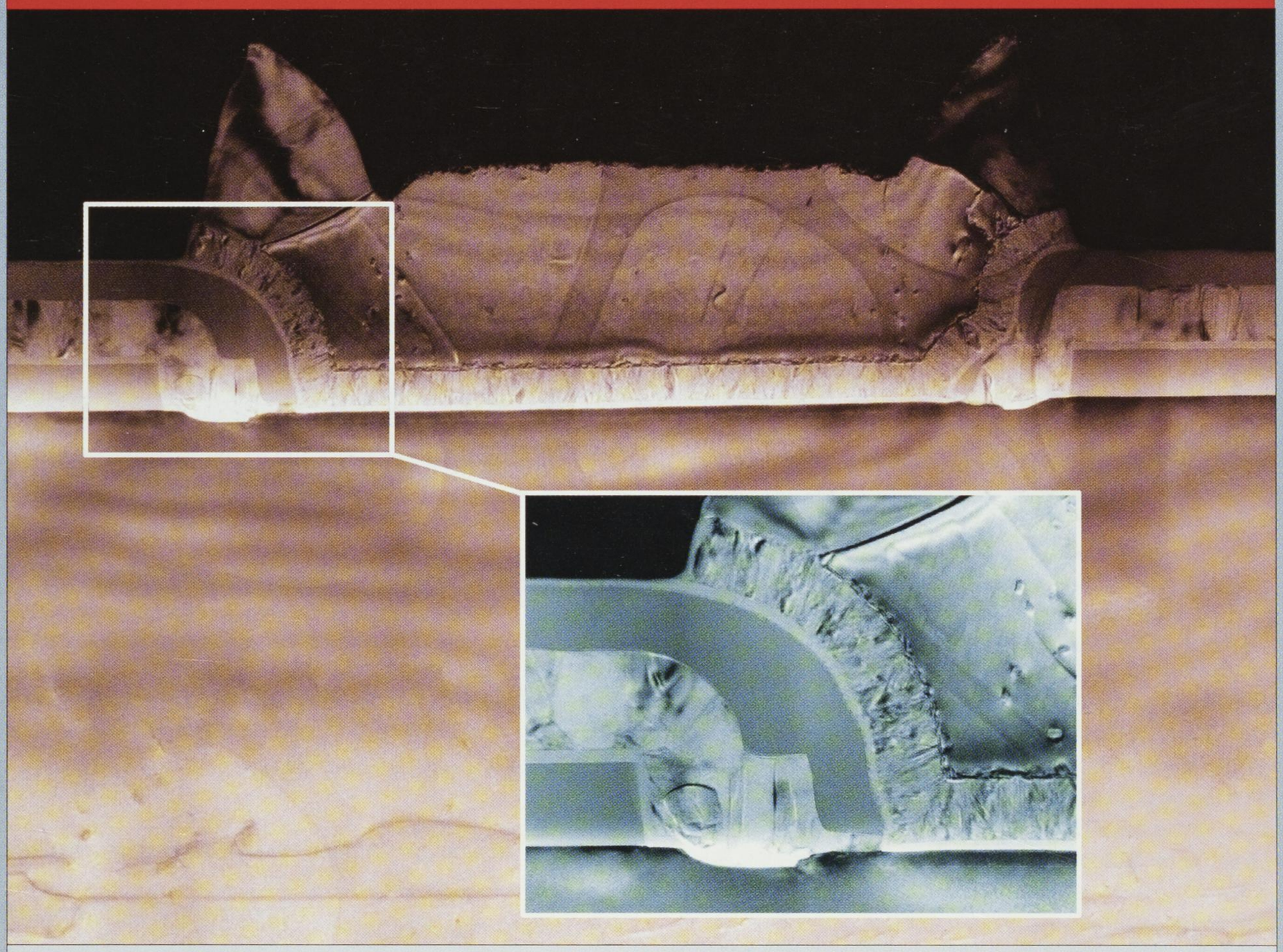
COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

March 2003 Volume 9 Number 2



CHARACTERIZATION

Material secrets revealed by FIB, PL and STEM techniques

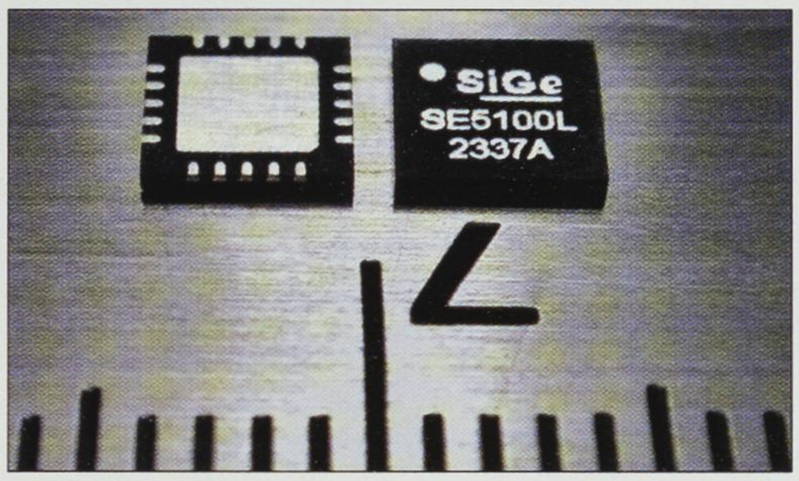
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More consolidation in opto components	Dow Corning buys SiC maker Sterling	High-power lasers and IR cameras

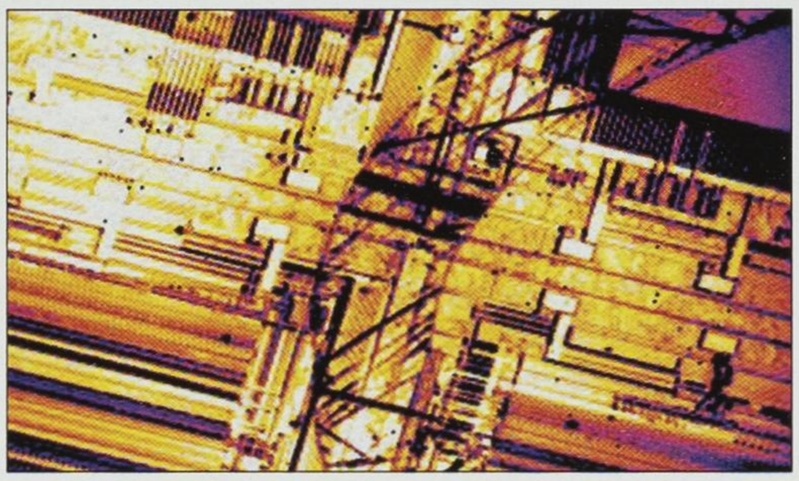
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Three-Fives and Silicon Heterostructures

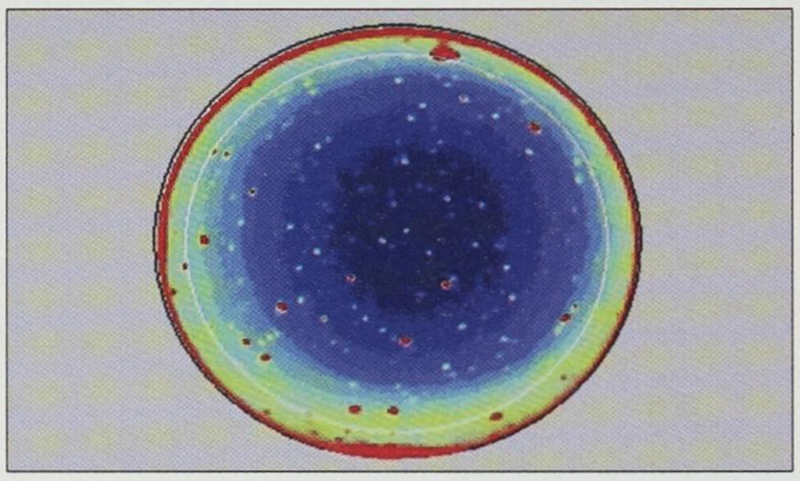
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On the cover: *A TEM image from a strained Si MOSFET sample prepared by focused ion beam milling (image courtesy of QinetiQ Advanced Analytics) – see p25.*

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US mailing information: *Compound Semiconductor* (ISSN 1096-598X) is published 11 times a year for $95 by Institute of Physics Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK. Periodicals postage paid at Middlesex, NJ 08846. POSTMASTER: send address corrections to Compound Semiconductor, c/o PO Box 177, Middlesex, NJ 08846. US agent: Pronto Mailers Association Inc, 200 Wood Avenue, PO Box 177, Middlesex, NJ 08846.

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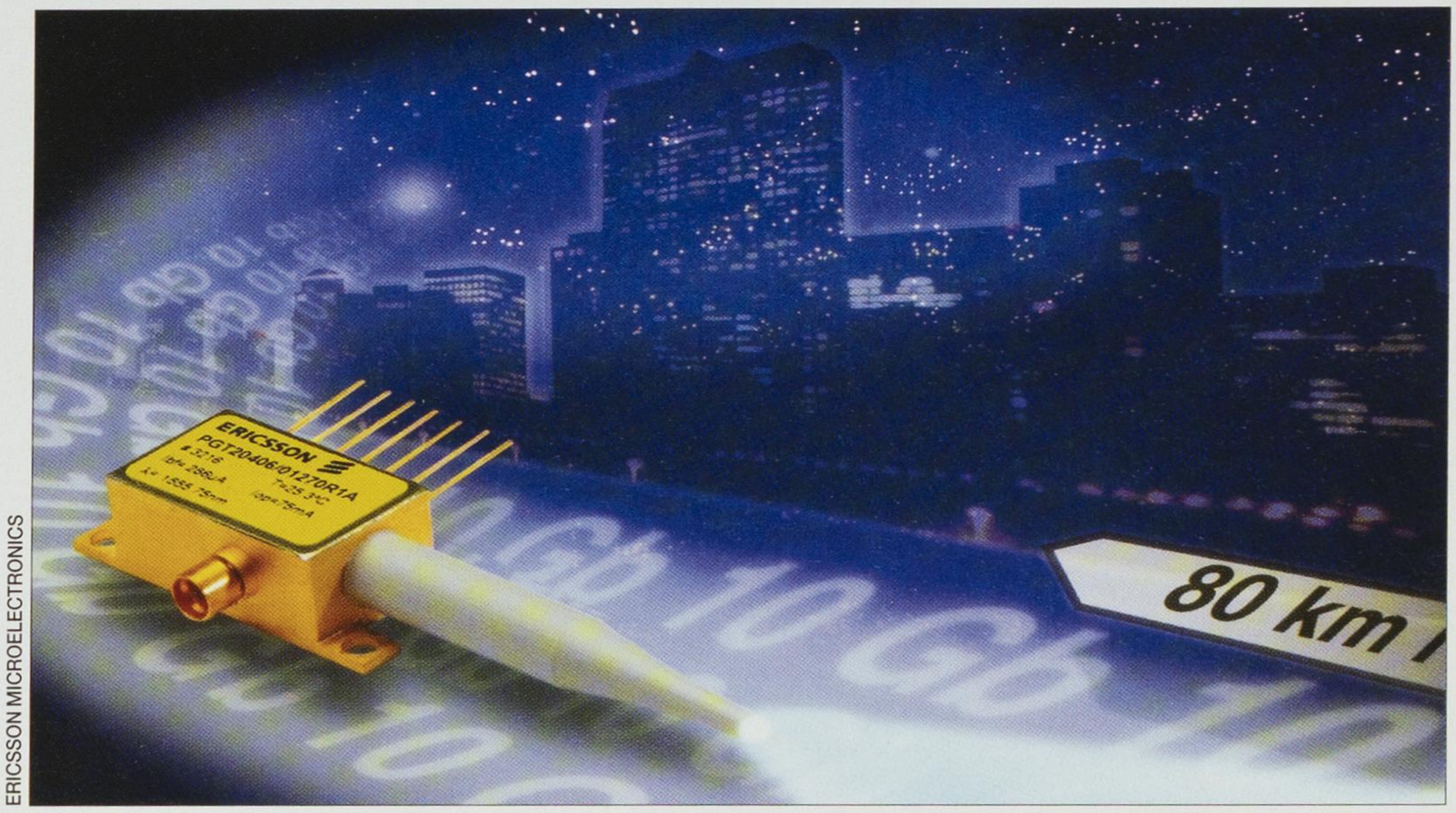
Change and consolidation continue in fiber-optic component industry

By Jon Newey and Tim Whitaker

The consolidation taking place within the fiber-optic components industry accelerated recently, with several companies being bought up by others keen to augment their existing product lines.

Although the telecom laser and transponder market is expected to grow by more than 30% in 2003 (see p15), there are still far too many component suppliers. "There is only business for a few key suppliers, plus some additional niche players," said Tom Hausken, Optical Communication Components Practice director at Strategies Unlimited. "The longer it takes to consolidate, the longer will be the pain. So far, there have been few consolidations or closures in this market segment, and many more are expected."

Agere, Ericsson and Gore have recently completed their plans to exit the optical component industry, joining Nortel, Marconi and ADC, while Alcatel may soon join them. Bandwidth9 is yet another start-up that appears to have given up the fight against the continuing recession in the fiber industry.



ERICSSON MICROELECTRONICS

As change continues within the fiber-optic component industry, Ericsson has sold its optoelectronics business to Northlight Optronics, a start-up company based in Sweden.

Ericsson sells optoelectronics unit

Swedish start-up company Northlight Optronics has bought Ericsson Optoelectronics, which designs and manufactures long-wavelength optical transmitters and receivers. The product range includes DFB-EA and DFB laser transmitters, and high-speed receivers operating at up to 10 Gbit/s. The deal is effective immediately, and Ericsson Optoelectronics' 48 employees will be transferred to the new company. The sale is part of Ericsson's ongoing drive to focus on its core business of providing systems and services for telecom operators. In June 2002, Ericsson sold its microelectronics business to Infineon for $378 million.

Northlight Optronics was set up specifically with this acquisition in mind by three executives with experience in optical component companies. They include Robert Green, formerly VP of business development at Bookham Technology, who becomes Northlight's COO. Funding has come from the executives' own pockets as well as from venture capitalists. The value of the deal was not revealed, but Ericsson has taken a 9.9% stake in the company.

While many may question the wisdom of entering this market in the current climate, Green has some convincing reasons why the acquisition is a good prospect. "Ericsson Optoelectronics has a tremendous amount of experience in making III-V devices," he told *fibers.org* website. "That's significant, because compound semiconductor devices such as DFB lasers are extremely difficult to make with good yields and reproducible processes that run economically."

Because of Ericsson's past investment in manufacturing infrastructure and processes, Northlight can benefit from low operating costs, and says that it is starting from a financial position where the breakeven point is much lower than its competitors. "We believe we can rapidly increase our market share and make this a profitable business in a reasonably short amount of time," said Green.

Emcore buys former Ortel from Agere

Agere has completed its exit from optoelectronic device manufacturing with the sale of its West Coast optoelectronics segment to Emcore for $25 million in cash. In October 2002, Agere sold the bulk of its optoelectronics business to TriQuint (*Compound Semiconductor* December 2002 p3).

The transaction includes assets, products, technology and intellectual property related to Agere's cable TV optical components, telecom access and satellite communications operations located in Alhambra and Irwindale, CA. The sale continues the recent pattern of large players in the fiber-optics industry selling off assets, which were built up or acquired at great cost during the boom period that ended two years ago. Agere's West Coast operation consisted primarily of the operations of Ortel Corporation, which Lucent Technologies acquired in April 2000 in a stock-based deal worth $2.95 billion.

Emcore estimates this business will have revenue of between $30 million and $40 million for the year ending September 30, 2003. As part of the agreement, 215 of the 230 Agere employees will join Emcore. Agere was planning to exit the Irwindale facility by the end of March, consolidating its operation in Alhambra, and Emcore is to continue with that move. Emcore now leases the Alhambra site and operates it as Ortel, a division of Emcore.

The acquisition further expands Emcore's presence in the optical communications arena. The company already manufactures VCSEL and *pin* diode arrays, as well as parallel optical modules that incorporate the arrays. In December 2002, Emcore also bought>>

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RFMD and Intel announce wireless compatibility

RF Micro Devices has announced that its quad-band Polaris radio is compatible with Intel's new PXA800F "wireless-Internet-on-a-chip" cellular processor, providing a total system solution for GSM/GPRS handsets that minimizes external components and power consumption while maximizing performance.

RFMD's Polaris Total Radio comprises a SiGe BiCMOS receiver, a CMOS mixed-signal processor and GaAs HBT-based PA module incorporating a CMOS control IC. It performs all major functions of the RF section, including both transmit and receive, and gives handset manufacturers the benefits of reduced component count, flexible baseband interfaces and lower cost of implementation.

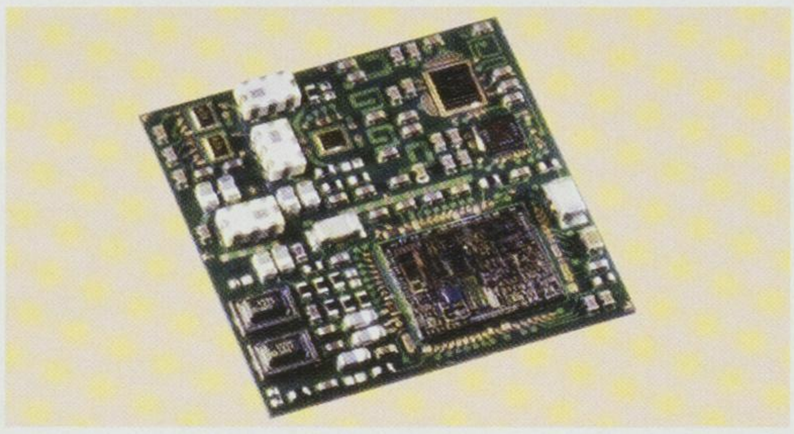
Intel's PXA800F cellular processor supports all key functions such as processing, flash memory and communications on a single 0.13 μm CMOS IC. Intel says that the chip will bring advanced functionality, longer battery life and more innovative designs to mainstream phones. The new chip marks Intel's first venture into the wireless handset market.

