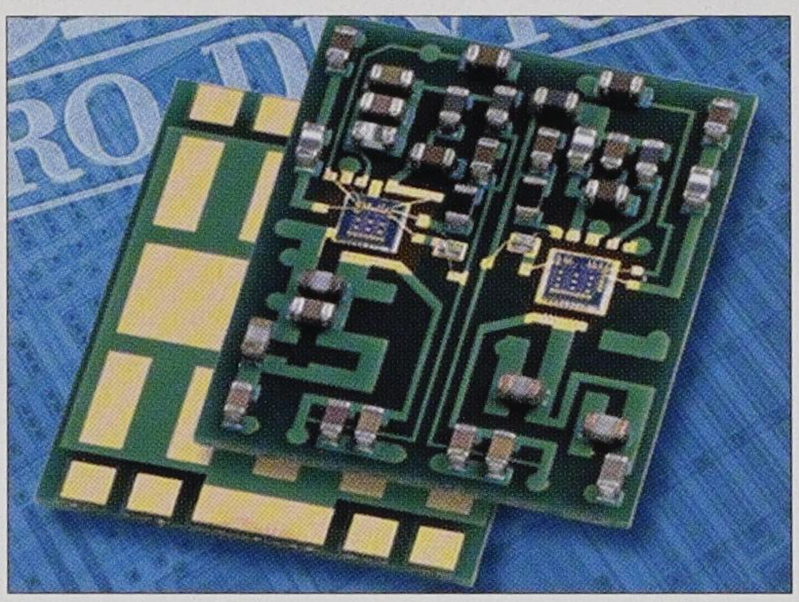
By Richard Dixon and Tim Whitaker

After a long wait, RF Micro Devices has at last started to produce GaAs HBTs at its second fab in Greensboro, NC. The new plant was first announced in the fall of 1999, at which time the company's plan was to complete a first phase of construction by the end of 2000. A second phase of expansion was due to have been finished by the end of 2001. However, the downturn in the wireless industry that hit all GaAs IC manufacturers, including RFMD, meant that the plans were put on hold. According to RFMD's director of investor relations Doug Delieto, the building was completed and the requisite equipment installed by last summer. However, the fab was only turned on at the end of last year, and qualification procedures still need to be completed.

The new fab is currently equipped to process 25,000 to 40,000 4-inch wafers per year, and was originally designed to have a total capacity of 210,000 4-inch wafers per year. RFMD's existing fab now has an annual capacity of 60,000 4-inch wafers, and the new fab will be equipped consistent with demand.

"We expect this new facility to help us to serve and further diversify our customer base as it strengthens our technology leadership and reduces cycle times," said David Norbury, RFMD's president and CEO. "The fab has not only contributed to the addition of new customers, but has also been instrumental in the development of recent strategic relationships, which represent incremental revenue opportunities for the company."

The decision to open the new fab is a positive sign that demand for GaAs ICs is picking up after a period of stagnation. "The capacity of our existing fab is now approaching 80–85% utilization, says Delieto. "We decided to open the new fab to prepare for qualification in readiness for an upturn in the wireless industry." The company is also seeing an increase in the semiconductor content of its products. "Previous module designs contained the GaAs HBT power amplifier circuit and up to 30 passive components," says Delieto. "These were integrated either onto the laminate substrate board or the GaAs die itself. Typically, more passives are now being integrated onto the die, which increases its size and places more demands on GaAs real estate."



RFMD

Modules now account for a large proportion of RFMD's business and consume large amounts of GaAs.

RFMD also appears to be well positioned for continued growth in an improving wireless market. While RFMD's biggest customer is handset market leader Nokia, Norbury says the company has also recently gained market penetration with handset makers such as Samsung, Siemens, Motorola and Ericsson. "We estimate that we are in more handset models than at any other time in the company's history," says Norbury. "Also, we have made significant strides in continuing to expand into high-growth opportunities outside the handset market, such as Bluetooth, wireless LAN and GPS."

"Our power amplifiers have been designed into multiple new-handset platforms, many of which are expected to ramp in the March quarter," adds Norbury. "We have also begun sampling a triple-band GSM/GPRS integrated radio chipset, which our customers tell us contain significantly fewer components than competing solutions."

The recent alliance with Hitachi has also boosted the utilization figures in RFMD's fabs (see *Compound Semiconductor* December 2001, p7). Under the agreement, RFMD is supplying GaAs HBTs to Hitachi, while Hitachi is providing design and assembly services for RFMD's module products. Modules, which integrate more functions and use more GaAs real estate than individual MMICs, are an increasingly important segment of RFMD's total revenue.

The InGaP HBT issue

Many of RFMD's competitors use InGaP HBT processes that are claimed to have improved performance and reliability compared with the AlGaAs HBT approach used by RFMD. At some time during the coming year, RFMD intends to commence the production of InGaP HBTs in its new facility. The company is also developing InP- and GaN-based ICs.

One issue with InGaP HBTs is the epiwafer material. RFMD has a huge suite of MBE systems, but MOVPE is normally considered as the best technique to grow InGaP HBT epiwafers. RFMD has already evaluated MOVPE-grown epiwafers from external sources, but is considering all options. "We are looking to either license, grow or source our InGaP requirements, and will probably implement at least two of these three options," says Delieto. "We are talking to well known suppliers about the possibility of MOCVD and also MBE material."

Agere restructures and closes plants

Agere Systems announced on January 23 a plan to combine its Pennsylvania and New Jersey operations in order to streamline its business, improve its operating efficiency and accelerate time to market. Over the next 12–18 months, Agere will move the majority of its operations from its Breinigsville and Reading manufacturing and development sites in Pennsylvania to its campus in Allentown, PA. Subsequently, the company will discontinue operations at the two facilities and will seek buyers for the properties. Agere is also looking for a buyer for its facility in Orlando, FL, which manufactures CMOS ICs.

In its 1.3 million sq. ft Reading location Agere manufactures a broad range of optoelectronic components and chips for communications networks. In its 645,000 sq. ft Breinigsville facility, the company focuses on the design, development and automated manufacturing of optoelectronic components. This flagship facility includes Agere's Manufacturing Realization Center for the manufacture of optical sub-assemblies and the packaging of transceiver and transponder products (see *Compound Semiconductor* August 2000, p13). Agere will move most of its optoelectronics >>

and IC assembly and test operations from Breinigsville and Reading into its assembly and test facilities in Thailand, Mexico and Singapore. The remaining operations, primarily development activities for assembly and test, will move to Allentown. By consolidating and continuing to invest in these operations, Agere hopes to ensure competitive advantage in cycle time and delivery performance.

The Reading facility has 1600 employees, while the Breinigsville location employs 1100. The company expects its consolidation plans to result in a net reduction of about 300 positions. Around 700 staff in multiple New Jersey locations will be relocated to Allentown and to a new site in central New Jersey. The consolidation of operations from nine sites to just the Allentown campus and the one New Jersey location, will reduce the company's square footage in the two states by around two million (about 50%), significantly lowering costs.

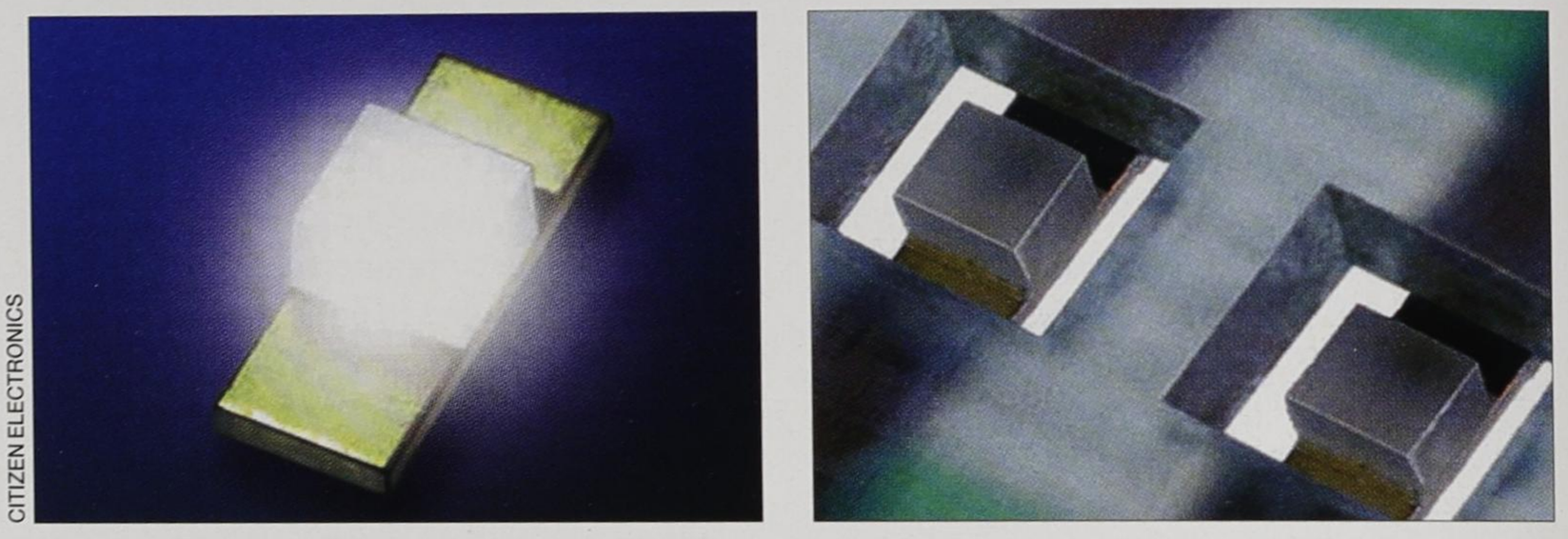
"We are streamlining our business to create an operating model that will best support Agere's future profitable growth and improve our ability to meet customers' needs," said John Dickson, Agere's president and CEO.

● Agere also announced its financial results on January 23. Revenues for the quarter ending December 31, 2001 were $537 million, down approximately 10% from the September 2001 quarter, and in line with guidance. Agere expects revenues to remain relatively flat in the March 2002 quarter. Its restructuring plans should allow the company to reach a break-even revenue of $700 million per quarter by the end of the calendar year.

Nichia enters white LED manufacturing agreement with Citizen Electronics

By Tim Whitaker

On January 8, Nichia Corporation and Citizen Electronics announced an alliance to produce and sell white LEDs. Citizen, one of the world's largest LED manufacturers, will purchase production quantities of blue InGaN LED chips from Nichia and manufacture white LEDs using technology licensed from Nichia. The agreement marks two significant changes in strategy for Nichia; the company has previously only sold packaged devices, and more importantly has consistently stated that it would not license its extensive intellectual property portfolio in the field of nitride LEDs. Nichia has been issued over 20 patents in eight countries for its white LED technology.



CITIZEN ELECTRONICS

Citizen Electronics' new surface-mount white LED (left) is available in top- and side-emitting varieties. The version shown measures 3.4 × 1.25 × 1.1 mm^3 and can be mounted from the bottom side of a printed circuit board, as seen on the right.

"The sale of unpackaged die and the licensing of Nichia technology are both a first for Nichia, so this alliance was not something we rushed into," said Noboru Tazaki, managing director and general manager of Nichia's Optoelectronics Products Division. "In Citizen Electronics we have found a partner that could take Nichia's technology to a broader market in a high-quality package, and that made the difference."

High-volume manufacturing

The new alliance combines the chip manufacturing capability of Nichia with Citizen Electronics' expertise in high-volume packaging. Citizen's core competency, from its years of experience in putting watches together, is the automated assembly and miniaturization of high-tech components. About 60% of Citizen's packaged LEDs (sold under the tradename CITILED) are used in cellular and cordless phones, and Citizen is the world's largest producer of surface-mount LEDs, according to Strategies Unlimited. Other common applications are back-lighting devices, indoor/outdoor displays, and car electronics.

"We are very excited to work with Nichia," commented Tsuneo Miura, director and chief general manager of Citizen Electronics' Electronic Parts Production Divisions I and II. "The combination of Nichia's patented white LED technology and Citizen Electronics' packaging expertise will expand the growth of the LED market, both in existing and new product applications."

The companies will look to increase sales of white LEDs, and at the same time establish a strong position in this competitive market by increasing the production volume, yield and reproducibility of their products while reducing manufacturing costs. The packaging process, in which the blue LED is combined with a thin phosphor coating that down-converts some of the LED's output to yellow light, has a strong effect on the performance of the white LED. Yellow light from the phosphor combines with blue light from the LED to create white. Subtle variations in the phosphor coating vary the tint of the white light from a bluish-white to a yellowish-white, making the packaging step critical for maintaining consistency in the color characteristics and quality of the finished white emitter. Unlike white LEDs manufactured by combining red, green and blue emitters, the color characteristics of phosphor-converted white LEDs cannot be altered after the packaging step.

White LEDs are manufactured by a limited number of suppliers, including Nichia, Osram Opto Semiconductors, LumiLeds and Toyoda Gosei. In recent years Nichia in particular has benefited from the strong demand for white LEDs from mobile-phone handset manufacturers; the white LEDs are used as backlights for the full-color displays that are included in most new handset models in Japan (see *Compound Semiconductor* April 2001, p67). To compete with Nichia, Toyoda Gosei is working with Toshiba to manufacture white LEDs that combine a 380 nm InGaN LED with a tricolor (red, green and blue) phosphor. This >>

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AIXTRON

European Headquarters
Aachen, Germany
AIXTRON AG
Kackertstrasse 15-17
52072 Aachen

Phone: +49 (241) 89 09 - 0
Fax: +49 (241) 89 09 - 40
E-mail: info@aixtron.com
www.aixtron.com

US Headquarters
Chicago, IL
AIXTRON Inc.
1670 Barclay Blvd.
Buffalo Grove
IL 60089

Phone: +1 (847) 215 - 7335
Fax: +1 (847) 215 - 7341
E-mail: usinfo@aixtron.com
www.aixtron.com

AIXTRON Korea
AIXTRON cshs
4F, Korea Exchange Bang B/D
358-1, Yatap-Dong
Bundang-Ku, Sungnam City
Kyoungki-Do, 468-828

Phone: +82 (31) 703 - 51 00
Fax: +82 (31) 703 - 51 10
E-mail: koreainfo@aixtron.com

AIXTRON Japan
Moritani & Co., Ltd
8th Machinery Dept.
1st Business Group
1-4-22 Yaesu, Chuo-Ku
Tokyo 103-8680

Phone: +81 (3) 32 78 - 61 31
Fax: +81 (3) 32 78 - 60 03
E-mail: mike@moritani.co.jp

AIXTRON Taiwan
Challentech International Corp.
Pateh Road No. 1
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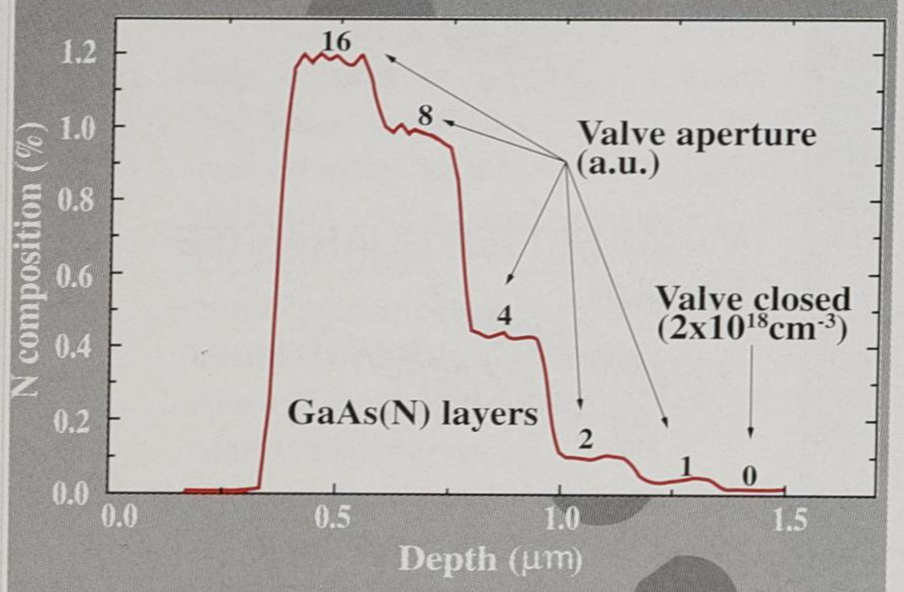

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combination has advantages because the output from the LED chip does not directly affect the white light output of the final device. Other companies, such as Cree and Uniroyal, are developing short-wavelength InGaN chips, while LumiLeds is concentrating on large-area, high-output power devices including white LEDs (see *Compound Semiconductor* Jan/Feb 2002, p35). A Nichia spokesperson told *Compound Semiconductor* that it is making progress with R&D activities looking at larger area, higher power white LEDs and near-UV LEDs for use with RGB phosphors, but no details were given.

Branding alternatives

Under the new agreement Citizen Electronics will sell packaged white LEDs containing Nichia InGaN die under the Citizen brand name. The Nichia spokesperson said that Citizen will also be packaging a quantity of Nichia InGaN die for sale by Nichia, and Nichia will continue to package specific white LEDs in-house. The two companies began discussing a working arrangement in March last year, and Nichia has been supplying die to Citizen since last summer.

So does the licensing agreement with Citizen mean that Nichia has changed its strategy and will now open up its patent portfolio to other potential licensees? "In the future Nichia will no doubt consider proposed transactions from potential purchasers of unpackaged die and potential licensees," said Nichia's representative. "For these instances, Nichia will evaluate how the proposed transaction complements our technology, marketing and future business strategy."

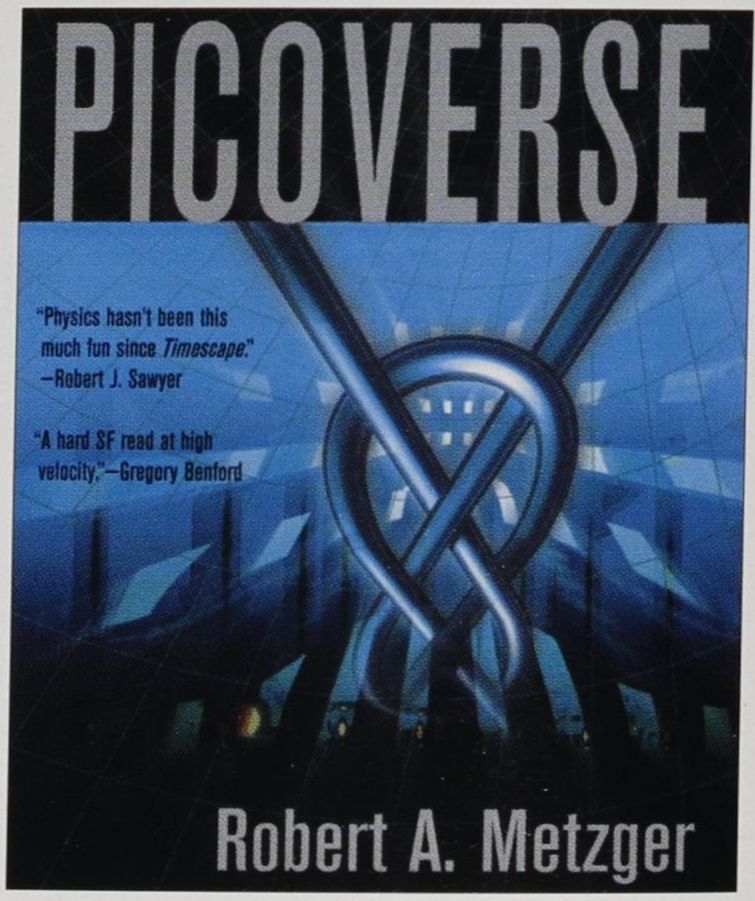
BOOK REVIEW

Picoverse – a big bang of an adventure

Professor Horst Wittkowski and his team have developed the Sonomak, a fusion reactor that is capable of creating regions of great energy density. The Sonomak project attracts the interest of the mysterious Alexandra Mitchell who puts it in the hands of Jack Preston, an unassuming Department of Energy project manager. During a test the Sonomak is pushed harder than ever before, creating a region of energy density so great that space-time itself is ripped apart and a new smaller universe, a Picoverse is created.

The team becomes trapped in the new Picoverse on an Earth still in the early part of the 20th century. The planet is governed by a Russian–German alliance, which is headed by an all-powerful being. Horst's group meet up with some of the 20th century's most famous scientists and begin a fight to understand the science that brought the Picoverse into being, and that threatens the very existence of their original universe.

Robert A Metzger has written a high-speed novel incorporating a rich variety of characters, many of whom turn out to be more than the reader might initially expect. The constant development of characters and situations will keep readers turning the pages, taking them from one bizarre situation to the next. In Picoverse, Robert A Metzger answers some of the philosophical questions about the universe in his own unique way.



RITA FRANGLE AND DANILO DUCAK

The opening chapters of Picoverse can be read at www.rametzger.com. Picoverse is published by Penguin Putnam ACE and is priced at $22.95.

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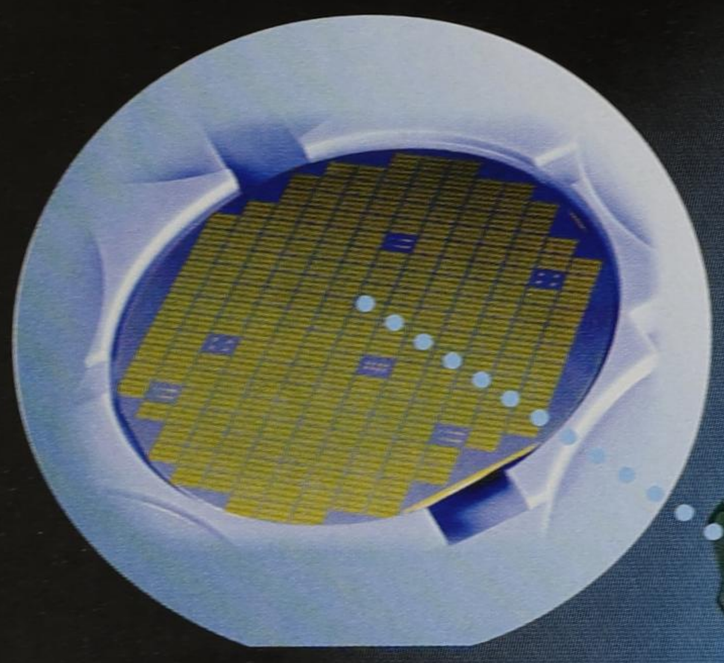

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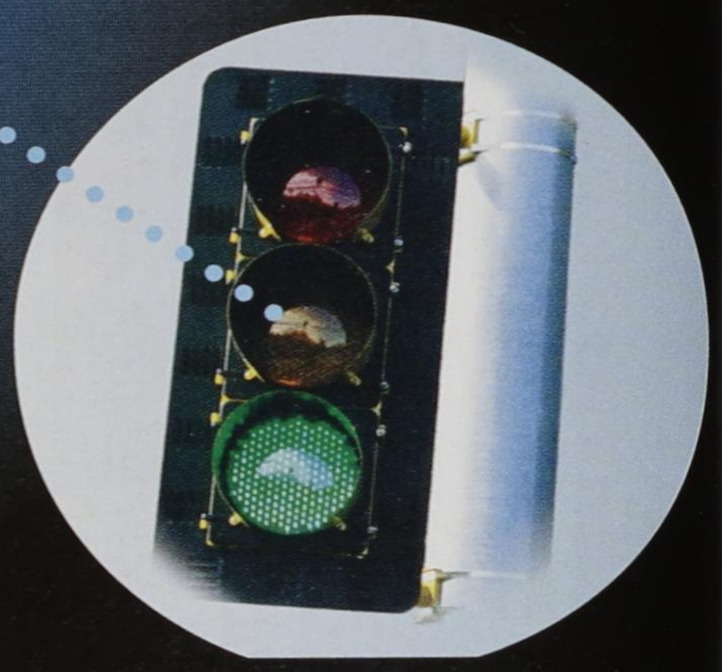

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ITRI shows off Taiwan's first GaN laser

By Tim Whitaker

Researchers at the Industrial Technology Research Institute (ITRI) have demonstrated Taiwan's first violet GaN-based laser diode. ITRI is the source of many of the technology breakthroughs in Taiwan that have lead to the growth of the country's booming compound semiconductor industry. Jung-Tsung Hsu, manager of the Opto-Electronics and Systems (OES) laboratories, reported that the InGaN/GaN MQW laser operated under pulsed conditions at room temperature, at a wavelength of 415.5 nm. The threshold current was 870 mA, corresponding to a threshold current density of 8.7 kA/cm^2.

The laser structure was grown by MOCVD on a sapphire substrate with a 4 μm n-GaN:Si buffer layer. The structure has $Al_{0.14}Ga_{0.86}N$/GaN strained-layer superlattices as cladding layers, and an active region containing five 2.5 nm $In_{0.15}Ga_{0.85}N$ QWs with 8 nm GaN barriers. After growth, 10 μm wide ridge waveguide lasers were made with a cavity length of 1000 μm. The sapphire substrate was thinned to 80 μm and mirrors were formed by cleavage. The facets were coated with dielectric multilayers (SiO_2/Ta_2O_5) to achieve front and rear reflectivities of 75% and 95%.

OES announced its GaN laser at an exhibition at the end of 2001, which also showcased recent R&D results relating to optoelectronic components such as 2.5 Gbit/s VCSELs and GaN-based LEDs for lighting applications. "In recent years, OES has been aggressively accelerating its development of LED lighting," says Yung-Sheng Liu, general director of OES. "We expect to bring about a boom in the LED lighting market and help domestic manufacturers gain global market share."

OES/ITRI

An LED module containing a total of 64 LED chips, which are surface-mounted to a board (measuring 5 × 5 cm^2) and coated to form focusing lenses.

Although LEDs offer many potential advantages over conventional light sources, such as high efficiency and long lifetime, a major drawback for illumination applications is the low light output per device. "To get enough light from an LED source, dozens or hundreds of LED chips are required," says Jung-Tsung Hsu. Some LED lighting products use many LED lamps packed within a large bulb, but such products suffer from poor heat dissipation, and aligning the output from the different LEDs is difficult. Although large chips can replace a number of small lamps, there is a drop-off in efficiency as chip size increases, and heat dissipation from large chips is again a major problem.

OES has developed a multichip module that overcomes some of these problems (see photo). A number of white LED chips are surface-mounted to a board and the light output is directed using both reflectors and focusing lenses. The assembly has good heat dissipation and parallel light output is achieved from each source, making the module suitable for packaging multiple and large-sized chips. The technique also simplifies the chip packaging process to reduce the packaging costs.

Ultraviolet GaN-based LEDs have also been developed by OES; these devices can be used to manufacture counterfeit currency detectors and disinfecting/deodorizing products, and can also be used with tri-color phosphors to create white LEDs.

China has blue LED breakthrough

An academic institution in mainland China has demonstrated the country's first high-brightness blue LEDs. Tsinghua University developed the 470 nm GaN-based devices in less than two years in collaboration with Shandong Incalcu Group, a company with a diverse product portfolio located in Shandong Province. When packaged, the devices had a luminous intensity of around 1 cd, putting them in the same league as commercial high-brightness LEDs.

Tsinghua University grows the blue GaN epiwafers using MOCVD and processes them into chips on a small-scale production line with a class 1000 cleanroom. The university has also invested in a production reactor (see p23). "Our blue LED chips feature a power greater than 1.5 mW from a forward voltage of 3.6 V and standard current of 20 mA," said Professor Yi Luo. "These results demonstrate that the main challenges of this project have, to a great extent, already been overcome."

Sharp develops 100 mW DVD laser

Sharp has developed a new red laser diode for DVD-R/RW drives capable of writing at 4× speeds. Higher write speeds require lasers with higher output powers, and the new 652–660 nm lasers have an output power of 100 mW under pulsed operation and 70 mW in CW mode. High power at low current is achieved using a special facet-coating process and through improvements in the active layer structure. The threshold current is 35 mA and the operating current and voltage are 95 mA and 2.6 V, respectively. Sharp's device will be available in May with a production volume of 100,000 units per month.

In brief...

Oki Data Corp cuts the cost of its LED print heads

Oki Data Corp has almost halved the manufacturing cost of the print head used in its LED printers. This has been achieved by making the chips used in the head more compact, by improving the yield of the device manufacturing process and by consolidating the assembly process at Oki's factory in Thailand.

Toshiba demos new 405 nm DVD system

Toshiba has demonstrated a rewritable optical disc and a read/write optical head with a 405 nm violet laser. The disc stores up to 30 Gb on a single-layered, single-sided disc, compared with 9.4 Gb for a current, double-sided DVD-RAM disc.

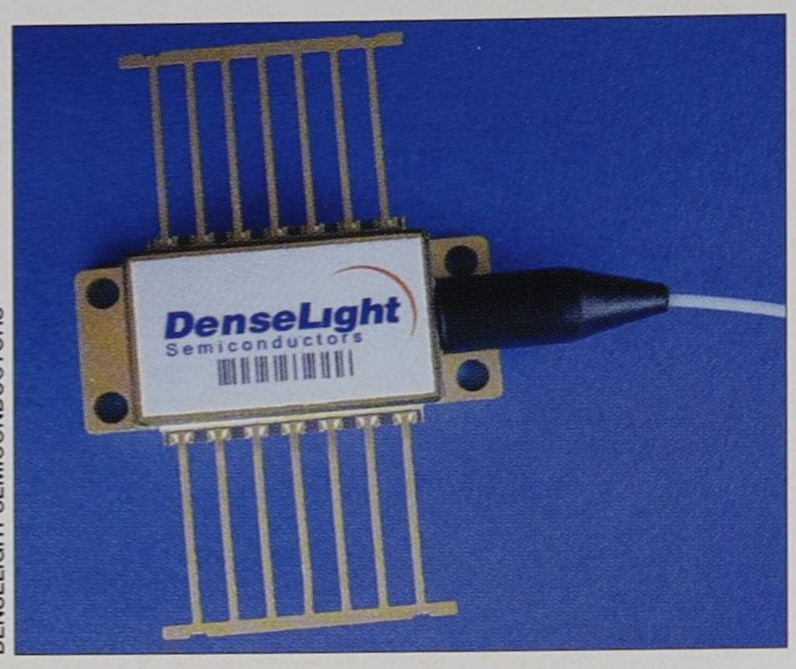
DenseLight gets funding of $30 million

By Jon Newey

DenseLight Semiconductors, a Singapore-based start-up, has received an investment of $30 million from venture capital group 3i. DenseLight was spun out of Nanyang Technological University (NTU) in 2000 to develop and manufacture InP-based photonic integrated circuits. The company uses quantum well intermixing (QWI) to fabricate its devices, which allows the bandgap of a quantum well to be altered enabling a number of functions to be integrated on a single chip.

Since receiving a $1.2 million seed investment from 3i in October 2000 the company has been working in stealth mode to develop its facilities, intellectual property and strategy for the production of components for optical networks. It now employs about 100 people in a purpose-built 50,000 sq. ft facility that brings its headquarters, R&D and manufacturing operations under one roof. The company will recruit more staff as it ramps production and develops more complex products. It also intends to keep its links to NTU and other universities through research contracts in order to access a ready pool of talent.

Products now sampling to potential customers include a directly modulated 2.5 Gbit/s DFB laser and a superluminescent diode. A Raman pump laser, an embedded optical channel monitor and a tunable laser are scheduled to be unveiled at the OFC show in March.



DENSELIGHT SEMICONDUCTORS

DenseLight's MQW directly modulated DFB laser has an output power of 10 mW and is designed for 2.5 Gbit/s DWDM systems.

The company has called its QWI process DensePIC, and sees this as the way ahead for integrating active and passive functions on a single chip. DenseLight holds a strong patent portfolio covering a range of QWI methods and at present is concentrating its efforts on intermixing by ion implantation. As Yuen-Chuen Chan, co-founder of DenseLight and VP of research, told *Compound Semiconductor*, "There are a number of process parameters one can use to change the amount of defects introduced, leading to different degrees of intermixing. These include varying the ion dose and energy, and implanting through a mask to control the intermixing." DenseLight sees the key advantage to ion implantation as the ability to apply different degrees of intermixing and thus different bandgaps to separate regions of the same wafer.

Though concentrating on ion implantation for its current products, DenseLight does not exclude other routes to QWI. "We are establishing the pros and cons of different QWI methods for different types of devices. We are exploring all options and can't afford to exclude any of these or combinations of them," says Siu-Chung Tam, CEO of DenseLight. "We see QWI as giving us lower manufacturing costs and higher performance, therefore bringing advantages to our customers."

DenseLight is not the only company pursuing QWI as a route to higher levels of integration using InP. Scottish start-up Intense Photonics has also received backing from 3i and is using a QWI method called impurity-free vacancy disordering (see *Compound Semiconductor* September 2001, p63). However, as Kian-Woon Yap of 3i explains, "The product roadmaps of the two companies are not overlapping and we do not see the companies competing against each other."

UEC glue-bonds its AlGaInP LEDs

United Epitaxy Company (UEC), a Taiwanese manufacturer of high-brightness AlGaInP LED epiwafers and chips, has launched the Giga Bright (GB) range of LEDs. The devices use UEC's newly invented glue bonding technology to bond the AlGaInP LED epiwafer to a sapphire substrate. The absorbing GaAs substrate is then removed from the AlGaInP epitaxial structure, resulting in improved light extraction (see *Compound Semiconductor* September 2001, p51).

The luminous efficiency of GB-family LED products in a standard 5 mm lamp package can reach 30–40 lm/W and, using flip-chip packaging techniques, this can be increased to over 50 lm/W. The GB-family LEDs are very similar in appearance to conventional GaN-based green and blue LEDs, in that they have both p- and n-electrodes on the same side, and they are also supported by a 100 μm thick sapphire substrate. This allows GB AlGaInP red LED chips to be mounted with GaN green and blue LED chips using flip-chip packaging. UEC is offering evaluation samples and mass production is scheduled to begin in March.

Mitsubishi launches ultra-small amplifier

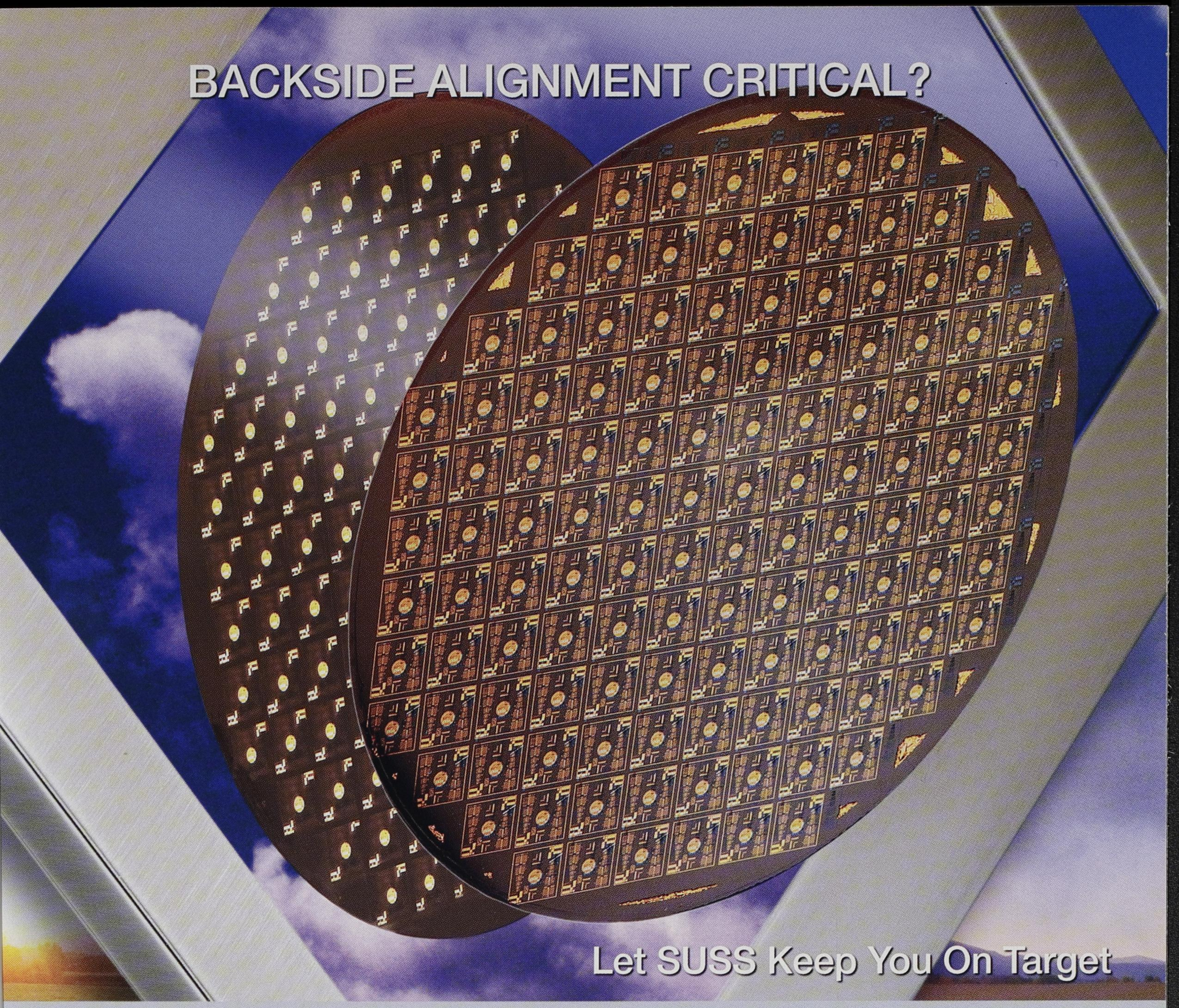
Mitsubishi Electric recently launched the BA01212 power amplifier, which measures only $6 \times 6 \times 1.5\ mm^3$, for W-CDMA applications. The module incorporates a two-stage GaAs HBT amplifier and a matching circuit for reduced distortion. It operates at 3.5 V with a standby voltage of 50 mA, and provides a power gain of 26.5 dB. The leakage power between neighboring channels is –37 dBc when detuning at ±5 MHz.

Omron enters optical components market

Omron, a Japanese component maker, is to invest ¥5 billion ($37.6 million) to develop and manufacture fiber-optic components. The devices will include transceivers, couplers, multiplexers/demultiplexers and VOAs. Core components including waveguides, lenses and actuators will also be developed. The production of active semiconductor-based components such as lasers and photodetectors will be outsourced, and supply alliances are being discussed with a number of companies.

Omron recently began packaging LED chips supplied by Stanley (see *Compound Semiconductor* October 2001, p15). Omron's key advantage in the fiber-optic market is its proprietary method of manufacturing polymer waveguides using finely patterned metal molds. The company expects this to reduce production costs and therefore prices in the very cost-conscious short-haul space.

BACKSIDE ALIGNMENT CRITICAL?



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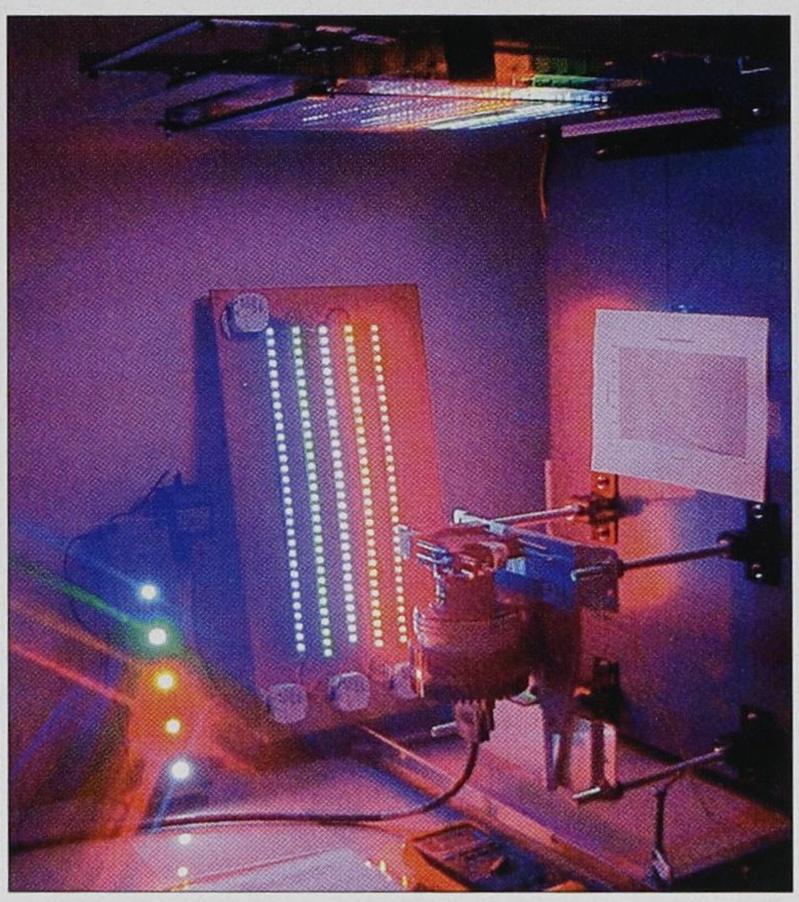
Lighting Research Center assists in adoption of solid-state lighting systems

The Lighting Research Center (LRC), part of Rensselaer Polytechnic Institute in Troy, NY, has introduced a program to support the development and widespread application of solid-state lighting systems. LRC is working with LED manufacturers and the private and public sectors as part of the new program, called ASSIST or the Alliance for Solid-State Illumination Systems and Technologies, which aims to overcome major technical hurdles and identify key applications for high-efficiency LEDs. This will primarily be achieved by facilitating pre-competitive collaboration between manufacturers. So far LumiLeds, GELcore, Osram Opto Semiconductors, B/E Aerospace and New York's State Energy Research and Development Authority have signed up as program sponsors.

The LRC acts as an independent research organization and resource for the US lighting industry, and has recently conducted reliability studies on white LEDs (see *Compound Semiconductor* January 2002, p45). Its director of research, Nadarajah Narendran, says the aim is to engage key LED manufacturers in a consortium early on in their technology/product-development phase.

"In a rapidly advancing environment such as solid-state lighting, OEMs will often develop non-standardized light sources for the marketplace," says Narendran. "Developing a general lighting product that can achieve market penetration depends on how well industry standardizes performance and designs products that provide a color and quality of light that is acceptable to end users. We believe that a collaborative effort will result in standardized, reliable products that are readily accepted."



LIGHTING RESEARCH CENTER

LEDs undergoing lifetime testing at the Lighting Research Center.

Speaking the same language

The consortium plans to develop standardized metrics and to evaluate the physical properties of LEDs as light sources. The LRC's role in ASSIST includes research, and the demonstration and evaluation of LED lighting technologies in different applications. One stumbling block at present, explains Narendran, is that the lighting industry and the semiconductor manufacturers need to be able to speak the same language over such issues as lamp life. "LED makers discuss light-source life in terms of a mean time to failure, whereas the lighting designer considers the time it takes for 50% of the light sources to burn out," says Narendran. "Unlike most light sources presently used in lighting applications, LEDs fade slowly over time rather than fail abruptly. Since the light level may become unacceptable for the application beyond a certain point, it is important to consider light output depreciation and color shift when developing a definition for LED life."

Uniroyal samples large-area LEDs

Uniroyal Optoelectronics is sampling new high-power blue (450–470 nm) LEDs that incorporate large-area die producing up to 60 mW of radiant power. The company is also working on 400 nm near-UV versions that are expected to produce similar power levels.

The blue LED measures approximately $1.0 \times 1.0\,mm^2$ and contains a monolithic array of InGaN-based emitters, which are electrically isolated from each other using a proprietary process. The emitters can be driven at currents of up to 50 mA each, and a key feature is that the number of devices within the array is scalable, although the overall chip size remains the same. In the 3×3 array being sampled to customers, each device measures $325 \times 325\,\mu m^2$ and is rated at 3.5 V. The total die is around three times larger than the company's standard chips, and can be powered by a 12 V supply. Uniroyal has so far demonstrated up to 5×5 emitters on a single die.

"Using scalable arrays on the same die size allows us to make a standard building block containing different array sizes," says president of Uniroyal Optoelectronics, David Miller. "This allows the fabrication of chips with different outputs that can be picked and placed for easy manufacturing. When scaling up, we don't have to re-engineer the device because each one is the same, and this reduces costs and allows more manufacturing flexibility."

The new LEDs can also be used in chip-on-board solutions such as those manufactured by Uniroyal's NorLux lighting subsidiary, says Miller. "We can envisage a family of light engines from small single emitters for certain applications, up to intermediate-sized multiple-emitter chips such as the new devices, and the much larger Hex chip-on-board designs," he says.

LumiLeds' LEDs power LCD backlight

Display manufacturer FIMI Philips is to use LumiLeds' high-flux LEDs in a new line of medical monitors, in order to improve color fidelity and extend product reliability and lifetime. Luxeon chips from LumiLeds will be used as backlights for LCD screens, producing brighter and more precise colors than those of traditional cold cathode fluorescent lamps. A more accurate representation of colors is advantageous in many medical applications such as endoscopy and ultrasound.

As the currents of the red, green and blue LEDs can be adjusted individually, the monitors also benefit from a tunable white point, enabling physicians working remotely to obtain the same image conditions, or to adjust for intensity degradation with time. The screens are also twice as bright as standard displays and last up to twice as long, says FIMI.

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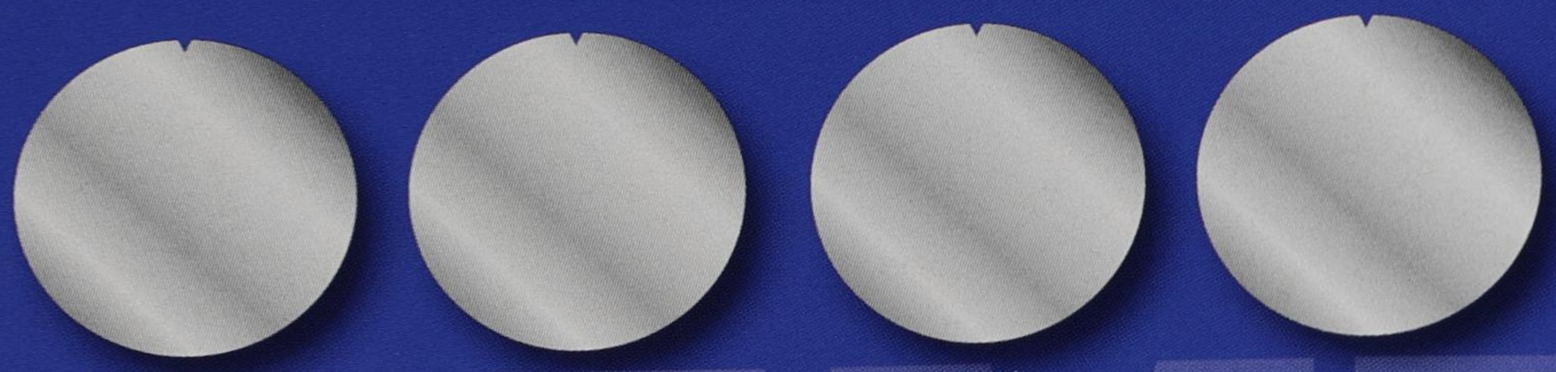

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Eagle-Picher grows ZnO layers with p-type doping

The Specialty Materials Unit of Eagle-Picher Technologies has recently demonstrated p-type ZnO thin-film layers. The films were grown by MBE on ZnO substrates which had been produced by the company's seeded chemical vapor transport method at its plant in Miami, Oklahoma.

Unlike GaN, conducting ZnO substrates up to 2 inches in diameter are available, but the development of ZnO-based devices, such as blue and UV LEDs, has until recently been held up by the inability to grow p-doped ZnO layers. Eagle-Picher's p-type ZnO layers were doped with Mg and exhibited carrier concentrations of approximately $1 \times 10^{18}/cm^3$, and a mobility of 2 cm^2/Vs. The results were verified by external sources.

"ZnO is an excellent light emitter because of an efficient exciton emission process that exists well above room temperature," says Gene Cantwell, project manager at Eagle-Picher. "Another attractive feature is the ability to grow ZnO layers on 2 inch conducting ZnO substrates, which have much lower dislocation densities than either GaN on sapphire or SiC substrates."

With the major stumbling block to short-wavelength optoelectronic emission now removed, devices should not be far away, says Cantwell. "As the material is naturally n-type, it is not difficult to make a *pn* structure by doping p-type," he explains. "It is also possible to produce a confinement region for electron-hole recombination using the wider bandgap provided by ZnMgO. We are currently targeting a mobility of 5 cm^2/Vs, and we are aiming to produce the first LEDs by the end of the year."

Cree introduces new Schottky rectifiers

Cree has introduced a new silicon carbide 600 V, 10 A Schottky rectifier, adding to its previous 1 and 4 A devices. The new diode, called a Zero Recovery rectifier, is intended for power conditioning applications in high-frequency power supplies and in power-factor correction, in addition to power conversion in motor control applications.

The use of SiC as the base material for the rectifier provides lower switching losses compared with silicon *pin* devices, in addition to providing faster switching speeds at similar breakdown voltages. Cree is currently sampling chips with strategic partners and packaged devices to the general market.

According to Cree, the new diodes are being manufactured on 3 inch SiC wafers, which were developed specifically for the production of Schottky devices. Cree has also demonstrated a 40 A Schottky rectifier at 600 V, which employs a single SiC chip.

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Japanese IDM qualifies WIN's process

WIN Semiconductors, which operates a 6 inch GaAs wafer fab in Taipei, Taiwan, has announced that its 2 μm HBT process has been qualified by a major Japanese integrated device manufacturer (IDM) for use in Bluetooth power amplifier applications. This is a first for Taiwan's emerging 6 inch GaAs foundries, which have struggled to gain acceptance. Achieving both process and product qualification for GaAs technology is very time-consuming. The interval from initial process qualification, through design-in and product qualification, to production can be as much as one and a half years. WIN first demonstrated its 2 μm HBT process in November 2000. In addition to being qualified by the Japanese IDM, WIN expects to complete qualification and begin production with several other customers this year.

WIN also reported that its 2 μm InGaP HBT process has demonstrated what it claims to be a record-setting level of performance, with 4 W output and 75% associated power-added efficiency at 1.9 GHz. This level of performance, which has been verified through internal testing and by several US customers, can greatly reduce power consumption and prolong the life of handset batteries. More than 40 international IDMs and design houses have accessed the process and started engineering runs for handset, wireless LAN and Bluetooth PAs.

WIN has reported that its 2 μm InGaP HBT process has demonstrated what it claims to be a record-setting level of performance.

In addition to its HBT products, WIN manufactures 6 inch PHEMT MMIC wafers using a 0.15 μm process, and has also started to make wafers with a final thickness of 50 μm accessible to its customers. WIN's fab currently has a capacity of 1500 6-inch wafers per month. With the completion of phase two cleanroom construction and the installation of new equipment, the capacity is expected to reach 4500 6-inch wafers per month by the end of this year. The full production capacity for this fab will eventually reach 100,000 wafers per year.

Qualification for AWSC

A second Taiwanese foundry, Advanced Wireless Semiconductor Company (AWSC), has also successfully developed an InGaP HBT process which has recently been qualified by a major customer for 3G cellular handset applications. AWSC expects to start production in the first quarter of 2002. The company operates a 4 inch GaAs line and has "temporarily" postponed plans to move to a 6 inch manufacturing line, citing "considerations related to the technological maturity of both 6 inch backside processes and epi materials" as the reason for its decision.

GCS secures funds of $17.5 million

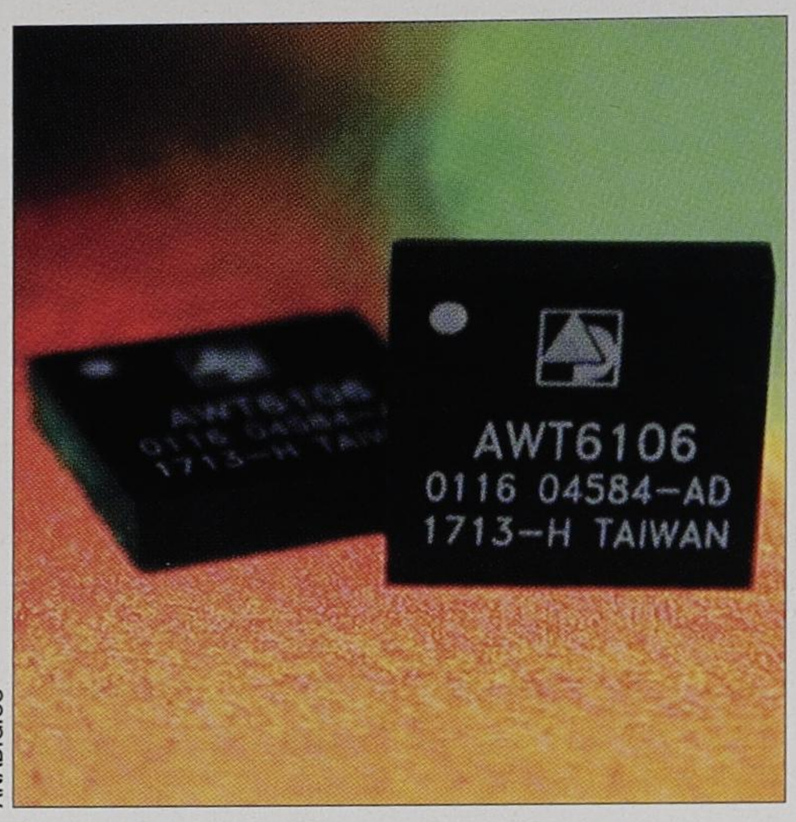
Global Communications Semiconductor (GCS), a GaAs foundry company based in Torrance, CA, has raised $17.5 million in a funding round led by TCW/YFY Investment Partners, an active investor in US and Asian design firms and foundries. GCS is developing InGaP and InP single and double HBT epiwafer processes for 40 Gbit/s circuits and power amplifiers used in 3G handsets and millimeter-wave transceivers, in addition to a long-wavelength InGaAs *pin* photodiode process for fiber-optic networks (see *Compound Semiconductor* Jan/Feb 2002, p15).

"The strength of our technology and proprietary world-class foundry process is evidenced by the substantial backing of our new and existing investors," said Owen Wu, who recently relinquished his position as president and CEO and now serves as chief strategy officer. "This round of financing should see GCS through to profitability and an eventual IPO. GCS will use these funds for the acquisition of tools to further enhance the technological and manufacturing capabilities essential to our company's success," added Wu, who will be replaced by COO David Wang until a new CEO is appointed.

Anadigics wins more CDMA orders

Anadigics has added to its recent design wins with two new contracts for InGaP HBT power amplifier modules from Korean manufacturers. Standard Telecom, a Korean wireless equipment manufacturer that has been supplying handsets since 1992, will employ the Anadigics' AWT6106 power amplifier module in its latest PCS mode CDMA wireless handset, the NCP7100. The AWT6106 PA is intended for CDMA-1X applications operating from 1850 to 1910 MHz. The IC measures $1.6 \times 6 \times 6\ mm^3$, includes full compensation and 50 ohms input/output matching and provides 35% PAE from a 3.5 V supply.

The second deal involves the supply of AWT6109 power amplifiers to Sewon Telecom for use in wireless modems in personal digital assistants. A low-profile package is employed to house the chip, which the company says is critical to fulfilling the required size limitations. The circuit delivers 35% PAE at a quiescent bias current of 60 mA, with an adjacent channel power rejection of –53 dBc.



ANADIGICS

The AWT6106 will be used in Standard Telecom CDMA handsets.

"Anadigics is now building a formidable presence in the CDMA marketplace," said Bami Bastani, who is president and CEO of Anadigics. "Korea is a leading player in the CDMA market and is responsible for much of the new product development activity in the wireless sector."

RF testing outsourced to UCOMM

In further news, Anadigics is to outsource its production RF testing operations to the Taiwanese company Universal Communications Technology Inc (UCOMM). The majority of Anadigics' RF testing will be transferred to move it closer to the module assembly plant in southeast Asia, which the company says will increase the efficiency of device manufacturing and further reduce product cycle times and manufacturing costs. All GaAs wafer fabrication will remain at Anadigics' headquarters in Warren, NJ, together with in-house RF testing and assembly capabilities for fast turnaround of engineering prototypes. UCOMM is based in the Hsinchu Science-Based Industrial Park, and provides wafer-level, IC and module testing, as well as tape-and-reel services and shipment.

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In brief...

Hexawave's new switches

Hexawave of Hsinchu, Taiwan has unveiled four new single-pole double-throw (SPDT) reflective switches for multiple air-interface standards, together with an SPDT terminated switch for base stations from DC to 2.5 GHz. The HWS3XX range employs a 3.0 V positive supply voltage for transmit/receive switching, antenna diversity, filter band selection and LO switching in analog and digital wireless communication systems. Based on GaAs FET technology, the typical insertion loss is 0.4 dB and isolation as low as 23 dB at 2.5 GHz, for 26 dBm power output.

GSM transceiver from Sony

Sony has unveiled a quad-band GSM transceiver with GPRS compatibility and EDGE receive/transmit capabilities. The SiGe-based DuettoDC is designed to interface with Sony's GaAs PHEMT 2-stage PA module, which features a PAE of 43% and 3.5 V standard operation. The DuettoDC is designed to enable GSM handset manufacturers to develop flexible common RF platforms covering all worldwide standards.

Fujitsu demos 40 Gbit/s module

Fujitsu has developed an optical transmitter module operating at 40 Gbit/s, and plans to begin shipping commercial samples in March. The module incorporates a lithium niobate Mach–Zehnder modulator, which provides excellent dispersion-tolerant characteristics at high-speed operation. The modulator requires a relatively high drive voltage of 5 V. A wide-bandwidth distributed amplifier MMIC was fabricated using a GaAs-based double-hetero-structure HEMT process to ensure adequate gain and drive voltage at high frequencies. The light source is a tunable laser with a wavelength locker, which allows the selection of any one of four wavelengths spaced at 100 GHz on the ITU grid. Tuning is achieved by altering the temperature. The module also incorporates a control circuit block that has automatic bias control for the modulator and frequency selection for the laser.

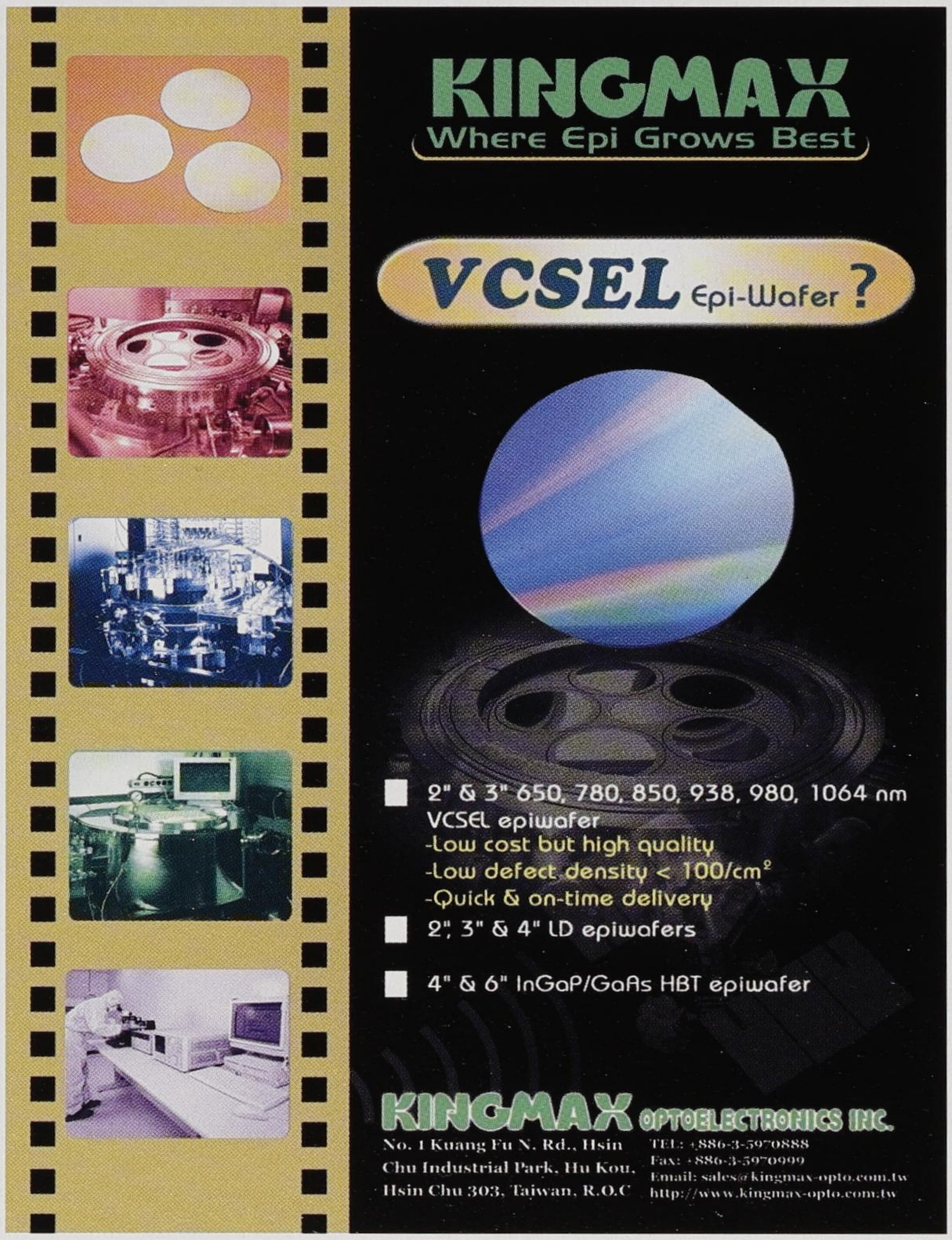
Lumics unveils 980 nm pumps

Lumics, a start-up manufacturer of laser diodes based in Berlin, Germany, has released a range of single-mode high-power 980 nm pump laser diodes operating at up to 330 mW. Designed for applications such as low-noise, high-power EDFAs, they are Telcordia-compliant and meet the Bellcore GR-468 requirements. They are available in bar, die or chip- on-submount form, as well as packaged into modules. Founded in November 2000, Lumics has received €3.3 million (around $2.9 million) in first-round funding. The company has built a process and test production line, and is concentrating on the development of higher-reliability, kink-free lasers offering thermal stability and a narrower vertical far-field output. Lumics has also developed a facet passivation process that is a key production step.

VSK Photonics receives more cash

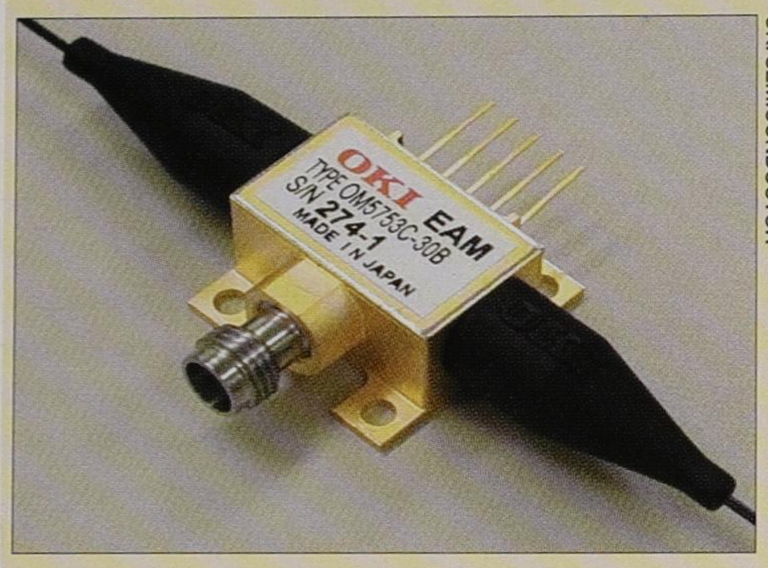
VSK Photonics, a start-up manufacturer of InP active components based in Lake Forest, CA, has extended its series A financing round with an additional $8.3 million, led by Rustic Canyon Ventures. Existing investors Morgenthaler and Intel Capital also participated. The company received a first-round investment of $18 million in March 2001 and plans to use the funds to expand its development and manufacturing base. Its first products are anticipated in the first half of 2002. Founded at the end of 2000, VSK recently opened a vertically integrated InP fab with an annual capacity of 10 million units. The company uses proprietary InP technology to develop 10 and 40 Gbit/s devices, including photodetectors, modulators and lasers, in addition to modules (see *Compound Semiconductor* May 2001, p15).

"We have a very strong development team and this round of financing will support our efforts to bring our high-end products to the market," said CEO Don Ackley.



New fiber-optic components

Oki Semiconductor's EA modulators hit 40 Gbit/s



OKI SEMICONDUCTOR

Oki has introduced 40 Gbit/s InP-based electroabsorption modulators.

Oki Semiconductor has released a new 10.7 Gbit/s InGaAs optical receiver module, along with two 40 Gbit/s electroabsorption (EA) modulators. The OD9652N receiver integrates a TIA and GaAs preamplifier, and is designed for OC-192 networks employing forward error correction (FEC). Typical responsivity is 0.8 A/W at 1550 nm.

The new 40 Gbit/s InGaAsP/InP EA modulators operate with a 2.5 V_{p-p} voltage at data rates up to 43 Gbit/s to allow FEC. Key features include a high modulation bandwidth of more than 30 GHz and an extinction ratio of 17 dB.

JDSU expands directly modulated laser range

JDS Uniphase has expanded its range of fixed and tunable 2.5 Gbit/s transmitters with a family of temperature-tunable, directly modulated lasers (DMLs). The new transmitters are suited to WDM metro architectures and CATV networks, where high optical output power and very low dispersion are required.

The CQF413 transmitters are two-channel tunable devices available with either 2.5 or 10 mW output power, and they operate over 100 or 180 km. JDSU says its DMLs meet performance requirements for the span lengths typical of metro and access markets; CW lasers with external modulators or electroabsorption-modulated lasers are too expensive for these markets but are well suited for much longer spans. The company notes that further costs are eliminated due to the absence of wavelength lockers, and the packaged lasers include TEC cooling, which allows operation up to 85 °C.

High gain receivers target fiber/wireless systems

Discovery Semiconductors has developed high-gain optical receivers for narrow-band applications at 28, 39 and 55 GHz. The R406 provides FWHM response over the 18 to 34 GHz range with a peak gain of 20 dB. The R407 provides a similar response from 34 to 49 GHz with a gain of 24 dB, while the R408 spans 39 to 64 GHz with a peak gain of 20 dB. The hermetically sealed modules target hybrid fiber/wireless systems, as well as optical phased-array radar. The company has also developed a 1.2–2.2 μm receiver for LIDAR.

Picolight draws up parallel module MSA with Emcore

Picolight and Emcore have entered into a multi-source agreement (MSA) for the manufacture and supply of connectorized 12-channel parallel optical modules operating at up to 2.7 Gbit/s per channel. The MSA defines common electrical, mechanical and optical specifications for pluggable parallel transmitter/receiver modules.

"Connectorized parallel optical modules are quickly gaining in popularity," said Robert Bryan, division VP at Emcore Fiber Optics. "With the pluggable optics MSA, Emcore and Picolight will be able to provide their customers with the assurance of having multiple sources for compatible modules. Parallel optics modules offer the most cost-effective method for resolving the bandwidth restrictions of legacy copper backplanes inside network equipment."

In further news, Picolight has announced the launch of its Extensus family of 1310 nm transceivers for metro and optical Ethernet applications. The first product is a small-form-factor pluggable transceiver that delivers 1.06 or 1.25 Gbit/s over single-mode fiber for 10–20 km links.

"The Extensus will be the first in what will become an extensive range of long-wavelength products ranging from 1 to 10 Gbit/s and spanning 10 and 20 km link distances," said Warner Andrews, VP of marketing. "The modules will initially be based on Fabry–Perot edge-emitting laser technology obtained from external sources, but will ultimately migrate to the long-wavelength VCSEL technology currently being developed by Picolight."

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Marconi takes a new approach to tunable lasers

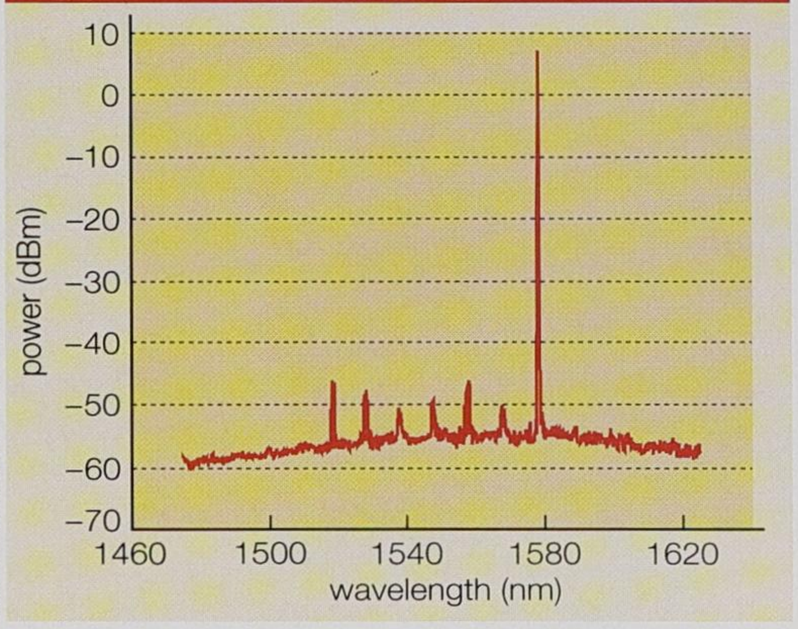
Marconi Optical Components (MOC), recently acquired by Bookham Technology, has developed a tunable DBR laser known as a digital supermode (DS) laser. The device takes a new approach to tuning that allows it to maximize optical power output while simplifying the tuning characteristics compared with currently available tunable DBR lasers.

Sampled grating (SG) and gain-coupled DBR tunable lasers require the tuning of three elements (front and rear gratings and the phase section) to select the required output wavelength. As a result, singlemode operation with high side-mode suppression is available in a small part of the three-dimensional tuning space. Fine control within this space requires a wavelength locker with feedback to a temperature-controlled heatsink. Coarse tuning to a band of wavelengths is done by tuning the front section. Finer tuning is then performed using the front and rear sections together.

The new DS-DBR also has front and rear InP/InGaAs reflectors with gain and phase adjust sections. A thermoelectric cooler keeps the temperature stable to avoid shifts in emission wavelength as the device heats up. The device differs from other approaches because the front grating is segmented to give it a number of individually addressable sections that each reflect a band of wavelengths several nm wide called a supermode. In SG-DBRs, the current applied to the front grating tunes all peaks reflected from it simultaneously.

The rear grating reflects at a discrete number of wavelengths within the supermode. Once the supermode has been set, varying the current applied to the rear grating provides the coarse tuning. Fine-tuning is done by adjusting the phase section, which reduces the tuning space to two dimensions. The optical output power is 5 mW and is stable across the tuning range, and the side-band suppression ratio is better than 50 dB with the side-mode emission coincident with the rear grating peaks (see figure). An advantage to this approach is reduced output power variation with tuning because of very low absorption in the front grating section. This removes the need to integrate an SOA to level the output power across the tuning range.

Digital supermode laser



MARCONI OPTICAL COMPONENTS/BOOKHAM

Spectra of peaks from one supermode of the DS-DBR laser. Fine-tuning allows the selection of a single peak with greater than 50 dB sidemode suppression.