Skyworks launches dime-sized complete handset radio system

Skyworks Solutions has unveiled the world's first complete handset radio system that fits into a single, dime-sized package. The SKY74073 Single Package Radio (SPR) solution combines all of the radio circuitry required for GSM/GPRS 900/1800 handsets into a single compact package that is one-third of the size of alternative solutions created from discrete components.

Skyworks says that the radio system and packaging breakthrough saves handset designers significant space, cost and design-cycle time, while providing a roadmap for quad-band and 3G handsets in the future.

The SPR solution comprises an HBT-based PA and CMOS controller, PHEMT switches, a MESFET directional detector, SAW filters and a silicon BiCMOS direct conversion transceiver. All these components are combined in a compact 40-pin laminate multichip module package measuring only 13 × 13 mm.



SKYWORKS SOLUTIONS

Skyworks' Single Package Radio combines all the radio circuitry required for GSM/GPRS handsets in a 13 × 13 mm package.

New distribution center expands Anadigics' presence in Asia

Anadigics has opened an Asian distribution center through its partnership with Taiwan-based Universal Communications Technology (Ucomm). This will enable Anadigics to reduce cycle times by minimizing handling and transportation time and expenses, creating a more efficient product flow to its growing Asian customer base. The announcement follows just a year after Anadigics' agreement with Ucomm for the offshore outsourcing of its production RF testing operations. Ucomm has also recently opened a new testing and assembly plant in China, which could offer Anadigics an even greater Asian presence.

Anadigics has grown its CDMA revenue significantly in the last year thanks to its pursuit of customers in Asia. Sales for the December 2002 quarter were $18.7 million, of which wireless business accounted for $11.4 million. During the quarter Anadigics' CDMA revenue grew 41.2% to $7.3 million, while its TDMA revenue declined 84%, as expected.

Handset products flood the market

Among a flurry of PA announcements in early 2003, Skyworks unveiled its System Smart family of 3 × 3 × 1.2 mm PA modules for CDMA cellular handsets. The reduction in size was achieved by integrating additional passive components into the InGaP HBT die. The PCS-band module now contains 30% fewer external components than Skyworks' standard 4 × 4 mm^2 CDMA PA module.

Philips launched the BGY284, a quad-band GSM PA module that measures only 8 × 8 × 1.5 mm and achieves a power-added efficiency of more than 55%. The module combines an InGaP HBT power amplifier, a silicon BiCMOS RF driver/power control circuit, and integrated passive components. "Because the BGY284 has such a small footprint and includes an integrated power control loop, manufacturers can save as much as 30% printed circuit board area, and up to 30 external components," said Robbert van der Waal, marketing manager for RF PA products.

TriQuint introduced five PA modules for the GSM cell phone market, based on InGaP GaAs HBT die manufactured on TriQuint's high-volume 150 mm production line. Selected models incorporate power control and quad-band capabilities to meet growing market demands for integration, flexibility and ease-of-use.

TriQuint finishes China test facility

TriQuint has completed a 1100 m^2 test facility in Tianjin, China. The facility will be operated by TriQuint's Sawtek subsidiary to provide assembly, test, mark, tape and reel support for TriQuint's products that serve the worldwide cell phone market.

WIN and ACCO form strategic alliance

Taiwanese foundry company WIN Semiconductors has formed a strategic alliance with ACCO, a design company with offices in Europe and the US. WIN and ACCO will provide a broad range of design services using WIN's full spectrum of GaAs process technologies and ACCO's expertise in designing leading-edge analog, RF and microwave ICs.

GaAs under threat from SiGe PAs

By Tim Whitaker

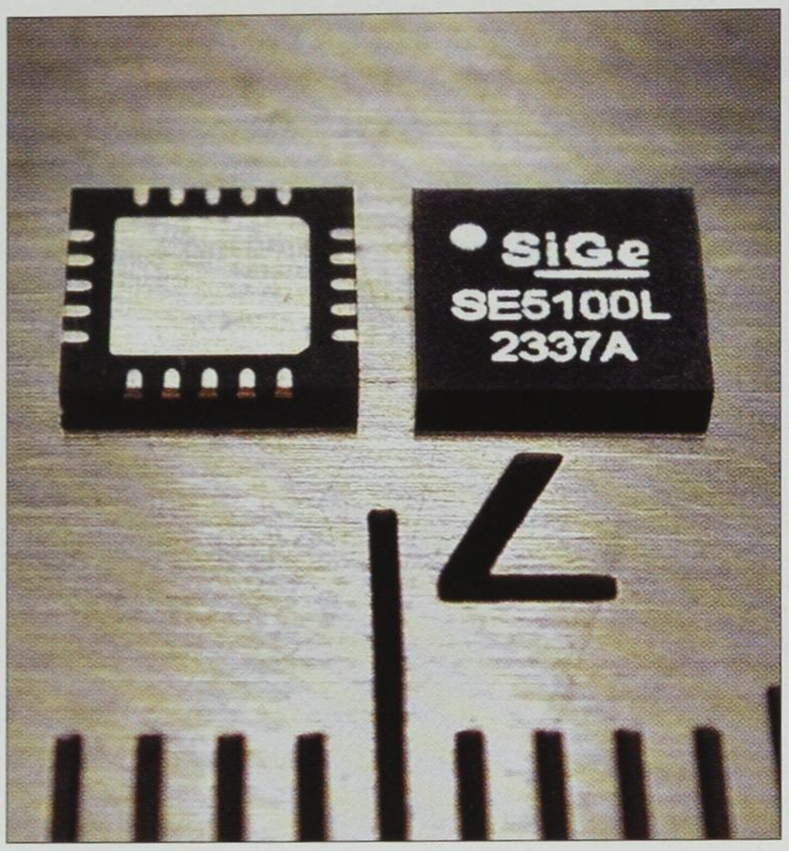
SiGe Semiconductor, a fabless supplier of SiGe-based ICs, has signed a licensing agreement with IBM in order to gain access to designs and intellectual property associated with IBM power amplifier (PA) products for cellular handsets. The company believes that SiGe-based PAs will displace GaAs alternatives in handsets as consumer pressures continue to drive handset prices down.

SiGe Semiconductor is currently sampling CDMA products for 2G and 2.5G handsets and will introduce other CDMA and GSM devices in the spring. The company's roadmap includes GPRS and EDGE capable quad-band GSM PAs for 2.5G handsets, as well as 4 × 4 matched CDMA PA modules for 2.5G and 3G handsets. The PAs are manufactured by IBM under a foundry agreement, while development work takes place at SiGe's new facility in Metheun, MA. According to Jose Harrison, product line manager for cellular PAs, the original team that worked at IBM on the development of these PAs moved over to SiGe Semiconductor. "We took the team and access to the IP and products that had been developed up until that point," says Harrison, "as well as lab equipment pertinent to PA development."

SiGe Semiconductor was founded in 1996 as a spin-off from a Canadian government research organization, and spent several years providing SiGe epitaxy services to foundries. In 2000, the company changed its business model to develop products, introducing Bluetooth PAs, cable tuners, GPS front-end ICs, and PAs for the cellular, wireless LAN and cordless phone markets, as well as optical ICs for fiber-optic communications.

"All the products are in the physical layer, between the communication medium (wireless, cable, optical) and the CMOS processing chips, where it makes sense to use silicon germanium technology," says Bill Cuming, VP of product marketing.

SiGe Semiconductor is fabless, but has relationships with a number of different fabs. "We're unusual in having lots of in-house process skill, unlike other fabless design houses," says Cuming. "We go to the fabs and help them to tweak and improve their processes, and enable their silicon germanium expertise. The relationships provide us with preferential access to volumes and favorable pricing."



SiGe SEMICONDUCTOR

The SE5100 is one of the new SiGe BiCMOS power amplifiers for handset applications.

Improved PA performance

Several years ago, there were debates about the feasibility of using a process with lower breakdown voltages in applications requiring output powers of 28 or 35 dBm, especially under high voltage standing wave ratio (VSWR) conditions. "While at IBM, the group that is now part of SiGe Semiconductor worked with process engineers to optimize the SiGe process for PA applications, and also developed novel ruggedness protection circuits," says Harrison.

However, the breakdown voltage issue proves to be less of an issue for SiGe. "Unlike GaAs, SiGe tolerates excursions far beyond its DC breakdown voltage in RF applications," says Mark Doherty, director of IC design for cellular PAs.

Harrison claims that potential customers have described the performance of SiGe-based PAs as being "every bit as good" as they've seen with GaAs. "In recent weeks, we've seen excellent performance in our next-generation CDMA products, due out in spring," he says. "At an output power of 28.5 dBm, we've measured linearity in the region of –50 dBc, and [power-added] efficiencies in the 38% range."

SiGe and GaAs in handsets

"The SiGe BiCMOS process allows us to integrate not only the bipolar RF paths, but also to use CMOS devices for logic and bias control," says Harrison. "Also, silicon is inherently a better thermal conductor than GaAs, and as a result the junction temperatures tend to run a little cooler at the same power levels." Furthermore, the current density handling capabilities of silicon lead to improved packing ability, reduced size and improved reliability. In fact, 8 inch SiGe BiCMOS wafers are handled like ordinary silicon, which allows standard pricing for assembly services. In contrast, however, GaAs technology often requires thru-wafer vias for backside grounds with wafers thinned to 3–6 mils (75–150 μm).

SiGe Semiconductor takes advantage of the very thick oxides in the IBM process to isolate passives from the lossy substrate. "This allows us to integrate more of the passive components onto the die," says Harrison. "This simplifies the module somewhat and reduces the bill-of-materials within the module." In turn, this results in smaller form factors for the final product, which is becoming more important as other features are added to the handset that take space from the radio portion.

Cost savings

Bill Cuming claims that SiGe also offers commercial advantages. "SiGe is an extension of BiCMOS, and there is only a small incremental cost over the standard process," he says. Cuming also claims that devices can be produced at higher yields and at a significant saving over the price of GaAs ICs. In Japan, environmental issues could come into play, as handset manufacturers will soon become responsible for recycling any products containing arsenic.

At the present time, there are no SiGe-based PAs designed into cellular handsets, although SiGe Semiconductor expects this situation to change. "Although we do not have any design-ins at this point, we have several very strong engagements with potential customers," says Harrison. "The use of SiGe is only now starting to be appreciated, and we've seen a tremendous amount of interest. I think in 2003 you will see some announcements of design-ins using SiGe."

LNAs and transceivers have moved from GaAs to SiGe, says Harrison, and the PA represents the last stand for GaAs. "Now that we are showing the performance levels that are accepted in the industry, we think that the trend [of replacing GaAs with SiGe] will continue into the PA as well," he says.

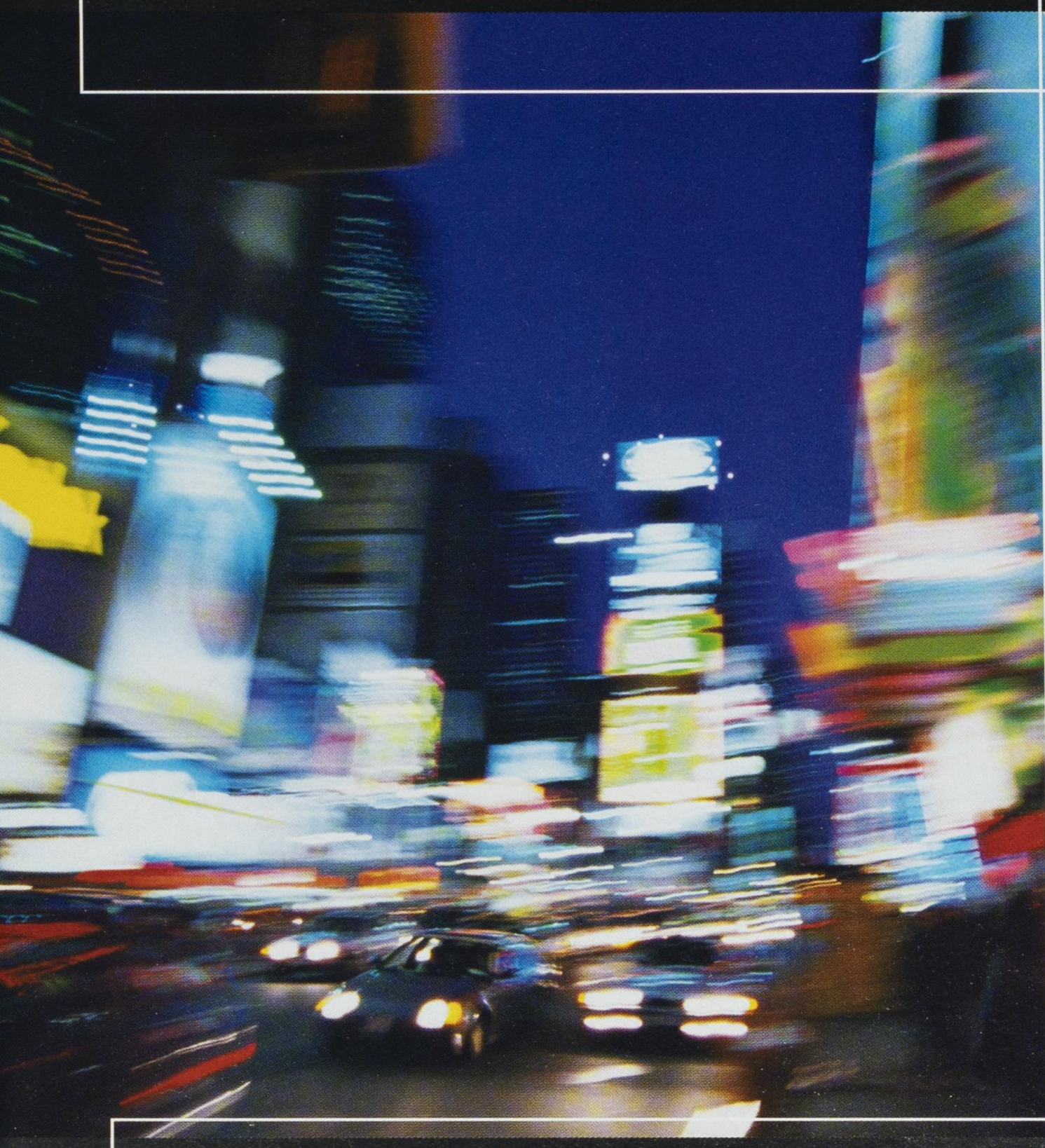
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Jazz and ASMC take SiGe BiCMOS to China

Jazz Semiconductor, the Conexant spin-off, and Advanced Semiconductor Manufacturing Corporation (ASMC), the largest wafer fabrication company in China, have announced plans to collaborate and create China's first pure-play foundry service for SiGe BiCMOS process technology.

Under the partnership, Jazz will contribute its BiCMOS and SiGe process technologies and engineering assistance. ASMC will provide capacity for SiGe processes in its new 200 mm wafer fab in Shanghai, which is expected to begin volume production in Q4 2003 and will have a capacity of 30,000 wafers per month.

Jazz says the alliance will provide its foundry customers with a second production source for the mixed-signal and RF chip processes currently manufactured in its plant in Newport Beach, CA. "One of the primary markets for SiGe products is wireless handsets, which require integration of RF functions at low power consumption and at low cost," said Theodore Zhu, VP of sales, strategy and business development for Jazz. "This agreement with ASMC provides Jazz customers with access to RF and mixed-signal process technologies in China, where the wireless market is expected to grow significantly. It also provides a second sourcing alternative."

China's Ministry of Information Industry has estimated that more than 200 million mobile phone subscribers now exist in the country, making it the world's second-largest market for mobile communications. The ministry estimated that 100 million wireless handset were sold in China during 2002.

Atmel collaborates with university on strained silicon process

Atmel, a major silicon IC manufacturer, is working with a team of researchers at Newcastle University in the UK to develop a strained silicon process for production. The project will be based at Atmel's fab near Newcastle, in the north-east of England, and will comprise a team of five university researchers led by Professor Anthony O'Neill.

The first phase of the project, which will involve integrating strained silicon into Atmel's CMOS process, is expected to take about a year. Both IBM and Intel have announced production processes including strained silicon, while Amberwave owns several patents in the area and is working with both AMD and UMC.

SiGe LNAs feature 0.52 dB noise figure

Toshiba has developed a SiGe-based LNA with a noise figure of 0.52 dB at 2 GHz. Toshiba claims this is the industry's lowest figure for a SiGe transistor, and is comparable with much more expensive GaAs transistors. The new parts are targeted for WLANs and GPS systems, and were developed through optimization of the SiGe bipolar process. The 4-pin package is the industry's smallest, at 1.2 × 1.2 × 0.52 mm.