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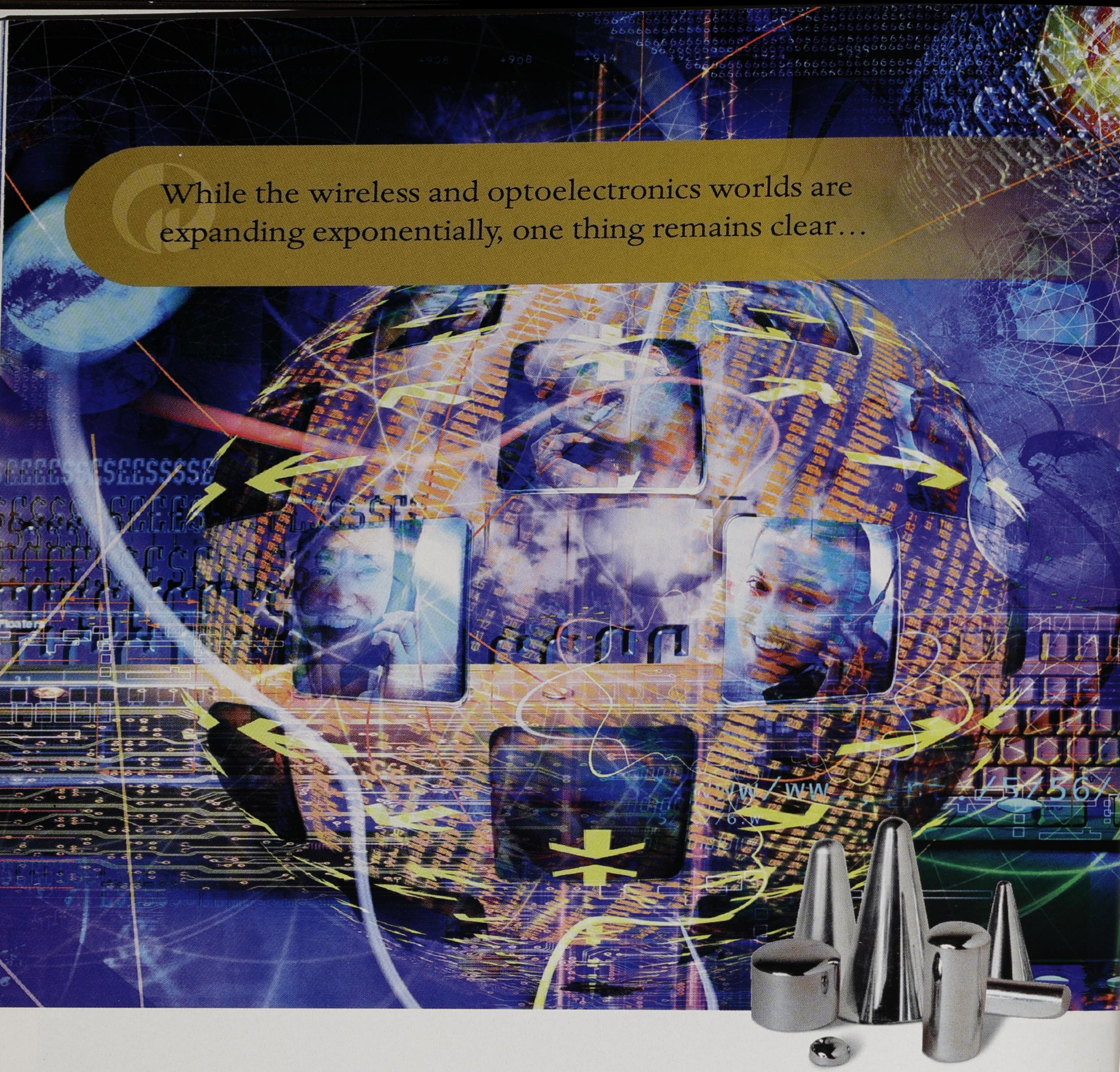

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EMAIL: YOSHIMITSU.NAKAGAWA@AP.RHODIA.COM
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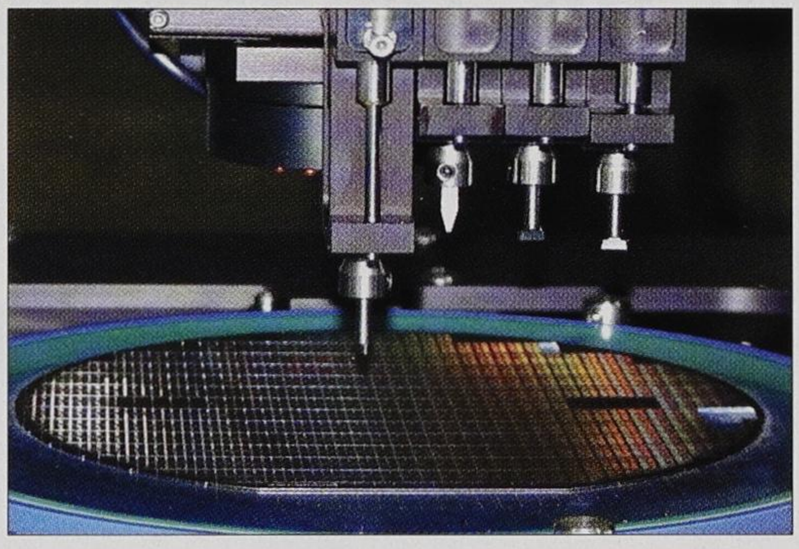
Newport to acquire MRSI

Newport Corporation has agreed to buy Micro Robotics Systems Inc (MRSI), a company that manufactures fully automated assembly and component dispensing systems. The transaction reflects a trend by fiber-optics component manufacturers to build more integrated automation into their manufacturing. MRSI, based in North Billerica, MA, manufactures automated die bonding assembly and packaging technology for optical modules that typically consist of laser sub-mounts, photodetectors, filters, receivers and transmitters. MRSI's products are also suited to eutectic bonding of GaAs-based RF components used in wireless applications (see *Compound Semiconductor* May 2001, p46). Newport, based in Irvine, CA, makes laser diode testers, power meters and detectors, and fiber alignment and assembly tools, as well as instrument systems for metrology and motion and vibration control.

"Newport is the leading supplier of automated fiber attachment systems to the photonics market, and MRSI is widely considered to be the premier designer and manufacturer of high-precision chip attach, dispensing and bonding systems with specific applicability to fiber-optic and high-speed electronic markets," said Robert Deuster, Newport's chairman and CEO. "MRSI's blue-chip customer roster is synergistic with our key customers, and its products are complementary to the automated assembly tools offered through Newport's Fiber Optics and Photonics Division. The combined product portfolio will allow us to provide a full range of solutions from chip qualification through assembly and testing."



MRSI manufactures component assembly dispensers and automated assembly and packaging systems, including this eutectic die-attach-from-wafer unit.

Merger forms new RSoft Design Group

RSoft and Network Design Tools Inc (NDTI) have formed RSoft Design Group, a merged company that will provide a full range of simulation and planning software and services for fiber-optic communications. The terms of the transaction were not disclosed. The new company consists of NDTI's Network Layer division based in Eatontown, NJ, and RSoft's Physical Layer division which is headquartered in Ossining, NY. RSoft provides device-level programs such as BeamPROP and FullWAVE, as well as LinkSIM tools for the design of link-level components. NDTI's programs range from optical network simulation to wireless network design and strategic analysis. The first products are expected to be released in the first half of this year.

In brief...

IQE and Intense link up

IQE and Intense Photonics have entered into a partnership that involves IQE supplying epiwafers to Intense in support of its efforts to further develop its quantum-well intermixing (QWI) process. IQE will also supply epi-structure design and modeling services.

Intense has already taken delivery of trial wafers to enable the fabrication of prototype devices as it commissions its new QWI wafer fab.

Appointments

Ian Smith has been appointed as chief executive of **Surface Technology Systems**, an equipment manufacturer based in Newport, UK.

Peter Blakey has been hired by **Accent Optical Technologies** as director of product marketing for the company's DIVA current-voltage measurement instrument. Blakey was most recently director of characterization, modeling and simulation at ON Semiconductor.

Equipment sales

- **Tsinghua University** has purchased and installed an **Aixtron** AIX 2000HT reactor for the growth of GaN-related materials, including blue LEDs (see News from Asia, p9). Aixtron says this represents its first production-type GaN MOCVD system sale in mainland China.

- **The University of South Florida** has purchased a dynamic current-voltage measurement instrument from **Accent Optical Technologies**. The DIVA system will be used in the Wireless and Microwave Center to analyze the pulsed current-voltage conditions present in RF, microwave and millimeter-wave circuits.

- **TRW** has placed a multiple system order worth several million dollars for InP etch systems from **Unaxis USA** (St. Petersburg, FL). Shipment of the Versalock units is scheduled during 2002 to TRW's InP wafer fab in Redondo Beach, CA. The Versalock system features up to three process modules that can be configured serially for sequential, *in situ* process applications, or in parallel for high throughput.

- **Aeronex** has sold an Infinity GPS gas purification system to **Quantum Photonics**, a manufacturer of optoelectronic components based in Jessup, MD. The GPS-300-I will be used to provide a continuous supply of purified gas and to remove gaseous contaminants such as H_2O, O_2, CO, CO_2 and hydrocarbons to sub-ppb levels.

- **Veeco Instruments** has received a multiple system order totaling $7.0 million for its Applied Epi MBE systems from an international customer. "The GEN2000 and GEN200 orders indicate that as companies invest in production MBE equipment, they are choosing our Si-style cluster tool systems," said David Reamer, president of Veeco-Applied Epi.

- Taiwanese company **Epistar** is preparing to ramp production of GaN-based LEDs with a recent order for an **Aixtron** AIX 2400G3HT reactor (11 × 2 inch wafers) equipped with a fully automated wafer loading system.

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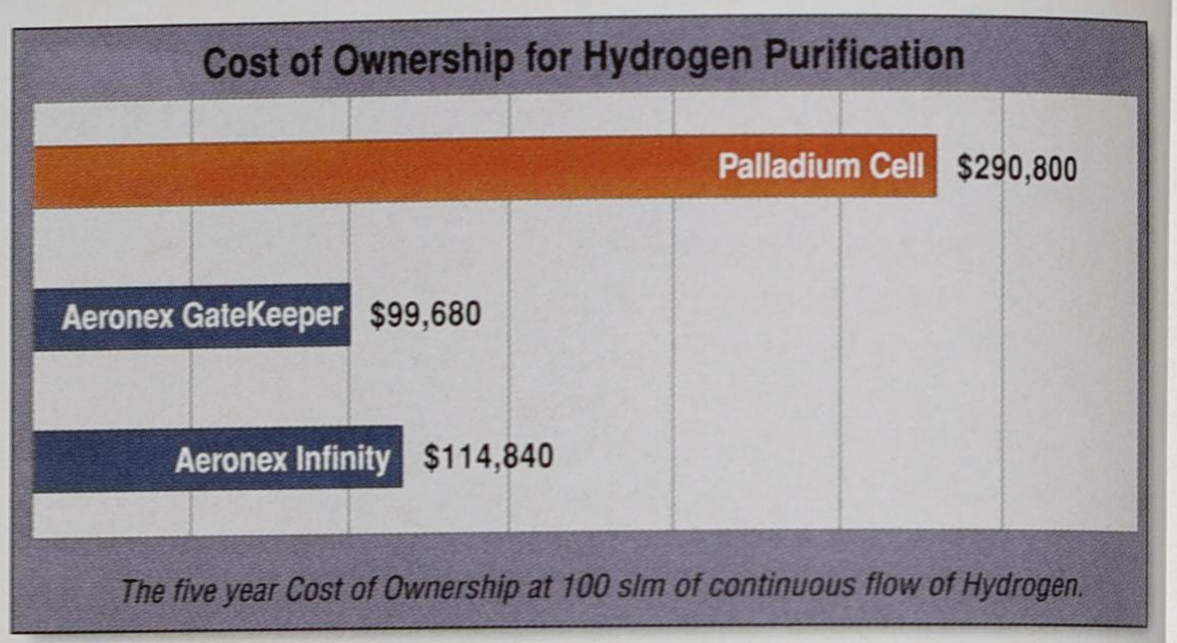
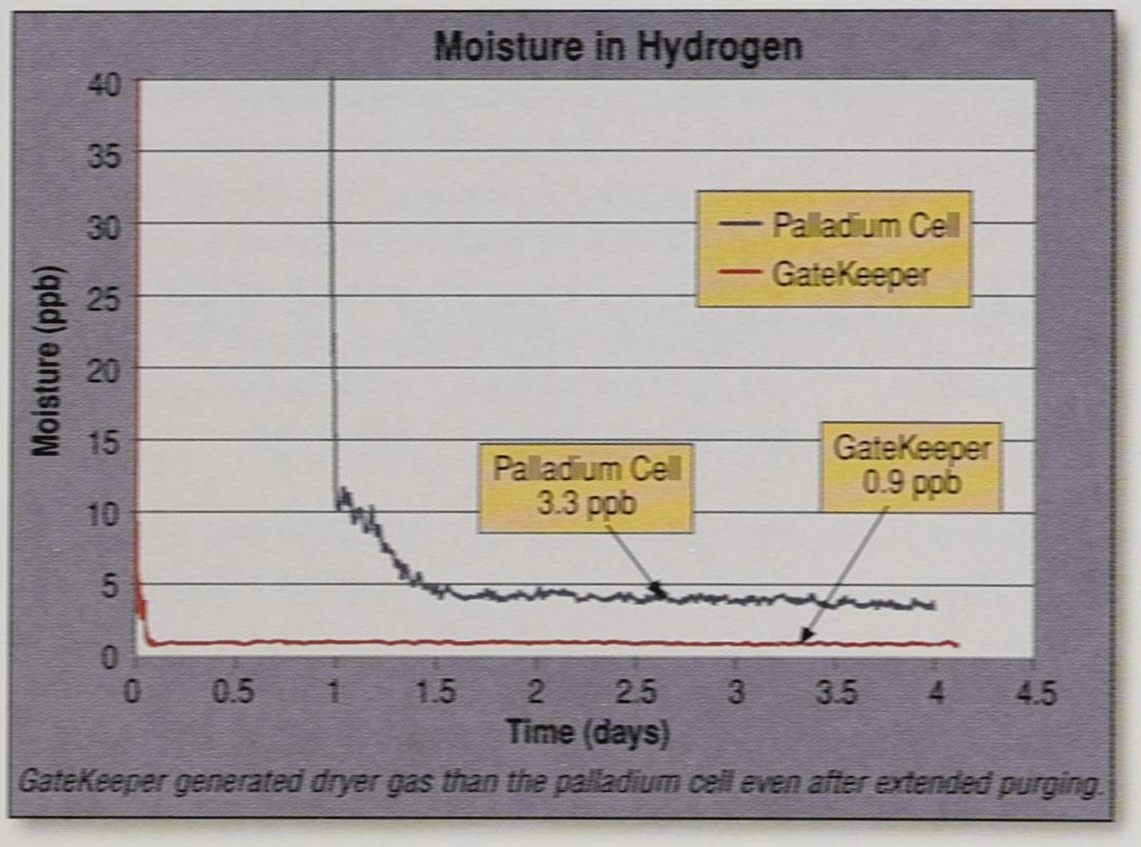
PERFORMANCE

Aeronex has developed the first inorganic purifier that out-performs palladium cells. GateKeeper Purifiers can be used with hydrogen from gas or liquid sources to provide the highest possible purity. Contaminants such as moisture, oxygen, CO, CO2, and NMHCs are removed to sub ppb.

Designed to operate at room temperature, this patented technology handles **high flows** at a **very low pressure drop**. The purifier requires no power and is unaffected by intermittent power failures that can cause cracking of palladium cells. The inorganic media is hydrocarbon free, so system upsets won't result in expensive tool repair or chamber clean up.



The five year Cost of Ownership at 100 slm of continuous flow of Hydrogen.



GateKeeper generated dryer gas than the palladium cell even after extended purging.

VALUE

Aeronex's patented technology enables the **lowest cost of ownership**. This clean design has a lower ASP than complex palladium cells. There are no heaters, controllers, or other electronics, nor delicate welded palladium assemblies (with rising commodity market pricing). Only two gas fittings need to be connected to be up and running, reducing installation costs. Power, nitrogen, instrument air/vent lines, and cooling water are not needed.

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Safety is a major concern at Aeronex. By enabling hydrogen purification at ambient temperature and low pressure, safety is increased. Aeronex products are regenerable, so there's no hazardous waste or toxic gas.

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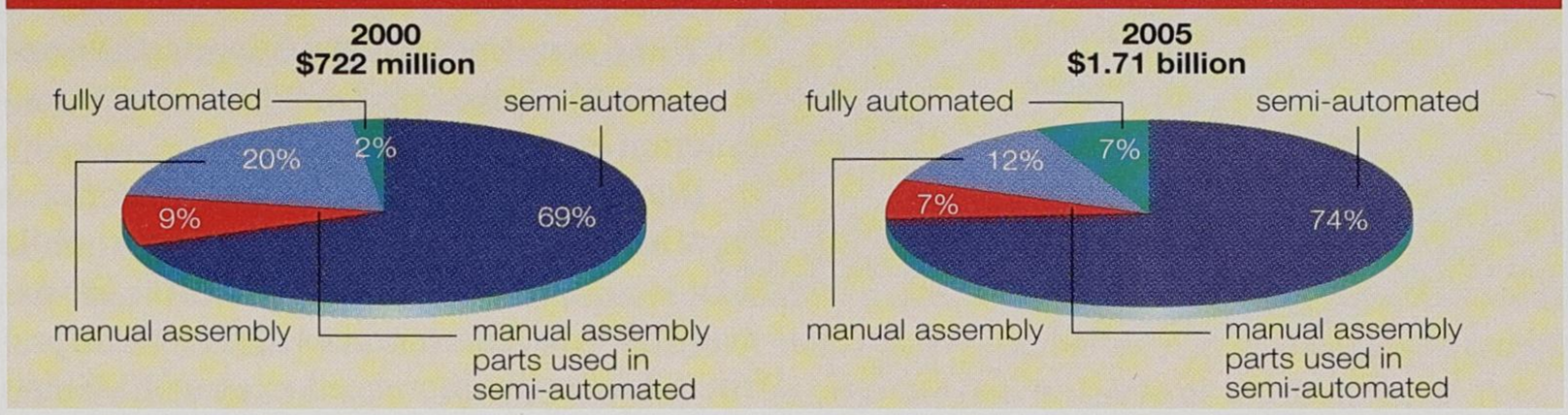


ELECTRONICAST

ElectroniCast has published a new report forecasting that the global consumption of fiber-optic component assembly and test equipment will show impressive growth by 2005. The report predicts that the $722 million market in 2000 will grow to $1.71 billion in 2005, despite a drop to $429 million in 2001.

With component manufacturers under pressure to lower prices, they are looking at ways to reduce costs and improve yields. Much of the market growth is expected to come from the installation of automated equipment. From 2000 to 2005, the share of fully automated equipment will rise from $14.4 million (2% share) to $119.7 million (7%). Semi-automated equipment will increase its share from $498.2 million (69%) to $1.27 billion (74%).

"Automated Assembly and Test of Fiber Optic Components Forecast" is available from ElectroniCast – see www.electronicast.com.

Slow start for 10 Gbit/s Ethernet

A market report from Communications Industry Researchers (CIR) describes the spread of the 10 Gigabit Ethernet standard over the next five years as "minimal". While the total Ethernet transceiver market is predicted to grow from less than $400 million in 2001 to $1 billion in 2006, CIR estimates that only 53,000 10 Gigabit Ethernet ports will be deployed in switches by 2006. Most of the Ethernet activity in this period will be in the established Gigabit Ethernet standard.

Some of the reasons being cited for the slow uptake of 10 Gigabit Ethernet are disagreement on transceiver design and the inability to get transceiver costs down to an acceptable level. Also, the combination of Gigabit Ethernet traffic with WDM is cheaper than going to 10 Gigabit Ethernet.

This spells trouble for newcomers to the 10 Gigabit Ethernet market unless they have large cash reserves or a broad product portfolio to carry them through until the standard becomes more widely adopted. CIR states that one way to gain a lead over established rivals is to use VCSELs in transceivers. These could reduce system costs, though 1310 nm VCSELs do not yet have the reliability of the 850 nm variant or 1310 nm edge-emitting lasers.

"Optical Ethernet: A Market Analysis of Gigabit and 10-Gigabit Ethernet Transceivers" is available from CIR – for further information see www.cir-inc.com.

EA modulators to expand market share

The global consumption of optical modulators is predicted by ElectroniCast to grow at over 40% per year to reach $1.37 bn in 2006, from $270 m in 2001. Beyond 2006 growth will slow, but will maintain a healthy 22.1% increase per year to reach $3.7 bn in 2011.

The report divides the optical modulator market into three: electroabsorption (EA), electro-optic (EO) and other modulator types. In 2001, EO modulators – mostly made from lithium niobate – held a 60% market share. ElectoniCast predicts that EA modulators will increase their share to over 50% by 2011.

"Optical Modulator Global Market and Technology Forecast" is available from ElectroniCast – see www.electronicast.com.

SOAs will find main use in the metro as optical switches

The communications technology analysts Cahners In-Stat are predicting that semiconductor optical amplifiers (SOAs) will find very limited use as amplifiers in metropolitan area networks (MANs). A report from the group estimates that the total market for optical amplifiers in long-haul and MAN applications will increase from $3.3 billion in 2001 to $4.7 billion in 2006, driven by new deployments and system upgrades. The report states that SOAs are more likely to find application as optical switches and that any use as amplifiers in MANs will be as replacements for low-cost EDFAs.

Communication Industry Researchers (CIR) has also produced a new report which analyzes the different technologies for optical amplification in long- and short-haul networks. The report describes how optical amplifiers are desirable components in larger MANs and how DWDM is becoming a solution to the bandwidth bottleneck. DWDM adds to system component count, and therefore signal losses, making optical amplifiers a necessity in such networks.

With the high cost of DWDM slowing its uptake in MANs, low-cost optical amplifiers are going to play a vital role in its success in this space. The conclusions drawn by CIR on the amplification technologies for the metro space are as follows:

- The existing EDFAs for single-channel amplification in MANs will need to be modified to reduce costs (by using uncooled pump lasers, for example).
- SOAs and erbium-doped waveguide amplifiers (EDWAs) may be better solutions for single-channel amplification.
- SOAs and EDWAs can allow smaller footprints and lower powers, though EDFAs are becoming more competitive.
- At present, the newer technologies are too expensive to enter the metro space.
- No single amplification technology will gain a monopoly, because all technologies will find use in MANs to some extent.

"Optical Amplifiers for Long-Haul and Metro Applications" is available from Cahners In-Stat – see www.instat.com.

"Optical Amplifiers: a Market and Technology Analysis" is available from CIR – see www.cir-inc.com.

Transmitter/receiver market set to reach $20.5 billion in 2006

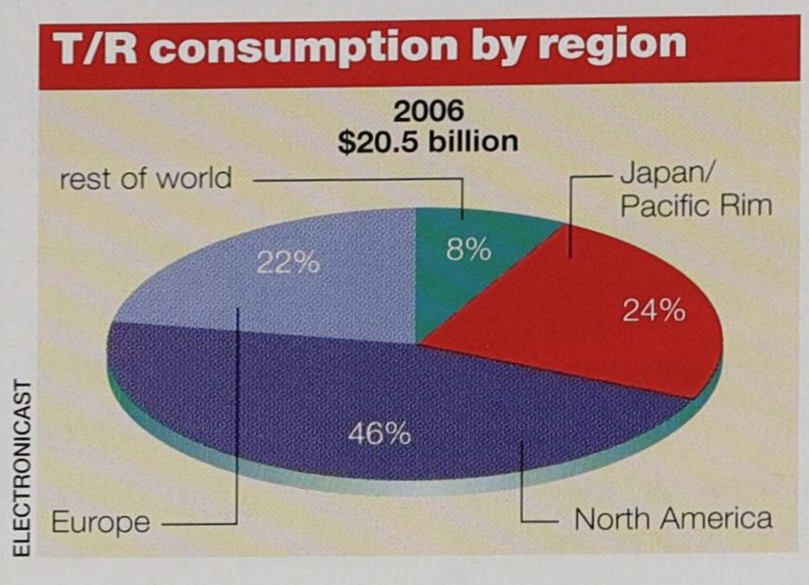
According to a report from ElectroniCast, the global consumption of transmitter/receiver (T/R) pairs for fiber-optic networks will grow from $4 billion in 2001 to $20.5 billion in 2006 – an annual growth rate of 39%. Although average selling prices are predicted to fall, this will be offset by an increase in the number of units sold over the period.

The growth in consumption is expected to come as demand for increased bandwidth forces the replacement of copper wires with fiber, and also moves fiber closer to the end user through short-reach links.

"For shorter links, transmitter/receiver pairs represent a substantial share of the total installation cost. The cost concerns are now being addressed by the installation of cheaper and easier to install transceivers with smaller footprints," said the president of ElectroniCast, Steven Montgomery.

In 2001, North America led the global consumption of T/R pairs with a 45% share worth $1.79 billion. Europe accounted for 22%, Japan and the Pacific Rim 23% and the rest of the world 10%. Although a large growth in consumption has been forecast, the geographical distribution of the market is expected to be much the same in 2006.

"Fiber Optic Optoelectronic Transmitter/Receiver Global Market Forecast" is available from ElectroniCast – for further information see www.electronicast.com.



GaAs industry to grow 15% per year

A forecast from Strategy Analytics says that the GaAs industry will experience growth with a CAGR of 15% through to 2005. The forecast concentrates on the GaAs IC, discrete FET and semi-insulating wafer markets, and also examines the reasons for the severe contraction experienced in 2001.

Recovery in 2002 is expected to come as new technology is incorporated into mobile handsets and as handset inventories are exhausted. Two major sources of growth are predicted to be the increased pace of 10 Gbit/s fiber-optic network implementation and the development of automotive radar for intelligent cruise control. GaAs MMICs are a key technology in both of these areas.

In a related report on GaAs epitaxial substrates, Strategy Analytics predicts that devices based on MOCVD-grown epiwafers will be the dominant GaAs-based devices by 2005, although it describes growth in this area as being conservative.

The huge growth of 159% in 2000 from 1999 levels ended up as excess inventory with only 55% of the total 2000 market representing actual use. The continued migration to epi-based devices will help the epitaxial substrate market recover in 2002 and beyond.

"GaAs Industry Forecast 2000–2005" and *"Markets for SI GaAs Epitaxial Substrates"* are available from Strategy Analytics – see www.strategyanalytics.com.

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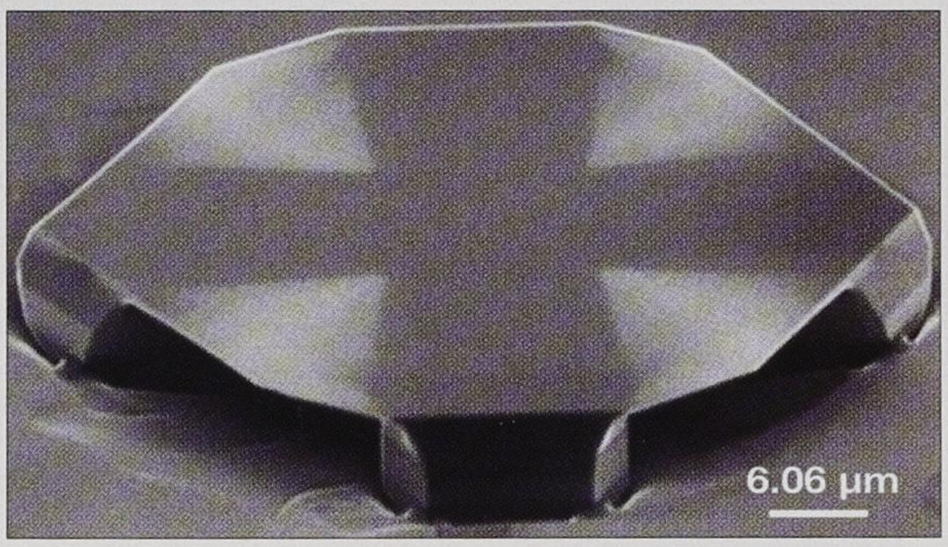
NASA grows step-free SiC surfaces

The growth of step-free SiC surfaces for use as substrates for epitaxial films has so far been limited by the high density of screw dislocations which originate from the substrate. These substrate-related defects cannot be flattened because of their continual spiral propagation through the growing epilayer.

Phil Neudeck and colleagues at NASA Glenn Research Center and the State University of New York have recently reported low defect density SiC surfaces produced on commercial on-axis 4H- and 6H-SiC wafers (ICSCRM 2001 *Tech. Dig.* 486). The authors used a dry etching technique to form an array of isolated cross-shaped growth mesas in the substrate. Growth occurs laterally from the mesa sidewalls leading to the formation of a web between the cross-arms of the etched mesas (see figure). This leaves an array of larger step-free surfaces. Because the crystal structure of the webbing is established laterally from the top of the mesa sidewalls, successful overgrowth of micropipes and closed-core screw dislocations in the substrate trenches below the webbing can be accomplished, leading to a four-fold enlargement of the area of step-free surfaces.



NASA

A step-free 4H-SiC surface grown using web growth. The original mesa is visible as the dark cross. The lighter V-shaped areas are the web-grown material.

The authors also used the web-grown 4H- and 6H-SiC mesa surfaces as substrates for high-quality cubic or 3C-SiC films (ICSCRM 2001 *Tech. Dig.* 730). This was achieved by lowering the growth temperature following the formation of the step-free surface, to induce island nucleation and growth of 3C-SiC. Each 4H- or 6H-SiC mesa nucleated only one of the two possible rotational variants. This eliminated the double-positioning boundary defects which are commonly found in 3C-SiC films.

The authors suggest that a single-island low-rate growth mode, where a 3C island nucleates and expands laterally to cover the mesa before a second interfering 3C island can nucleate, is required during the initial stages of growth. However, a low nucleation rate growth mode was no longer required after the initial bilayers of the 3C films were grown.

The findings indicated that the lattice mismatch between 3C- and 4H-SiC (around 0.08%) was at least partially relieved without generating stacking faults. The technique is being extended to the fabrication of prototype 3C-SiC devices and step-free surface heteroepitaxy of III-N films on 4H- or 6H-SiC substrates.

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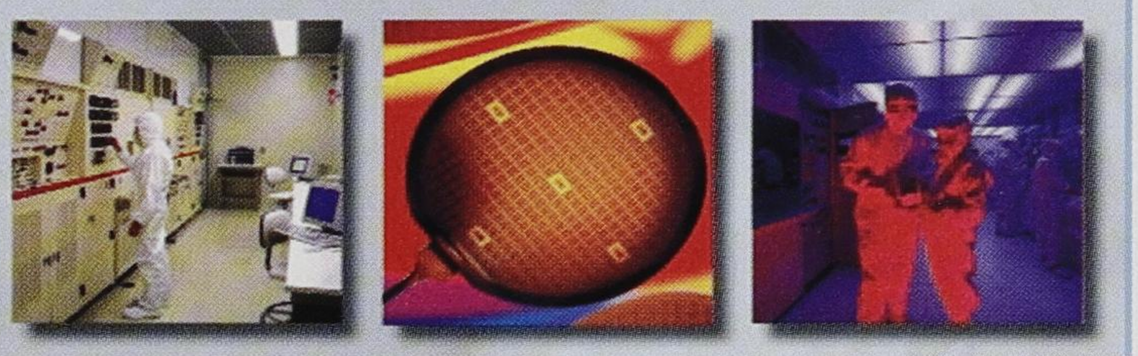

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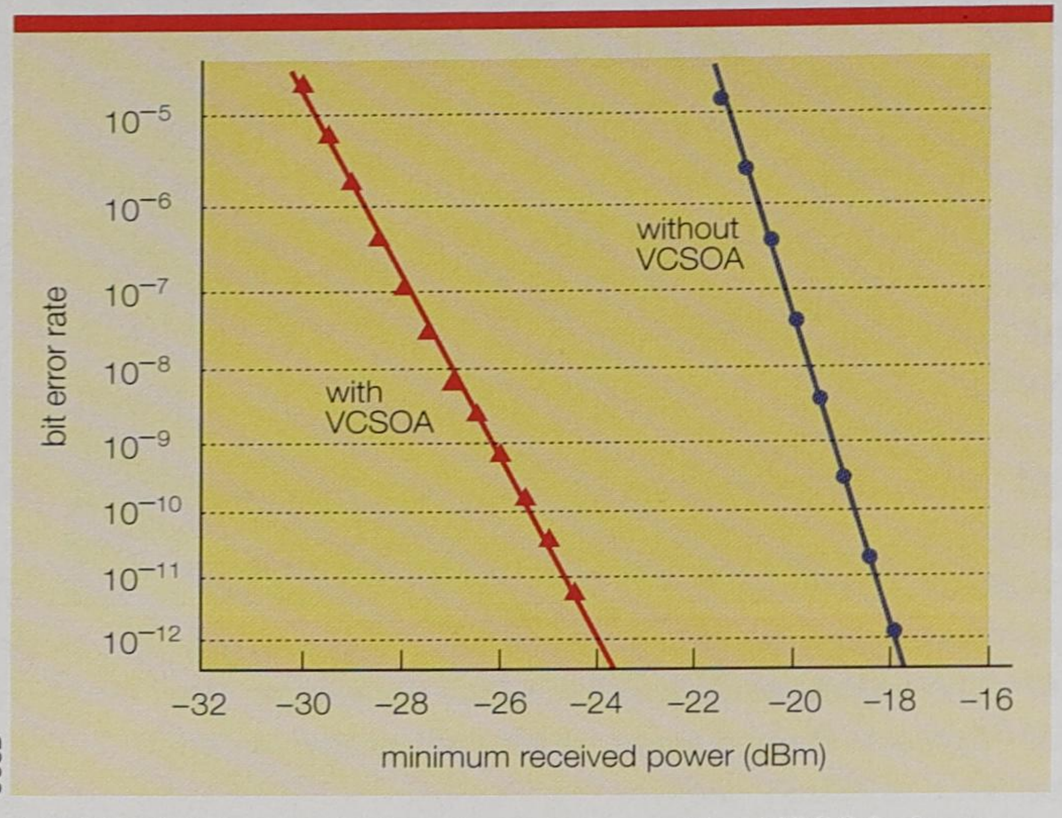
VCSOAs improve receivers for metro networks

Component cost is a crucial issue in metropolitan and other short-haul networks. Inexpensive and highly sensitive receivers are important components in these networks. At higher bit rates (10 Gbit/s and beyond) APDs are limited by their gain-bandwidth product. Optical preamplification is a route towards improving the sensitivity of *pin* receivers without compromising high-speed performance. With this in mind, Staffan Bjorlin and colleagues from the University of California at Santa Barbara have developed an optical receiver that uses a vertical cavity semiconductor optical amplifier (or VCSOA) as a preamplifier (*Elec. Lett.* 2001 **37(24)** 1474).



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At 10 Gbit/s transmission, the receiver with a VCSOA shows a considerable improvement in minimum received power.

The VCSOA structure consists of an InGaAsP/InP MQW active region wafer-bonded to two GaAs/AlAs DBRs. The device operated at 1300 nm and was optically pumped using a 980 nm laser diode. The receiver sensitivity was measured both with and without the VCSOA preamplifier, and the minimum powers detected were found to be –26.2 dBm and –19.2 dBm, respectively. With the VCSOA pumped at 80% of the power required to reach the lasing threshold, the fiber-to-fiber gain was 11 dB and the optical bandwidth was 37 GHz. The variation in bit error rate with received optical power for the receiver with and without the VCSOA is shown in the figure, left.

While VCSOAs can be fabricated across a range of wavelengths (unlike EDFAs for example), and can provide better fiber-coupling efficiency than in-plane SOAs, there remains work to be done in order to commercialize the VCSOA approach and make it a viable rival to other technologies. "Using an external pump laser is not a commercially practical way of pumping the device," explained Bjorlin. "The next step is to look into integration of the pump laser, which has been done with long-wavelength VCSELs, or electrically pumping the VCSOA."

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Monolithic GaAs OEIC transmits and receives

Weidong Zhou and colleagues at the University of Michigan and IQE have fabricated a GaAs-based monolithically integrated heterojunction phototransistor (HPT) and resonant cavity (RC) LED (*Photon. Tech. Lett.* 2001 **13(11)** 1218). The MBE-grown optoelectronic integrated circuit (OEIC) uses a low-resistance tunnel junction to efficiently couple the HPT and the RCLED. The device works via the detection of an incoming optical signal by the HPT. The absorbing region of the HPT is placed in a resonant cavity to improve its responsivity. The generated photocurrent drives the RCLED which emits at a different wavelength.

The optical gain and DC characteristics of the HPT were measured using an 850 nm laser as the photon source. The HPT showed a dark current of 1 μA and a breakdown voltage of over 6 V. With 1 μW input power, the optical gain was 1 A/W. The RCLED had a maximum output power of 250 μW for an injection current from the HPT of 36 mA. A phototransceiver OEIC with a 90 μm aperture had an optical gain of 13 dB for an input power of 5 μW.

Arrays were also fabricated with up to 13 × 13 elements. The output intensity variation across the 13 × 13 array was within 10%. Cross-talk between adjacent elements was measured for different element spacings (d) and distances between the apertures and the light source (h). For a 6 × 6 array with d = 50 μm and h = 1200 μm, cross-talk was −10 dB, and at d = 300 μm and h = 200 μm, cross-talk was −100 dB, indicating that the cross-talk was almost entirely optical.

Novel epi technique enables 305 nm UV-LEDs

Due to their potential use in solid-state white lighting, bio-chemical detection and high-density data storage, the demand for high-power, short-wavelength (280–340 nm), compact UV light sources has rapidly increased. Asif Khan and colleagues at the University of South Carolina and Sensor Electronic Technology, NY, have pioneered the development of deep-UV III-nitride LEDs with emission wavelengths of ≤ 340 nm using high Al-content AlInGaN MQWs in the active region (*Jpn. J. Appl. Phys.* 2001 **40 (Pt. 2, 12A)** L1308). The team's goal is to fabricate LEDs and lasers with emission wavelengths down to 280 nm, and to use them with conventional fluorescent lighting phosphors for solid-state lighting.

The team used a novel low-pressure MOVPE technique called pulsed atomic layer epitaxy (PALE) to grow the LED structures. This enabled growth temperatures as low as 750 °C to be used, and as a result high indium levels (up to 6%) could be incorporated into AlInGaN layers with high aluminum mole fractions, thus improving the structural and optical properties of the MQWs.

Mesa type and stripe geometry LEDs with record low emission wavelengths from 305 to 340 nm were successfully fabricated. Pulsed powers measured on the wafer were as high as 1 mW at 340 nm, 0.2 mW at 315 nm and 0.05 mW at 305 nm. Series resistance for the 340 and 315 nm devices was 50 Ω, but increased to 600 Ω for the 305 nm LED, causing excessive heating and limiting the emission efficiency. The team is currently packaging the LEDs which, as previously demonstrated, should increase the output powers by a factor of three to five.

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Bipolar silicon passes the half-century mark

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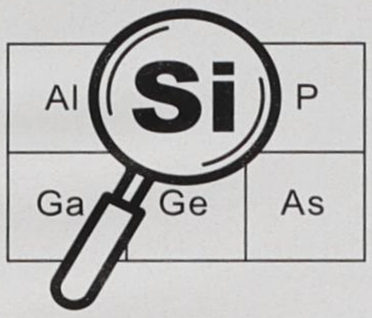

When SiGe devices are characterized as having GaAs-like performance, this is simply untrue when comparable devices are being evaluated.

The November 2001 issue of *IEEE Transactions on Electron Devices* celebrated the 50th anniversary of the silicon bipolar transistor. The issue featured a wide range of papers that detailed not only the history of the bipolar transistor and the personalities involved (Brattain, Bardeen and Shockley), but also a snapshot of the current state-of-the-art. One paper in particular by IBM's Tak Ning, a member of the original team that developed the double-polysilicon self-aligned bipolar transistor in the late 1970s, is ideally suited to this column (Ning). The author presents a clear and concise comparison between IBM's SiGe HBT and a GaAs HBT. He takes great pains to make sure that the devices he compares are of a similarly advanced structure and design rule, and operate at the same collector current densities – in essence "normalizing" the two transistors (typically never done when comparing different technologies). Once the normalization process is accomplished, a fair comparison of different devices can be made by examining intrinsic device parameters.

Silicon *vs* SiGe transistors

The first point Ning makes in the case of a linearly graded Ge profile base structure (such as in IBM's SiGe process), is that the device is not a heterojunction bipolar transistor, but can be more accurately described as a graded bandgap bipolar transistor. The paper compares a Si bipolar to a SiGe bipolar transistor, in which both transistors employ the same polysilicon emitter. Since the base current of a bipolar transistor is a function of the emitter parameters only, and is independent of the base parameters, the Si-base and SiGe-base transistor have the same base current – only the collector currents (which depend on the base parameters) are different for the two transistors. Because a wide-bandgap emitter is not used in a SiGe-base transistor, these devices face the same scaling limitations as a Si-base transistor, i.e. base widening at high current densities, and relatively low avalanche breakdown voltages at the base-collector junction. However, the inclusion of Ge in the base of a Si-bipolar does result in improvements in current gain, Early voltage and base transit time.

When the emitter-base junction in a linearly graded SiGe-base transistor is examined, it is found to have the same emitter-base junction depletion layer capacitance (C_{dBE}) as a Si-base transistor. However, the emitter-base heterojunction of a GaAs HBT (with the wide-bandgap emitter) suppresses the base current and allows its emitter to be very lightly doped. As a result, a GaAs HBT has a much smaller C_{dBE} than a SiGe-base transistor. Furthermore, the wide-bandgap emitter of the GaAs HBT allows the intrinsic base to be more heavily doped, and so the base resistance (r_b) can be 10 to 100 times smaller than that of a SiGe-base transistor.

Transit times

In terms of the base transit time, the field-aided enhancements, which are due to the Ge-grade in the base, reduce the transit times to a level that is comparable to that in a GaAs HBT. Ning notes that the GaAs HBT could also employ a bandgap-graded base to enhance base transit time, but this is not typically done in a standard GaAs HBT process.

In the collector region, the two transistors have similar collector doping concentrations when designed to operate at the same current density. As a result, both the SiGe bipolar and the GaAs HBT have approximately the same base-collector junction depletion layer capacitance (C_{dBC}) and the same base-collector junction depletion layer transit time (t_{BC}).

Consequently, when determining the cutoff frequency (f_t), the only real difference between these two devices is due to C_{dBE}, and as a result, for these normalized devices, the GaAs HBT will always have a larger f_t due to the smaller C_{dBE}. Because the maximum oscillation frequency (f_{max}) is proportional to $(f_t/r_b)^{1/2}$, and r_b is significantly lower in the GaAs HBT, the resulting f_{max} for the GaAs HBT is always larger than that of a SiGe bipolar. Furthermore, the larger bandgap of GaAs compared with Si means that the GaAs HBT is much less susceptible to base-collector junction avalanche effects. This means that a GaAs HBT can be designed to operate at a much higher collector-current density compared with a SiGe bipolar transistor for a comparable breakdown voltage requirement. Another way to view this is that a GaAs HBT can be scaled to much smaller dimensions (which require higher current densities) than a Si-base or SiGe-base transistor.

In light of the preceding discussion, it becomes clear that when SiGe devices are characterized as having

It is important to realize that, despite Si bipolar's inferior performance, it is still able to handle many, if not most, of the commercial applications in the 1–5 GHz regime.

GaAs-like performance, this is simply untrue when comparable devices are being evaluated. Ning goes on to explain that the possible advantages of SiGe bipolar devices over GaAs HBTs are not related to performance, but to compatibility with silicon VLSI processes. If SiGe devices and circuits are needed in large volumes, and with large transistor counts, and are folded into a BiCMOS process, Ning believes that a SiGe bipolar may have an advantage over a GaAs HBT from a cost perspective.

Good enough is good enough

I suggest that you get a copy of this paper and hand it out to every person you encounter who tells you that SiGe is just as good as GaAs. But before those of you in the GaAs camp claim victory over Si and SiGe bipolar devices, it is also important to remember that when it comes to the fabrication of circuits and systems, good enough is good enough. No one is going to pay more for a system because it is using high performance GaAs, unless every bit of that high performance is needed.

While GaAs HBTs may always be the better performer, Si bipolar continues to improve (as do GaAs HBTs). An example of this, presented in the same anniversary issue of *IEEE Transactions on Electron Devices*, is the work from Infineon Technologies on their all-implanted Si-bipolar process (Bock *et al.*). Unlike GaAs, SiGe or most fast Si-bipolar processes, this 0.4 μm self-aligned double-polysilicon process does not require epitaxial steps. It exhibits an f_t of 52 GHz (at 1 V bias), an f_{max} of 65 GHz (2 V bias), and minimum noise figures of 0.7 and 1.3 dB at 3 and 6 GHz, respectively. When the process was used to fabricate a dynamic 2:1 frequency divider, this IC operated over an input frequency range of 15–52 GHz. These are outstanding characteristics that some would still insist are GaAs-like. So before you get comfortable with the intrinsically superior performance of GaAs HBTs, it is important to realize that, despite Si bipolar's inferior performance, it is still able to handle many, if not most, of the commercial applications in the 1–5 GHz regime.

Further reading

T Ning 2001 History and future perspective of the modern silicon bipolar transistor *IEEE Trans. Electron Devices* **48(11)** 2485.

J Bock *et al.* 2001 High performance implanted base silicon bipolar technology for RF applications *IEEE Trans. Electron Devices* **48(11)** 2514.

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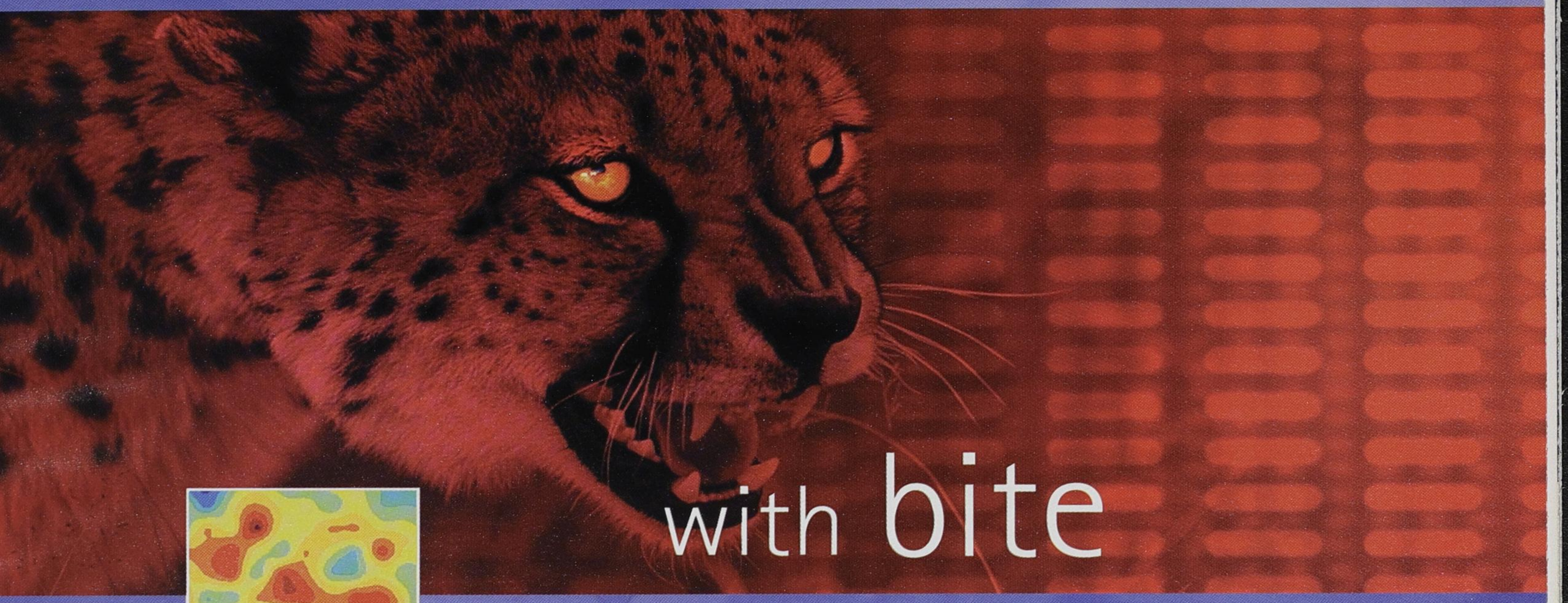
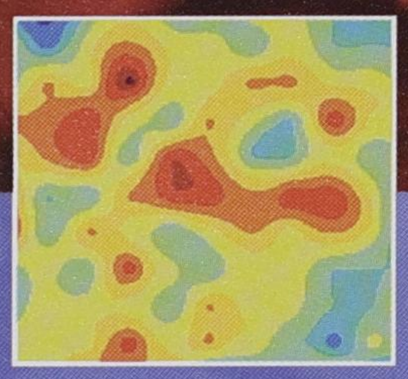
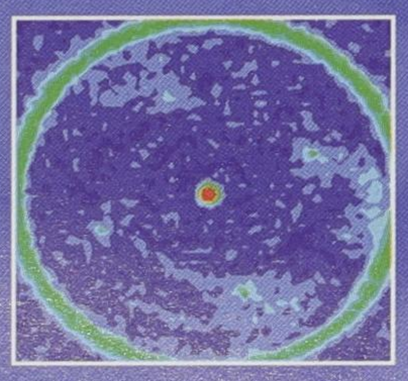
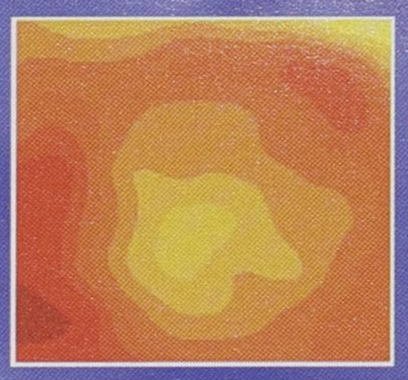




SiGe Wafer Map; data collected on a Bede QC200™. Data courtesy of Dr Peter Zaumseil, IHP, Germany.



Texture pole figure - MnFe/Co/Cu Spin Valve Stack - taken on a Bede D1.



Rocking curve analysis of GaN (10-12) reflection taken on a Bede QC200™. Data courtesy of Dr Joong Seo Park, EpiValley, Korea.

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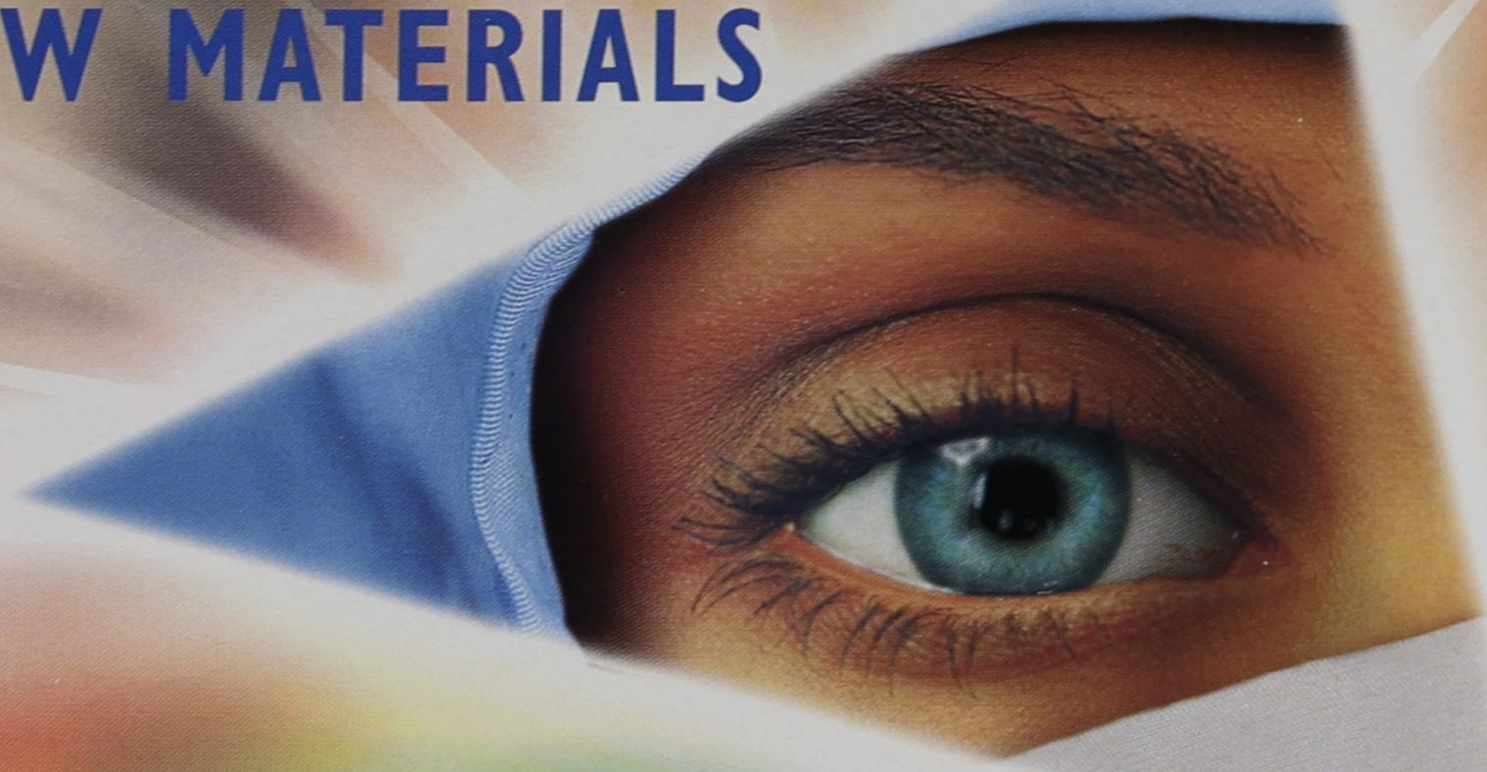

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New analytical techniques improve production control

Iain Calder describes how characterization equipment is being integrated into the process flow to provide increased measurement reliability, low cost and rapid turnaround.

Electronic and optoelectronic component manufacturing for the optical telecommunications industry has until recently consisted of low-volume engineering-intensive production lines. However, with the rapidly increasing demand for compound semiconductor components, manufacturing is changing to a high-volume, automated, silicon-like model. There is therefore a drive to reduce costs in all areas, including characterization and analysis.

On the other hand, compound semiconductor device processing is inherently more variable than silicon production, and a full toolkit of analytical techniques is required to maintain process control and performance. In many cases a particular technique is applied to every wafer, and in others a high sampling rate is needed. These requirements are expensive, and reconciling them has led to several new trends in material and device characterization.

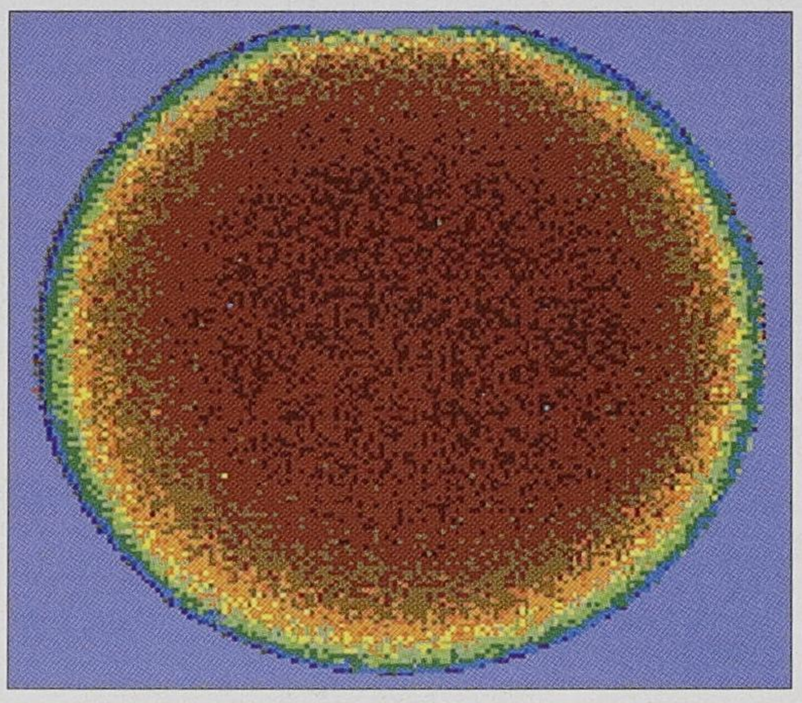

Fig. 1. PL map obtained with a resolution of 0.5 mm over a 75 mm substrate containing a 1310 nm laser epiwafer structure. A full spectrum was acquired at each position and the entire map was completed in 3 minutes.

Characterization terms

AES – Auger electron spectroscopy
AFM – atomic force microscopy
DCDM – double crystal X-ray diffraction mapping
EDX – energy dispersive X-ray
EELS – electron energy loss spectroscopy
FTIR – Fourier transform infrared
PL – photoluminescence
PR – photoreflectance
SCM – scanning capacitance microscopy
SEM – scanning electron microscopy
SIMS – secondary ion mass spectrometry
SSRM – scanning spreading resistance microscopy
STM – scanning tunneling microscopy
TEM – tunneling electron microscopy
XRD – double crystal X-ray diffraction

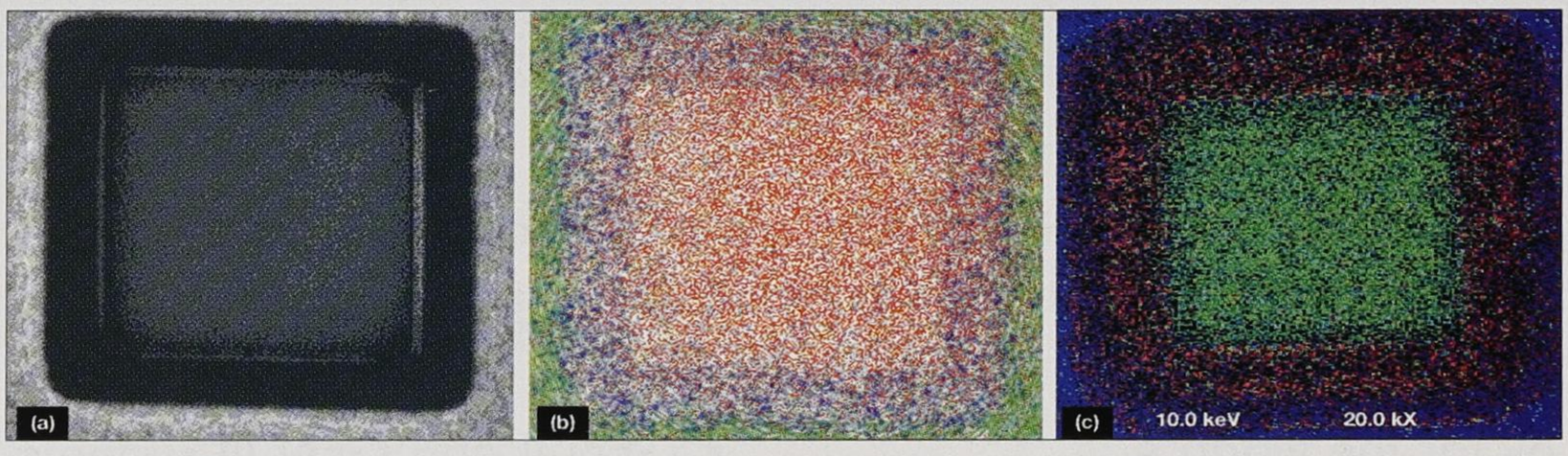

Fig. 2. (a) SEM and (b) EDX images of a 2 μm contact hole in an HBT device. In the EDX image the green contrast is Au, the blue is Si and the red corresponds to Ga. (c) AES image of the same HBT providing additional information on the Pd surface metal (the blue contrast represents Pd, the red indicates Si and the green indicates Ga).

Analytical requirements

From the point at which new wafers are received the manufacturing process can be divided into six main stages: epitaxial growth, device processing, full wafer testing, packaging, final test (including reliability and life test) and shipment. A variety of characterization and analysis techniques are required; these include *in situ* measurements as an integral part of the growth and processing stages, as well as in-line characterization to provide monitoring as part of the process flow. More complex, expensive, or time-consuming characterization is handled off-line, but the results may be used to gate a later point in the process. Finally, there is the analytical work that is required for engineering, problem solving, root cause analysis and analysis of field returns.

These requirements have benefited from some significant trends in the characterization and analysis of compound semiconductor materials and devices. These include: i) high-throughput wafer mapping and imaging; ii) wider use of scanning probe techniques; iii) high-resolution site-specific analysis; iv) accurate, multivariate computer simulation; v) extensive cross-calibration and improved reliability of calibration; vi) increased use of *in situ* and in-line characterization. This article discusses examples of some of these approaches, drawn from MQW and buried heterostructure lasers, detectors, and GaAs or InP HBTs.

High-throughput mapping

Full-wafer PL and reflectance mapping of every wafer after epitaxial growth has been an established practice for several years (Carver *et al.*). Recent developments in equipment using infrared array detection have enabled a combination of high-speed and high-resolution mapping, which is capable of improving the quality of the characterization while lowering the cost for large volumes (Wang *et al.*).

The example shown in figure 1 was obtained in around 3 minutes from a 3 inch wafer containing an MQW laser. Since the entire spectrum is obtained at each of the 20,000 positions, any extracted property – and in

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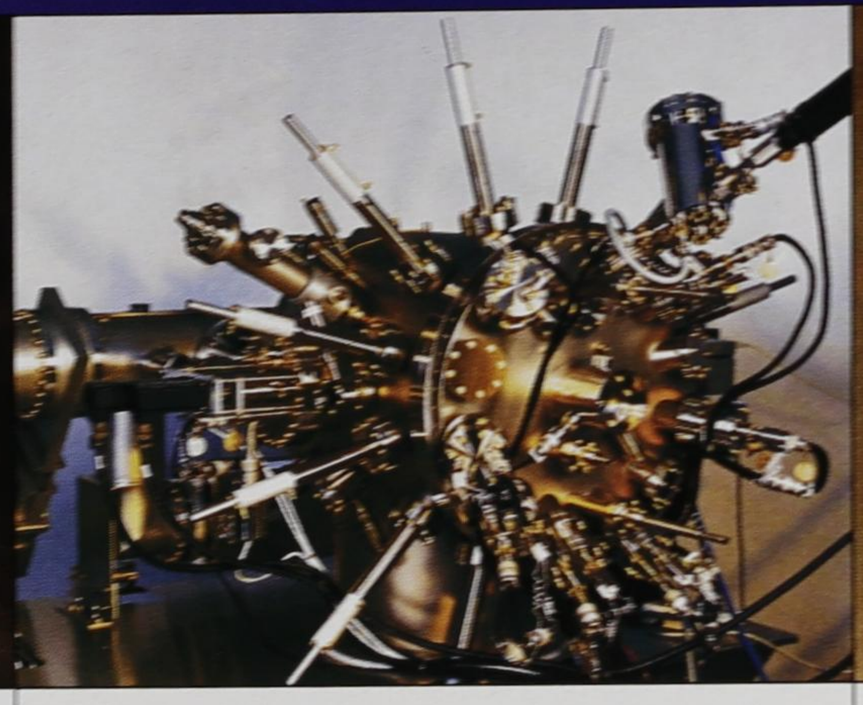

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this case, peak wavelength – can be mapped through post-processing.

With the advent of high-power DCDM systems, it is now feasible to map a wafer by taking a full rocking curve at each position. As each map still takes several hours to complete, a single rocking curve is usually measured for routine characterization requirements. However, the full mapping capability is now available for analytical or diagnostic purposes, or on a sampled basis.

SIMS is another technique that can now make use of mapping, and it is already a standard tool for routine in-line growth characterization. New equipment provides automated multiwafer SIMS characterization with *in situ* real-time depth measurement. It is therefore feasible to collect many profiles over a wafer without operator intervention, and then to create a coarse map.

High-resolution imaging

EDX mapping of material composition has been available for some years now. Figure 2 shows an HBT contact imaged with by SEM (2a) and an EDX map (2b). The outermost region visible in the SEM image is the Pd/Au metallization, while the dark ring is a silicon oxide side-wall. The center square is open to the GaAs semiconductor. It has also become practical in recent years to obtain a high-resolution AES image of a sample surface. Figure 2c shows an AES image of the same HBT structure as in figure 2a. While EDX probes up to a micron below the surface, AES is sensitive to the surface, and the two techniques provide complementary images. AES reveals the Pd metal on the surface, without detecting the Au.

Scanning probe techniques

Scanning probe techniques such as AFM are employed in the high-resolution analysis of surface morphology (STM still has limited application in the compound semiconductor industry). A wide variety of probes can now be added to characterize temperature, surface potential, SSRM, SCM and magnetic properties. In addition, many optical measurements, including PL, PR modulation, reflectivity, optical-beam-induced current, photoconductivity, ellipsometry and optical emission, are possible with AFM. Here we will focus on the two techniques – SSRM and SCM – which provide nanometer-scale resolution analysis of electrical properties, and hence provide doping and structural information.

Figure 3 compares cross-section images

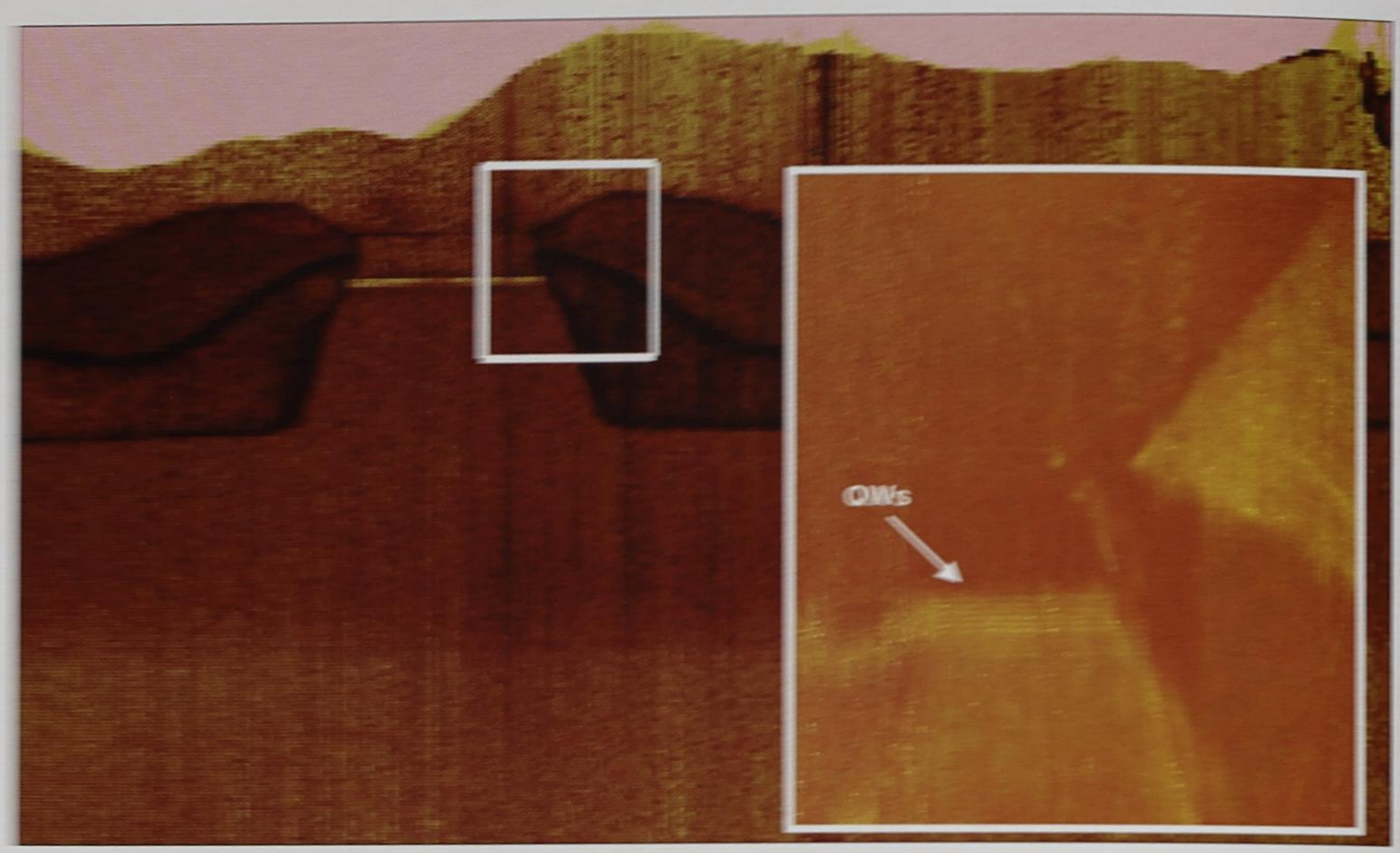

Fig. 3. Cross-section SSRM image and (inset) expanded view of the active area in an InP buried heterostructure laser. The lateral extent of the main image is 10 μm and the inset resolves the ~5 nm quantum wells (QWs).

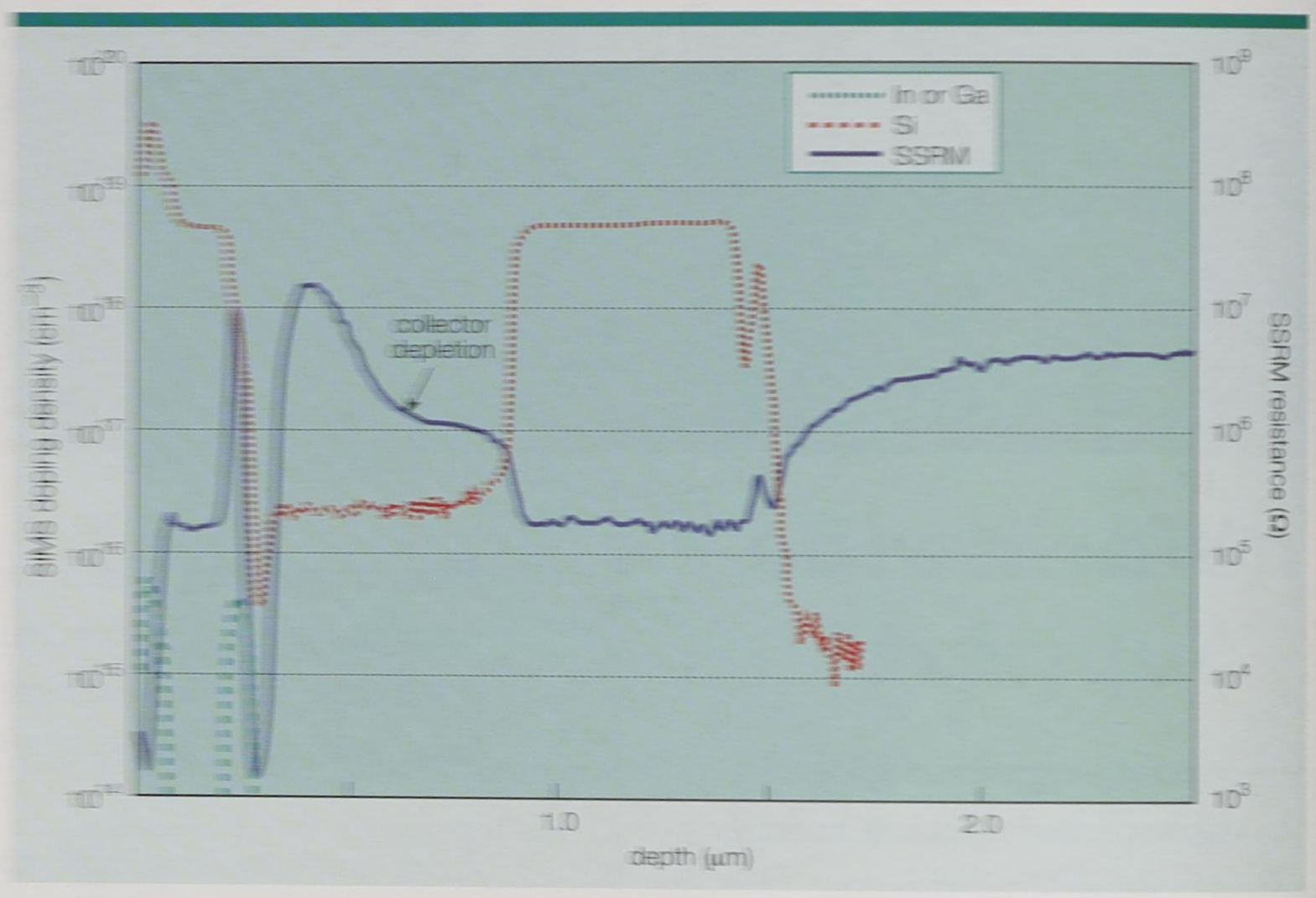

Fig. 4. A comparison of the SIMS and SSRM profiles of a GaInP/GaAs HBT structure. The SSRM scale on the right (resistance) accurately correlates with the doping density as measured by SIMS. In this structure a depletion region is evident in the collector.

obtained by SSRM from a buried heterostructure DFB laser. The power of these techniques is shown by the clear delineation of the various regions, even though all are composed of InP. SSRM is capable of resolving quantum wells with a dimension of 50 nm.

With careful calibration, SSRM can also quantitatively measure doping levels (Lu *et al*). In figure 4, SSRM and SIMS profiles of an HBT structure are compared. The fit is good, and the SSRM scan reveals some interesting effects in the collector region, where depletion is observable.

Site-specific analysis

For site-specific, or cross-section analysis of individual devices in a circuit or on a wafer, sample preparation is as important as the measurement procedure. For this approach, analytical techniques are predominantly elec-

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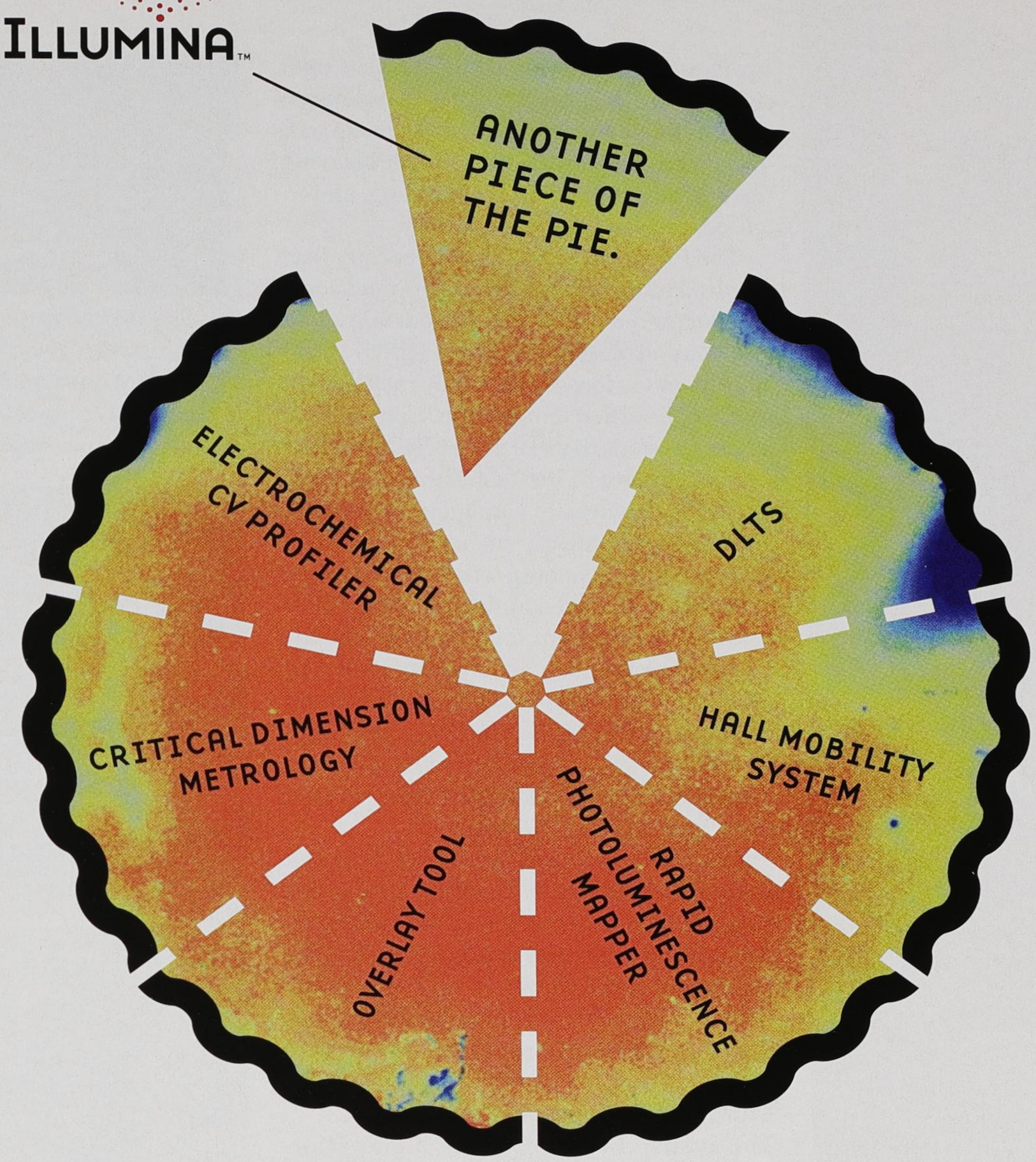

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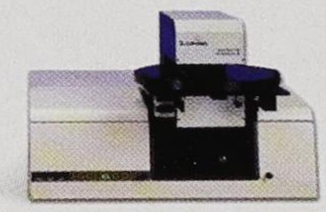

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tron-beam-based (i.e. SEM, TEM, Auger, EDX, EELS), or scanning probe techniques such as those described above. To make samples, sectioning techniques include cleaving, mechanical polishing, ion thinning, and focused ion beam (FIB) sectioning.