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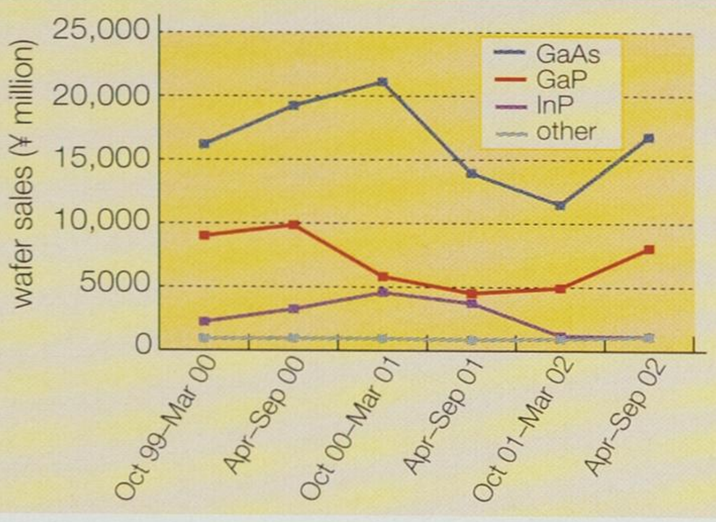
GaAs, GaP wafer shipments on the rise

Japanese manufacturers of compound semiconductor wafers reported a massive surge in sales of almost 46% in the six month period from April to September 2002, compared with the previous six month period. Total wafer sales amounted to ¥27,195 million ($231 million), only 18% lower than the peak figure recorded in April–September 2000. Most of the discrepancy can be attributed to declining sales to domestic customers, while export sales are close to their highest-ever level.

Figures were supplied by the Japanese Manufacturers' Society of Compound Semiconductor Materials (JAMS-CS), which conducts a twice-yearly survey of wafer shipments among its nine member companies.

Most of the growth came from renewed sales of GaAs and GaP wafers. GaAs shipments rose 46% compared with the previous six month period, reaching ¥16,837 million.

Japanese wafer shipments

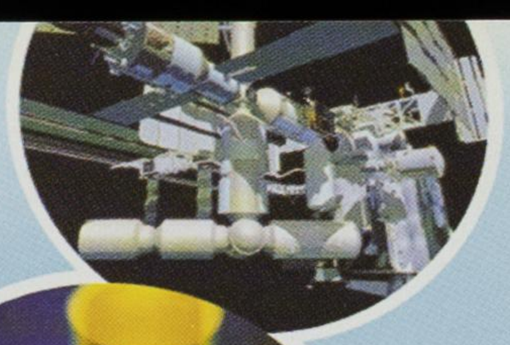


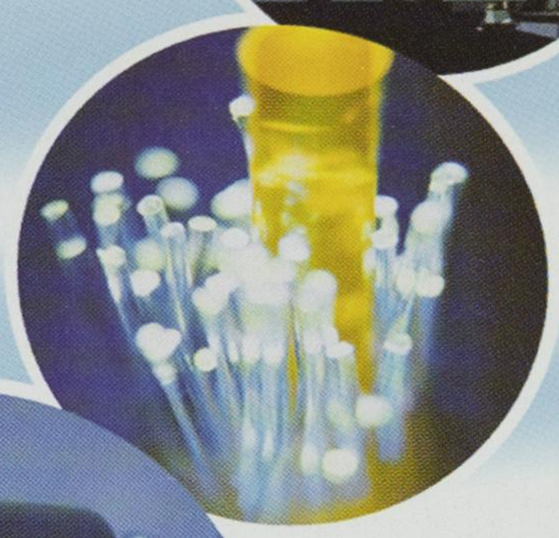
Shipments of GaAs and GaP wafers by Japanese suppliers rose sharply in the April–September 2002 period, although there is no sign of improvement for InP.

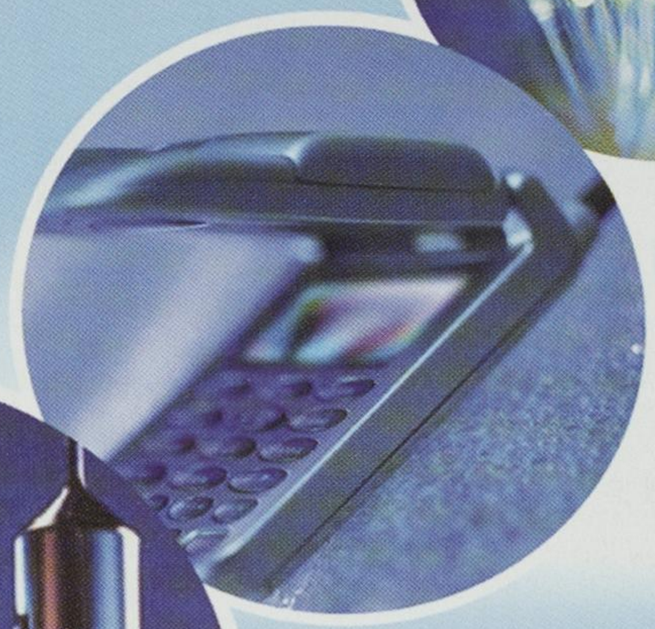
The figures have partly reversed a steady decline in GaAs wafer sales since the end of 2000; GaAs shipments fell by almost a half in fiscal year 2001, mirroring the slowdown in the wireless handset market. Around 62% of GaAs sales were to domestic companies, while export sales were at their highest-ever level of ¥6330 million.

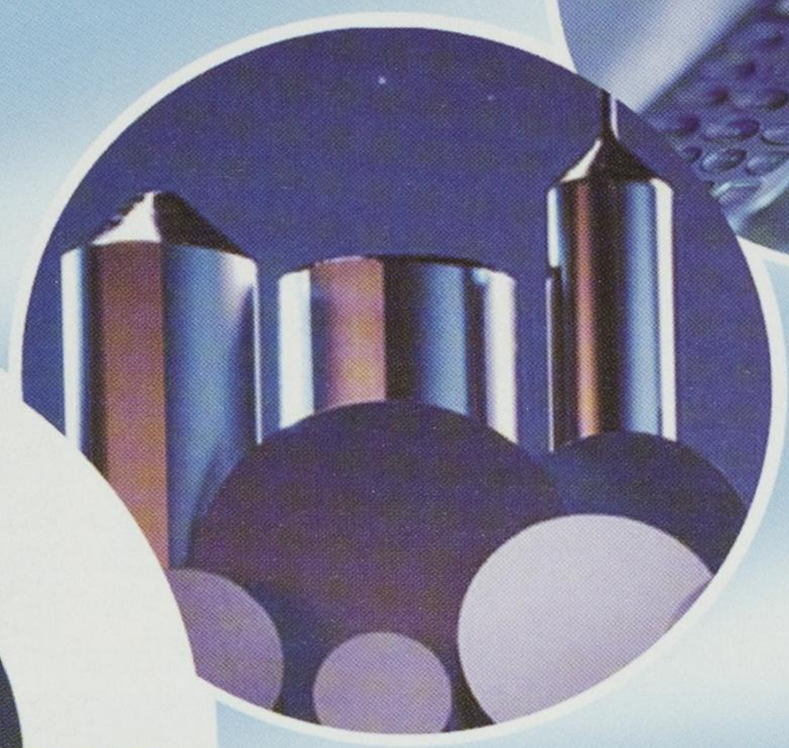
Meanwhile, GaP shipments rose by almost 63% sequentially to ¥8085 million. Sales of GaP wafers, which are used almost exclusively in the production of low-to-mid-brightness LEDs, peaked at ¥9812 million in the April–September 2000 period, and fell by 40% in the subsequent six month period. In the most recent period, 64% of GaP sales were for export, with Taiwan being the major recipient.

However, InP sales declined by 6% to ¥1149 million in the April–September 2002 period. At only one-quarter of the peak value of shipments at the end of fiscal 2000, the InP wafer sales figure reflects the continuing stagnation in the fiber-optic components market.









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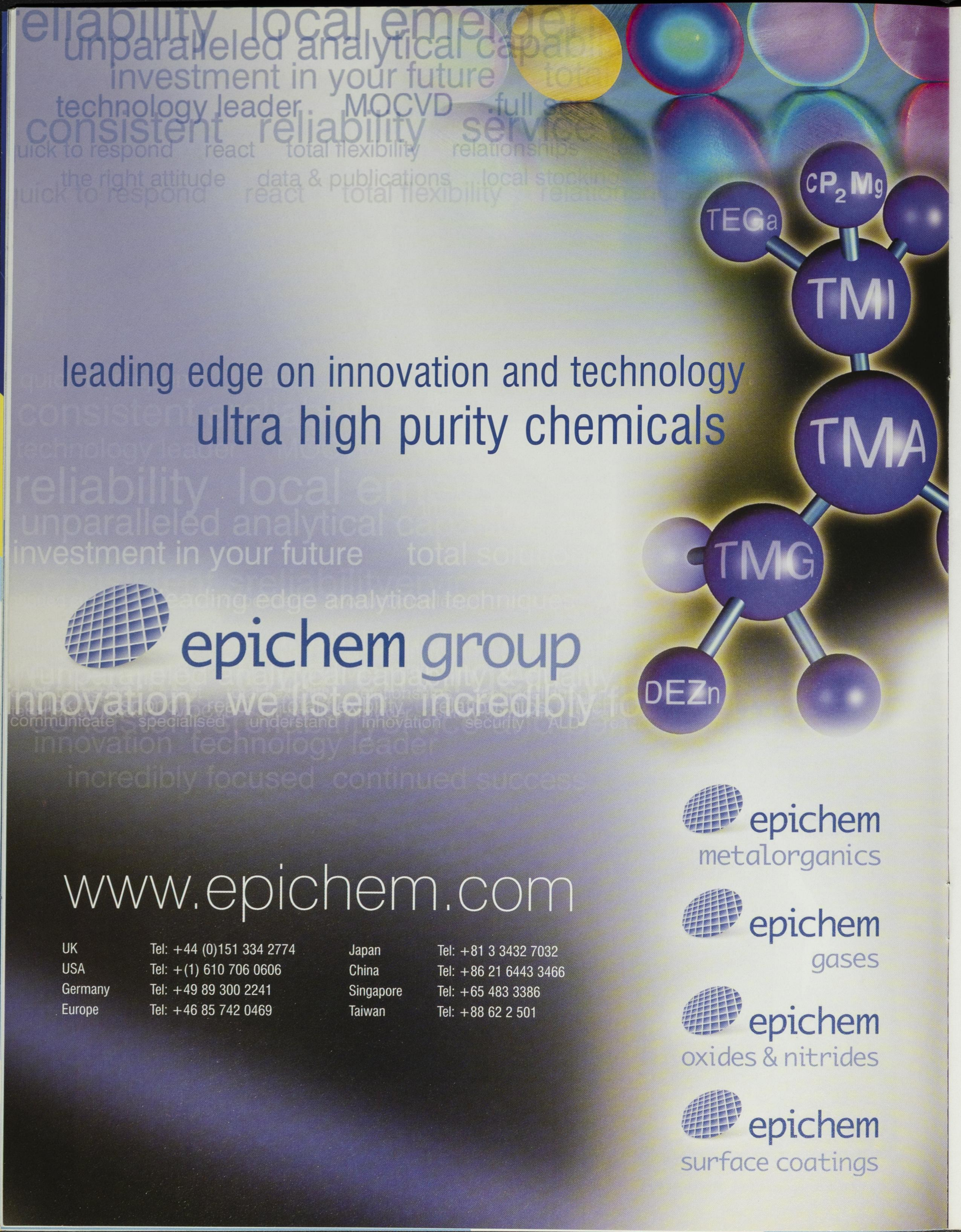
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SemiSouth wins contracts

SemiSouth Laboratories, a developer of SiC-based electronic devices, has announced two more new small business innovation research Phase I contract wins from the US Department of Defense (DoD).

In the first contract, monitored by the Office of Naval Research, SemiSouth is developing high-current, high-voltage SiC diodes for power rectification to meet new needs in on-board ship energy conversion.

"SiC opens up new possibilities in megawatt power-switching applications for both DoD and commercial applications," said William Draper, SiC product development engineer. "What has limited development to date is the ability to scale devices up to large current operation (over 10 A) with acceptable cost and yield. SemiSouth has innovative technology, which we are examining as a promising solution to this roadblock."

In the second contract, monitored by Air Force Research Laboratory, SemiSouth is looking at insertion of SiC RF transistors into near-term L-band missile defense radar applications.

"We are excited about the possibilities of this contract to explore proprietary SemiSouth technology as a way to accelerate the technology readiness of SiC for several key near-term radar system programs," said J B Casady, president and CTO of SemiSouth.

The awards represent the seventh and eighth DoD contracts in the first 18 months of operation for SemiSouth. "We are proud of the faith shown in our technology by DoD sponsors," said Casady.

Based in Starkville, MS, SemiSouth Laboratories is a privately held developer and manufacturer of silicon carbide electronic devices, and a merchant supplier of SiC-based epitaxial material. The company's devices manage and control or regulate power, protect against transient voltage spikes and transmit/amplify signals for applications in radar, power conversion and space.

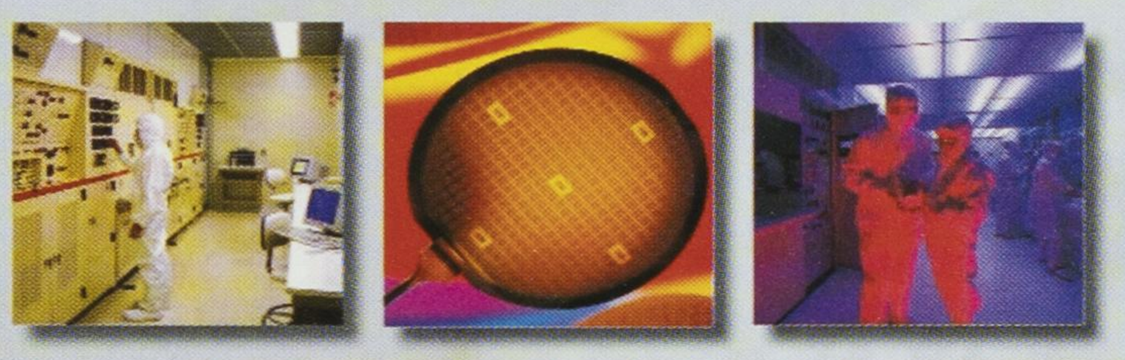
SiC-based 1200 V Schottky rectifiers unveiled by Cree

Cree has broadened its SiC Schottky rectifier product family to include 1200 V devices, which are now being sampled alongside 600 V devices that are in production. The 1200 V products consist of a 5 A Schottky diode in a TO-220 package and a 10 A device in a TO-247 package.

The SiC Schottky rectifiers are targeted for applications such as the antiparallel diode for high-frequency inverters, snubber diodes for high-current IGBT inverters, the boost diode for 480 V input power factor correction, and high-voltage multipliers.

Initial testing in a motor drive showed a reduction of losses which should save energy and increase the performance of electrical variable-speed motors typically used in light industrial automation or heating, ventilation and air-conditioning (HVAC) units.

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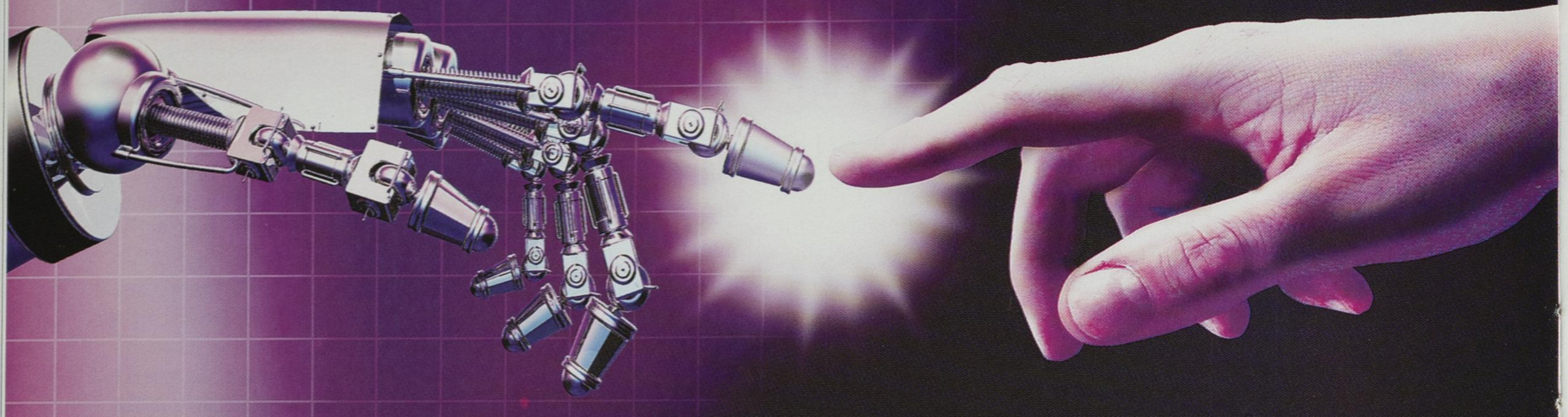
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Aixtron acquires TriJet patents from JIP Elec

Aixtron has acquired a patent and license portfolio for its TriJet technology from the French company JIP Elec, in which Aixtron has a 7.4% stake. TriJet provides reproducible delivery and evaporation of liquid precursors during atomic vapor deposition of oxide-based materials, and is a key part of Aixtron's Tricent tool. In this latest transaction, Aixtron has divested its shareholding back to JIP Elec, acquired the patent and license portfolio related to TriJet, and has granted patent licenses for niche applications back to JIP Elec.

The agreement with JIP Elec is part of Aixtron's strategy to be a key player in the technology for depositing the thin, high-k dielectrics required by the CMOS industry to shrink device dimensions further.

MicroChem forms joint venture

Photoresist manufacturer MicroChem (based in Newton, MA) has formed a joint venture company with Tokyo-based chemical and resist manufacturers Nippon Kayaku and Tomen Corporation. The new company, which is called Kayaku MicroChem Corporation (KMCC), is headquartered in Tokyo and imports and distributes resists for MEMS and electronic materials manufacturing in Asia. KMCC also provides sales, marketing and technical services for newly developed photoepoxy resists that have resulted from a joint development effort between Nippon Kayaku and MicroChem.

Equipment sales

● **Emcore** has sold two E300 GaNzilla MOCVD tools to **Shanghai LanBao Photoelectric Materials**, a Chinese manufacturer of GaN-based blue and green LED epiwafers.

● **Thomas Swan Scientific Equipment** is installing a 3 × 2 inch close-coupled shower head (CCS) MOCVD system for GaN epitaxy at **Harvard University**'s Nanoscience and Nanotechnology Research Center. The system will be used for the growth of a broad range of nitride-based nanoscale photonic and electronic structures including nanowires. The company has also announced the sale of a CCS MOCVD system designed for the growth of GaAs- and GaN-based materials to **Helsinki University of Technology**.

● **EMF** (Cambridge, UK) has announced the sale of a custom-made 2 inch multi-wafer MOCVD system to **Vancouver University** (BC, Canada). The system is configured for GaN research and development.

● **DCA Instruments** has received an order from **Uppsala University** in Sweden for a unique UHV deposition system. The MTD 450D features an MBE module combined with a UHV sputtering module, and will be used for the growth and preparation of devices made of magnetic layers of rare earth metals.

● **United Epitaxy Company** (Hsinchu and Tainan, Taiwan) has ordered an additional AIX 2600G3 24 × 2 inch HT MOCVD reactor to further increase its production of III-nitride yellow, blue and green LEDs.

● **Veeco Instruments** has received orders from **RF Micro Devices** (RFMD) and **Massachusetts Institute of Technology** (MIT) for MBE systems. RFMD has ordered its second GEN2000 7 × 6 inch MBE system for the production of HBT epiwafers, and MIT has purchased a Dual GEN200 R&D MBE system. This first-of-a-kind system will be used by MIT for research into integrated optoelectronics and future applied microphotonics. The dual MBE system features two growth modules, each capable of 1 × 6 inch, 1 × 8 inch, or multiple 2, 3 or 4 inch wafer production.

Aeronex able to beat the downturn

Gas purifier manufacturer Aeronex experienced a 34% increase in sales and a 6% increase in profits in 2002. The company puts its success in a very challenging climate down to a significant number of design wins during the year. In addition, Aeronex has added 20% to its research and development laboratory space at its headquarters in San Diego, CA. The new lab has state-of-the-art gas delivery systems to all instruments and test stations, and is designed with future expansion in mind.

Evans Northeast opens for business

Evans Analytical, a provider of materials characterization services, has opened a new laboratory in Peabody, MA. Evans Northeast Analytical Laboratory (ENE) is the seventh facility in the Evans Group's global network of laboratories, and the second on the east coast of the US. The lab is equipped with a Phi quadrupole SIMS, a Cameca magnetic sector SIMS and a Technos 300 mm-wafer-capable TXRF system.

Instrument Systems expands into France

Instrument Systems, a German manufacturer of optical instrumentation for light measurement, has established a new subsidiary near Paris, France. The company says that its decision to establish a greater presence in France is in response to the rapid growth in demand for its LED and display analysis equipment in the region.

AWR's European HQ moves to new offices

Applied Wave Research (AWR), a provider of high-frequency electronic design automation tools, has relocated its European headquarters in Hitchin, UK. The new larger offices, also in Hitchin, will continue to provide sales and technical support throughout Europe. The company is hoping to double its sales in Europe over the next few years, necessitating a move to larger offices with customer demonstration and training facilities.

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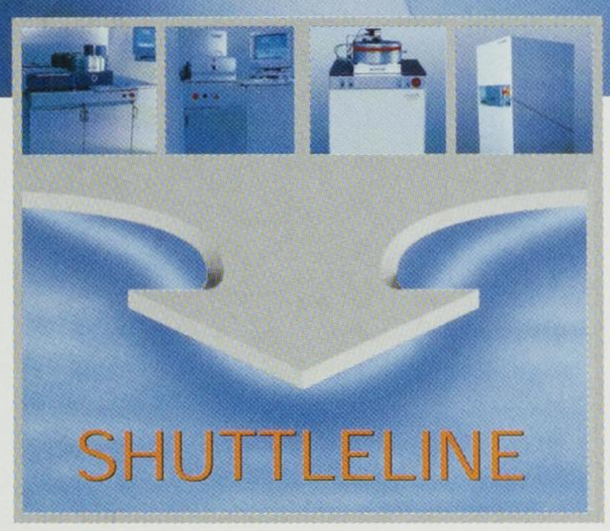
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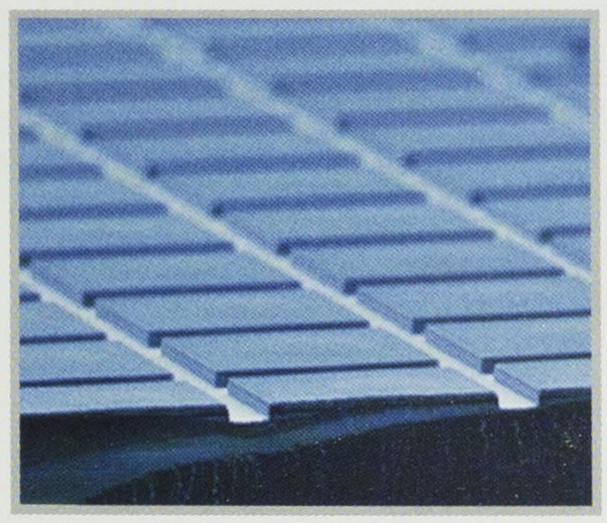
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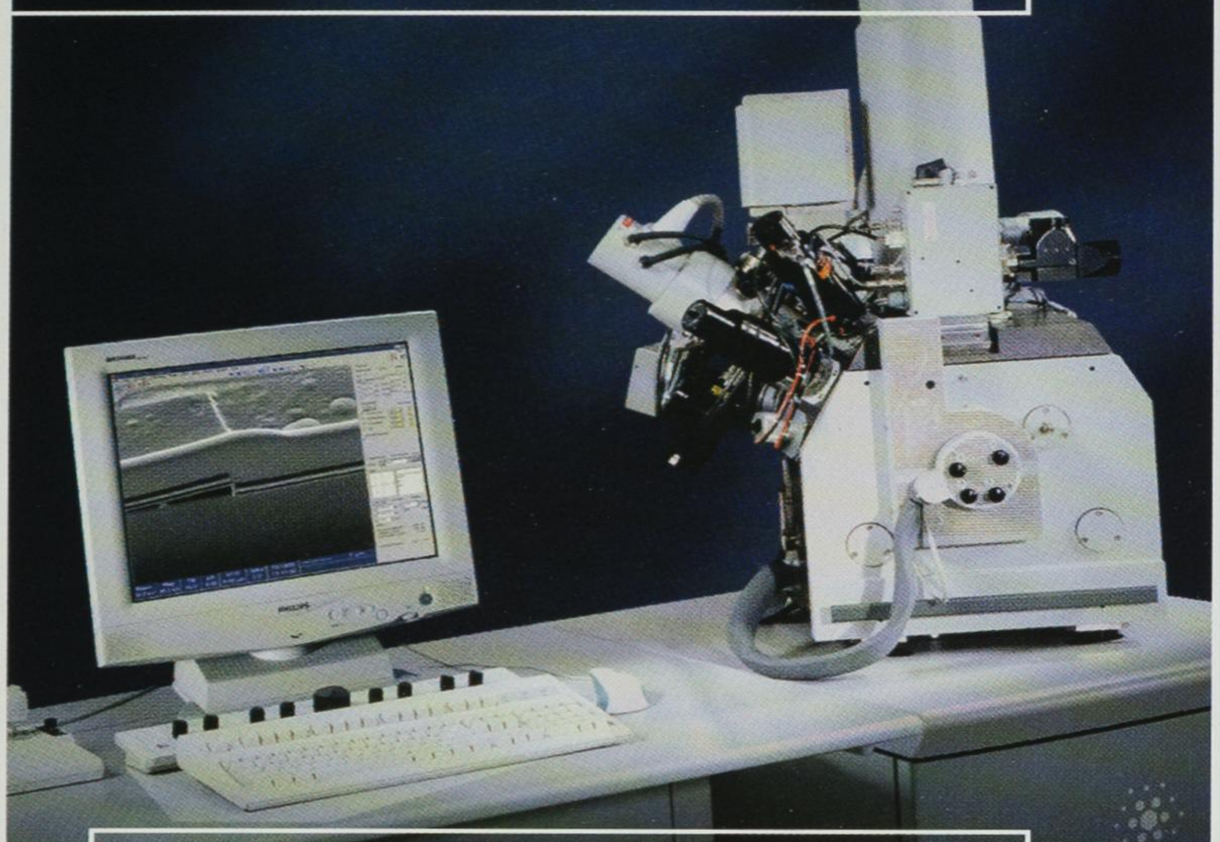
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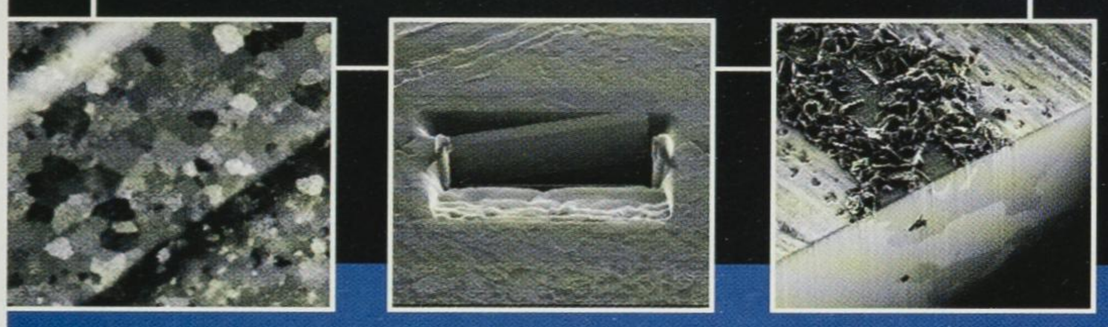
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Deep UV emission from structures grown on AlN

Although good progress is being made towards producing large-area (50 mm diameter and above) AlN substrates, these are still some way from being commercially available. However, in preparation for this eventuality, researchers are already investigating the growth of GaN-based structures on the small bulk AlN samples that can currently be made. A collaborative effort between Sensor Electronic Technology, the University of South Carolina, Rensselaer Polytechnic and Crystal IS has resulted in the growth of high-quality MQW structures containing AlGaN wells with Al contents of up to 50% between AlN barriers (*Appl. Phys. Lett.* 2002 **81(24)** 4658). The ability to grow high-quality AlN barriers on the AlN substrates means that thin, highly stressed AlGaN wells of high structural quality can be grown.

The team used low-pressure MOCVD to grow an AlN buffer layer on the bulk AlN substrate, followed by a structure containing three 5 nm thick $Al_{0.5}Ga_{0.5}N$ QWs between 20 nm thick AlN barriers. For comparison, the same structure was grown on SiC. The photoluminescence (PL) characteristics of the samples were measured, including the evolution with temperature and the PL peak intensity as a function of pump intensity. PL spectra of the samples on SiC and AlN were measured at room temperature with an excitation wavelength of 193 nm. The PL intensity peaked at 259 nm for both, but the intensity from the sample on AlN was 28 times that from the sample on SiC. This is consistent with the data on the crystal quality of the two samples obtained by X-ray diffraction. These results, coupled with the steady advances in growing larger-diameter AlN substrates, demonstrate the strength of this approach for the future production of deep UV LEDs and lasers.

X-band AlGaN/GaN HEMTs set power record

A joint effort by researchers at General Electric Global Research Center in Niskayuna, NY, and Lockheed Martin in Syracuse, NY, has resulted in 9.2 W/mm (13.8 W total) output power at 10 GHz from 1.5 mm AlGaN/GaN HEMTs (*Elec. Lett.* 2003 **39(2)** 245). The devices were characterized under pulsed conditions with a 50 μsec pulse width and 5% duty cycle. The associated PAE at peak RF power was 33% and drain biases were up to 55 V, the highest ever for similar-size devices.

The device structure was grown by MOCVD on 2 inch 4H-SiC semi-insulating substrates. The T-gate length was 0.25 μm as determined by cross-sectional SEM. The 1.5 mm devices were formed with six gates at 250 μm per gate with 49 μm gate pitch. The dies were mounted into conventional Mo/Cu-based packages, and the large signal characteristics were measured at room temperature without the benefit of package cooling.

A power density of 10.7 W/mm has been reported for 150 μm AlGaN/GaN HEMTs at 10 GHz. However, realizing comparable power densities from larger gate periphery devices has been difficult due to pronounced self-heating effects and an increase of trapping at defects. The team has largely circumvented these issues by device design. Three-dimensional thermal analysis has indicated that self-heating effects may be further reduced, enabling realization of power densities of more than 10 W/mm for moderate-size devices.

FIB process takes materials analysis into new realms

The novel integration of ion and electron beams into one tool with precision sample handling abilities is providing a one-stop shop for many characterization needs, writes **Lloyd Peto**.

The examination and analysis of multi-layered films and complex structures is often challenging. Site-specific analysis, as required for single-site semiconductor device failures, is especially demanding. Problems are exacerbated when working with materials that are sensitive to the preparation techniques being used and/or environmental factors during preparation. Laser devices, for example, are almost impossible to remove from can-type packages without damage, so the detailed analysis of laser facets or failure sites on returns is normally only attempted when essential. Recent advances in equipment and analysis techniques are now removing many of the existing limitations that are imposed by complex structures and sensitive materials.

Focused ion beam (FIB) instruments are widely used in the semiconductor and data-storage industries for many applications, including 3D materials analysis, photolithographic mask repair, circuit edit and general nanoengineering. The ability to focus a beam of ions onto an area of a sample with precision and accuracy means that specific sites can be machined by the beam to modify the structure by sputtering away material. Buried structures such as HBTs can also be cross-sectioned and imaged using the ion beam. Imaging the area of interest is accomplished by scanning the ion beam across the sample and detecting the electrons emitted as a result of the interaction between the ion beam and the surface. Scanning ion microscopy has evolved to a point where it rivals high-resolution SEM as a microscopy technique in its own right.

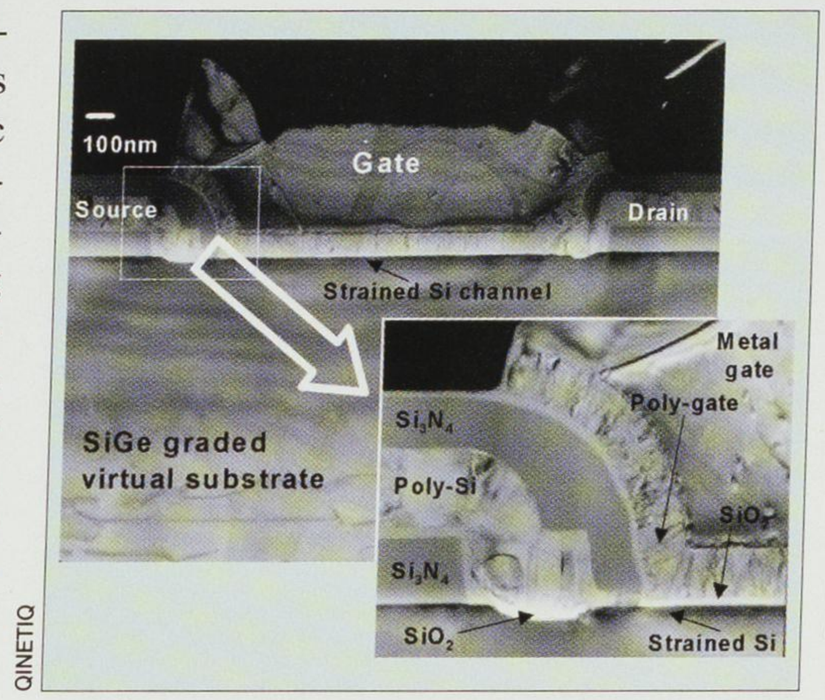


Fig. 1. TEM image of a foil machined by FIB from a strained silicon MOSFET device. The dark layer at the top is tungsten deposited as part of the FIB sample preparation.

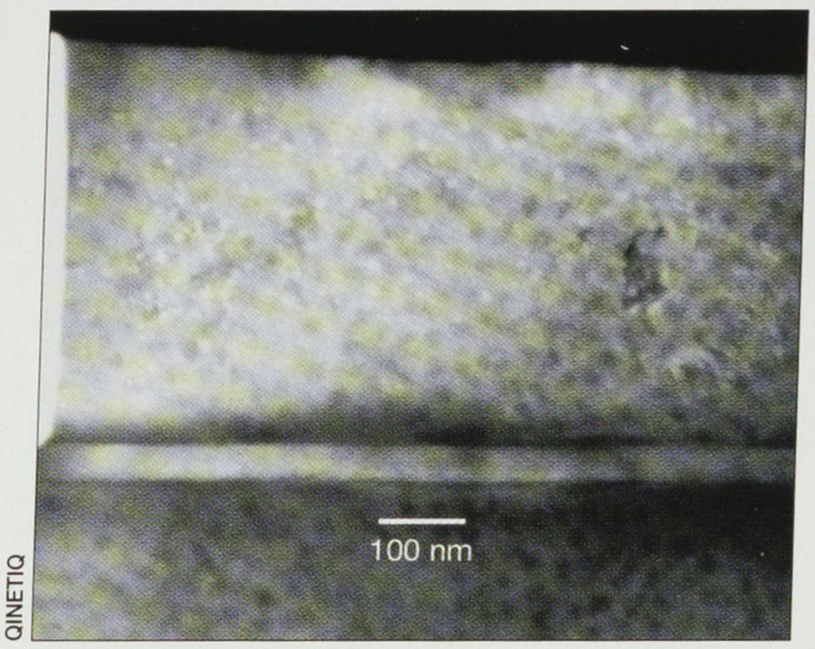


Fig. 2. High-magnification TEM image from part of a FIB foil taken using a single-beam instrument from an InGaP HBT. The speckled appearance is due to materials redeposited during the final ion-beam polish of the foil.