The FIB technique has only recently been applied to the analysis of compound semiconductor materials. FIB lift-out allows the preparation of samples for the TEM by using a beam of Ga ions to mill away material and produce a section thin enough to be transparent to electrons. By making a FIB cut on each side of the site of interest, a thin foil of the order of a few tens of nanometers is created. Slots are subsequently cut on each end of the foil so that it is hanging only by tiny bridges (see region indicated by arrows in figure 5).

Using micro-manipulation tools, the foil can then be snapped out at these points and placed directly on a TEM grid. Not only is the foil site specific, but the material is uniformly thin so that the TEM image contrast contours caused by thickness variation in the specimen are eliminated from the images.

Figure 6 shows the power of this technique in two TEM images taken from the ridge of a single DFB laser, where one cut was made perpendicular to the ridge, and one parallel. The top image clearly shows the ridge and metallization structure, while the bottom image shows the quantum wells and grating structure.

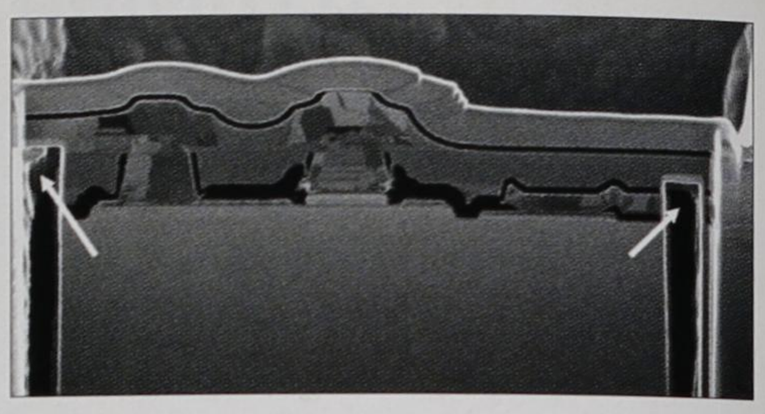

Fig. 5. SEM image of a completed TEM lift-out sample obtained from an HBT, thinned using FIB. The resulting foil contains slots (indicated by arrows) where the specimen is snapped off for imaging in the TEM.

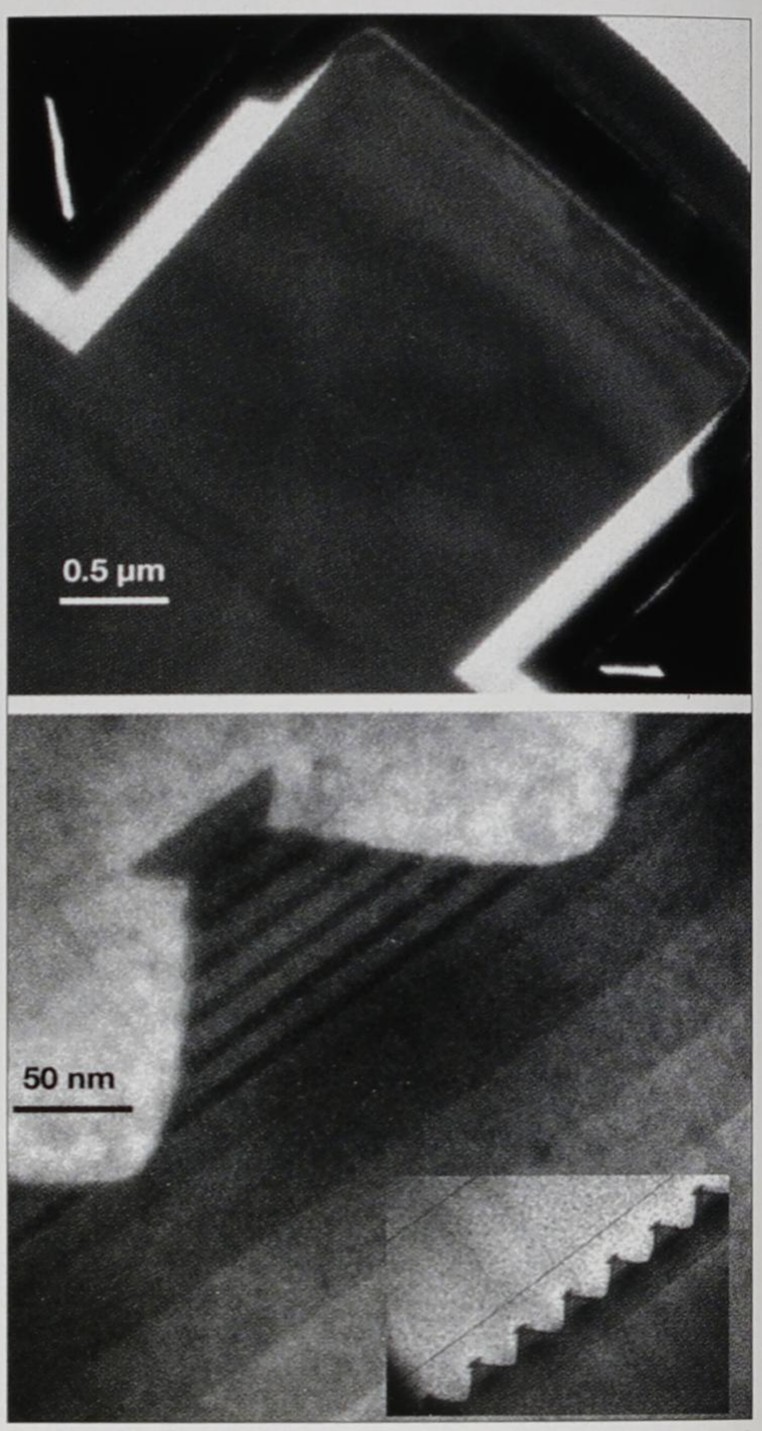

Fig. 6. TEM images of the same DFB laser. The top image is taken perpendicular to the ridge, while the lower image is parallel to the ridge, and shows details of the InGaAsP quantum wells and laser grating (inset).

Multivariate computer simulation

The availability of low-cost, high-performance PCs has enabled the complex mathematical simulation of measurements to be performed in the manufacturing environment as well as in the research lab. Enough physics can now be included to make these models highly accurate. This technology is used for the simulation of reflectivity, variable angle spectroscopic ellipsometry, FTIR, surface photovoltage spectroscopy, PR modulation spectroscopy and Hall effect field spectroscopy. The two examples presented below are from simulations of X-ray rocking curves and PR.

Figure 7 shows rocking curves taken for two different X-ray reflections from the same sample, which consists of an InAlAs MQW laser structure. The rocking curves were simulated using RADS Mercury software from Bede (Bowen), with parameters maintaining their values across both simulations. Each reflection is sensitive to a different set of parameters, but taken together accurate high-resolution values can be extracted for the thickness and composition of both wells and barriers, and for the bulk InP and InAlAs layers.

The example shown in figure 8 is obtained using photoreflectance modulation spectroscopy to investigate a double heterostructure InP HBT. PR is an optical method that obtains precise measurements of direct transition energies in semiconductors, and of electric fields in the vicinity of surfaces, interfaces or junctions (Pollak and Shen).

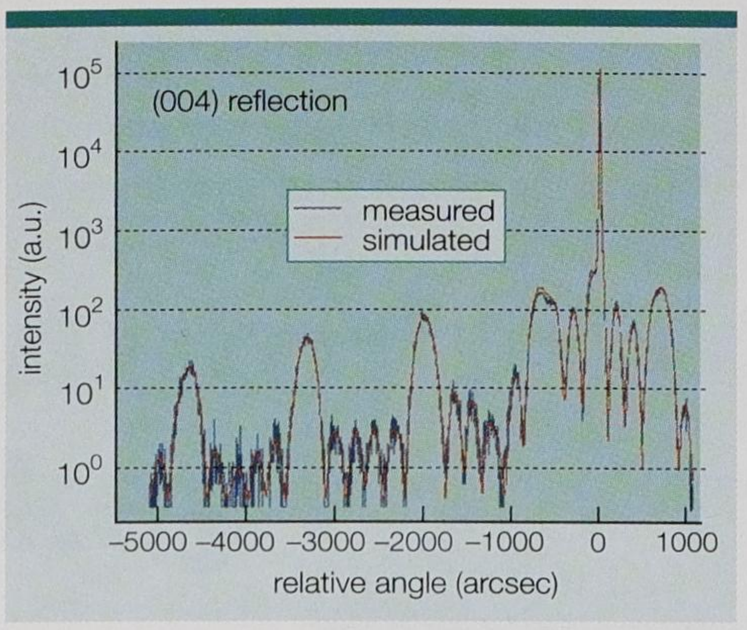

Fig. 7. High-resolution computer simulations of rocking curves obtained for an InAlAs MQW laser structure. The large peaks arise from the MQW period, while the higher frequency peaks are generated by the bulk InP layers.

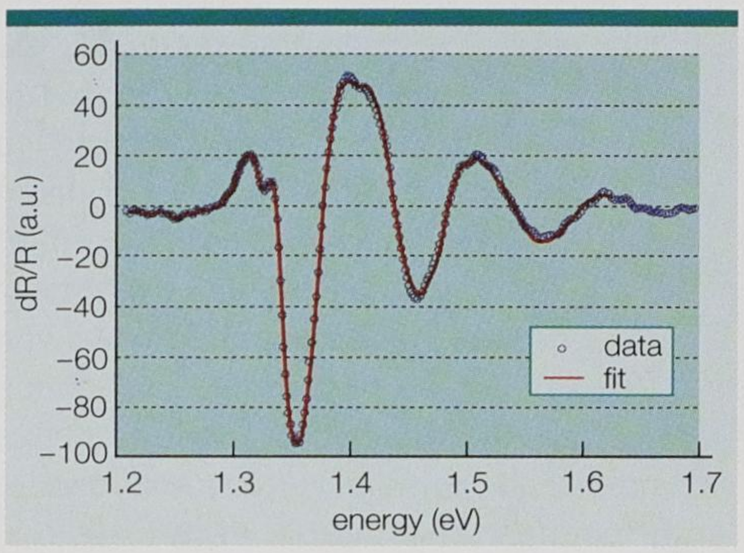

Fig. 8. Simulation of a photoreflectance modulation spectrum taken from an InP double heterostructure HBT. The simulation deconvolves the spectrum of the more heavily doped emitter (higher bandgap and field) from the lightly doped collector.

The electric fields are modulated (either directly or optically), and spectroscopic measurements are made of the ensuing reflectance variations. Useful information is obtained near and above the transition energies, and signals from different regions of the sample will be coincident if they come from materials with similar bandgaps.

There is an additional complication with compound semiconductors: since all direct transitions contribute to the spectrum, each signal is a superposition of at least two contributions (i.e. from the light-hole and heavy-hole valence bands).

In figure 8 the simulation is in fact constructed from six convolved spectra fitted to the light, heavy and split-off band transitions in InP for each of the emitter and collector regions. Each spectrum was resolved and bandgaps and electric fields were obtained for the InP in each region. There is also a small contribution from excitonic transitions just below the bandgap, which are responsible for the oscillation at about 1.36 eV.

Other trends

As the industry embraces volume manufacturing of high-performance optoelectronic and microelectronic devices and circuits, more use is being made of multiple analytical tools (often from different manufacturers) for a single specified measurement. In addition, both internal and external suppliers of analytical services may be used. Much more emphasis therefore needs to be placed on improving the reliability and standardization of calibration procedures. These needs are most critical in PL, DCXRD, SIMS, Hall effect measurements and various techniques for dimensional measurements (especially at the nm scale).

There is also now a greater reliance on in-line and *in situ* material and process characterization. In-line characterization can be performed either internally or outside the fabrication facility. The former category includes such techniques as SEM, spectrophotometry, FTIR and AFM. External to the fab, we find PL, PR, SIMS and double-crystal XRD as steps that gate parts of the process flow, especially the transition of wafers from growth to fabrication.

In conclusion, there are several important developments in materials characterization and analysis. Some are a response to the higher volume and lower cost requirements of a modern manufacturing facility. Others represent the implementation of new capabilities that are either novel to compound semiconductors or have been imported from silicon technology. It is certain that many more techniques are and will be moving from the lab to the fab in the next few years. ●

Further reading

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Iain Calder is manager of analysis and growth engineering at Nortel Networks in Ottawa, Canada. Email icalder@nortelnetworks.com.

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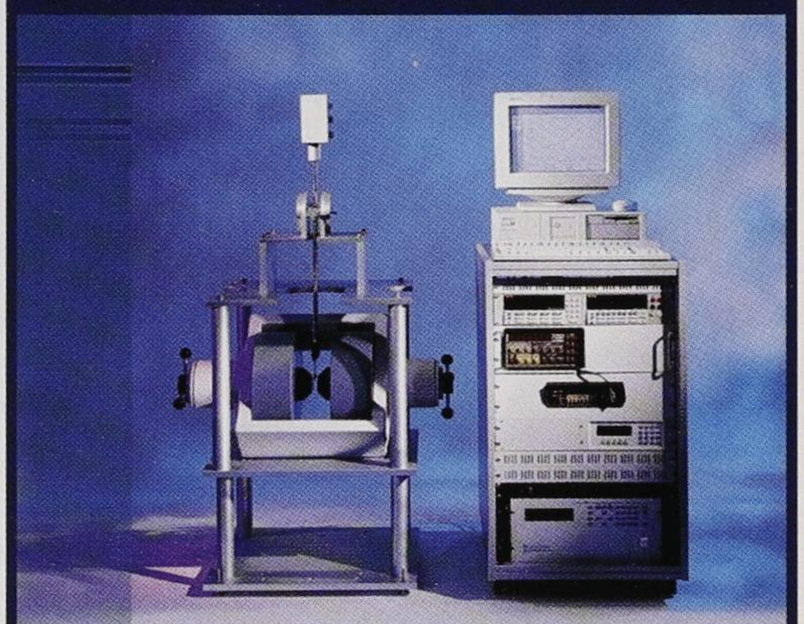
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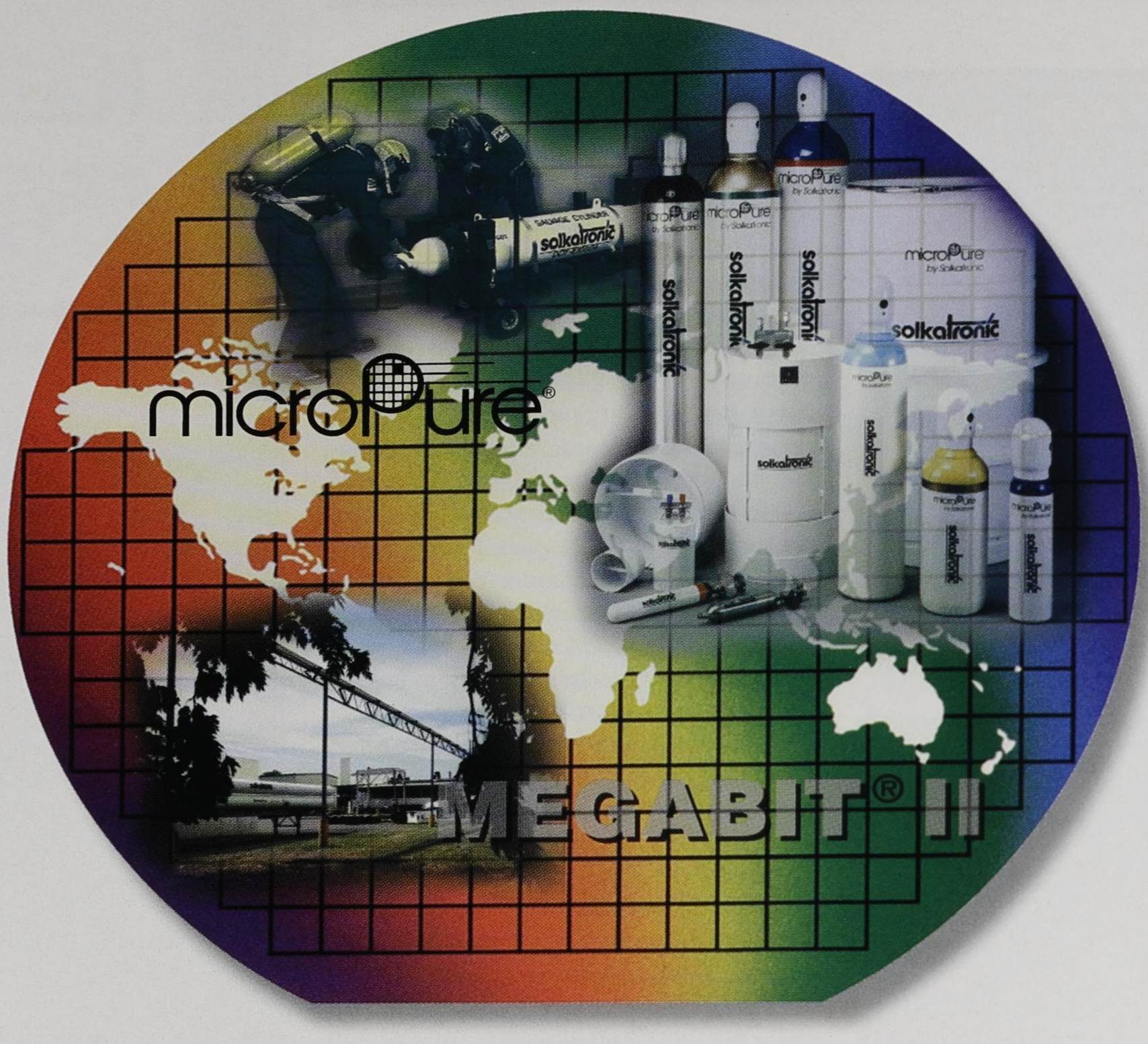

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Automation strategies hold the key to manufacturing success

Component makers that incorporate automation into their manufacturing strategies are likely to emerge as market leaders as the industry matures, writes **Charlie Duncheon** of Adept Technology.

Automation is rapidly becoming a key feature of fiber-optic component manufacturing. The assembly and test of active and passive devices using manual processes does not meet market requirements in terms of cycle time, yield and cost. In the past, robot automation was only considered when focusing on labor savings, but nowadays manufacturers of fiber-optic components see automation as a requisite. Yields and throughput alone justify investments in robotic automation. However, when tolerance is measured in nanometers, automating a manufacturing process is not simple. Compounding the automation challenge is a lack of standards in this emerging industry and the small number of suppliers of automation equipment. This article will focus on the importance of forming a strategy in order to execute automation for high-volume fiber-optic component production.

Current assembly procedures

There are a number of challenges relating to the automation of fiber-optic component manufacturing. Most first-generation products were developed in laboratories by scientists without manufacturing backgrounds, which resulted in a focus on innovation rather than automation. In the photonics market there is a lack of standards throughout the supply chain, and there has been a limited resource pool of advanced manufacturing engineering in many fiber-optic component companies. Products have short life cycles, so manufacturing processes not only need to be automated but also must include flexible tooling and software for fast product changeover. Lastly, working with optical components and fiber has created new material handling challenges compared with other industries.

Fig. 1. An automated laser welding system manufactured by Adept Technology.

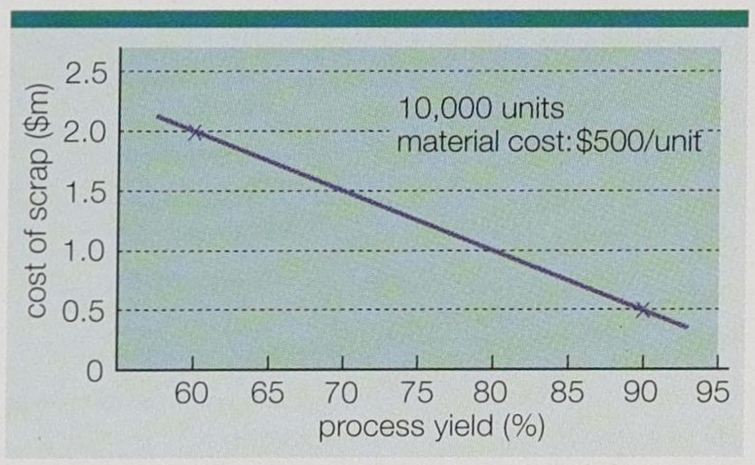

Fig. 2. Reducing scrap costs by improving yield through automation saves more money than reducing labor costs.

Facing these challenges, leading companies have begun using new tools and services to design the newest generation of products (see figure 1). Companies that blend these tools and services into an overall strategy for high-volume automated manufacturing are likely to gain success as the fiber-optic component industry continues to mature.

Of course, automated assembly processes are not new in the compound semiconductor industry, and an interesting parallel can be drawn with the manufacture of optical modules for CD players. Like laser sources for fiber-optic applications, CD optical heads contain a laser which is packaged with a photodiode and various other optical components (although there is no fiber coupling). Using automated processes, optical CD heads are assembled in around 2.5 seconds at a cost of about $1, with yields of around 99.7%. Manual assembly of a typical telecom transmitter takes about three hours and has a yield of less than 60%. The message to fiber-optic manufacturers is that someone will find a route to low-cost, high-volume manufacturing.

Financial justification

Photonics products require assembly tolerances and process control beyond the capabilities of manual labor. When technicians attempt to assemble these products they are unable to maintain consistent product quality, resulting in poor yields. This is because of the difficulties in repeatedly maximizing alignment, maintaining peak power during epoxy cure and delivering exact adhesive volumes.

For component manufacturers, the annual scrap costs due to poor yield are currently larger than the annual labor costs by an order of magnitude. For example, a photonic component that sells for $1000 might cost $500 and require two hours of assembly and test labor. A yield of 60% is typically achieved when the component is assembled by hand, which means that $200 of scrap (i.e. 40% of $500) is generated for each acceptable product. Two hours of labor might cost $30 in North America or $4 in China but either amount is dwarfed by the scrap cost.

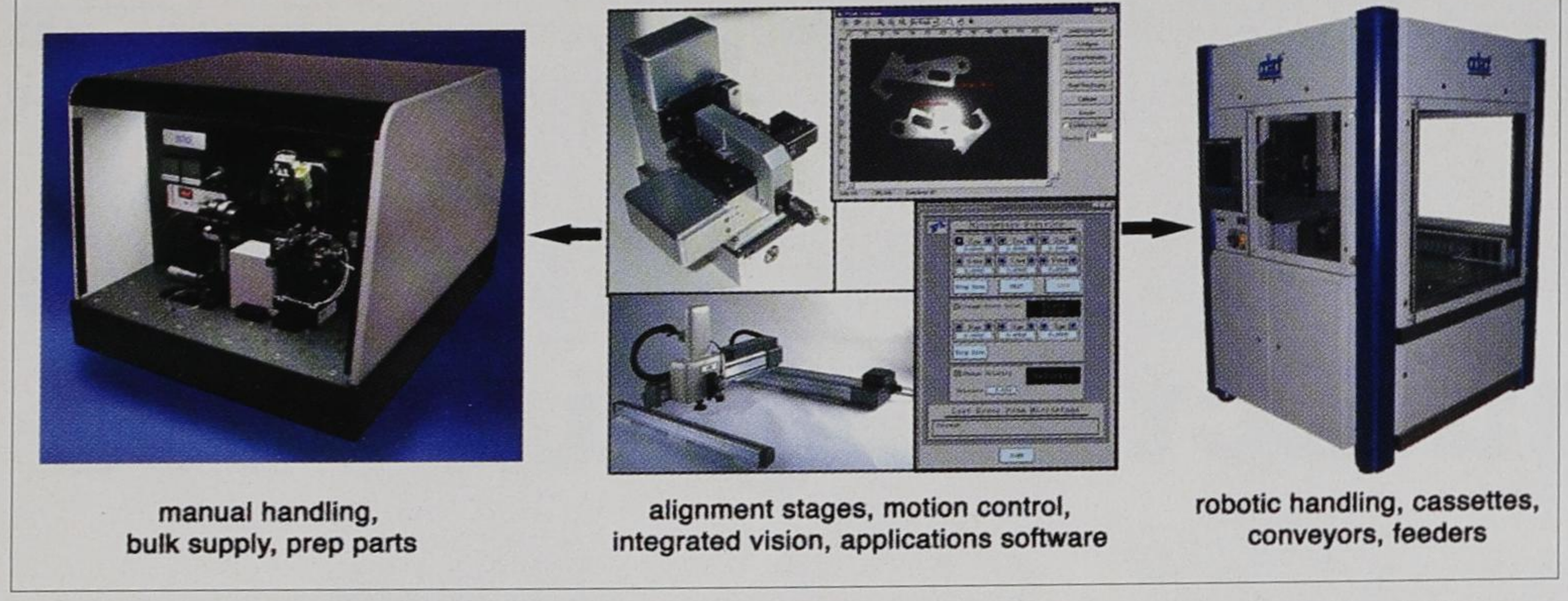

Fig. 3. Proven automation building blocks are used to assemble semi-automatic platforms like the Adept NanoBonder EBS (left), used for epoxy bonding, and fully-automatic machines (right) that utilize robotic loading and unloading.

Comparison of different levels of automation

		high-volume production	*product stability*	*process stability*	*parts handling standards*	*supply chain control*	*capital investment*	*support infra-structure*
manual assembly								
semi automated	automated alignment					×		
	automated process	×	×	×		×	×	
	automated cassettes	×	×	×		×	×	×
fully automated	robotic material handling	×	×	×	×	×	×	×
	automated intercell transfer	×	×	×	×	×	×	×

On the other hand, automated assembly processes typically generate yields in the mid-to-high 90% range. Typical first-pass yields for a circuit board with 300–500 components mounted on it are 94–96%. In the example discussed overleaf, an increase in yield from 60% to 90% results in a scrap saving of $150 per unit. At a modest annual volume of 10,000 units, scrap savings will provide a one-year payback of $1.5 million, in both North America and China (see figure 2). As yield and cost issues become more fully understood, component makers are quickly concluding that automation will be critical to their success, regardless of manufacturing location.

A well-defined, stable process

Before embarking on any automated assembly project, it is imperative that the manufacturer develops and proves the assembly process, and fully understands the process capability, because automating a weak process will only result in weak automation. There are two main areas in need of automation: the process itself, and the material handling that feeds the process. The former is necessary to ensure high yields and competitive manufacturing costs, while automation of material handling ensures a smooth path to high-volume manufacturing.

Component manufacturers should first develop a roadmap to high-volume manufacturing, which begins with proving the process manually and defining the assembly procedure. Bonding process options, such as laser welding, epoxy bonding and soldering, must be evaluated and their effect on cycle time and on yield defined. After quantifying both part and process tolerances, these values should be considered with future automated handling.

Next, the manufacturer should develop a repeatable, documented assembly process and establish tight control of process variables, identifying those variables eliminated by automation. Inspection and test requirements should also be established, making the choice between integrating these steps within the process or using separate cells.

The next step is to design the product for automated assembly. This is done by quantifying the cumulative product and process stack-up, and evaluating the tradeoffs between tight product tolerances that can lead to assembly challenges, as opposed to less stringent product tolerances by using sensor-driven automation equipment for precision assembly. At this stage, product design modifications are needed for automated handling.

It is then necessary to perform optical performance modeling, including complete optical tolerance analysis, and to establish the effect of product and process tolerance on insertion loss. The process design is completed by selecting the process equipment, by looking ahead to automation equipment selection and by building prototype tooling. Further steps are to implement a semi-automated process, to gather factory-floor data and results, and finally to execute full automation design and implementation for subsequent capacity expansion and high-volume production.

Choose level of automation carefully

There are different levels of automation; some components are assembled using a completely manual process, for example the alignment and epoxy bonding of a fiber-optic collimator. Precision tooling is used to hold the components for alignment, but the alignment and application of the epoxy after alignment is performed manually using an active source laser. The laser beam enters the first component and is measured as it leaves the last component (often the fiber in the case of a pigtailed device). Manual alignment is performed with positioning stages to minimize the insertion loss. The epoxy is applied manually with a dispenser, and some minor manual adjustments are made to offset misalignments caused by stresses from the curing process.

The next level of automation is to perform active alignment using programmable nanopositioning stages. State-of-the-art piezoelectric stages can align in the X–Y direction with a resolution of a few nanometers. These auto-alignment systems continue to perform active alignment, maximizing coupling during the initial phases of the curing process. The application of epoxy can be automated with a small, high-precision Cartesian robot that moves over the top of the tooling holding the components (see figure 3, left). Automating the application of epoxy can significantly reduce process variables once the

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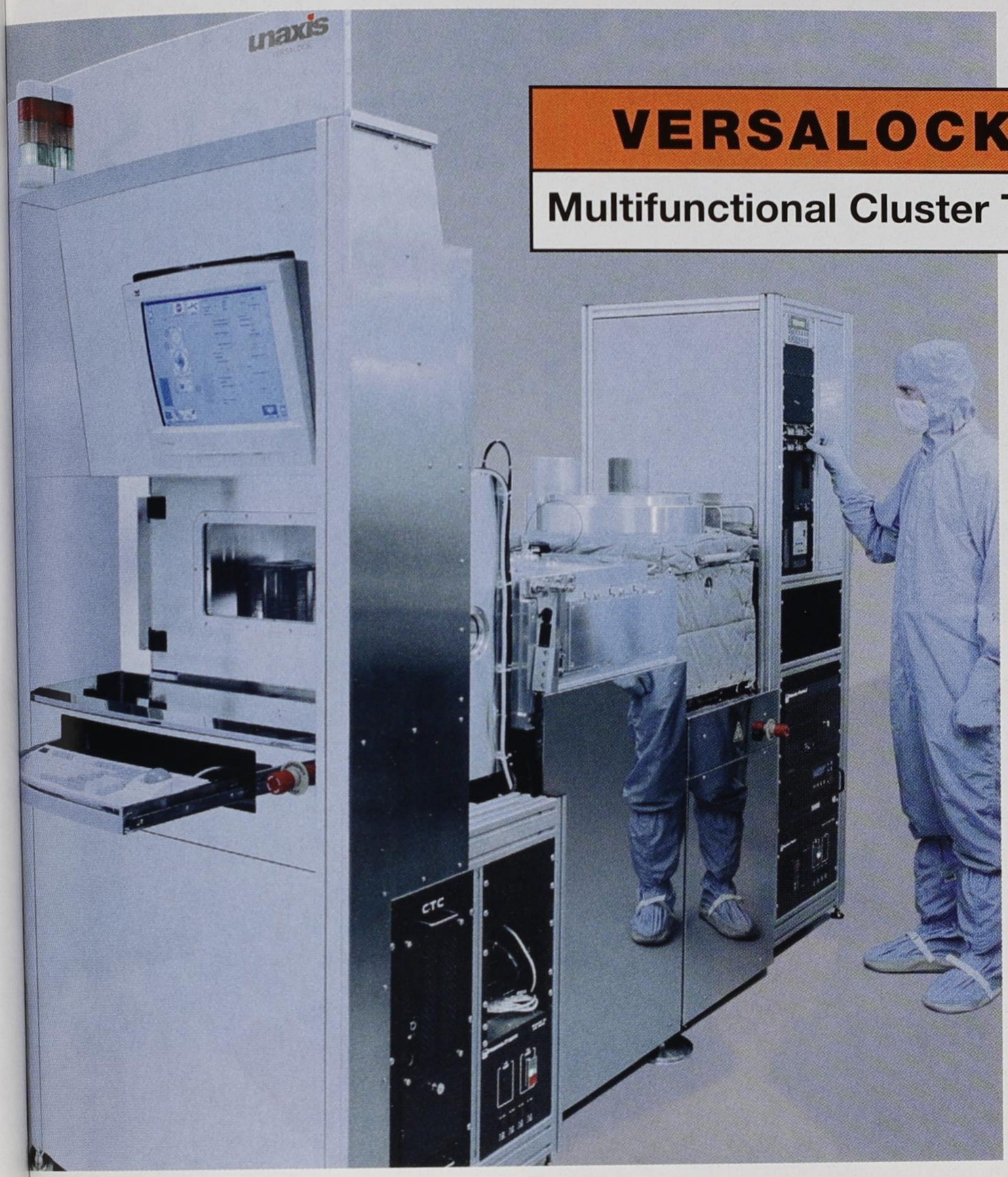

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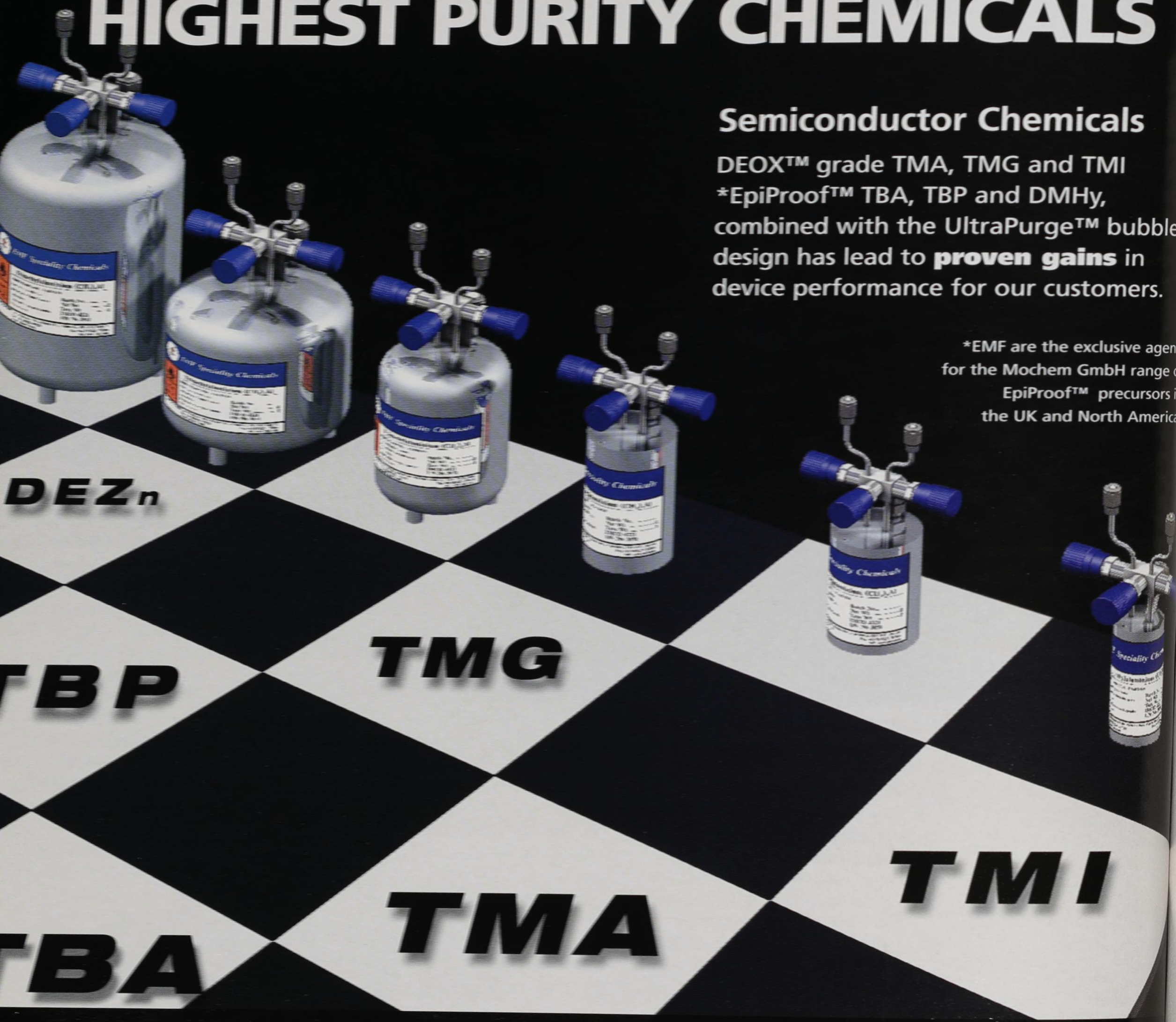

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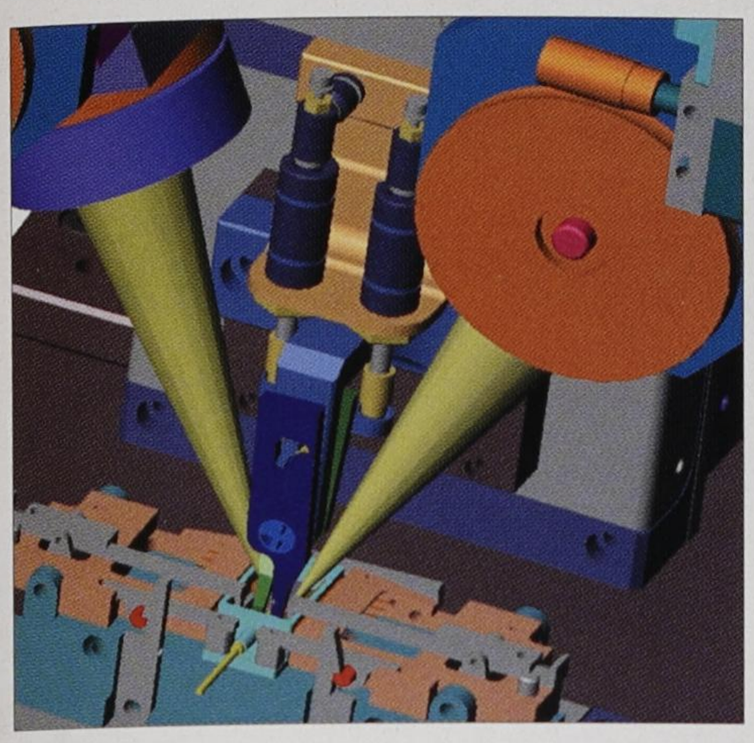


Fig. 4. Collision detection analysis can be carried out by 3D simulation.

proper epoxy process is characterized. The full automation level involves automated material handling. Components enter the cell on small trays and pallets. Vision-guided robots pick up the components from the trays and place them into the tooling for the assembly process. Finished assemblies are loaded onto trays that exit the cell (see figure 3, right).