Recent developments have resulted in a unique integrated dual-beam system that combines a field emission electron beam with an ion beam.

FIB sample preparation

Preparing thin samples by FIB machining for subsequent TEM analysis is a widely accepted technique in the silicon-based IC industry (see figure 1). The benefits of using FIB technology in this way are very clear; the process is very fast and labor saving when compared with sample preparation by mechanical grinding and polishing. It is very site specific (placement accuracies down to ±500 Å), independent of different material hardnesses within a single foil and is the only fully instrumental technique that does not require any mechanical preparation of the bulk sample. These physical benefits are now routinely combined with multi-site automatic operation of the FIB instrument.

Recent developments at FEI Company, a manufacturer of FIB instruments and a provider of FIB analysis services, have resulted in a unique dual-beam system that combines a field emission (FE) electron beam with an ion beam. This gives the ability to prepare a thin section of material and perform electron-beam analysis of that section within a single tool called a DualBeam instrument. The developments described within this article are specific to FEI's Strata DB235 DualBeam tool, and the TEM images were taken by the materials characterization group at QinetiQ in the UK.

The DualBeam advantage

The advantage of the electron and ion beam integration system developed at FEI's laboratories is that all of the benefits offered by FIB and high-resolution FESEM instruments can be used without compromising either technique. The beams can also be used simultaneously in a single-point operation. This mix-and-match capability allows the user the freedom to select the excitation method, imaging technique used and the analysis preferred depending on what is available from the specimen. This affords a level of instantaneous investigation that was not previously possible. However, the effectiveness and precision of a dual-beam instrument is highly

dependent on the way the instrument is designed and operated. The design of an instrument with co-located ion and electron beams, each with its own requirement for electrostatic beam steering and focusing optics, is a non-trivial exercise. High-resolution imaging places stringent requirements on vibration isolation, and the ability to move thinned samples inside the instrument requires precision in mechanical placement and alignment, combined with high levels of repeatability.

FIB systems are used for an increasingly wide variety of materials including ceramics, polymers, superconductors, piezo-electrics and many different types of compound semiconductors. Some aspects of the FIB-SEM process offer unique advantages for compound semiconductors. The most commonly used foil size ($20 \times 10 \times 0.1$ μm) makes this process ideal for looking at structures fabricated on the surface of any type of semiconductor substrate and for analyzing thin films or surface treatments. Compound semiconductors are generally more sensitive than silicon to crystalline damage at the surface when prepared using FIB techniques. During the final ion-beam polishing stages of making a TEM foil with a single-beam FIB instrument, it has become common practice to avoid imaging the face of the foil with the ion beam to minimize any unnecessary crystalline disturbance. The effect of this practice means that the foil surface cannot be quality checked by imaging after the final polish.

Although high-quality foils are possible with both single- and dual-beam instruments, only the dual-beam systems can give direct feedback through the use of their electron-beam imaging capability during this final sensitive part of the foil production process. This extra degree of control permits thinner, higher quality foils to be made routinely, with a higher degree of confidence in the final results. Optimization of the final polishing methodologies in both FIB and dual-beam instruments means that high-quality foils with a thickness of 50–100 nm can be produced routinely, with no observable crystalline modification in the final specimen. The facility to take electron images in immersion (ultra-high resolution) mode while milling is possible because the electron and ion columns have been designed so that the beams are coincident at the sample stage's eucentric tilt axis, which is only 5 mm from the electron-beam lens.

Figure 2 shows a TEM image of part of a TEM foil sectioned from a GaAs/InGaP HBT structure in a single-beam instrument. The

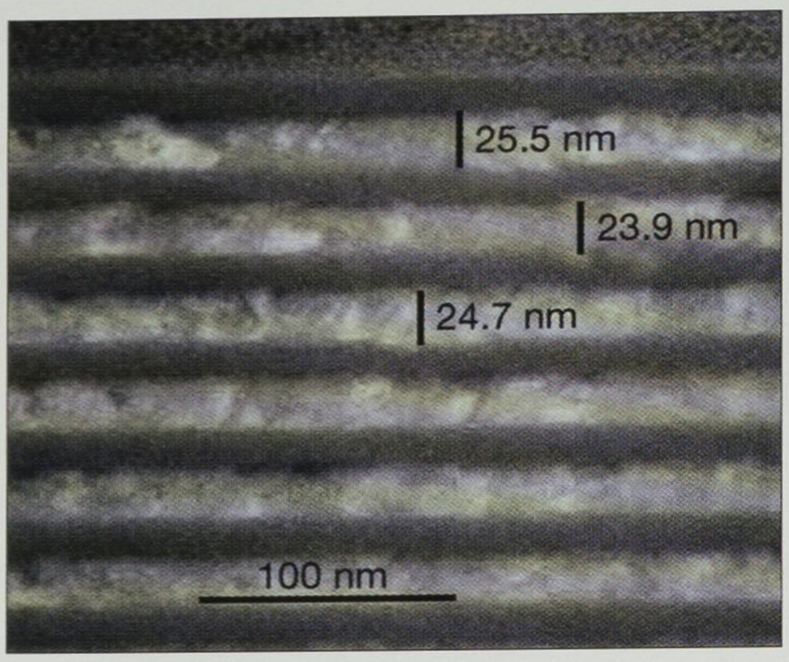


Fig. 3. A DualBeam STEM image of a GaAs/AlGaAs QW laser structure. The foil was prepared using a dual-beam system and the final surface is clear of redeposited material.



Fig. 4. The sample in this image was mechanically pre-thinned before being placed into a FIB system where the thin foil in the center was machined.

speckled appearance is the result of milled material that has been redistributed during the final polishing step. This might have been avoided or removed if the system operator had been aware of it. Figure 3 is a GaAs/AlGaAs QW laser structure prepared in a dual-beam instrument, which permits the final foil quality to be guaranteed and even examined (here by STEM) before transfer for TEM analysis.

Advances in detectors

Electron detectors are an area where technological advances are now yielding significant improvements in analysis capabilities. STEM imaging using conventional FESEM

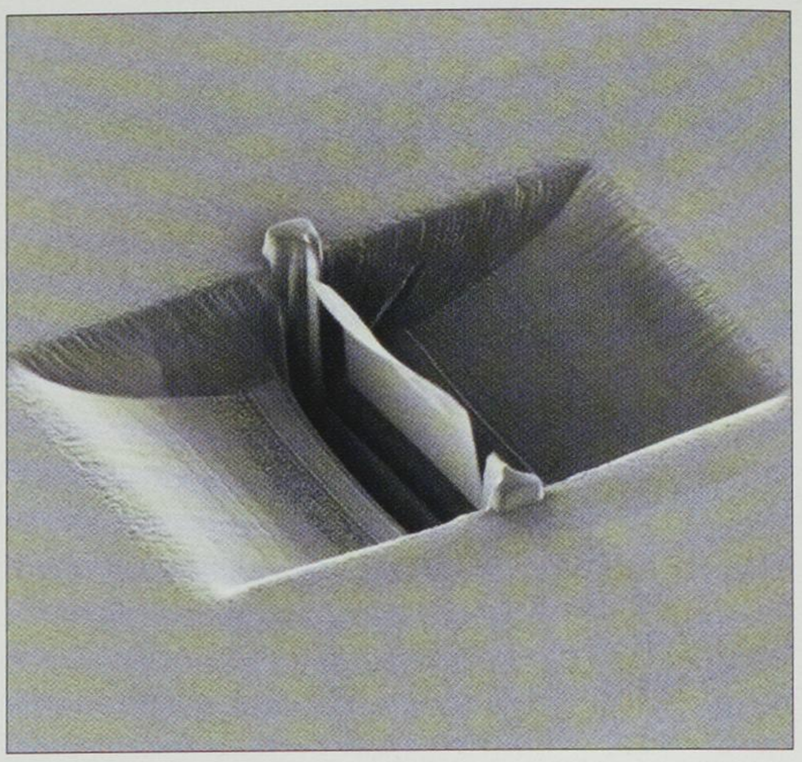


Fig. 5. Image showing a FIB-prepared TEM foil before *ex situ* extraction.

accelerating voltages can be added to new FESEM or DualBeam instruments. Thin samples can therefore be examined in transmission mode inside a DualBeam instrument. This has had several effects on the analysis procedures currently in routine use. Firstly, TEM can now be reserved for only the most challenging of investigations. Secondly, all samples for TEM can be pre-imaged in transmission mode to ensure that they are of the correct quality and thickness before any TEM time is used. Finally, many routine investigations can be solved without using valuable TEM instrument time, as the improved resolution (0.6–1.0 nm) offered by *in situ* STEM detection will be sufficient to provide the answers in many cases.

STEM detection does not permit diffraction information to be obtained, but it does permit good metrology information to be gathered because of the high levels of materials contrast seen with this technique. Low-contrast imaging can be a problem with transmission mode studies of thin specimens. This pre-examination and filtering of samples means that a significantly higher level of efficiency can be introduced to the analysis. Many more samples can be produced and successfully analyzed, and more information can be obtained in a shorter amount of time without a significant increase in costs or by having to change the existing laboratory equipment.

Advances in sample management

Several strategies are employed for extracting thin-foil TEM samples prepared by FIB. Conventional (old style) FIB-TEM sample preparation involved removing the material from whatever packaging it was enclosed in

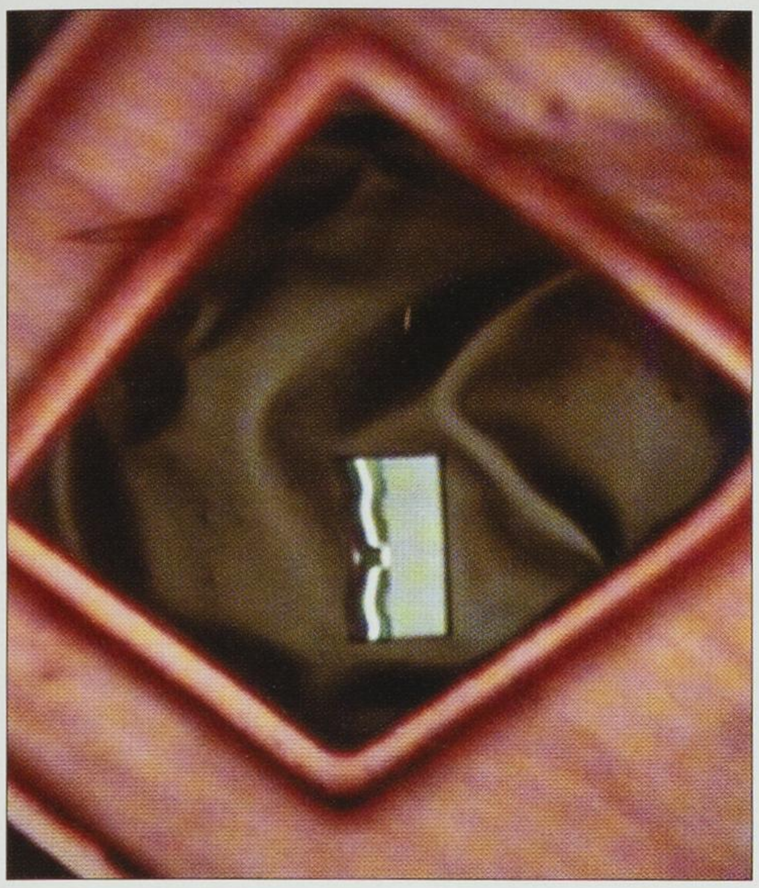


Fig. 6. Image showing a FIB-prepared foil in a copper TEM sample grid.

and then cleaving up the sample and grinding it down to less than 50 μm thick. This pre-thinned slice is then attached to a modified TEM sample grid and mounted in the FIB instrument prior to ion-beam thinning (see figure 4). After FIB processing, the grid was then removed from the FIB vacuum and transferred to the TEM for analysis. This procedure took 2.5–3 hours and required considerable operator skill.

Ex situ extraction is currently the most widely used technique. Any sample can be mounted and loaded into the FIB instrument with no mechanical preparation. Samples do not even need to be removed from packaging, as long as access to the top surface of the sample can be achieved with the ion beam. A thin foil can then be cut out by the ion beam, leaving it free standing in a FIB-milled trench on the surface of the sample (see figure 5). This sample is then removed from the instrument and with the use of an optical workstation, an electrostatic needle is used to extract the thinned foil and transfer it to a support film (normally holey carbon) on a copper TEM grid (see figure 6). This extraction technique requires a little experience before success rates of equal to or greater than 95% can be achieved routinely. However, it is highly effective and can be used on an enormously wide variety of materials, even ones with poor structural rigidity such as compressed powders and samples with voids or cracks. Unfortunately, exposing the sample to the atmosphere during transfer to the TEM can be problematic for materials such as those with a high aluminum content, which can suffer from immediate degradation when exposed to atmosphere.

In situ extraction has been made possible by the addition of a micromanipulator to transfer the sample to a TEM grid and a further manipulator, known as a FlipStage, which flips over the sample onto the STEM detector. As a result, all of the steps from sample preparation through to STEM analysis can take place without ever removing the material from the vacuum in a DualBeam tool. This technique requires a lower level of operator training to complete, and has a success rate as high as *ex situ* extraction for an experienced operator. The procedure relies on the specimen being able to support itself (so powdered or brittle samples are less suitable), but it does permit re-thinning by the ion beam for specimens that require it.

Elemental mapping

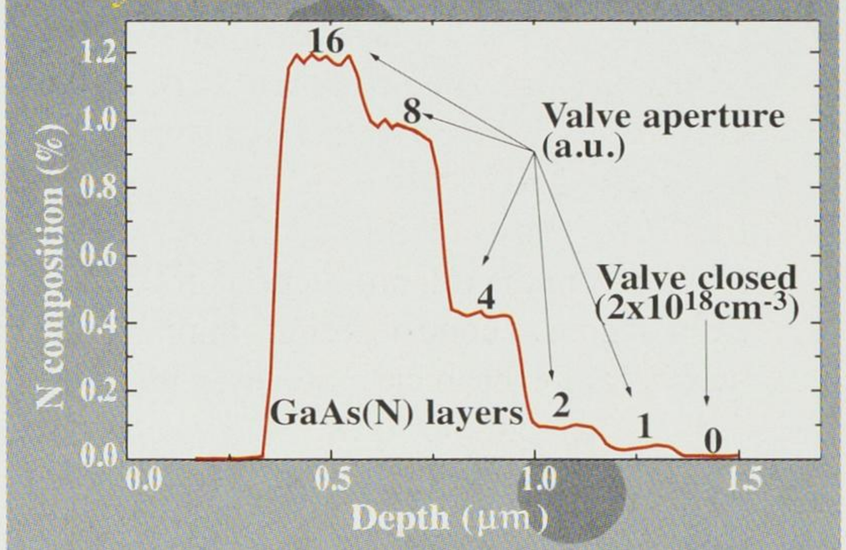
By allowing thinned samples to be examined *in situ* using the SEM function in a DualBeam instrument, it becomes possible to use other techniques that are available to SEM users. The energy dispersive X-ray (EDX) unit, which is mounted on most SEMs for elemental mapping, is an excellent example. The volumetric effect that reduces the mapping resolution to about 1 μm for thick samples is removed when analyzing thin foils. EDX mapping of foils using this *in situ* method can achieve spatial resolutions of 35–50 nm. When these elemental results are then combined with the 0.6–1 nm high-contrast STEM imaging, we have some complementary analysis capabilities that are fast and very useful, and on a sample that can be made from bulk material without any mechanical preparation at all.

Tools such as the Strata DB235 bring together a total sample preparation and high-resolution imaging and analysis capability on a single-chamber system. Such an instrument complements existing sample-preparation techniques and also reconfirms TEM as a high-end analysis instrument. It enables the rapid production of many more thin samples and takes on a high proportion of the routine analysis work, providing efficiency improvements at all stages of the analysis process.

Lloyd Peto is the business development manager for FIB and DualBeam products at FEI Company, The Aztec Centre, Aztec West, Bristol BS32 4TD, UK. E-mail Lloyd.peto@uk.feico.com.