There is much to be considered when deciding how much automation is needed. The table (p44) shows the criteria for the assembly and bonding of a collimator that relates to the appropriate level of automation.

Recommendations for making the migration from semi to fully automated cells for fiber-optic components are as follows:

- Develop a process that ensures a high level of component consistency.
- Stay close to standards being developed for part packaging and design for automation (DFA) initiatives.
- Prove-out automated part-handling viability and repeatability before integrating with the assembly and bonding process.
- Define the impact of automated part handling on cycle time.
- Use simulation tools for cycle time and layout analysis.
- Create a full system specification.
- Minimize customization by using suppliers able to provide full automation with standard "building block" automation components to take advantage of true flexible automation as well as minimizing risk.

Product design for automation

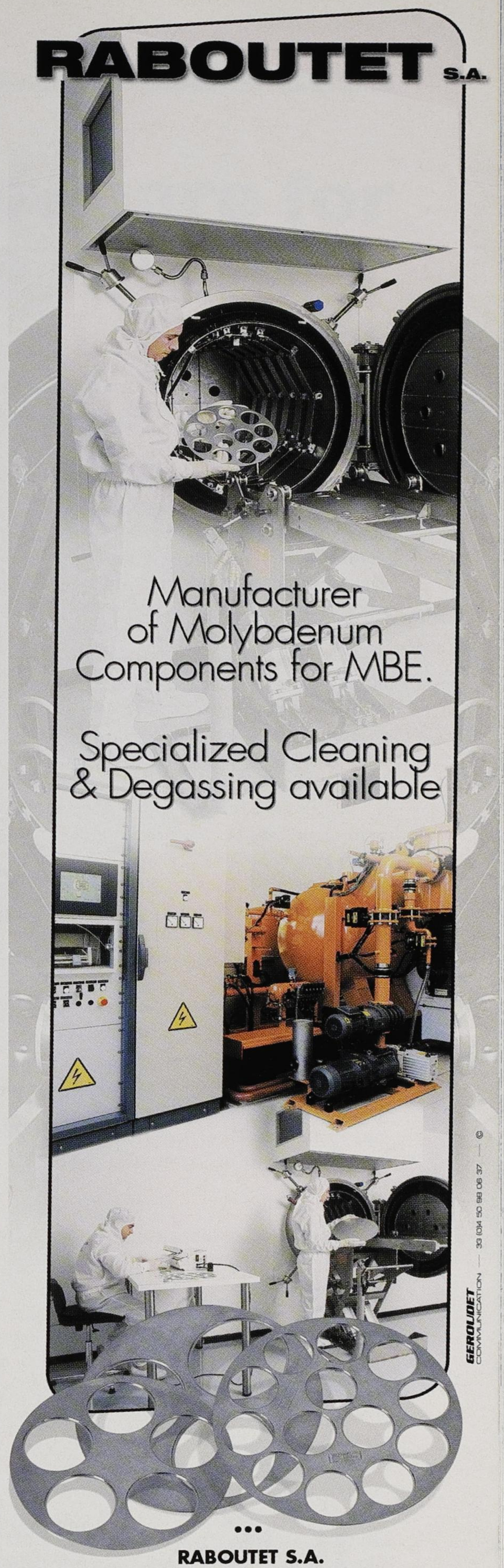
Several tools have been developed for product design for manufacturability and design for assembly. Adept Technology and Sony have worked together to combine Adept's Production Pilot 3D simulation tools and Sony's DAC (design for assembly and life-cycle costing) to provide an analytical scoring approach for product DFA. The assembly process is broken down into a series of basic operations, each of which is evaluated for ease of assembly and scored accordingly. This process leads not only to product design modifications to improve the ease of automated assembly, but also to reduced product costs through the evaluation of product tolerance requirements – versus the use of robotic sensing tools like machine vision.

Initial product CAD files can be transferred into the Production Pilot simulation environment for the purposes of both DFA and process simulation. The Production Pilot tool allows the process and product designer the ability to analyze the cumulative tolerance stack-up of both part and process tolerances. Other benefits include 3D automation work-cell layout requirements and system cycle time and capacity. A particularly valuable simulation tool for fiber-optic assembly process design is collision detection (see figure 4). Given the costs of precision alignment tooling, precision robot grippers and the components themselves, it is highly advantageous to establish robot part-handling paths and alignment tool paths in a magnified 3D graphical environment to ensure against collisions.

Summary

Developing an automation strategy for the assembly of fiber-optic components begins with an analysis of financial justification. Other key features are to design, characterize and verify the process manually, to use 3D simulation tools, and to implement a design for the automation process during the product design phase. Automation should be implemented in phases, and the manufacturer should partner with equipment suppliers that are offering standardized, flexible automation components, because this will minimize the risk and the timescales and will maximize the redeployment capabilities. There seems to be little doubt that fiber-optic component manufacturers who manage to successfully develop and execute automation strategies will have a first-to-volume advantage in their respective markets.

Charlie Duncheon is senior VP of business development at Adept Technology, San Jose, CA, a manufacturer of factory automation components and systems. Web www.adept.com.



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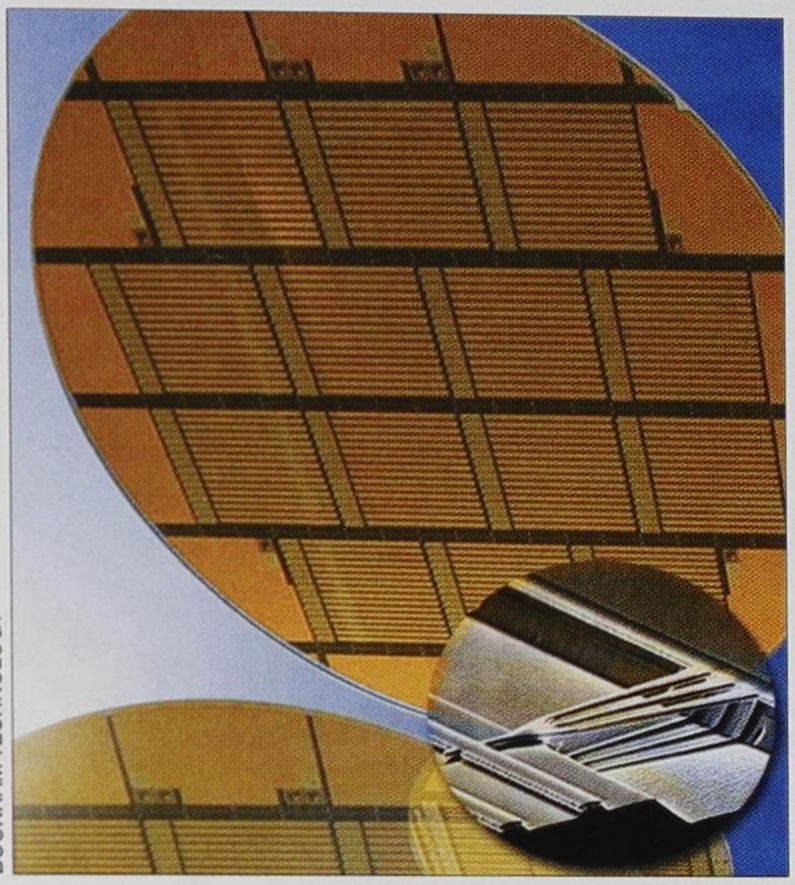
Optical modulators prepare for a high-speed network future

Lithium niobate is a well established modulator technology, but it is seeing some stiff competition from alternatives in the compound semiconductor industry, writes **Jon Newey**.

The modulators that are used in optical networks can be broadly divided into two types: those that work electro-optically (EO modulators) and those that work by electroabsorption (EA modulators). Both modulation schemes can be realized in a variety of materials, with lithium niobate EO modulators being the dominant ones at present. InP and GaAs also exhibit strong EA and EO effects and are finding applications as modulators in optical networks. Lithium niobate may occupy a dominant position, but compound semiconductor technologies are snapping at its heels. A recent report from market researchers ElectroniCast predicts that EA modulators will comprise more than 50% of the market by 2011. At present, lithium niobate accounts for 60% of the market.

EO modulators rely on the application of an electric field to change the refractive index of the material through which the light is passing. They are generally deployed in a Mach–Zehnder (MZ) interferometer format. The modulator has two arms and the incoming light is divided and passed into these (see figure). A field is applied to one or both of the arms (single or dual drive), changing the refractive index so that the light emerging from one arm will be out of phase with that emerging from the other. When the light is recombined, it interferes destructively, effectively switching the light off. Without an applied field the light is in phase and remains on.

In an EA modulator an applied electric field shifts the absorption band edge in such a way that the material becomes opaque to the light at the wavelength of interest. Modulating the field turns the light on and off.



BOOKHAM TECHNOLOGY

A processed 6 inch GaAs wafer showing MZ optical modulator bars. In the inset SEM image, two waveguide arms can be seen as ridges. The air bridge contacting the right ridge feeds the RF signal to the modulator arm.

A recent report from ElectroniCast predicts that EA modulators will comprise more than 50% of the market by 2011. At present, lithium niobate accounts for 60% of the market.

Lithium niobate

Lithium niobate MZ modulator technology is the most mature of the various options. It is well entrenched in optical networks and because of this has an edge on the newer technologies, the cost and performance of which are not as well understood as those of lithium niobate. The material is inherently very broadband, meaning that a device optimized to work in a particular spectral region can also perform in another region with some adjustment to its drive voltage. This is important in DWDM systems where ideally a single device is required to handle a variety of wavelengths.

Lithium niobate is being challenged in both size and functionality. As bit rates go up, the modulator size also increases. At 40 Gbit/s, lithium niobate modulators are about 5 inches long. Those working with lithium niobate are constantly looking at ways to reduce package sizes. "A lot of people want to offer 4 inch transponders and our challenge is to fit the modulator in that package," says Dan Wilt, components product line director in Agere's optical networks division. "The Holy Grail would be a 2 × 3 inch case that some lower-end transponders are in."

Lithium niobate is very much a single-function material, unlike its semiconductor rivals. As Ian Croston, a product development manager with JDS Uniphase, concedes, "GaAs and InP are streets ahead in getting more functionality in a smaller volume than lithium niobate. But there are ways of integrating lithium niobate with other functions that will give GaAs and InP a run for their money." For example, increasing the functionality of the modulator box by putting the control electronics into the modulator package without impacting its size is an area that the modulator suppliers are currently concentrating on.

Drive voltage

One of the areas where the different modulator materials compete is drive voltage. This is an important consideration, because a large voltage swing – the change in voltage between the on and off states – gets harder to produce as bit rates get higher. Those working with lithium niobate's competitors are quick to point out its high drive voltages, quoting anything from 6 to 8 V_{p-p}. Fujitsu has recently announced a 40 Gbit/s product that requires a drive of about 5 V_{p-p}. Drive voltage is dependent on variables such as waveguide width and degree of optical confinement, and those involved with lithium niobate seem confident about their ability to reduce it further.

NRZ and RZ data transmission

There are two formats being used for optical data transmission: return-to-zero (RZ) and non-return-to-zero (NRZ). A data stream of 1s and 0s is represented by the presence or absence of light. In the NRZ format the light source stays on where there are a number of consecutive 1s, only extinguishing when a 0 is reached. In the RZ format the light pulse returns to 0 between each 1, even where 1s are consecutive (figure 1).

The dominant modulation scheme at present is NRZ, though high-performance long-haul submarine links have been using RZ for some time. As bit rates increase it's likely that RZ will become more widespread in optical networks. The longer pulses in NRZ data streams are more susceptible to nonlinear effects and polarization mode dispersion in fibers.

Moving to RZ at high data rates brings added complexity. Such a system places heavy demands on pulse shaping and spacing and also requires high peak pulse powers. Implementing an RZ system requires two modulation stages: one to pulse the laser and one for data modulation (figure 2). Some form of pulse synchronization is required between the two, and a high-power laser must be used to compensate for insertion losses at the two stages.

RZ also makes greater demands on the modulator driver electronics, which need to operate at speeds well above the data rate. If InP is used for this application the devices can be fabricated with high f_t and breakdown voltage. However, InP is not necessarily the best choice. Inphi, a fabless IC designer, has launched 50 Gbit/s multiplexer and demultiplexer ICs in InP but will use GaAs HEMTs for modulator drivers. JDSU and Fujitsu are using GaAs MMICs as drivers for lithium niobate modulators operating at about 5 V_{p-p}. As developers find ways of decreasing the drive voltages for modulators and Si and SiGe device technology reaches new levels for f_t and breakdown voltage (*Compound Semiconductor* January/ February 2002, p31), the need for InP electronics may become less pressing.

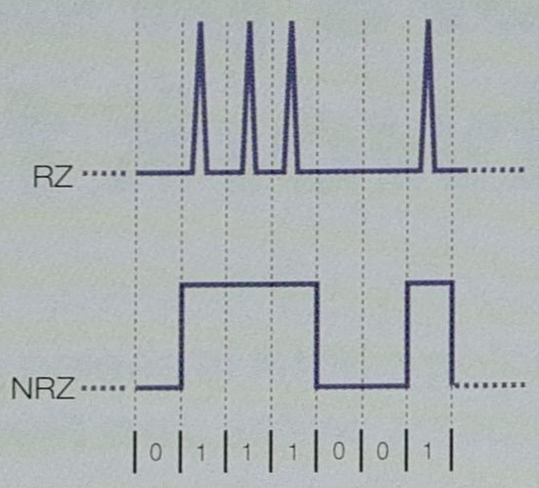


Fig. 1. In RZ modulation a light pulse represents a 1 in the data stream. The light returns to 0 after each 1, even if there are consecutive 1s. In NRZ modulation the light stays on until a 0 is encountered.

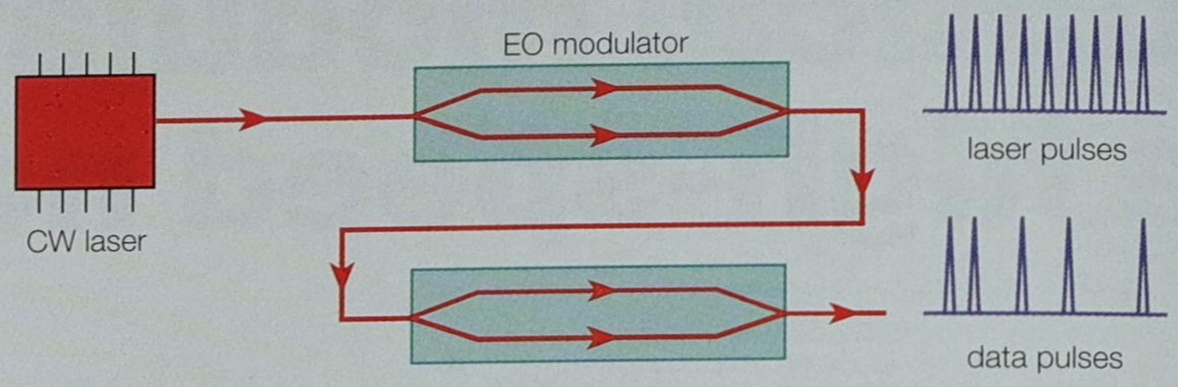


Fig. 2. Two modulators are required for RZ modulation. The first generates a stream of pulses from a CW laser. The second modulates these pulses to generate the data stream.

Agere is now sampling a 40 Gbit/s product that has benefited from new etching processes and electrode structures that have reduced drive voltage to 5 V_{p-p} compared with 7 V_{p-p} for its older technology. Both Agere and JDSU are looking at getting this nearer to 4 V_{p-p}.

Apart from the difficulties involved in producing big voltage swings at high frequencies, another reason for lowering the drive voltage is to enable the use of cheaper semiconductor materials in the drive electronics. "We want to drive our devices with ICs that are made using the cheapest possible technology. Our goal is to use SiGe. At the moment, 4 V_{p-p} is a bit of a stretch, but it is certainly not unthinkable," says Wilt.

Indium phosphide

The electrical and optical properties of InP enable a large number of functions to be realized in one material system. The most obvious advantage of using InP as an EA modulator is that the device can be made relatively small. The bandgap energy of InP-based materials is close to the photon energies at telecoms wavelengths, so electro-optic and electroabsorption effects can be brought into play at low voltages and over short distances. In an InP-based EA modulator, light absorption can be achieved in about 300 μm with about 3 V.

As a material for EA modulators, InP is at present finding most widespread use in electroabsorption modulated lasers (EMLs), where a DFB laser is monolithically integrated with an EA modulator. Modulating a laser externally as opposed to direct electronic modulation of the laser itself reduces laser chirp. Chirp is particularly troublesome over longer distances because a chirped pulse is badly affected by chromatic dispersion.

At present, lithium niobate wins in the longer-reach (more than 100 km) high-bandwidth applications. In the shorter-reach applications it is being challenged by the use of EMLs. The development of EMLs is not stopping lithium niobate from continued penetration into shorter-reach applications. Indeed, JDSU is part of a multisource agreement for short-haul transceivers into which lithium niobate parts are being supplied.

The availability of cheap lasers is also being seen as a helpful nudge for lithium niobate modulators in cost-wary markets. "With the price of CW lasers falling rapidly, a lithium niobate modulator does not look all that unattractive now compared with EAs or EMLs," says Agere's Wilt. It's a close trade-off, with the decision becoming less one of price and more to do with application.

Hybrid EMLs

Though EML manufacturers are refining their designs to improve performance, enabling such lasers to be used over increasing transmission distances, other companies are adopting a hybrid approach. One such company is CyOptics. It is taking an InP-based laser and EA modulator and co-packaging them to produce a hybrid EML, and by doing so the company aims to avoid the performance trade-offs that often arise from monolithic integration.

The laser and modulator that comprise the hybrid EML can be individually optimized to give very low chirp and a high extinction ratio. Using this approach, the hybrid EML is able to transmit up to 125 km at 10 Gbit/s. With amplification and dispersion compensation, this can be increased to 500 km, which is

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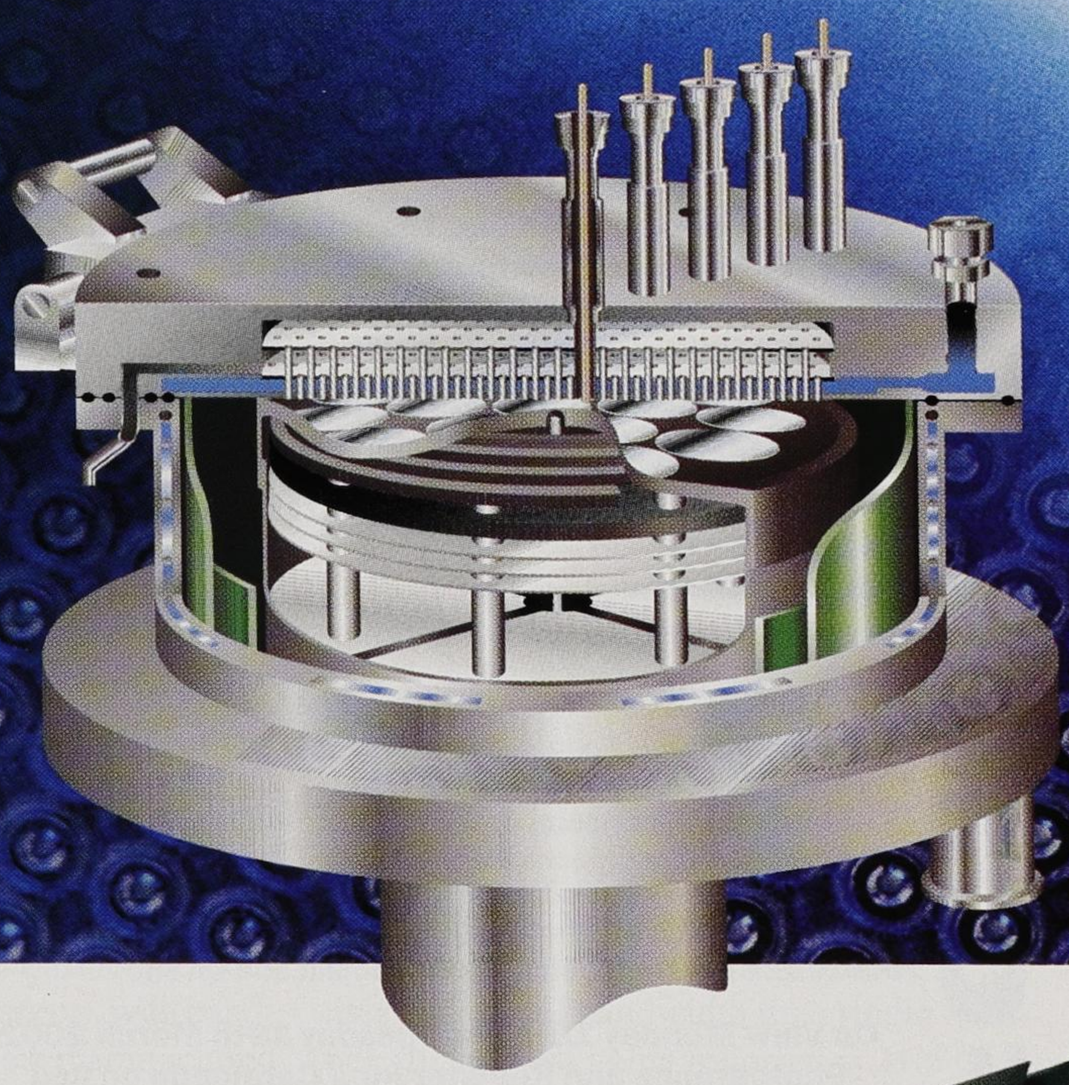

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InP's critics will point to its high coupling losses – a result of the small device dimensions that can be realized in InP – and internal absorption, which is a result of the close proximity of its bandgap energy to the photon energy. Internal losses may be up to 4 dB higher than for a lithium niobate modulator. Irving Wang, CyOptic's product marketing manager, does not see the extra couplings inherent in the hybrid approach to EMLs as a big problem, however. "Laser power is cheaper now," he comments. "If you only have 10 mW laser power then you need low insertion losses, but there are 40 mW lasers on the market. Now we can make very compact devices with InP and do not need to make design trade-offs to cope with losses."

Gallium arsenide

As a semiconductor technology, GaAs is relatively mature when compared with InP. GaAs is readily available as semi-insulating 6 inch wafers and, taken with standard lithography and processing methods, lends itself to the high-volume production of optical modulators. Marconi Optical Components, recently acquired by Bookham Technology, has an RZ 40 Gbit/s EO modulator that is approximately 45 mm long. A 6 inch wafer can yield about 250 devices, compared with about 60 from a 3 inch wafer. Though InP EA modulators can be made smaller still, 6 inch InP wafers are not yet available. GaAs MMICs are also being used as the basis for the modulator driver electronics (see box).

Like lithium niobate, GaAs is optically broadband and is able to cover the C- and L-bands. As Andy Carter, a technical director at Bookham, explains, "Unlike GaAs, InP EA modulators are hard to make optically broadband as they rely on the proximity of the band edge to give absorption. You either can't get them to cover the whole band, say C or L, or you get chirp and high losses."

Though GaAs may fall down on the monolithic integration possibilities, like CyOptics, Bookham Technology is looking to reap the benefits of hybrid integration. Bookham is integrating its InP-based lasers, both tunable and fixed wavelength, with its GaAs optical modulators to provide transmitters with optimized lasers and modulators.

Lessons from electronics

The debate about which modulation material or approach is best is being argued not only between companies but also within them. "Our EML team always feel challenged to demonstrate that they can transmit just as far as lithium niobate," says Agere's Wilt.

Many of the arguments surrounding the materials for modulators and methods of integration with lasers are relevant to many of the functions needed for optical networks, not just modulators. The monolithic versus hybrid debate and the quest to reduce package size may seem to favor compound semiconductors, but as JDSU's Croston explains, the same arguments were being had 15 years ago about electronic hybrids. "People said that the way to go was to have everything in Si or GaAs," he says. "This is not the way things have gone. There are applications where hybrids win over monolithic, and vice versa." ●

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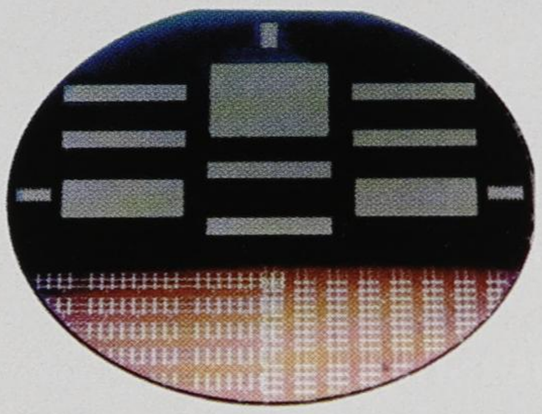

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Flip-chip bonding increases bandwidth of VCSEL arrays

Two-dimensional VCSEL arrays offer the next step forward in bandwidth for parallel optical transceivers, according to **Martin Grabherr and colleagues** from ULM Photonics.

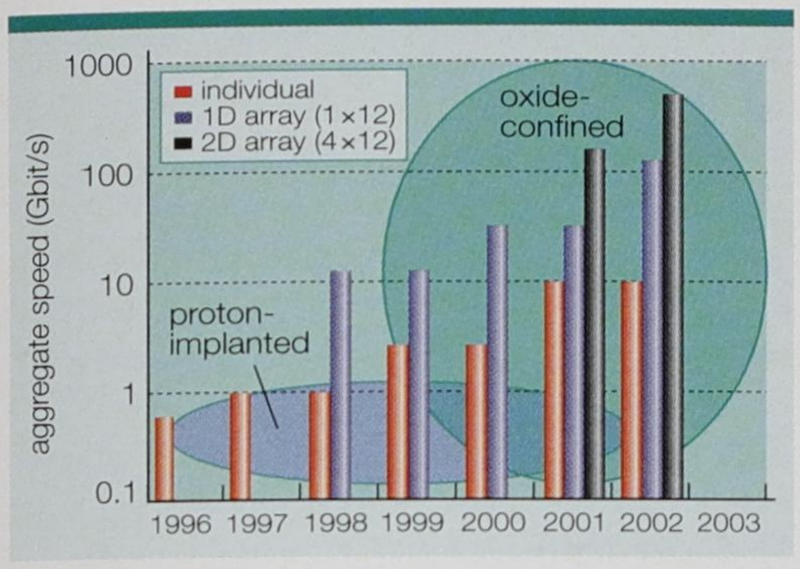


Fig. 1. Since the first appearance of VCSELs, the aggregate bandwidth has been increased due to the higher modulation speeds of individual lasers, and the fabrication of 1D and 2D arrays.

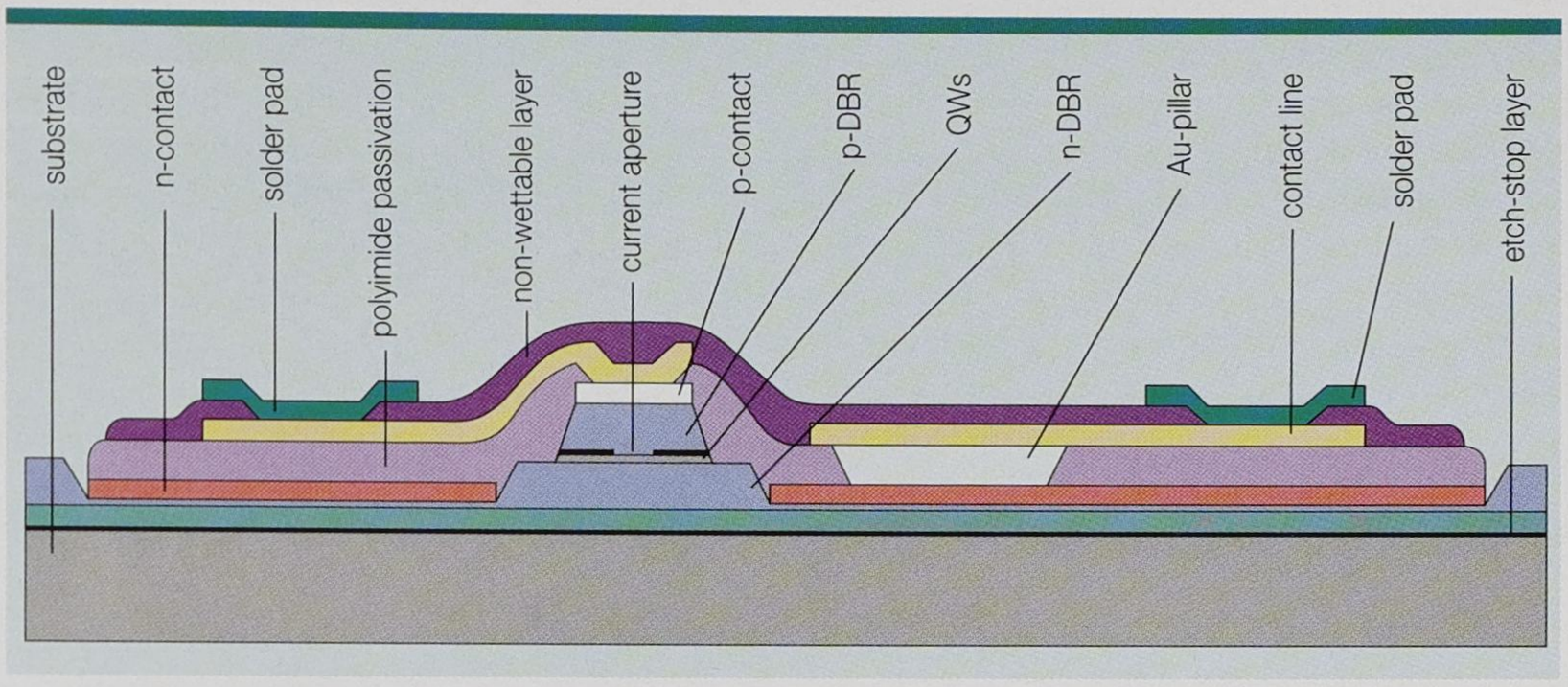


Fig. 2. Cut-away view of an ULM Photonics bottom-emitting VCSEL with solder pads for flip-chip mounting and an etch-stop layer for substrate removal.

VCSELs are widely used components in optical data links, due to their low power consumption, circular low-divergent beam profile, high modulation bandwidth, and scalability through monolithic integration. The challenge of increasing the aggregate bandwidth of future optical transceivers can be answered by increasing the speed per single channel and/or by increasing the numbers of channels. Data rates of 10 Gbit/s are anticipated to become the new standard of operation for oxide-confined VCSELs. While the devices themselves are capable of achieving the necessary speed, open questions regarding driver specifications need to be addressed.

Along with coplanar waveguide structures, flip-chip technology has been proposed as a solution for high-frequency demands. Increasing the bandwidth of multi-channel devices (e.g. 2D arrays) is not simply a matter of multiplying single channels; it is also necessary to find new solutions to integrate the VCSEL into the driver and to develop appropriate packaging. As well as facilitating high-frequency operation, flip-chip technology cuts down assembly time, increases yield and optimizes heat flow.

Towards two dimensions

Two-dimensional VCSEL arrays are key components for achieving the highest aggregate bandwidths in tomorrow's parallel optical transceivers. Despite operating at 850 nm, arrays can be designed to emit through the bottom side of the device, making them suitable for flip-chip bonding. This allows the arrays to meet customers' needs in terms of speed, power consumption, reliability and compact integration. Based on advanced technology, arrays target the requirements of transceivers in the OC-192 very-short-reach (VSR) and 10 Gigabit Ethernet arenas. This article will describe the static and dynamic device characteristics and reliability data for a 4 × 12 bottom-emitting 850 nm VCSEL array.

The first commercial VCSELs were proton-implanted single-channel devices, and were followed in 1998 by oxide-confined devices (figure 1). The first VCSEL arrays, with bandwidths of 4 and 12 Gbit/s, were manufactured by Motorola (Optobus) and Infineon (Paroli). Today several suppliers sell 1 × 12-channel VCSEL products offering 12–30 Gbit/s, including Agilent, Picolight, Emcore, Cielo, Avalon Photonics, Zarlink and ULM Photonics. All the VCSEL components mentioned so far have top-side emission and at least one top-side contact, which usually requires wire bonding. The optical sub-assembly developed by Mitel (now Zarlink) was the first without wire bonding. Next-generation transceivers will benefit from low power consumption, data throughput above 10 Gbit/s, simple beam-shaping optics and outstanding reliability (Mederer *et al.*, Jung *et al.*, Tatum *et al.*).

Flip-chip technology

Extending VCSEL arrays into two dimensions requires a very different device design that permits flip-chip bonding and provides electrical and thermal contacts through the top surface (Michalzik *et al.*). Advanced bottom-emitting technology enables single-side contact pads for flip-chip integration, and also overcomes the fundamental absorption of the GaAs substrate at 850 nm. Looking at the maximum 3 dB bandwidth for a single channel, the highest value reported is 21.5 GHz (Lear *et al.*), but typically bandwidths are around 10 GHz. It is not obvious that the highest bit rates per single channel achieved up to now can be exceeded to a significant extent. Increasing the capacity of a point-to-point connection requires an increase in the num-

ber of channels. The best way to achieve this is by flip-chip bonding of a VCSEL array directly onto the driver chip, which provides excellent lateral and vertical integration.

The epitaxial structure used for fabricating bottom-emitting devices contains high-contrast top and bottom AlGaAs DBR mirrors, typically built of 32 and 24 layer pairs, respectively. The active region contains three GaAs QWs with $Al_{0.2}Ga_{0.8}As$ barriers. Mesas with a diameter of 10 μm are formed, then wet chemical etching is used to fabricate via holes. The formation of n- and p-contacts, polyimide passivation, electroplating of gold pillars and lateral structuring of metal pads completes the epi-side processing (see figure 2). To achieve flip-chip bonding, solder bumps are placed onto solder pads either on the VCSEL chip or on the driver chip. After soldering, the absorbing GaAs substrate is removed by selective wet chemical etching. In the standard VCSEL arrays manufactured by ULM Photonics the devices measure 225 × 225 μm^2 on a pitch of 250 μm. Custom-designed arrangements that match driver circuits can easily be realized within a few general design rules.

Static electro-optical characteristics

Typical characteristics of a flip-chip bonded 4 × 12 array after substrate removal are plotted in figure 3. A silicon subcarrier with metal lines and PbSn solder bumps is used as a substitute for a CMOS driver chip. Typical threshold currents and voltages are 1.1 mA and 1.7 V, respectively, and the series resistance is 70 Ω at an appropriate operational current of 4 mA.

The differential quantum efficiency of 0.3 W/A results in typical wallplug efficiencies in excess of 10% at 1 mW output power. The variation of output power at 4 mA within the 4 × 12 VCSEL array is less than 10%, accompanied by a voltage variation of less than 3%. The emission wavelength is centered at 850 nm and shifts by around 0.2 nm/mW with increasing dissipated power. The thermal resistance of a 10 μm diameter VCSEL flip-chip soldered onto silicon is calculated to be 2.8 K/mW. Due to emission in multiple modes, the spectral width is about 2 nm within a 10 dB drop, with respect to maximum spectral power. The broad spectral width is a result of the optimization for low mode partition noise, which is necessary for high-speed modulation.

Operation up to 10 Gbit/s

By optimizing resonator design and minimizing on-chip parasitics, it is possible to reach appropriate modulation bandwidths for data transmission rates up to 10 Gbit/s. The extracted 3 dB modulation bandwidth at an optical output power of 2 mW amounts to 8 GHz. The modulation bandwidth is not limited by the VCSEL, but by the photodiode in the detector, which has a 3 dB bandwidth of 8 GHz. The eye diagram shows a reasonable opening at 10 Gbit/s, although the inherent problems of multimode VCSELs can be seen, such as increased jitter and amplitude noise. Singlemode VCSELs would be the better choice, but they still suffer from worse reliability and more complicated fabrication.

Bit error rate (BER) measurements taken at 10 Gbit/s showed values below 10^{-12} for back-to-back transmission along 500 m of multimode fiber (50 μm core diameter). The VCSEL was biased at 7.6 mA and modulated by a 50 Ω impedance driver with 0.5 V_{p-p}. The BER was also measured at different VCSEL heat-sink temperatures from 25 to 70 °C. The required optical power for a certain BER decreased slightly with temperature. The VCSEL is biased at a constant output power of 2.6 mW. The modulation voltage has a temperature coefficient of 7 mV/°C – a good value with which to compensate temperature effects. In order to obtain high modulation bandwidth the VCSEL has to be driven at a higher current density, which might affect device reliability.

On-wafer testing and reliability

Among the many advantages of VCSELs, the ability to conduct on-wafer testing results in a significant reduction in manufacturing cost. However, on-wafer testing is more demanding for bottom-emitting devices operating at 850 nm since the absorbing GaAs substrate is still present at the wafer level and therefore light emission through the substrate is not possible. To overcome this restriction, all devices are first supplied with top-side ring contacts, which give access to a defined portion of the total emitted light. After 100% on-wafer testing, the emission windows are covered by an additional metal cap prior to flip-chip bonding; this avoids illumination of the CMOS circuits, which could have a potentially disruptive effect.

Several performance characteristics can be obtained by using this approach, including threshold current, threshold voltage, differential series resistance and a good approximation of differential quantum efficiency, which can be calculated from the top/bottom emission ratio. Figure 4 shows a map of a 3 inch VCSEL wafer, with bright dots indicating devices in specification and dark dots representing an aggregation of all kinds of failures, including processing losses as well as crystal dislocations and measurement errors. The dominating failure mechanism is imperfect lithography, leading to group losses of some adjacent devices.

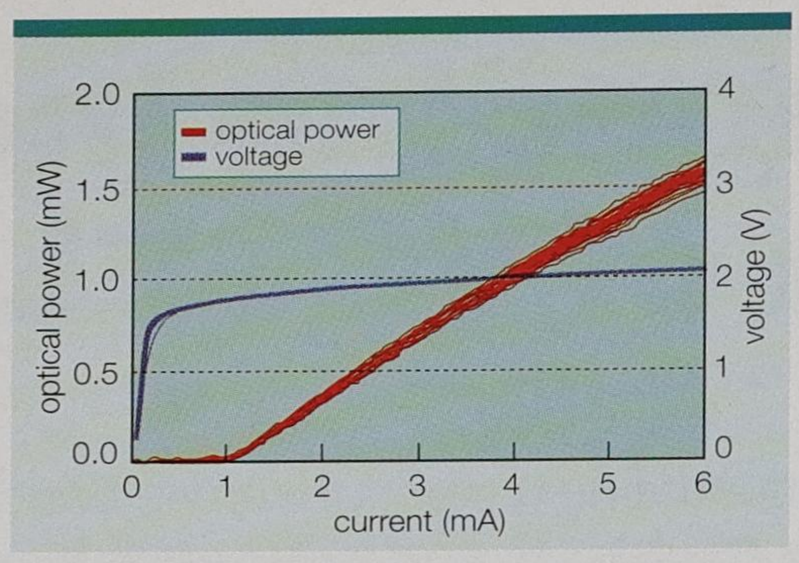


Fig. 3. The LOI characteristics of a 4 × 12 bottom-emitting VCSEL array flip-chip that has been mounted on a subcarrier after substrate removal. The active diameters are 10 μm and measurements are taken at room temperature.

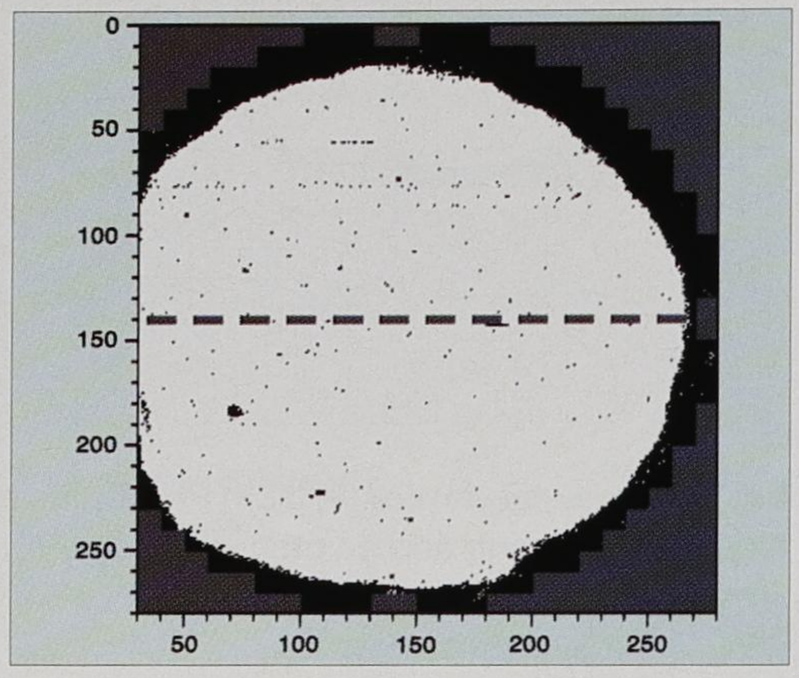


Fig. 4. Wafer map of a 3 inch bottom-emitting VCSEL wafer. The dark dots are VCSELs out of specification, and the bright dots are good devices.

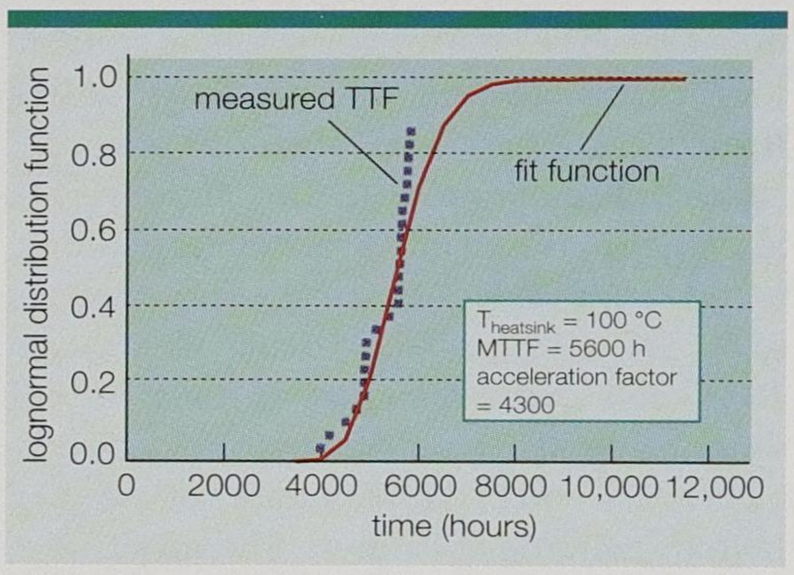
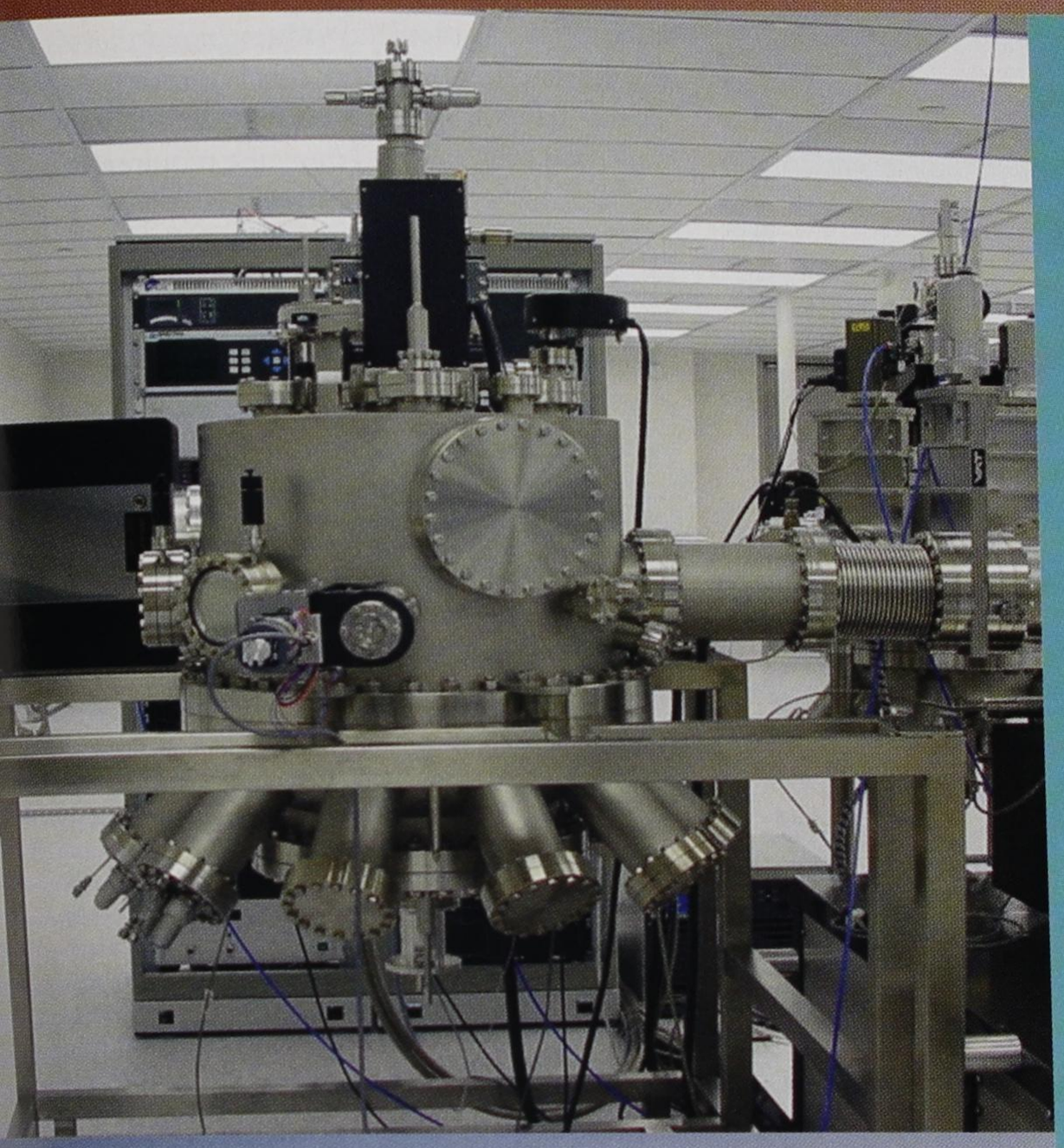
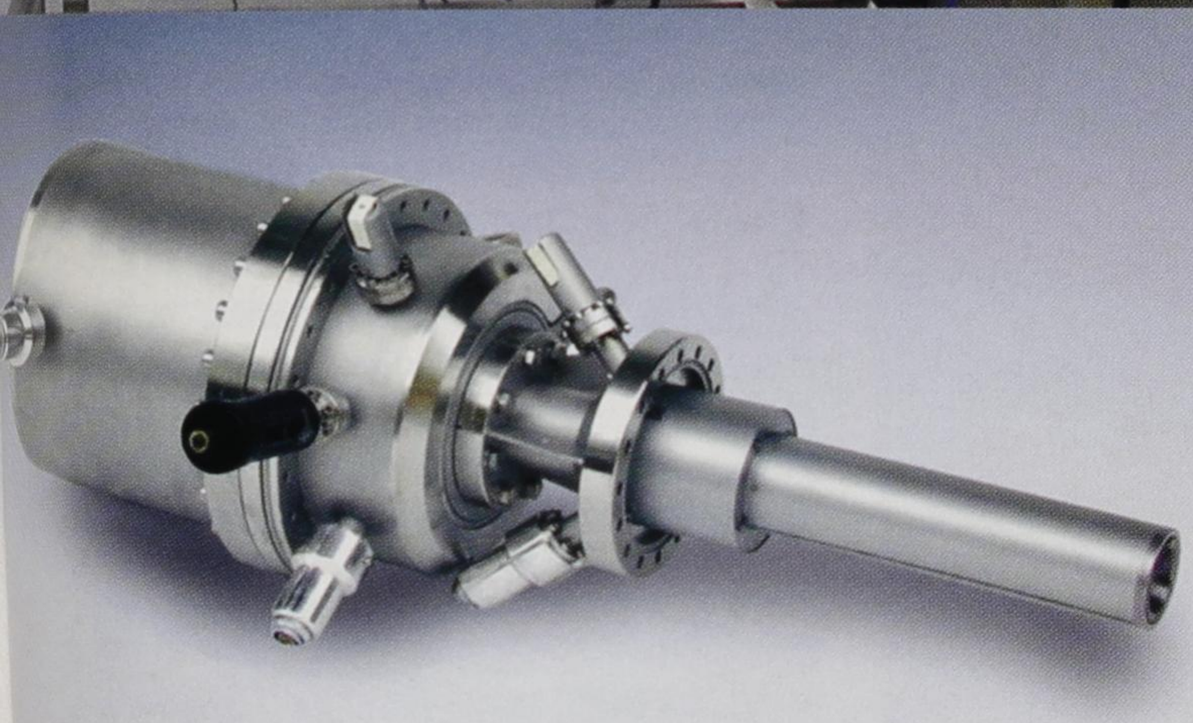


Fig. 5. Log normal plot versus time-to-failure (TTF), which is used to determine mean-time-to-failure (MTTF) values.

Proven Technology for Production MBE





DCA production MBE systems now cover run capacities of 3x2", 4x4" and 7x6". The P600 and P900 systems, with 3x2" and 4x4" capacities, are designed for the precise production of high-quality complex compound semiconductors.

The P7X6 system provides the highest throughput with the possibility to process seven 6" wafers simultaneously.

These production MBE systems complement DCA's wide range of R&D systems for III-V, Ga-N and Si/Ge epitaxy.

DCA High Capacity Effusion Cells and Crackers are known for their rugged design and long lifetime. The cells and crackers are now available as a retrofit for most production MBE systems on the market.

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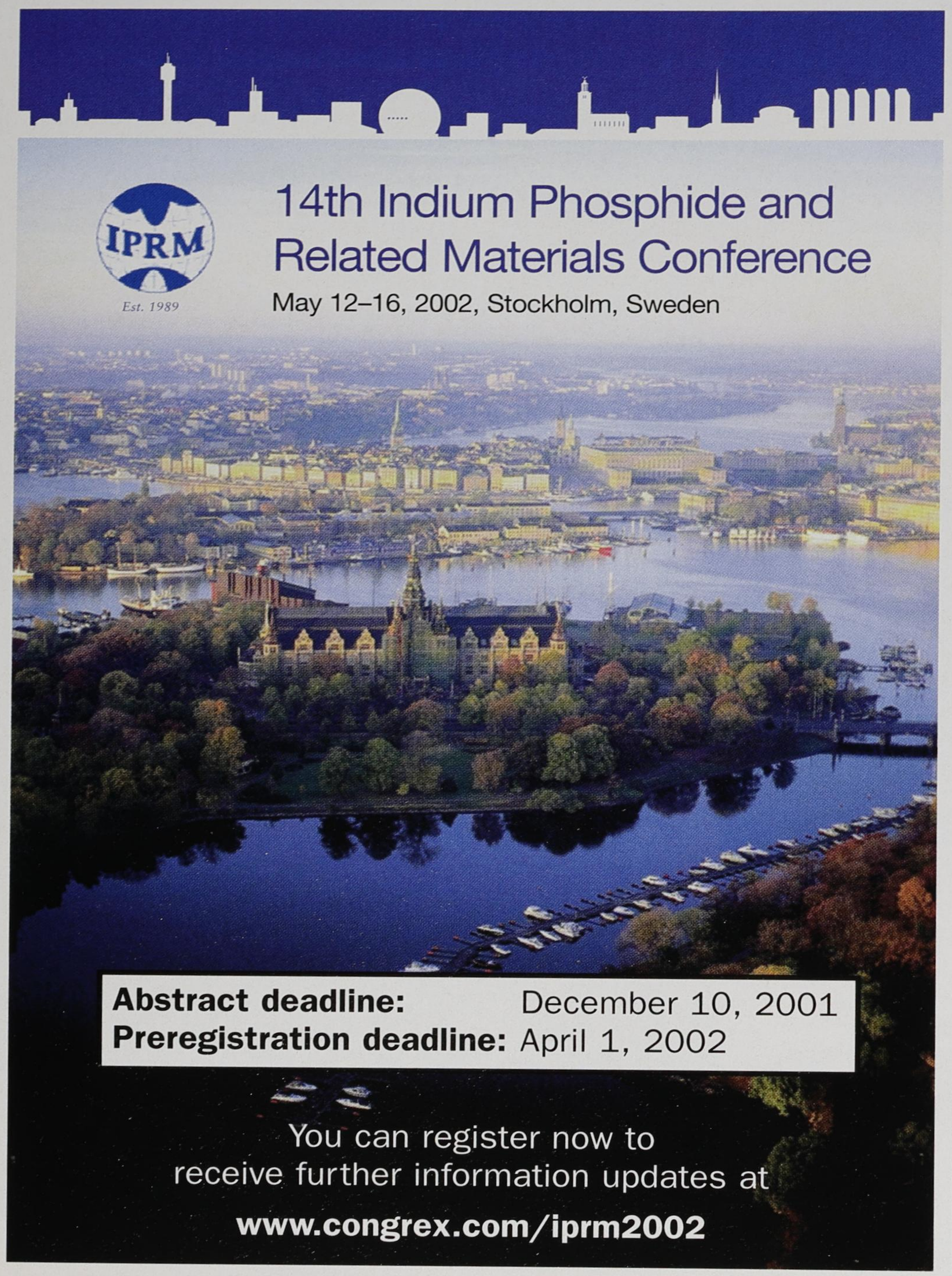
INSTRUMENTS

At ULM Photonics, specially designed devices with larger bonding areas are also processed on each wafer. These devices can be easily wire-bonded for accelerated lifetime testing. Long-term operation is observed at different values of current density, ambient temperature and humidity. Counting device failures (defined as a 2 dB drop of output power at constant laser current) in a VCSEL ensemble provides a database of failure statistics. The output power of 31 VCSELs were monitored for over 2000 hours at an ambient temperature of 140 °C. The failure statistics can be described by a log-normal distribution function, which is fitted to the measured data (figure 5). From fitted parameters the mean-time-to-failure (MTTF) rate and variance are obtained. At a heat-sink temperature of 100 °C, the MTTF was 5600 hours with a very low variance. Extracting the MTTF of every ensemble and plotting it in an Arrhenius plot allows the activation energy for the failure mechanism to be determined; this can be used to predict reliability at other temperatures. For first-generation VCSELs at ULM Photonics, MTTF values of about 120 years at room temperature were predicted, whereas next-generation devices show an improvement by a factor of 10 to about 1200 years. The database is not sufficient to give final values; nevertheless, the clear indication from this is that improvements in technology result in better reliability data, and these should meet the requirements of manufacturers of parallel transceivers.



Summary

In conclusion, bottom-emitting 2D arrays operating at 850 nm are highly suited for flip-chip integration on CMOS circuits. The fundamental absorption of radiated power by the GaAs substrate is overcome by selective etching of the substrate subsequent to flip-chip mounting. On-wafer testing of static electro-optical characteristics is carried out by measuring the residual emitted light through the high reflective DBR. Laser characteristics are a good match for the requirements of OC-192 VSR and 10 Gigabit Ethernet. Flip-chip VCSELs are therefore ideal light sources for tomorrow's optical transceivers operating in the terabit/s regime.

Further reading

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R Michalzik *et al.* 2001 *Proc. SPIE* **4534** B-17.
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M Grabherr (head of production), D Wiedenmann (CTO), R King, R Jäger and B Schneider (CEO) work for ULM Photonics, a VCSEL manufacturer based in Ulm, Germany. Email martin.grabherr@ulm-photonics.de.

New facilities

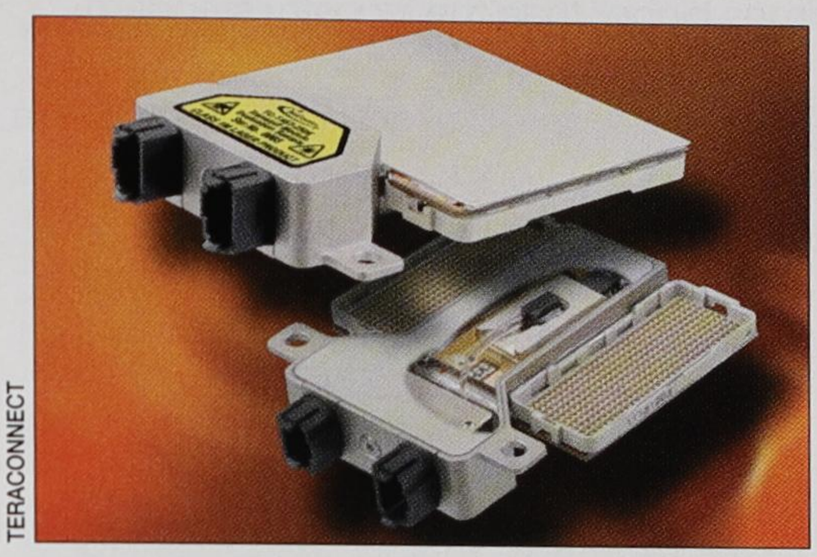
On January 22, ULM Photonics opened a new manufacturing facility in Ulm, Germany, equipped with a new MBE system. The company is shipping flip-chip-ready VCSEL arrays and high-speed devices at up to 10 Gbit/s to more than a dozen European and North American customers.

TeraConnect pushes VCSEL arrays into another dimension

The demand for high-bandwidth optical interconnects has prompted companies such as TeraConnect to make modules with 2D arrays of VCSELs and detectors, writes **Tim Whitaker**.

Increasing the bandwidth of optical data links requires an increase either in the data rate per channel or in the number of channels. One way to achieve the latter is to move from using one-dimensional sources and detectors to the use of two-dimensional arrays (see p53). Modules containing 2D arrays of VCSELs and photodetectors have already been commercialized by companies such as TeraConnect of Nashua, NH. In June last year, TeraConnect launched its T48 Terminator series of transmit and receive modules, which enable 48-channel data links at an aggregate data rate of 120 Gbit/s (2.5 Gbit/s per channel). At the heart of TeraConnect's transmitter is a 2D array of oxide-confined VCSELs. The receiver module contains an equivalent 4 × 12 array of GaAs-based detectors.

The core technology behind TeraConnect's products was developed at Sanders (now part of BAE Systems), which is also located in Nashua. TeraConnect bought the intellectual property for the array fabrication process from Sanders' former owner, Lockheed Martin, which remains a shareholder in TeraConnect. The company was founded in the last quarter of 2000 and received $40 million in funding from several venture partners.



TERACONNECT

TeraConnect's modules contain arrays of VCSELs or detectors aligned with ferrules that feed into polymer waveguides, which are visible in the foreground of the cutaway.

TeraConnect's 2D array technology

The active optical device arrays of VCSELs or detectors are directly hybridized to SiGe driver ASICs using bump-bonding technology developed at Sanders. After bonding, the GaAs substrate is removed from the VCSEL array to allow emission through the backside.

"We have the capabilities to fabricate our own VCSEL and photodetector arrays, and we also buy them from outside sources," says John Langevin, TeraConnect's VP of marketing. Langevin explains that TeraConnect has access to the microelectronics facility at BAE Systems, including its state-of-the-art GaAs processing fab. "We have a flip-chip bonding machine that enables multidimensional alignment for bump-bonding the arrays to the ASICs, and to couple light away from the VCSELs and out of the unit," he says.

One issue is how to get the light out of the VCSEL-based transceiver module and couple it into the optical fiber. Since the VCSELs emit perpendicular to the plane of the transmitter, the light must be bent through 90° to get it out of the side of the module. "We align an array of ferrules on top of the VCSEL array with micron tolerance," says Langevin. "The ferrules feed into a polymer waveguide assembly that joins into the fiber connectors."

TeraConnect will continue to use BAE Systems' foundry capabilities and will also develop specialized ASICs and VCSELs. "The plan is to maintain our current capability and also to bring a contract manufacturer online that would be able to do this in high volume," says Langevin.

The ability to bump-bond the VCSELs and detectors to the driver ICs without using wire bonding provides cost and performance advantages that Langevin believes are very important for 2D arrays. "Most of our business will be in high-density arrays in two dimensions," he says. "Density is critical in certain applications that require bandwidths of hundreds of gigabits per second. Modules using 2D arrays take up much less space than the equivalent number of 1 × 12 VCSEL modules." The T48 measures about 2 × 2.5 in^2 and has 4 times the bandwidth of a 1 × 12 array (assuming 2.5 Gbit/s per channel for all of the devices). Four 1 × 12 modules, which are about 1 inch wide, take up about twice as much space as the T48. Plus the power dissipation of the T48 is 6 W, which compares favorably with the 2–2.5 W power for each 1 × 12 module.

So what are the limits? "We have built 64 × 64 arrays," says Langevin. "Array size is limited by the market, not the technology." ●

Xanoptix hits 225 Gbit/s

A second company, called Xanoptix, has also introduced modules for high-data-rate interconnects. Based in Merrimack, NH, it introduced its XTM-72 transceiver in March 2001. The product provides 72 channels of data, 36 in each direction and each with 3.125 Gbit/s for an aggregate total of 225 Gbit/s. Like TeraConnect, Xanoptix also has links to Sanders (now BAE Systems). Xanoptix's CTO, John Trezza, was the head of the Electro-Optics group at Sanders and took his entire team with him when he left to join Xanoptix. On January 28, 2002, Xanoptix received $40 million in its second round of funding, making a total of $70 million since its inception in March 2000. In August last year, Xanoptix announced a joint demonstration with Corning of an optical networking system capable of transmitting data at a rate of 225 Gbit/s (36 channels at 3.125 Gbit/s in both directions) over 1 km.

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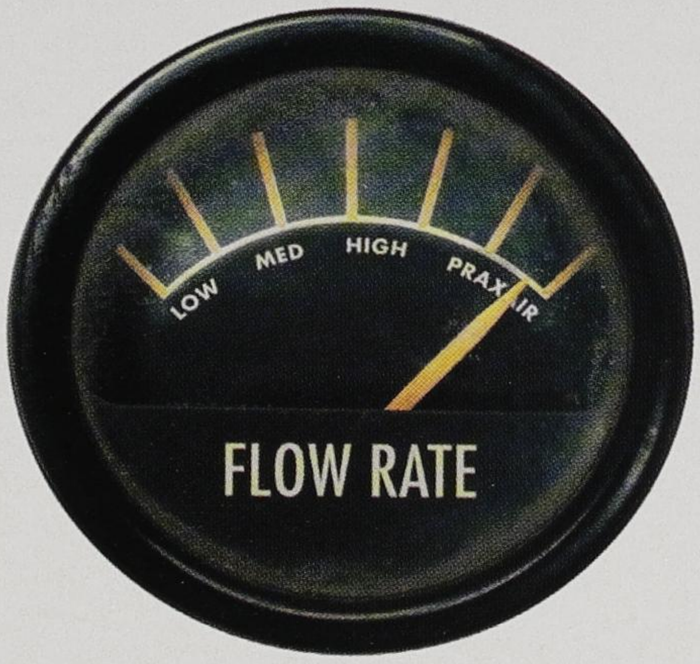

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Downturn brings opportunity for integrated InP devices

Wouter Deelman and **Chrétien Herben** look at how indium phosphide is answering the call for cheaper and more compact components for optical communication networks.

The period from 1998 to late 2000 represented a bubble in the demand for optical network systems and components. The sudden downturn in demand from network operators in late 2000 (see figure 1) took the industry by surprise. Since then, the system and component suppliers have found themselves in a recovery period with capital expenditure well below the historical average. The most optimistic estimates of analysts show that a rebound in late 2002 could result in 2002 revenues equaling those of 2001. This is far from the CAGR of 40% for the North American market during the bubble years.

With capital expenditure dropping from $90 billion in 2000 to $70 billion in 2001, a shakeout of both technologies and suppliers is inevitable. Analysts at JP Morgan H&Q Equity Research have described the predicament that manufacturers of components for optical communication systems now face (see *Compound Semiconductor* July 2001, p69). Because there are a wide variety of technologies, there is no dominant manufacturing process, material system or generally applied set of core building blocks. Compare this to the semiconductor industry where silicon is the material, CMOS is the manufacturing process and transistors are the building blocks. In the supply-driven market that existed until the end of 2000, the lack of dominance by any material or technology was not a problem. Cost was less of an issue and so the incentive to change manufacturing processes in order to improve productivity was practically non-existent. In some cases prices even rose when in the semiconductor industry they might have fallen.

With network operators under great pressure to reduce investment and operating costs, the component vendors who supply them find themselves in a demand-driven market with a great incentive to optimize manufacturing processes and find that all important dominant technology and material.

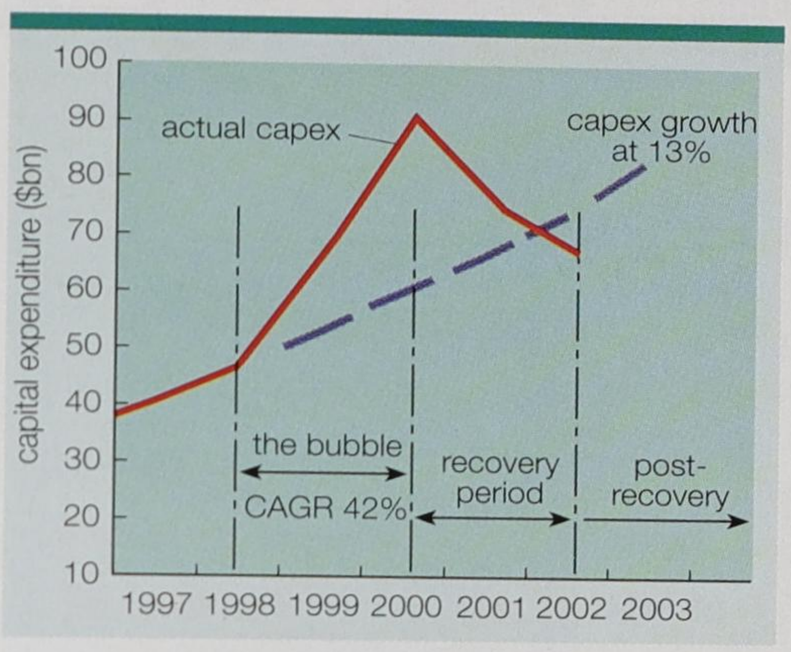


Fig. 1. Carrier capital expenditures in 1999 and 2000 exceeded the historical trend by up to 60%. The current slump in the components industry is the reaction to this bubble. The dashed line shows the growth in capex had the previous trend continued.

Cost, footprint and power

The tighter requirements of telecommunication system suppliers focus in three specific areas: cost, footprint and power consumption. The downward pressure on the unit cost of equipment is intensified by even more new systems being deployed in metropolitan and access networks, where larger quantities of systems and components are needed. Over the past year the focus has been mostly on long-haul connections: coast-to-coast, transatlantic and transpacific backbones. Now these backbones are in place (and often under-utilized) it is time to expand the feeder networks. Because of the large volumes involved this is a segment where every cent of unit price counts.

The volume factor creates a demand for physically smaller system sizes. Building space impacts investment and operational cost, especially in metropolitan environments. Network operators would like to see the systems that are currently filling their racks shrink to the size of a single system board. For this to happen boards will have to be reduced to packages, and packages in turn will have to fit on a single chip.

In some areas the third requirement, reduced power consumption, is even more important than the other two, and the cost of power is not the only issue. The recent energy crisis in California, as well as some incidents in Europe, are warnings of what can happen when the power supply falls out of step with an increasing demand for energy. In many large cities network operators are limited in their location selection by the availability of electrical power. Since an upgrade or expansion of the power grid can take many years, the only realistic way out is to reduce the power consumption of telecommunication systems.

One answer to the demands of today's telecommunication network operators is a technology that allows the monolithic integration of electronic functions as well as both active and passive optical functions. A growing force of industry watchers and players believe that indium phosphide is the most promising platform for subsystem-on-a-chip integration.

Indium phosphide fits the bill

For over 20 years, researchers have been investigating practical methods to realize the benefits of InP. The first attractive feature of InP is that it allows the construction of extremely compact devices, which is an important consideration for mass production. Small devices can be realized in this material because of the relatively high refractive indices of InP and its ternary and quaternary derivatives, such as InGaAs and InGaAsP. A high refractive index allows a smaller radius of curvature leading to components that are at least 10 to 100 times smaller than current state-of-the-art silica-on-silicon technology.

Another characteristic of InP is its direct bandgap, leading to very easy and fast quantum transitions when photons are either absorbed or emitted. This, combined with its strong electro-optic effects, makes InP a suitable material for applications that require short

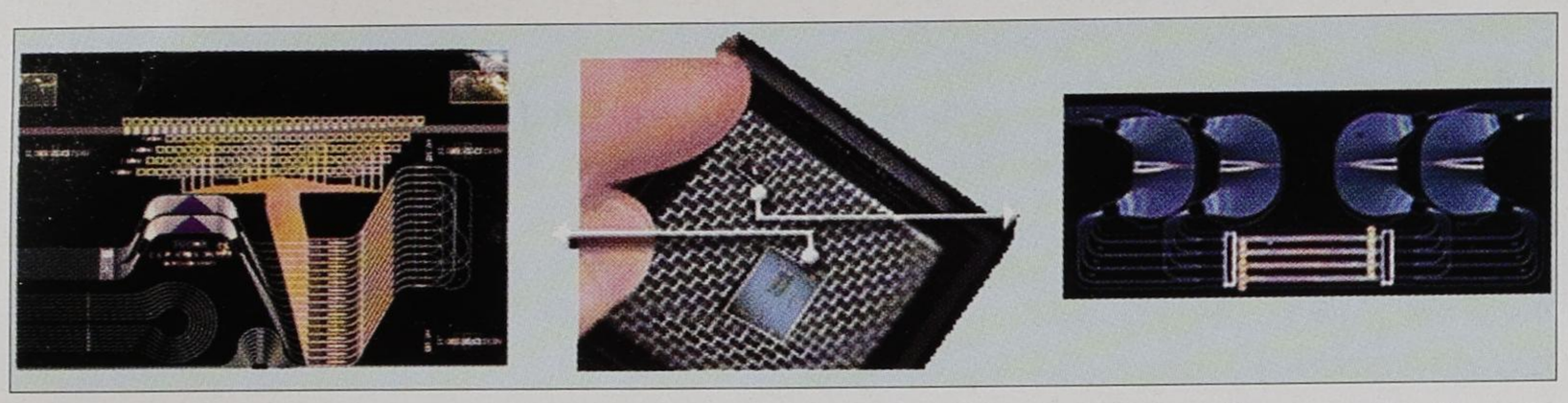


Fig. 2. The chip on the left measures 12 mm × 9 mm and demonstrates the complexity of optical waveguide structures that can be fabricated in InP. The chip on the right is a four-wavelength 2 × 2 optical cross-connect measuring 1.5 mm × 3.3 mm^2. This device is fabricated from InP and is the smallest ever produced.

switching times, such as packet switching.