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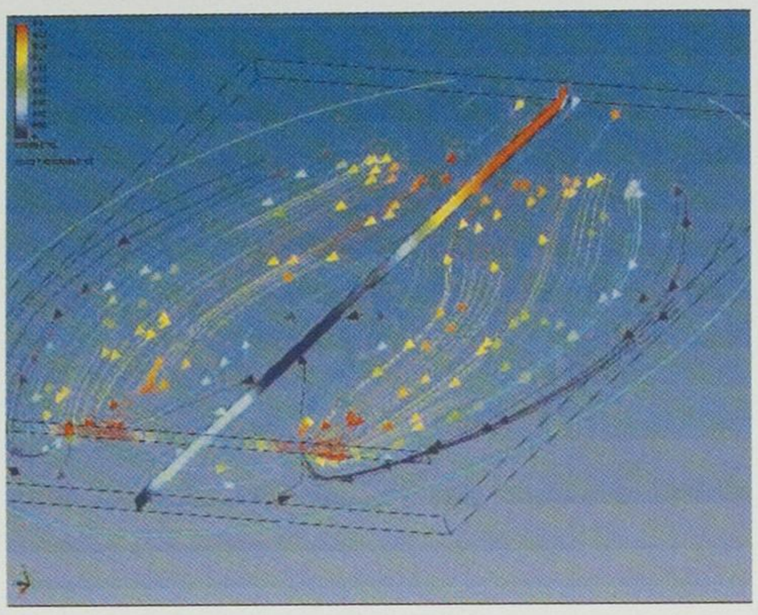
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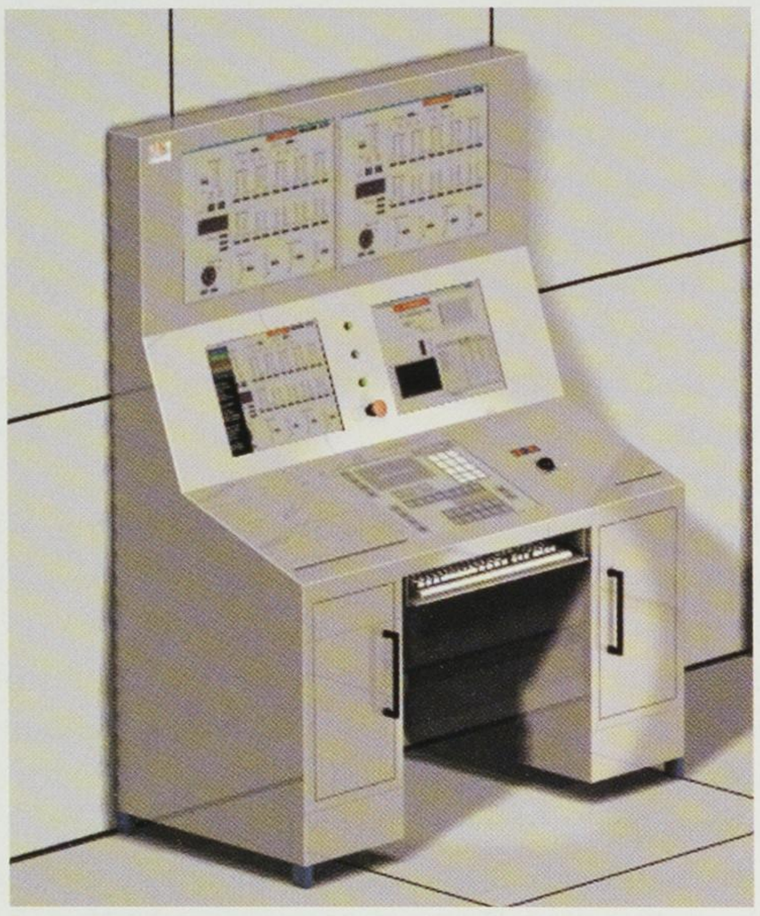
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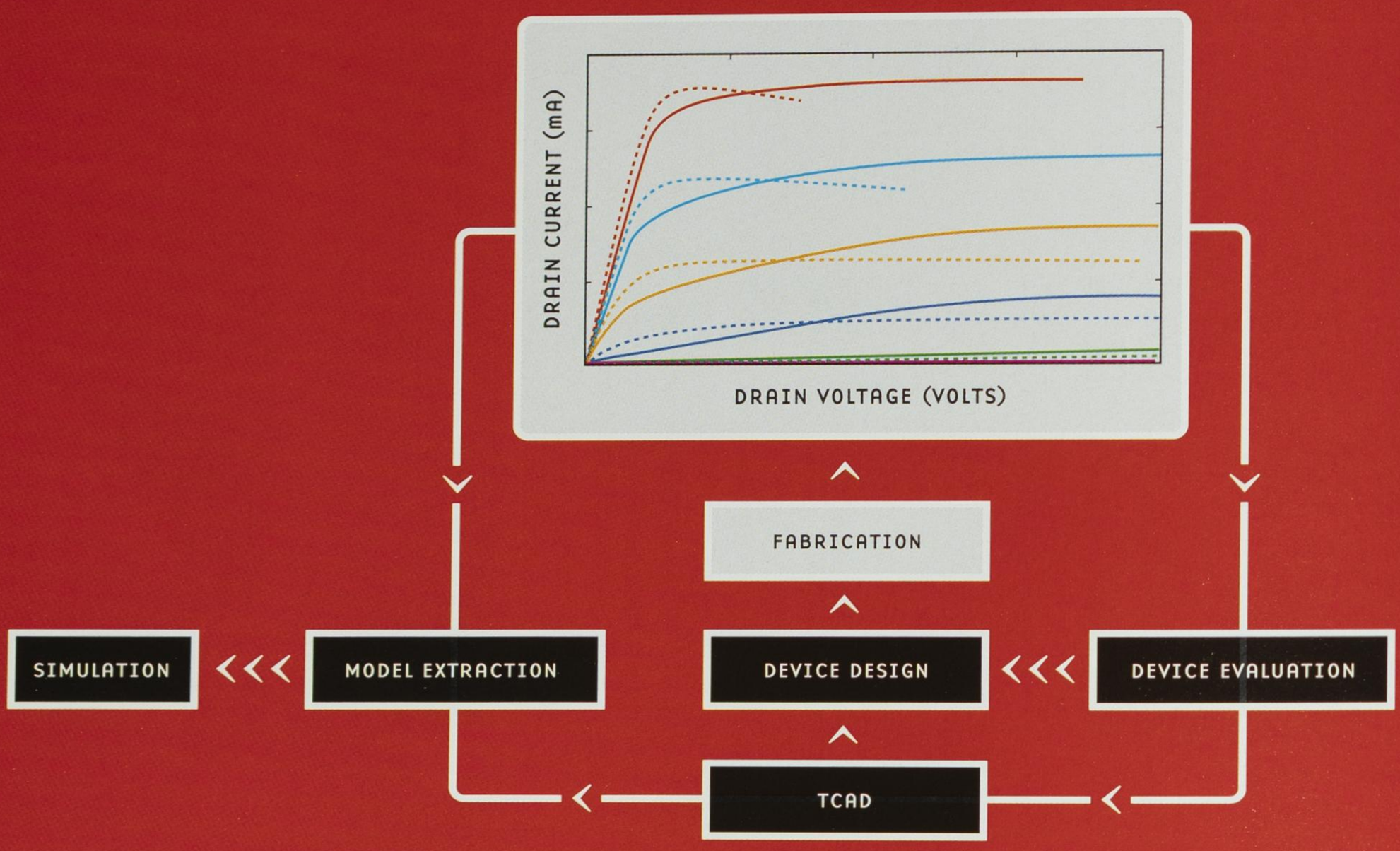
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CHARACTERIZATION

Using photoluminescence for characterizing wide-bandgap materials and devices

Using a pulsed short-wavelength laser improves the accuracy and usefulness of photoluminescence for characterizing wide-bandgap semiconductors, according to **Colm Mac Mahon** and colleagues.

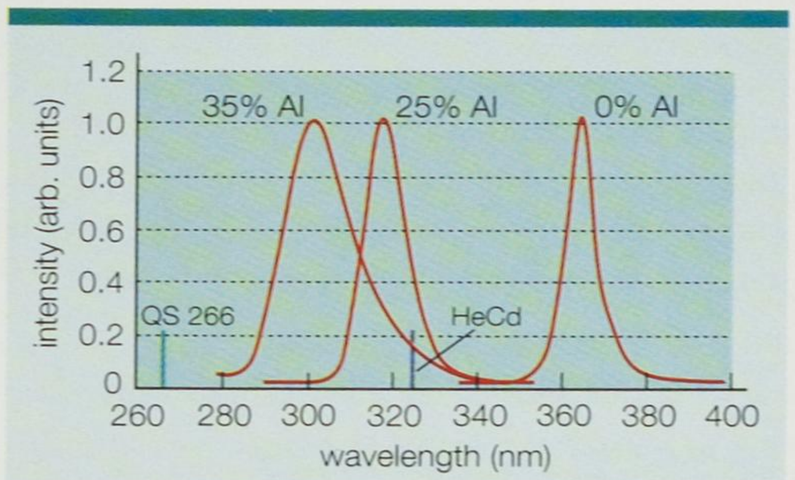


Fig. 1. Linescans taken with an Accent rapid PL mapper of $Al_xGa_{1-x}N$ for x = 0, 0.25 and 0.35 using QS 266 nm laser. Emission wavelengths for the QS 266 nm and 325 nm HeCd lasers are marked.

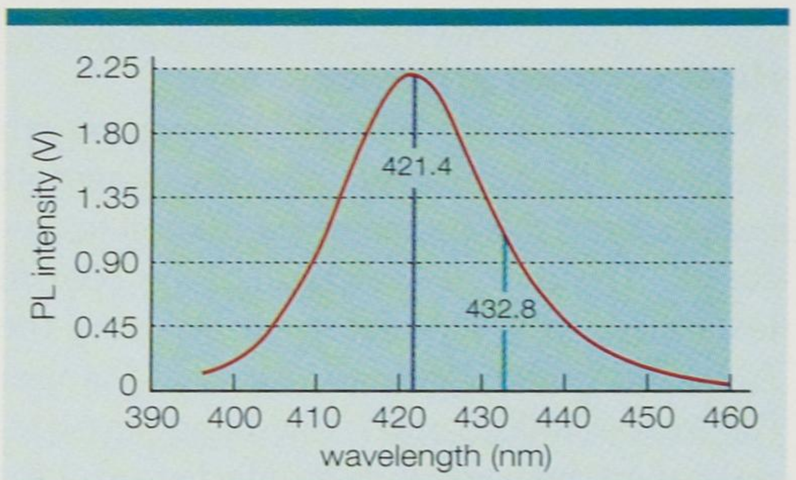


Fig. 2. A line spectrum showing the dominant wavelength (432.8 nm) seen by the eye as calculated from a CIE diagram for a PL spectrum with a peak wavelength of 421.4 nm.

Pump laser parameters for wide-bandgap PL

Laser parameters	*CW HeCd 325 nm or Nd:YAG 266/355 nm*	*QS 266 nm*
power/energy	50 mW	1 μJ
pulse width	CW	500 ps
repetition rate	CW	10 kHz
average power	50 mW	10 mW
peak power	50 mW	2 kW

Table 1. Comparison of the typical parameters of CW and QS lasers for use in the PL characterization of wide-bandgap semiconductors.

A great deal of research is currently focused on wide-bandgap materials, specifically on the III-nitrides and SiC for applications such as LEDs, laser diodes and photodiodes. The combination of high electric breakdown field and high saturation velocity also makes these materials suitable for high-temperature and high-power RF transistors. The importance of these materials is highlighted by the involvement of DARPA, which has recently launched a program called the Wide Bandgap Semiconductor Technology Initiative (WBSTI) to help accelerate improvements in material quality and device performance. Materials characterization plays a crucial role in such development efforts, and photoluminescence (PL) studies can reveal much about epitaxial structures before expensive device processing steps are carried out (*Compound Semiconductor* March 2001 p68).

PL studies of wide-bandgap materials are complicated by effects that are not seen, or that are uncommon, in other material systems. The PL from the quantum well (QW) structures required for LEDs and lasers is influenced by the quantum confined Stark effect (QCSE) and elemental clustering. These phenomena are discussed below, and their influences are explained using real data. The type of laser used in PL studies has a great influence on these effects, allowing improved correlation between PL and electroluminescence (EL), which is crucial for manufacturers of LEDs and lasers.

Materials and choice of laser

For PL to occur, the laser excitation needs to have a higher energy than the bandgap of the material under investigation. There are currently a number of lasers available that are suitable for the PL characterization of wide-bandgap semiconductors. The continuous-wave (CW) options include the Ar^+ ion (244 nm), Nd:YAG (266 nm), HeCd (325 nm) and Nd:YAG (355 nm). There is also a Q-switched (QS) Nd:YAG option, which emits a pulsed beam at 266 nm. A comparison of the typical parameters of the CW and QS lasers for use in PL characterization is shown in table 1.

CW lasers for use in wide-bandgap characterization tend to be large, and are mounted outside the PL system. Fiber-optic coupling is necessary to get the light to the sample being measured. Over time, fiber-optic coupling can lead to decreased laser power due to fiber degradation, which means frequent coupling changes. CW lasers also have long warm-up and cool-down periods, are expensive and have a short lifetime. The CW 325 nm HeCd commonly used in the characterization of wide-bandgap materials is not suitable for materials with higher bandgaps and for structures requiring high laser power densities. While high power densities can be achieved by focusing the spot to a smaller size (<10 μm), for lasers with an output power above 50 mW, heating effects influence the emission wavelength and in extreme cases may cause thermal damage.

An alternative to the CW 325 nm HeCd laser is the QS 266 nm laser, which at a relatively large spot size can still deliver a peak power density in the kW range as shown in

table 1. High excitation density is needed to generate PL when the layer of interest is between highly doped p- and n-type layers, as is the case in laser diode structures. It is also required for devices with a thick cap layer that absorbs the incident radiation, for example when looking at the base region of HBTs. Other advantages of the QS 266 nm laser are its shorter wavelength, longer lifetime, lower power consumption and cost. In addition, its smaller size means that it can be mounted internally in PL systems.

High-content Al devices

The bandgap energy of AlGaN increases with Al content, and consequently these materials require shorter wavelength excitation to create PL. The short wavelength of the 266 nm laser allows PL characterization using the Accent Rapid Photoluminescence Mapper (RPM 2000/4000) of all wide-bandgap materials of interest, and is particularly useful for high Al content $Al_xGa_{1-x}N$. The peak wavelength variation of $Al_xGa_{1-x}N$ with various Al concentrations, obtained using a 266 nm laser, is shown in figure 1. The HeCd laser is only capable of measuring low Al concentrations in GaN. In comparison, the maximum Al concentration measurable using the 266 nm laser is 35%, which is suitable for most present applications. Al contents of up to 25% are currently being used in GaN-based HEMTs.

Stokes shift

The emitted PL wavelength from a material is always longer than the absorbed wavelength, and the difference between these is known as the Stokes shift. The Stokes shift increases with increasing doping, and the energy difference between absorption and emission is due to charge relaxation to lower energy levels. In InGaN/GaN QW structures, it is also possible for In-rich regions to form due to phase separation at the interfaces, which leads to a band-tailing effect. Real devices electroluminesce because they are pumped hard with an electric current. High-power lasers are required to photoexcite carriers to the highest energy levels, which can lead to undesirable heating effects. By using a QS laser, these heating effects can be reduced, while maintaining a high power density. Consequently the wavelength shift is also reduced, giving a more accurate comparison between PL and EL measurements.

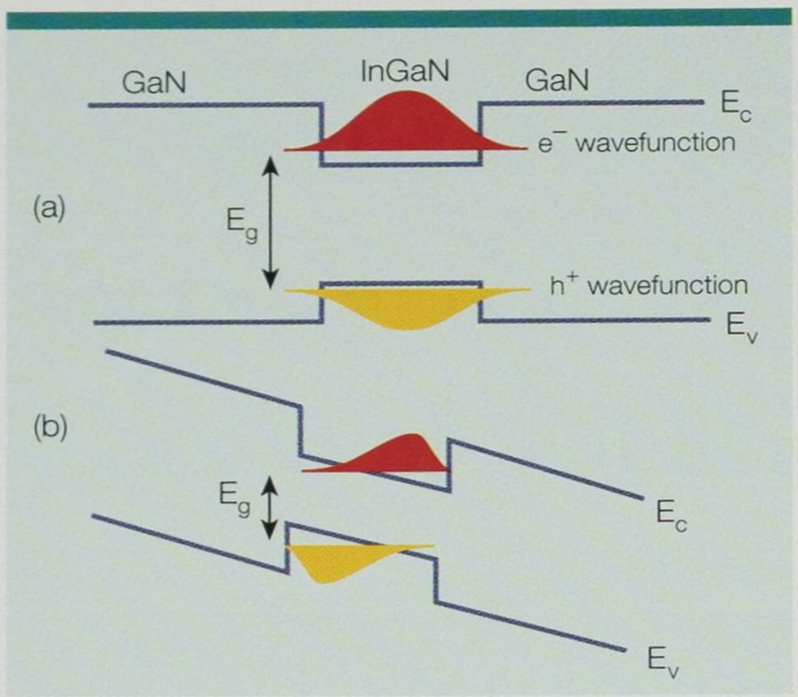


Fig. 3. Non-piezoelectric (a) and piezoelectric (b) InGaN QW. The band bending in (b) gives rise to the QCSE, which causes the emission wavelength to shift.