It is fortuitous that the bandgaps of InP and its derivatives translate to the wavelength range that is used for optical communications. Furthermore, it can be tuned anywhere between 0.92 μm and 1.65 μm by varying the In(GaAs)P composition. This also influences its absorption and electro-optical characteristics, enabling the construction of transparent waveguide structures, photodetectors, modulators, switches, lasers and semiconductor optical amplifiers (SOAs) for a wide range of wavelengths. SOAs can find application not only as optical amplifiers, but also – because of the non-linear properties of InP-based SOAs – for all-optical signal regeneration, a function that is in high demand. Finally, the derivates of InP are extremely well suited for the creation of high-speed electronic devices.

Of course none of this is new. InP had proven itself long ago as a suitable material for both electronic components and lasers. But it was only recently that the technology required for integrating various components on a single chip has become available. An example of what can be achieved by integration can be seen in figure 2. The integrated WDM optical cross-connect (the right-hand image) is the world's smallest to date at 1.5 mm × 3.3 mm^2 and was made in 2000 by the optoelectronic devices group at Delft/ Eindhoven University of Technology.

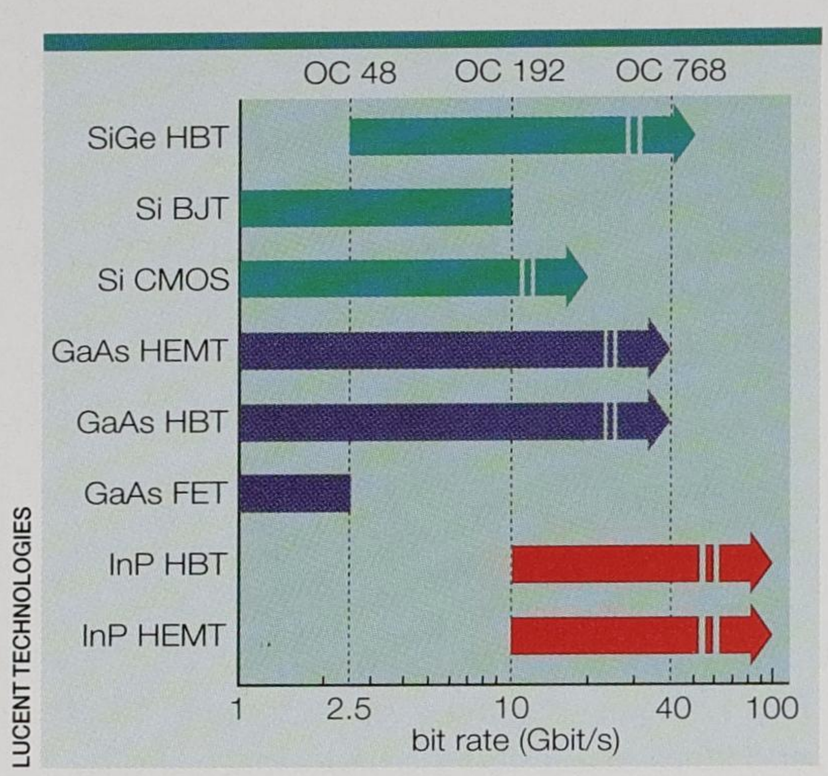


Fig. 3. As silicon ICs approach maximum operating speed, InP electronics could be a full order of magnitude faster. Since it can also outperform GaAs, InP is the preferred platform for monolithic integration.

Why monolithic integration?

Over the past three decades, the demand for lower prices, smaller footprints and reduced power consumption has always been met by pushing the limits of the standard technology, silicon, to the next level. Moore's Law describes this process for the electronic domain, but this law does not apply in photonics. What the industry needs is a technology that allows the integration of electronic and optical (active and passive) components. For a number of reasons silicon – or more precisely silica-on-silicon – cannot meet this demand.

Active components such as detectors, lasers and optical amplifiers at the important 1310 and 1550 nm wavelengths cannot be made using silica-on-silicon. Secondly, due to the small difference between the refractive indices of the silica waveguide core and the surrounding cladding, the radius of curvature of waveguide bends cannot go below several cm, which places a severe limitation on the miniaturization of components. Finally, while silicon microelectronics has advanced to the point where it is suitable for many of the functions needed in systems at 10 Gbit/s and higher, it is unsuitable for the functions that require high speed and high breakdown voltages.

One logical step in the technological evolution, which has been explored extensively, is the combination of discrete components of varying technologies, each providing their own specific functionality. But it is exactly this solution that created the manufacturing bottleneck mentioned earlier, because building a subsystem from discrete components is extremely labor intensive. It is also expensive because of the high costs of packaging the individual components. And finally it is extremely difficult to manufacture reliable and effective subsystems because of the large number of fiber connections that cause signal losses and are potential causes for failure.

Hybrid integration of silicon electronics with passive silica-on-silicon photonic components and active InP- and GaAs-based components will realize a considerable reduction in size. However, this introduces complicated packaging problems as well as issues that arise from the difference in thermal expansion for different materials that are tightly connected.

All of this is avoided with monolithic integration of all system functions on a single chip. It is inevitable that technological dominance will shift over time from discrete components to hybrid integration and eventually to monolithic integration. In our view the material of choice for monolithic integration will be InP. Its only serious competitor is GaAs, which also allows the manufacturing and integration of active and passive optical structures as well as electronics. However, the critical drawback is that many active structures in GaAs will only work at wavelengths below around 1 μm. Also while GaAs electronics is faster than silicon, it is still outperformed by InP (see figure 3).

Towards a subsystem-on-a-chip

The roadmap to a complete telecommunication subsystem on a single chip shows a phased development of products with increasing complexity and functionality. The approach being taken at ThreeFive Photonics is based on three types of elementary components: passive waveguide devices, electro-optical phase modulators and SOAs, from which most of the functions required in advanced optical systems can be realized.

Passive waveguide devices, such as splitters, couplers and wavelength multiplexers/demultiplexers in InP are typically one or two orders of magnitude smaller than their current counterparts in other materials. The drawbacks of this small size are the more stringent demands on fabrication technology, especially lithography and etching. Furthermore, fiber-chip coupling is difficult due to the large mismatch between the waveguide and the fiber mode.

The strong electro-optical effects in the quaternary compound InGaAsP can be used to induce a change in its refractive index and/or optical absorption, which in turn can be used for either phase modulation or amplitude modulation. One application of this principle

is the Mach–Zehnder interferometer-based space switch. By monolithically integrating two arrayed-waveguide gratings with 16 of these switches, a WDM cross-connect has been constructed that can independently cross-connect signals at four wavelengths from two input ports to two output ports. By combining these switches with active devices, such as lasers and amplifiers, high-speed transmitters can be realized.

The integration of SOAs makes it possible to improve the performance of the photonic circuits as well as to increase their functionality. SOAs can provide on-chip gain to compensate for the internal losses in devices and the fiber-chip coupling losses. Furthermore they can be used for gate switching of optical signals. The non-linear characteristics of SOAs can be used to add functions, such as wavelength conversion and signal regeneration.

Telecommunication systems in the future will have to be able to handle the complexity of multiple-wavelength signals in WDM applications. Consequently the required integration will not only be serial – where different components that sequentially process a signal are integrated on one chip – but also parallel, where a large number of identical components, each processing a separate signal, are integrated. ThreeFive Photonics currently pursues both types of integration.

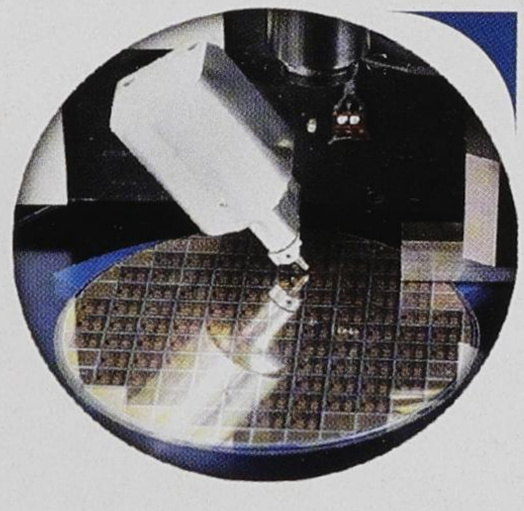
An indium phosphide future?

The downturn in network operator capital expenditure that occurred at the end of 2000 has reshaped the market for optical telecommunication systems. Now that the market has become demand-driven, the fragmented supply chain – supported earlier by manufacturing practices that could only be expanded with brute force – is likely to be replaced by one or more scalable, cost-effective, compact and generic technologies. InP is the premier candidate for this. It offers the potential to monolithically integrate ultra-compact optical components for signal generation/regeneration, amplification, detection, conversion and multiplexing/demultiplexing as well as ultra-high-speed electronic components. The development of a generic InP-based technology in which these optical and electronic functions can be realized will represent a fundamental change to optical networking.

Wouter Deelman is CEO and Chrétien Herben is CTO at ThreeFive Photonics, Delft, The Netherlands. Email info@35ph.com, Web www.threefivephotonics.com.

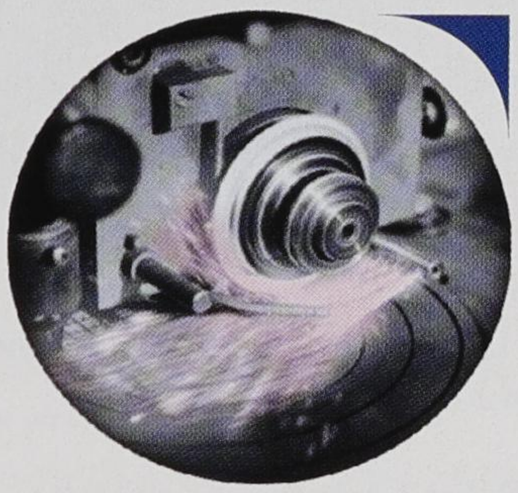
Wafer/Laser Bar Dicing

solutions for all substrates



Dry Process Dicing

Scribe & Break Technology is ideal for III-V substrates, silicon wafers, hard materials including sapphire, glass and ceramics, and ultra clean devices. Advantages are speed, high reliability, up time, and no water contamination.



KerfAid™ Coolant/Lubricant System

Designed to give excellent boundary lubrication and surface tension reduction, KerfAid prevents device chipping and cracking as well as extends blade life.

WaferGrip™ Bonding System

WaferGrip temporary adhesives can be used to bond wafers to other substrates such as sapphire or glass during dicing, grinding, lapping and polishing operations.

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Automated system for photomask patterns

Micro-Metric has unveiled a system designed to fully automate the measurement of photomask patterns at line resolutions down to 0.25 μm. The MicroLine 800AV employs a laser interferometer to accurately position the stage during the measurement of contacts, line features, defects, corner rounding, or intrusions and extensions.

The system measures features with sizes in the 0.25–200 μm range, with an accuracy of 0.01 μm and repeatability of 5 nm. The positioning stage traverses an 8×8 inch^2 area with an accuracy of 0.5 μm and a resolution of 10 nm.

Contact Jennifer Kihano, Micro-Metric Inc, 1050 Commercial Street, Suite 102, San Jose, CA 95112-1404, USA
Tel. +1 408 452 8505
Fax +1 408 452 8412
Email jkihano@micro-metric.com

Dry process from SSEC aids wafer cleaning

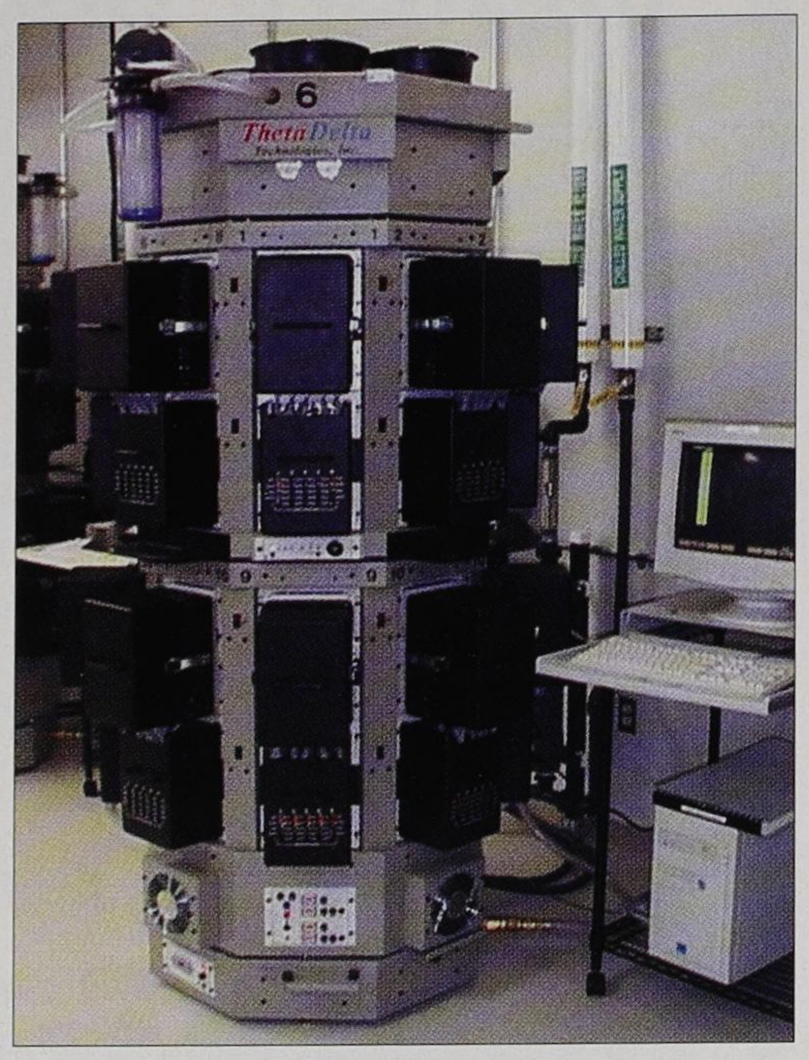
Solid State Equipment Corporation's Trilennium wet cleaners and processors are intended for cleaning, coating, developing, etching and solvent processing. The company has now added a dry cleaning step prior to wet cleaning. The new system employs irradiation with 172 nm UV light to remove organic contaminants, rendering the surface of the substrate more hydrophilic and improving the effectiveness of subsequent wet cleaning steps.

Contact Terri Kolodziejski, Solid State Equipment Corporation, 185 Gibraltar Road, Horsham, PA 19044, USA
Tel. +1 215 328 0700 ext.737
Fax +1 215 328 9410
Email tkolodziejski@ssecusa.com

ThetaDelta provides laser burn-in service

ThetaDelta Technologies is providing burn-in and qualification services for laser diodes and semiconductor devices. The service is intended as a qualification aid for new or smaller photonics companies.

ThetaDelta's burn-in system is capable of testing up to 1600 laser diodes simultaneously. The LD1600 is configured



for sub-mounted diodes and can be modified to meet the specific requirements of the customer.

Contact Debra Lacharite, ThetaDelta Technologies, 50 Island St, Lawrence, MA 01840, USA
Tel. +1 978 689 0136
Fax +1 978 685 4619
Email dlacharite@thetadelta.com

OAR unveils UHV deposition source

The latest UHV deposition component to emerge from Oxford Applied Research is the Nanocluster source. The NC200U sputters material into a high-pressure, cold clustering zone, producing a beam of nano-crystalline particles with a narrow size distribution.

The beam allows zero-dimensional systems to be investigated without recourse to thermal or lithographic processing, says the company. Alternatively, an ionized cluster beam can be accelerated towards the substrate to produce highly adherent and uniform coatings. Emerging applications include contact hole filling, magnetic and optical data storage and catalysis.

Contact Steve Rothstein, Oxford Applied Research USA Inc, One Gateway Center, Suite 2600, Newark, NJ 07102, USA
Tel. +1 866 669 4627 (toll-free in the US)
Fax +1 973 622 3423
Web www.oaresearch.com

New low-cost manual flip-chip/die bonder

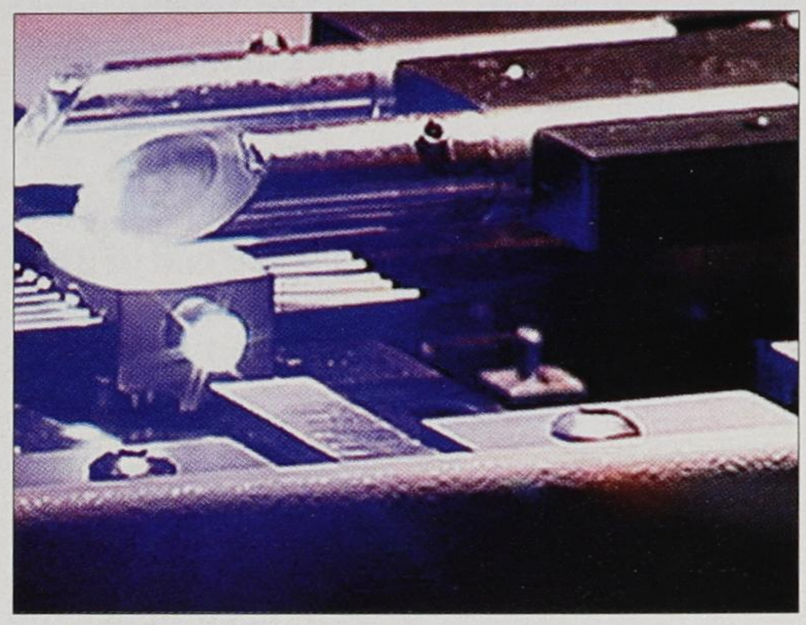
RD Automation has introduced a low-cost manual flip-chip/die bonder. With a placement accuracy of ±2 μm, the M-9A features air bearing components, a granite base, autocollimator/planarity control, closed-loop temperature and force feedback.

The system also includes an optical probe with bright and dark field illumination, in addition to an on-screen joystick-controlled menu. Both low- and high-force systems (up to 100 kg) are available.

Contact Dana Mendenhall, RD Automation, 121 Ethel Road, West Piscataway, NJ 08854, USA
Tel. +1 732 572 4800 ext.127
Email danamendenhall@ rdautomation.com

In situ ultraviolet curing assembly system

Palomar Technologies is providing an *in situ* option for its die bonders that allows components to be set in place and cured with a UV-catalyzed epoxy. This eliminates



drift in the assembly of lenses, collimators or passive components. The UV option also avoids two-part epoxy cures that can outgas and lead to clouding of optical lenses.

The bond tool stays in contact with the part during the entire process and does not release until the adhesive has achieved a minimal tack.

Contact Arnoux Abraham, Palomar Technologies, 2230 Oak Ridge Way, Vista, CA 92083, USA
Tel. +1 760 931 3406
Fax +1 760 931 3444
Email aabraham@bonders.com

Uniroyal abandoned by investors following report

Uniroyal's impending cash crunch has led to a 50% drop in its share price. Fellow LEC maker Cree has also floundered in a down market, but for vastly different reasons.

If UTC cannot restore investor confidence soon, it faces delisting from the NASDAQ exchange.

Shares in Uniroyal Technology Corporation (UTC) dropped below $0.35 in mid February as investors continued to flee the company after it disclosed an impending financial crisis.

Between April and October 2001 shares in UTC trended generally downward, sinking from a high of $10 to a low of $2.50. But they then rallied slightly and appeared to stabilize in the $3–4 range in November and December. UTC announced its most recent financial results on December 26. While they were not pretty (a fourth-quarter loss of $35.1 million on sales of $8.1 million) the market reaction during the slow period between Christmas and New Year was only mildly negative.

But support for the company completely collapsed on January 2, when the share price dropped by 50% to $1.60. Over 2.5 million shares changed hands that day, compared with a typical volume of 50,000 shares per day for the previous month. The sell-off was apparently sparked by pessimistic language in the company's annual report, issued on December 31. It highlighted issues that UTC's management did not raise a week earlier in their earnings announcement and conference call. For the first time it was revealed that the company would face a liquidity crisis if it could not reduce operating costs and sell some of its assets. Analysts who follow the company surmised that UTC's accountants required the warning to be inserted into the annual report, which, unlike the earnings announcement, requires the approval of an independent auditor.

February 14 saw a second day of huge volume, as the stock briefly dipped to $0.25, closing the day at $0.35. The company's report for the December quarter, released the previous day, revealed that as of early February the company had stopped making interest payments on debts, and has "delayed certain vendor payments".

UTC has lost money in each of the last three years, and the annual report predicts a negative cash flow in 2002. Cash on hand has dwindled to $2 million from $36.6 million a year ago.

Since 1998, UTC management has been trying to reposition the company away from mature, industrial-based activities in favor of the high-growth compound semiconductor industry. In February of that year Uniroyal formed a joint venture with Emcore to manufacture HB-LED wafers and package-ready dies. However, Emcore pulled out of the deal in August 2001.

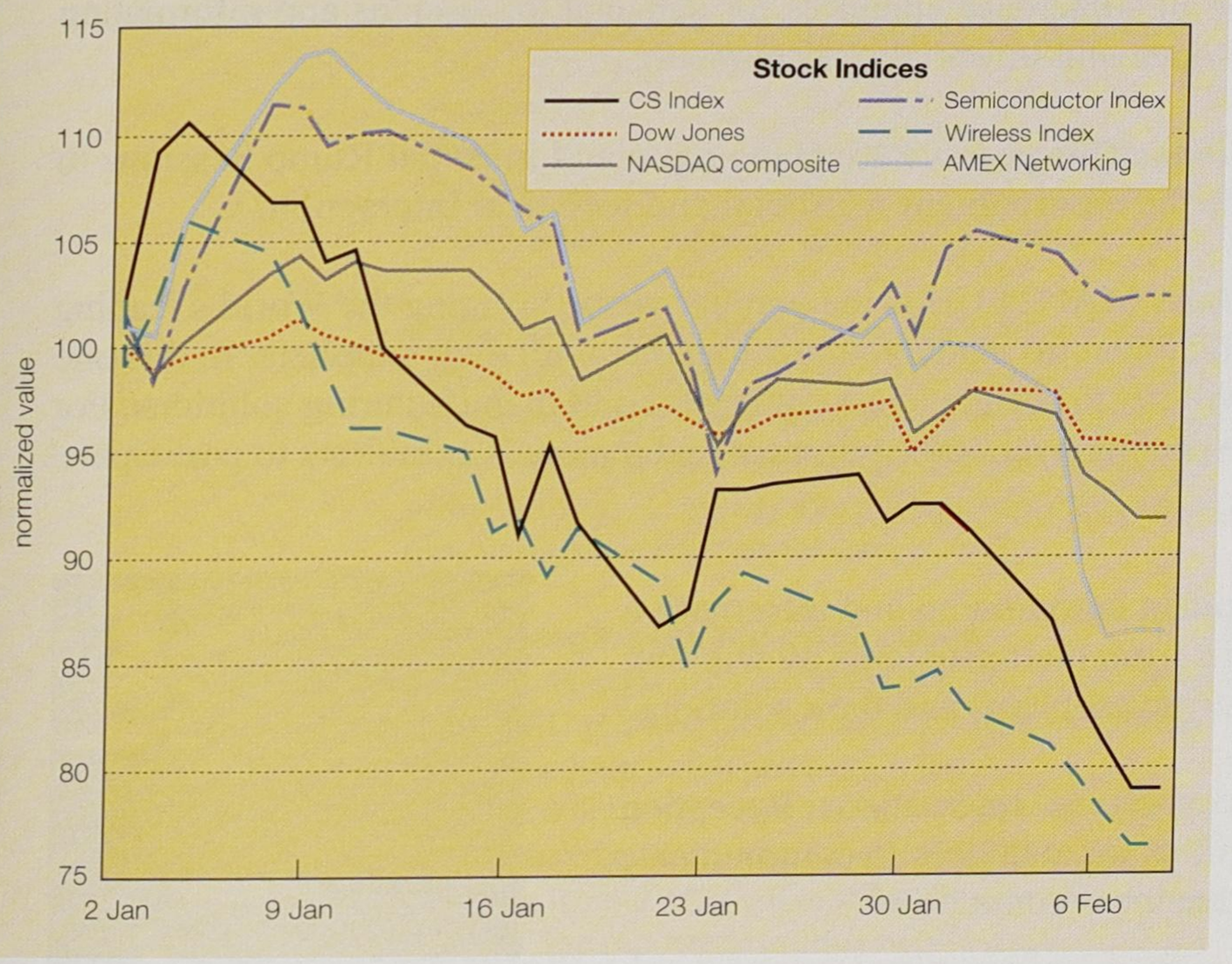
As of September 30, 2001 the UTC compound semiconductor operation had an accumulated deficit of more than $60.4 million. It incurred net losses of approximately $46.5 million in 2001 and $27.0 million in 2000. In the six months ended December 2001 the compound semiconductor-related activities generated a loss of $28 million on sales of $4.1 million.

Recent operations at UTC have been funded by selling off the company's older businesses. Coated Fabrics, the last remaining legacy business, is expected to be sold soon. This division accounted for 85% of UTC's sales in 2001.

On February 13 the company announced that it had settled a lawsuit stemming from UTC's cancellation of a building contact for its Sterling Semiconductor subsidiary. The plaintiffs were originally asking for $8 million in damages; the case was settled for $785,000.

If UTC cannot restore investor confidence soon, it faces the dreaded prospect of delisting from the NASDAQ exchange, which has a minimum-price requirement of $1. Delisting is a potentially disastrous

Industry indices



2002 International Conference on Compound Semiconductor Manufacturing Technology

April 8-11, 2002

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Web address: www.GaAsMANTECH.org

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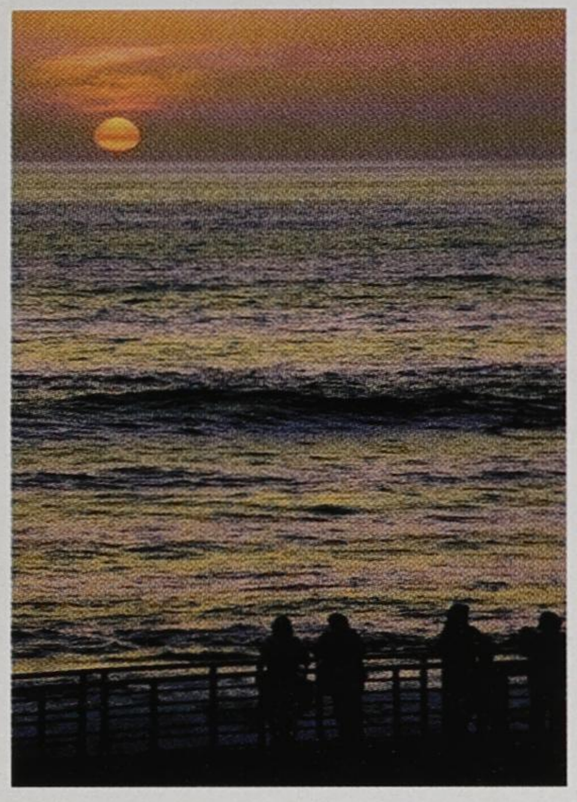
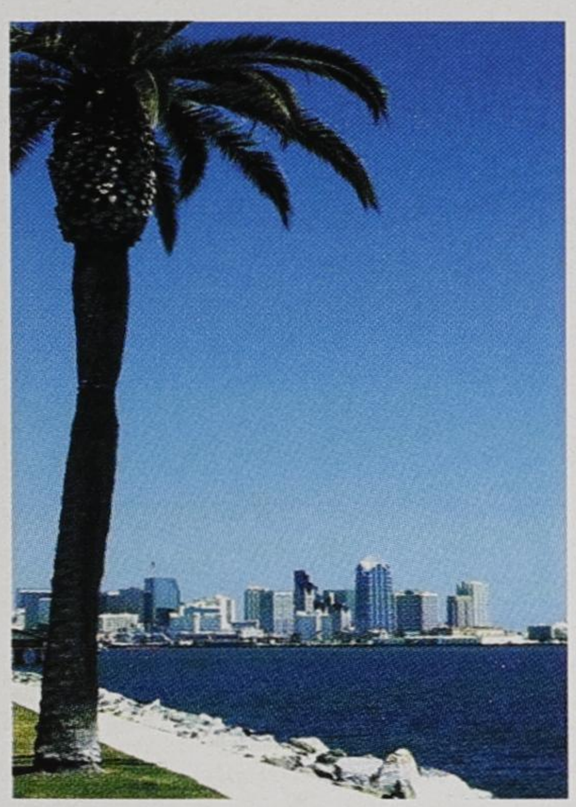




In our 17th year, the 2002 MANTECH conference will present:

❑ **Technical Sessions:** over 60 papers addressing manufacturing, processing, reliability, device technologies, optical devices, materials (GaAs, InP, GaN) and packaging. The plenary session includes talks by leading technologists from around the world. Edgar Martinez from DARPA will provide an "Overview of Emerging Compound Semiconductor Technologies." Additionally, future business trends and new paradigms in the industry will be discussed.

❑ **Workshop:** To meet the rapid demand, GaAs MANTECH will again sponsor an intensive four-topic workshop led by industry experts on April 8th, the day before the main conference. Workshop topics include:

- InP Technology
- Semiconductor Band Gap Engineering
- Fundamentals and Modeling of III-V MOVPE
- Telecom Basics: The Role of Compound Semiconductors

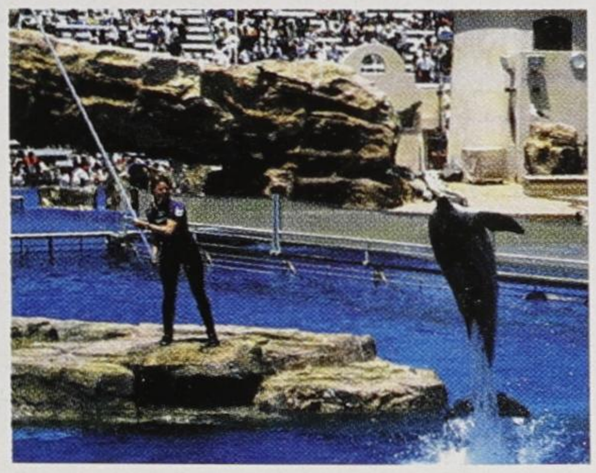
❑ **Interactive Forum:** This popular session provides an excellent and informal opportunity for all conference attendees for personal discussions and information exchange in an open and informal environment.

❑ **Rump Sessions:** This year we are planning to add informal Rump Sessions to further enhance the environment for social and technical interaction.

❑ **Exhibits:** GaAs 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. For 2002 we are expecting over 100 equipment and materials exhibitors to participate.

❑ **Ugly Picture Contest:** This is a very popular, entertaining and informative contest. It gives everyone a chance to benefit from their problems by winning a prize for the worst examples of manufacturing problems and their solutions.

❑ **Social events**, including 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 advanced program, please visit us at www.GaAsMANTECH.org**

Several analysts remain positive about the ability of Cree's management to execute on their strategy.

Market overview

Company	Symbol	Closing price on February 8	52-week low–high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha Industries	AHAA	20.40	13.0625–41.4500	900.1M	N/A
Anadigics	ANAD	11.31	10.2200–25.3800	343.3M	N/A
Celeritek	CLTK	9.84	9.0000–17.125	119.0M	N/A
Conexant	CNXT	12.26	6.5700–18.875	3.134B	N/A
Endwave	ENWV	1.12	0.6000–4.3125	40.1M	N/A
Multilink	MLTC	4.15	3.2000–18.4000	284.3M	N/A
RF Microdevices	RFMD	17.55	8.7500–37.5000	2.924B	N/A
Sirenza Microdevices	SMDI	4.20	2.9800–24.5625	123.7M	N/A
TriQuint	TQNT	10.49	9.0400–35.5625	1.366B	N/A
Vitesse	VTSS	10.64	6.6500–73.1250	2.127B	N/A
Opto companies					
Agilent	A	25.98	18.0000–55.0000	12.047B	N/A
Agere	AGRa	4.60	3.1000–9.5000	7.523B	N/A
Alcatel Optronics	ALAO	5.55	4.0400–50.2500	91.6M	N/A
Coherent	COHR	27.96	25.0500–47.3750	797.8M	39.94
Cree	CREE	14.85	12.2100–36.6500	1.078B	N/A
JDS Uniphase	JDSU	6.60	5.1200–47.3750	8.763B	N/A
Stratos Lightwave	STLW	4.60	3.1800–14.2500	294.8M	N/A
Uniroyal Technology	UTCI	0.45	0.3799–10.1100	12.5M	N/A
Semiconductor materials and equipment companies					
ATMI	ATMI	28.09	14.5000–32.7300	852.8M	N/A
AXT	AXTI	10.45	9.2100–45.0625	233.7M	N/A
Emcore	EMKR	8.58	7.6700–44.1300	313.0M	N/A
Kopin	KOPN	9.54	4.0000–19.0500	652.8M	N/A
Tegal	TGAL	1.45	1.0000–3.5000	18.3M	N/A
Trikon	TRKN	11.02	6.9600–16.7200	141.3M	5.51
Veeco	VECO	27.43	19.9000–57.5000	788.3M	22.86
European companies (currency data in €)					
Aixtron	AIXG.F	22.20	13.50–59.85	1.43B	N/A
Bede	BED.L	3.04	1.93–3.54	88.00M	N/A
Bookham	BHM.L	2.01	1.19–25.00	285.10M	N/A
Filtronic	FTC.L	5.70	1.37–8.58	420.13M	N/A
IQE	IQE.L	2.11	1.39–4.53	346M	99.45
Picogiga	PGIG.LN	4.60	2.60–34.00	29.73M	N/A
Riber	RIBE.LN	3.75	2.51–23.00	70.20M	9.34
ST Systems	SRTS.L	2.50	1.61–4.13	78.33M	19.38

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

event, as it makes it extremely difficult to raise new capital via traditional outlets. The company will have a bit of breathing room, however, as the exchange has temporarily cut-back on its delisting activity in light of September 11, giving struggling companies more time to improve their performance.

Cree margins up, but price down

Two factors seem to have tripped up UTC: a slowdown in the LED market, as well as much slower than expected ramp-up to full production status.

While fellow-LED manufacturer Cree undoubtedly has the manufacturing issues well in hand, they are also suffering from a drop-off in sales. For the December quarter Cree reported revenue of $41 million, down slightly from the year-ago period. Income was $5.8 million. In a conference call, Cree executives said that they expect revenue growth may be flat, or will not exceed 6%, in the next six months compared with the previous six months. This represents a downturn of around $10 million from the previous guidance. In the days following the announcement shares dropped $15 to around $16.00. For the 2002 fiscal year (beginning in July), Cree executives foresee revenue increasing by 20–25%. This would equate to between $202 million and $216 million, below the previous consensus estimate of $232 million. On the basis of this more conservative growth forecast, Prudential's Hans Mosesmann downgraded Cree to a "hold" and lowered his target price on the stock to $17 from $26.

For the first time it appears that Cree is ahead of Nichia in terms of LED performance.

Despite the current disappointments, there is no doubt that Cree is a vastly different company than UTC. Several analysts remain positive about the ability of Cree's management to execute on their strategy. Even though revenues declined in the last quarter, the company was able to achieve gross margins of 47%. Product margins averaged 50%, with LED margins being even higher. Dale Pfau of CIBC World Markets notes that these are the highest margins of all the companies that his group covers, and he believes that Cree is the "technology and cost leader in an increasingly important class of semiconductor that will show explosive growth over the next few years".

Cree is undergoing a major upgrade of its manufacturing capabilities and will switch its entire product line from 2 to 3 inch production over the next year. A one-time charge of $18 million was recorded during the December quarter for the write-off of 2 inch equipment. Cree's management said in a conference call with investors that the new 3 inch wafers should improve yields and further boost gross margins, which is especially important given the constant erosion of average selling prices (ASPs) for its LED products. In the last quarter unit volumes for Cree LEDs increased approximately 5% but ASPs dropped 4%.

The company has also delivered on its earlier promise to focus on new product development in the current downturn. They have unveiled a new, brighter class of blue and green LEDs. These new "X-Bright" products are 50% brighter than Cree's previous high-performance products, the "Megabright" LEDs. That earlier category has received a warm welcome in the marketplace since it was introduced in May. In the December quarter Megabright LEDs accounted for 37% of LED sales.

For the first time it appears that Cree is ahead of Nichia in terms of LED performance. Pfau believes that Nichia and other competitors are accelerating their own ASP reductions in order to remain competitive. Cree has also begun to see blue laser revenue for the first time. In the December quarter Cree began shipments to Rohm as part of a new agreement with the Japanese electronic company. R&D spending in the December quarter increased by 64% compared with the year-ago period to total $6.7 million.

One murky area of Cree's accounts is a one-time only $12.4 million charge taken during the quarter for the decline in value of Cree's investments in privately held companies. Analysts at Stephens Inc report that Cree has a number of off-balance-sheet-type programs where it takes a stake in a private company in exchange for R&D work. After the Enron debacle, companies and their auditors are under pressure to make the fullest possible disclosure of the potential downside of these types of arrangements. At the end of the September quarter Cree had $29.3 million in private-company investments recorded as "other assets" on the balance sheet. The current charge was described as a reserve against the decline in value of these investments, due to the difficulty that many small technology companies are having in obtaining capital in a tough economic environment. ●

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