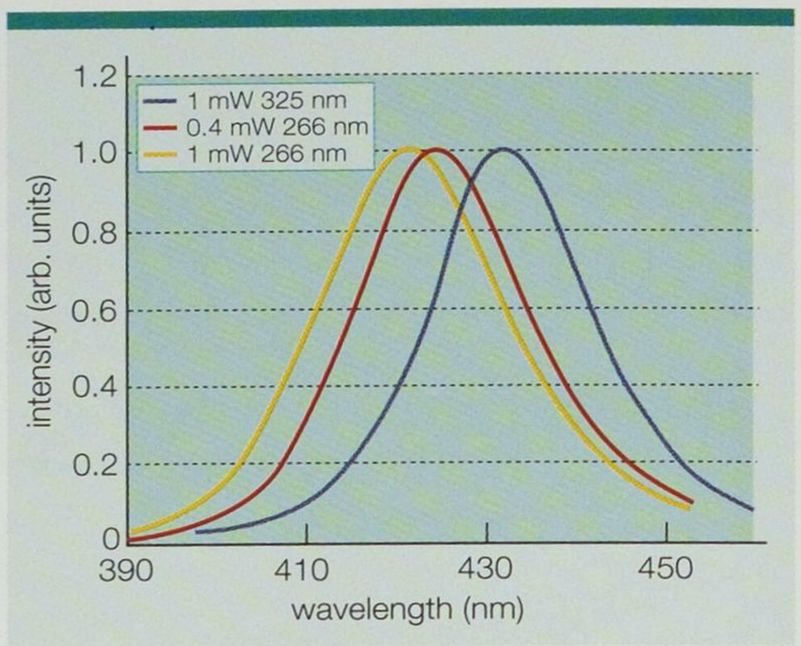


Fig. 4. PL comparison of an InGaN sample using QS 266 nm and CW 325 nm lasers. As the power density of the QS 266 nm laser is reduced, there is a shift to a longer wavelength emission.

There are a number of lasers currently available for use in wide-bandgap material characterization, and it is important to match the correct laser with the right application.

Dominant wavelength

A key issue for manufacturers of LEDs for displays, indicator lights and general lighting applications is the colour of the LED. The peak wavelength determined using a CCD detector is different to the dominant wavelength seen by the eye, due to their different spectral responses. The dominant wavelength from the measured PL spectrum can be calculated by using a chromaticity (CIE) diagram. When a straight line is drawn from a reference point (usually $x = 0.333$ and $y = 0.333$) and the measured colour CIE xy co-ordinate, the intersection with the boundary of the CIE diagram is defined as the dominant wavelength. The distance between these co-ordinates and the dominant wavelength on the diagram is a measure of saturation, which gives an idea of how pure the PL is. Accent's Accucolor software enables the colour of the LED to be determined by calculating the dominant wavelength and saturation on an LED wafer prior to device processing. In figure 2, there is a difference of 11 nm between the measured peak wavelength of the PL curve and the dominant wavelength (432.8 nm), calculated from a CIE diagram, which would be seen by the eye.

Quantum confined Stark effect

InGaN/GaN and AlGaN/GaN MQW structures can exhibit large piezoelectric polarization due to the lattice mismatch between InGaN/AlGaN and GaN. This polarization results in large internal electric fields. In figure 3, the band energy diagram and electron/hole wavefunctions are shown for an InGaN QW for the non-piezoelectric (a) and piezoelectric (b) situations. Wurtzite QW structures can also exhibit a spontaneous polarization, even without strain, due to the difference in polarization across the heterointerface, which also causes an internal electric field. The band bending which occurs as a result of the piezoelectric and spontaneous fields is known as the QCSE. As a consequence of the QCSE, the energy gap narrows and the wave-function overlap is reduced, resulting in a shift of the emission wavelength from the QWs, weaker PL emis-

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sion and peak broadening (Nakamura 1999).

Using a QS 266 nm laser, which has a high excitation density, results in band-filling of the localized states and photogenerated carriers, which screen the piezoelectric and spontaneous fields within the QW. The effect of the QCSE is therefore reduced, and the emission peak wavelength shift and the FWHM of the peak are decreased.

The number of QWs and their thicknesses have a strong influence on the optical properties of AlGaN/GaN and InGaN/GaN QW structures. The PL of such structures requires a high laser power density to carefully characterize their output spectrum and reduce the impact of the QCSE. A shift of 10 nm to a shorter wavelength is seen in figure 4 when comparing the PL obtained for an InGaN sample using QS 266 nm and CW 325 nm lasers.

Indirect materials

Indirect gap semiconductors such as SiC have a very low PL efficiencies, and therefore require high excitation densities. Integrated intensity maps can be used as a quantitative measure of the quality of epitaxial growth. Figure 5 shows an integrated PL map (obtained with a QS 266 nm laser) of a SiC wafer, showing defects that occurred during growth. The white line marks a 3 mm edge exclusion zone. Due to the low PL efficiency of SiC, these defects would be difficult to observe using a lower power density laser.

Conclusion

There are a number of lasers currently available for use in wide-bandgap material characterization, and it is important to match the correct laser with the right application. AlInGaN and other wide-bandgap materials require high-energy excitation for their PL characterization. High power density is required to increase PL for indirect semiconductors and structures with absorbing layers, and is also required to overcome QCSE and band-tailing effects in InGaN/GaN QWs. Stokes shifting can also be reduced to give more accurate PL results using a high-powered laser. All of the above requirements are met using a QS 266 nm laser.

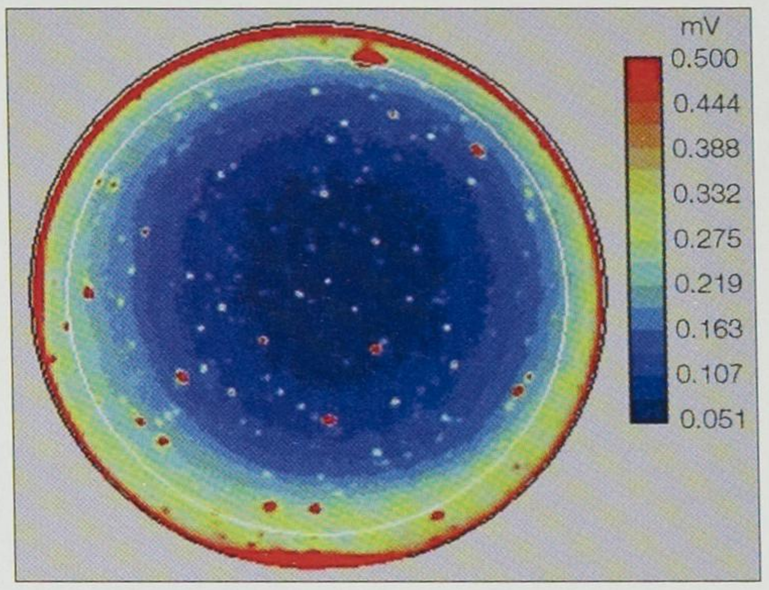


Fig. 5. PL intensity map of a SiC wafer obtained using Accent RPM 2000.

Further reading

S Nakamura (ed.) 1999 *Introduction to Nitride Semiconductor Blue Lasers and LEDs* (Taylor & Francis, London).

Colm Mac Mahon, Shouyin Wang, Clive Meaton, Muriel de la Fargue and Dale Page are with Accent Optical Technologies, Hemel Hempstead, UK. E-mail cmacmahon@accentopto.com.



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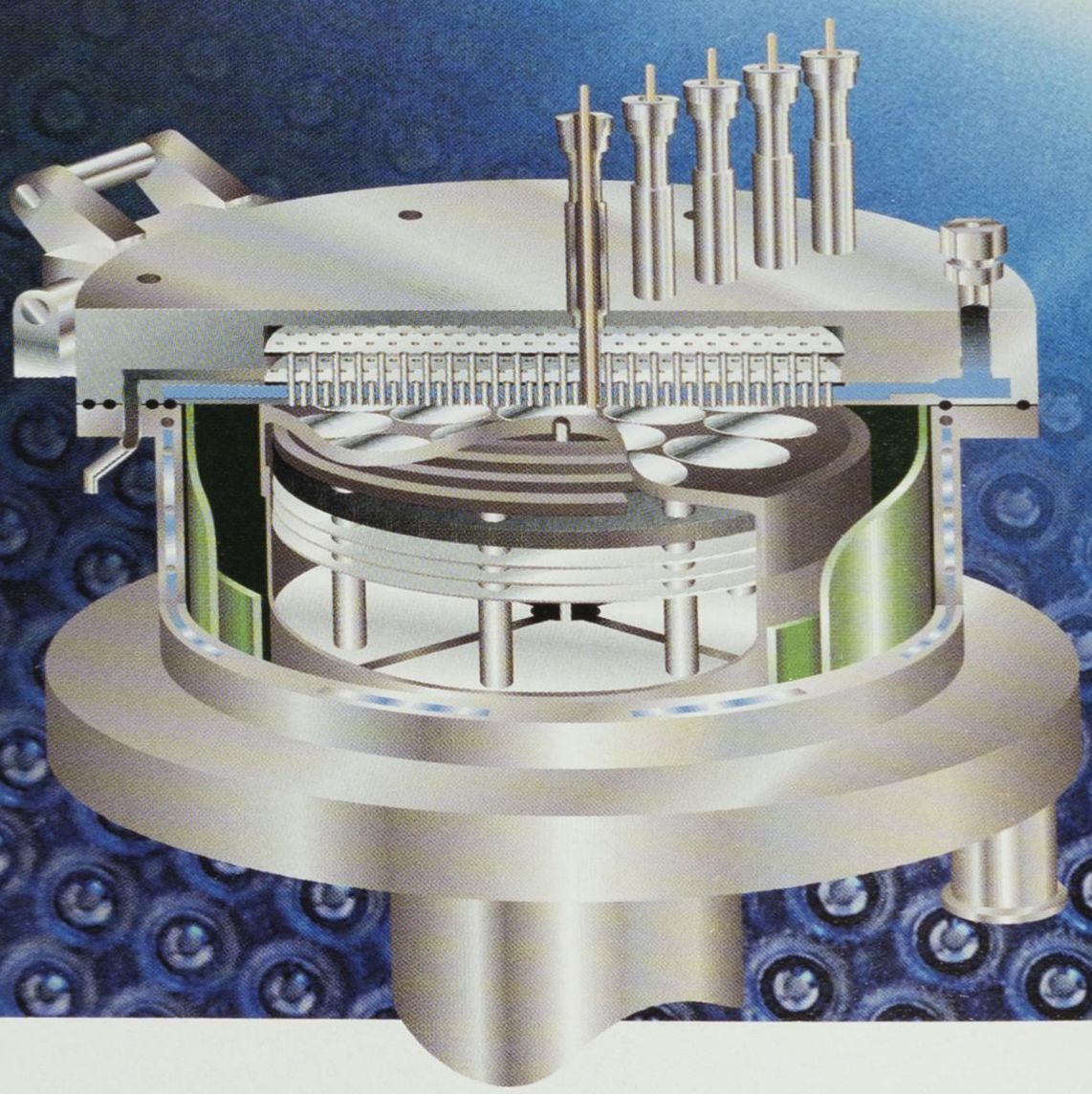
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STEM provides the answers to some difficult questions

STEM is helping to reveal information about interfaces and diffusion during device processing that is almost impossible to determine using other techniques, write **Jia-Sheng Huang** and **Cathy Vartuli**.

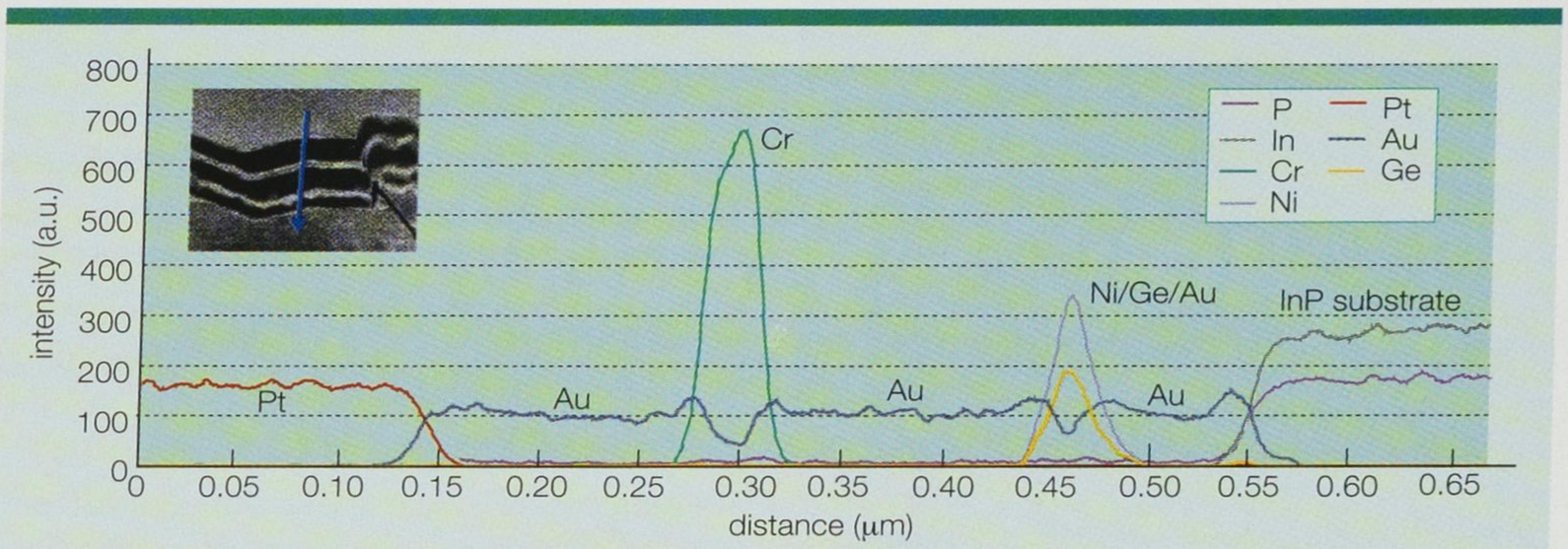


Fig. 1. The STEM spectra of a sample of n-InP/AuGe/Ni/Au/Cr/Au after alloying.

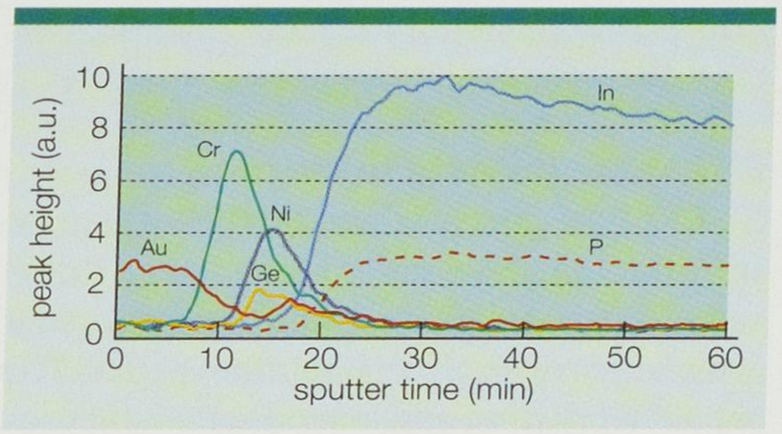


Fig. 2. AES depth profiles of a sample of n-InP/AuGe/Ni/Au/Cr/Au after alloying.

Yield improvement, cycle-time reduction and failure analysis are key elements in microelectronic chip manufacturing. To achieve high-yield and low-cost manufacturing, materials characterization is indispensable. Although there are differences in the physics and design of III-V and silicon devices, the techniques used for materials characterization are similar. Examples of the techniques routinely used for III-V and silicon materials characterization include scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), transmission electron microscopy (TEM), Auger electron spectroscopy (AES), Rutherford backscattering spectrometry (RBS), secondary ion mass spectrometry (SIMS), X-ray diffraction and atomic force microscopy (Wolf *et al.*).

These analytical techniques cover a range of important characterization needs. However, as device dimensions continue to shrink, the need to rapidly evaluate the elemental distributions within thin films only nanometers thick has become increasingly challenging. Recently, a dedicated scanning transmission electron microscopy (STEM) system has been introduced. The Hitachi HD-2000 thin-film evaluation system operates at 200 kV and images using secondary electrons, transmitted electrons (bright field), scattered electrons (Z-contrast or dark field) and X-rays (EDS) (Hashimoto *et al.*). The use of cold field-emission coupled with its lens configuration, gives a spatial resolution of 0.24 nm in bright field. The collection angle for the EDS detector is larger than a conventional TEM, giving the STEM a 2.5 times higher sensitivity for elemental analysis. The column setup allows samples too thick or rough for a traditional TEM to be evaluated, making sample preparation easier. The most powerful and unique feature of the STEM for microelectronic applications is its ability to rapidly provide high spatial resolution, high sensitivity, elemental mapping and concentration depth profiles.

The STEM technique has many applications in the characterization of III-V and silicon devices. STEM imaging can provide atomic or near-atomic spatial resolution for the study of quantum wells and dots, surfaces and interfaces, crystalline defects, grain boundary segregation and crystal tilts. Using EDS, electron energy loss spectroscopy (EELS), or Z-contrast (dark field) imaging, information about the chemical makeup of a sample or layers can be determined. Data on the sharpness of an interface, diffusion and the reaction of components can be gathered. One of the more pragmatic and alluring aspects is STEM's elemental concentration profiling for the study of interfaces in III-V or silicon materials. In the STEM concentration profile, spatial and chemical information about layers nanometers thick, as well as diffusion distance and stoichiometry, can be clearly revealed.

Strengths and limitations

STEM EDS can provide a spatially and chemically accurate elemental profile. In comparison with the various other elemental profiling techniques, STEM perhaps offers the most accurate information about the layer thickness and diffusion distance.

For AES, *in situ* sputtering is necessary to study the depth profile of a sample. Information from the sample is gathered from the top 2 nm, making this technique extremely useful for analyzing thin surface layers. It is difficult to determine the layer thickness in concentration profiles with high precision, due to the material dependence of the sputtering rate and the ion beam induced mixing of the sample that artificially broadens otherwise sharp interfaces. In addition, volatile elements may be preferentially removed from the material during sputtering, producing a low AES reading. Finally, the ions used for sputtering can be implanted, giving an inaccurate signal.

For RBS, the depth profile is a result of all the superimposed backscattered ion signals from the elements encountered by the probing ions within the sample. This makes the correct deciphering of a raw RBS spectrum difficult. Determining the density of the materials analyzed is important for calculating

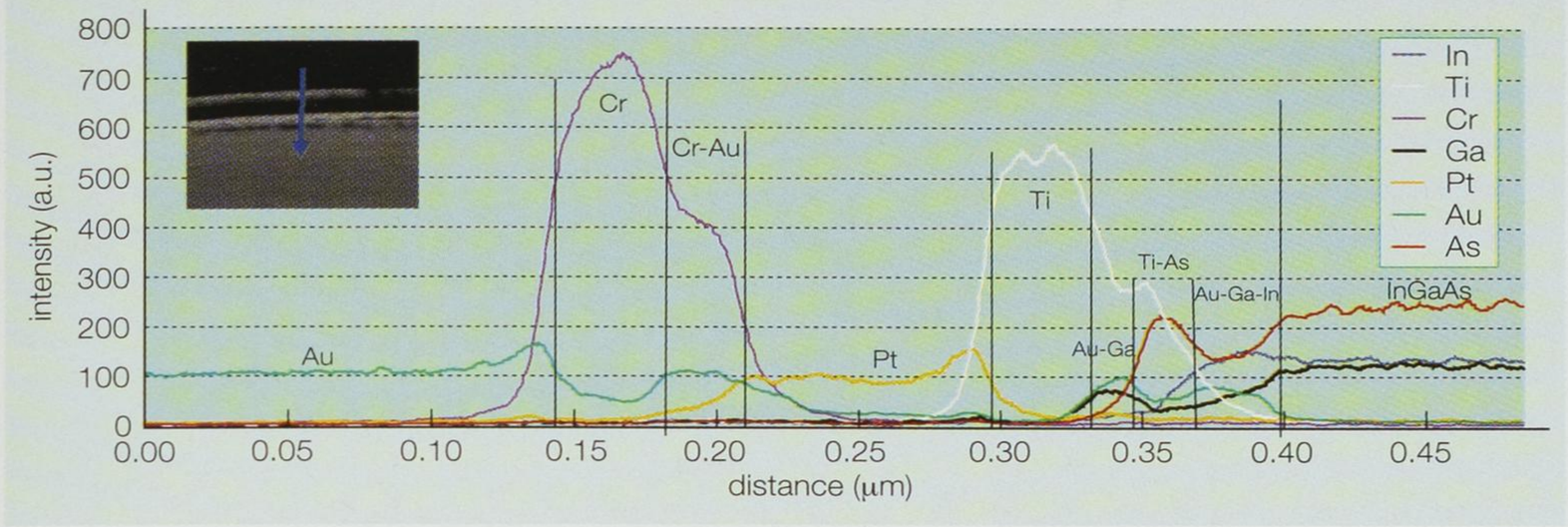


Fig. 5. An STEM EDS spectra of a sample of p-InP/p-InGaAs/Au/Ti/Pt/Au/Cr/Au after alloy.

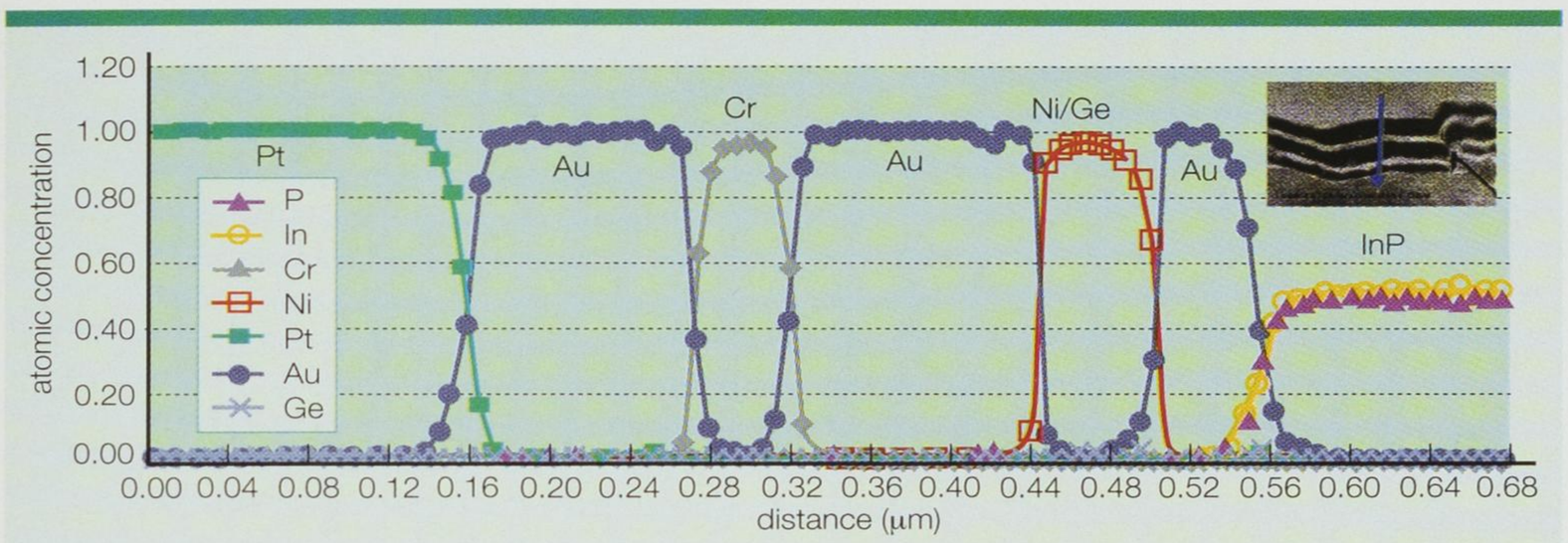


Fig. 6. An STEM atomic concentration profile of a sample of n-InP/AuGe/Ni/Au/Cr/Au replotted from fig. 1. There is no significant diffusion of In or P into the metal layers.

430 °C. There were several redistributions in elemental signals after anneal. First, a shoulder began to develop on the Cr signal and overlapped with the underlying Au, indicating a Au/Cr layer. The reaction between Cr-Au at 430 °C was also observed in the Au/Zn/Au/Cr/Au metallization systems. Second, the Ti and Au diffused downwards while Ga and As diffused upwards. Consequently, the interdiffusion between species led to the formation of three compound layers: Au-Ga, Ti-As and Au-Ga-In (from top to bottom). The STEM again uniquely captured the process of phase transformations in thin layers (5–10 nm).

Thin-film stoichiometry

Figure 6 shows the STEM concentration profile replotted from figure 1, where the intensity is converted to atomic concentration. By quantifying the concentration of the various elements in each layer, the chemical composition of the thin-film layer can be determined. In the Cr-rich layer, the atomic concentrations for Cr and Au are 0.98 and 0.02, respectively. In the Ni/Ge/Au layer, the atomic concentrations for Ni, Ge and Au are 0.96, 0.03 and 0.01, respectively. For InP, the atomic concentrations of In and P are 0.51 and 0.49, respectively.

Conclusions

STEM EDS enables rapid, high spatial and elemental resolution for characterizing III-Vs and silicon devices, and is especially strong when data on multiple thin layers is required. The chemical makeup of each layer can be determined, and data on the sharpness of interfaces, diffusion and the reaction of components can be gathered. Concentration profiles, spatial and chemical information about layers nanometers thick, and diffusion distance and stoichiometry can all be analyzed with this technique.

Acknowledgments

The authors acknowledge Larry Cote for support of the work, P C Chen for reviewing the manuscript and M Jamison for the FIB work.

Further reading

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Huang *et al.* 2002 *J. Mater. Res.* **17(11)** 2929.
Wolf *et al.* 1986 *Silicon Processing for the VLSI Era* vol. 1 (Lattice Press, Sunset Beach, CA).

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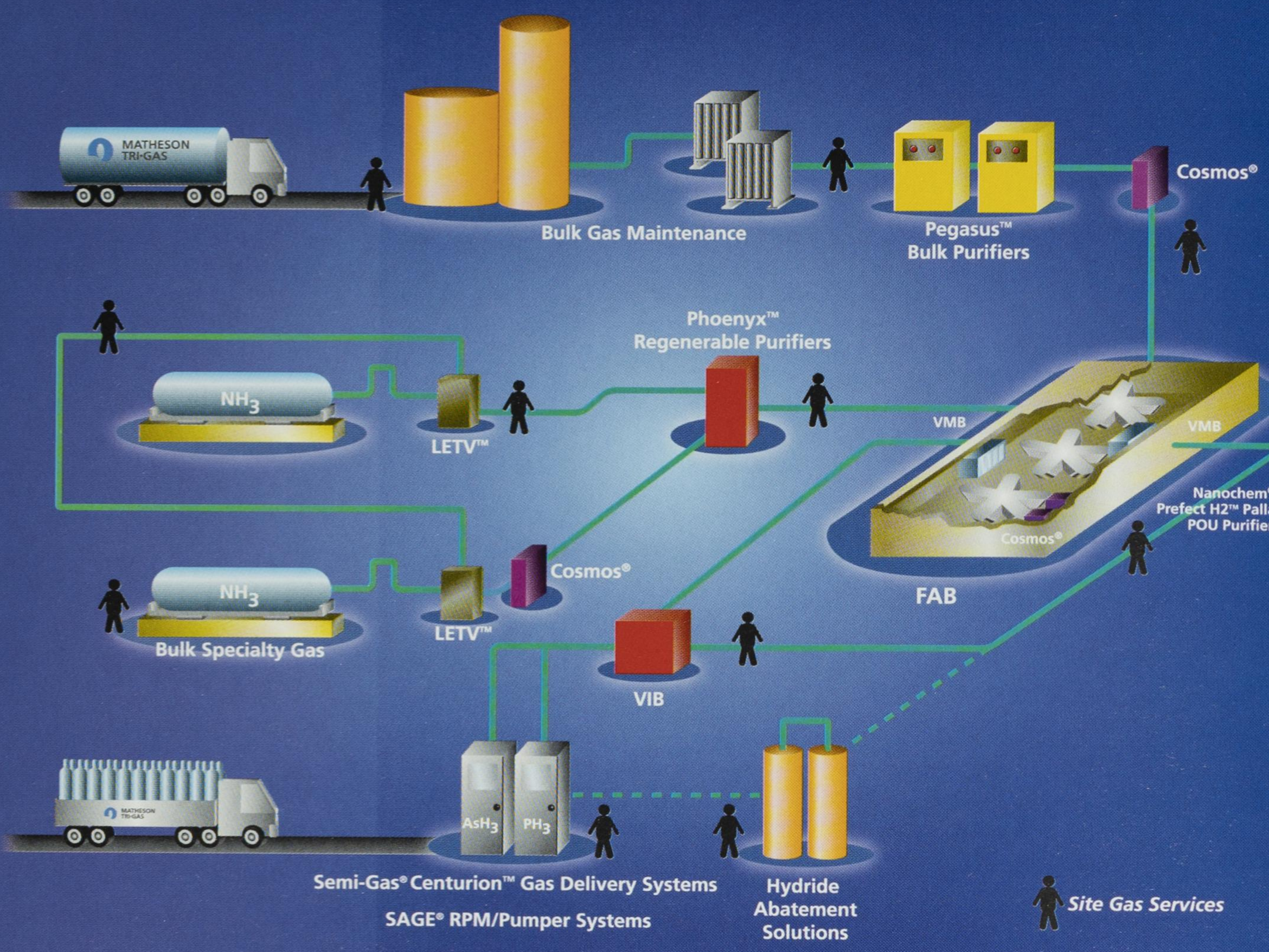
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AlGaInAs broad-area lasers exhibit outstanding reliability

Low failure rates at high output power make broad-area AlGaInAs lasers suitable for industrial applications, write **Victor Rossin**, **Toby Strite**, **Erik Zucker** and **Teh-Hua Ju** of JDS Uniphase.

Massive investment driven by the 1990s telecom boom stimulated great progress in the available output power of single-mode AlGaInAs pump lasers. From 1997 to 2002, the peak operating power of 980 nm chips increased five-fold, while reliability was maintained at or below 200 failures in time (FIT; ~0.2% annual failure rate). Less attention was directed towards applying these advances to the AlGaInAs broad-area lasers used widely in fiber lasers and other industrial applications. The current telecom crash has led to this situation being redressed. This article presents the current state of the art for broad-area AlGaInAs diode laser reliability and output power.

Diode structure and performance

The AlGaInAs lasers described below feature an InGaAs strained-layer quantum well (QW) active region and a separate confinement heterostructure waveguide region. Through fine epitaxial adjustments, the basic structure can emit throughout the 900–1000 nm wavelength range at broadly similar efficiency and reliability. The laser diode chips are of a planar design, simplifying both the laser fabrication and the junction-side-down mounting to a heat sink. Straightforward processing forms the 100 μm emitting aperture, and a simple and robust coating technology greatly enhances facet durability.

Figure 1 plots the key L-I, V-I and power conversion efficiency characteristics of 100 μm aperture lasers at 25 °C. Threshold current values around 300 mA with a slope efficiency just above 1 W/A are typical. Power conversion efficiency peaks around 60% just above 2.5 W optical output power. An output power of 8 W can be sustained at 9 A drive current. The maximum CW output power levels for individual devices are in the 8–12 W range, limited by catastrophic optical damage, heat-sink thermal resistance and heat-sink temperature. The inset shows the typical multimode output spectrum featuring a smooth power distribution within a FWHM band of several nanometers.

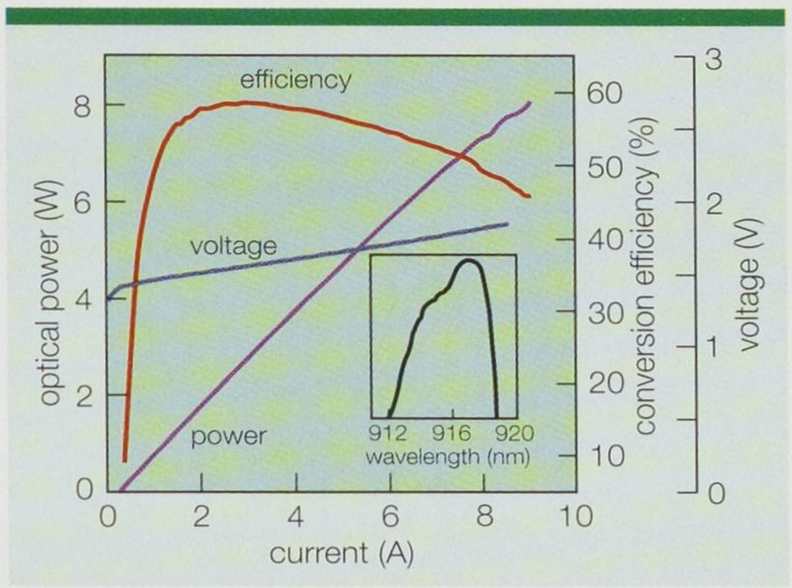


Fig. 1. Key electrical and optical characteristics of an InGaAs 100 μm active-area broad-area laser at 25 °C as a function of drive current. Inset: typical multimode wavelength spectrum featuring a smooth power distribution within several nanometers FWHM without sideband emission.

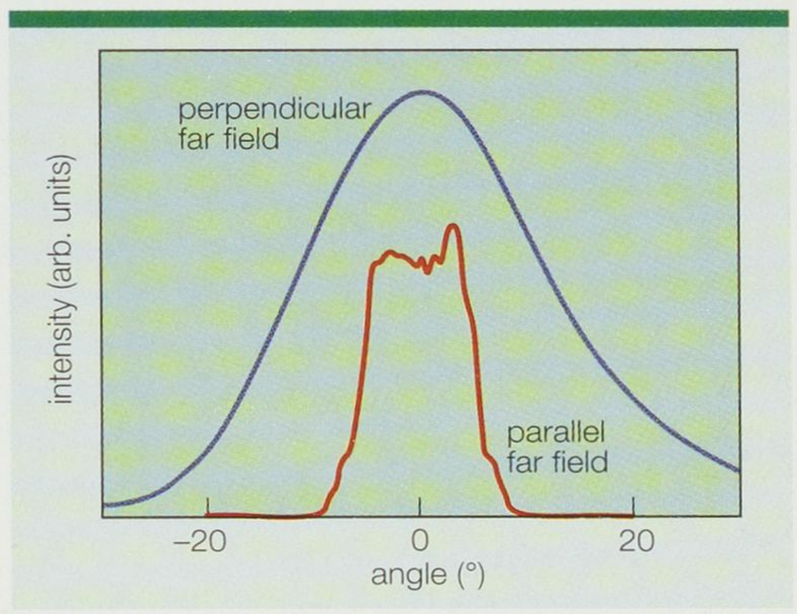


Fig. 2. Far-field pattern of an InGaAs 100 μm active-area broad-area laser at 4 W output.

The 100 μm AlGaInAs lasers feature a Gaussian-shaped spatial light output. Typical far-field values are 26.5° FWHM in the plane perpendicular to the QW, and ≤12° FWHM in the plane parallel to the QW, allowing efficient fiber-coupling in the production environment of around 80%. Figure 2 illustrates a typical far-field power distribution for a laser diode operating at 4 W.

Overview of diode laser reliability

Over the past decade, telecom vendors learned to manufacture laser diodes whose reliability is well understood. The low failure rates of advanced diode technologies make it uneconomical to perform reliability testing under normal operating conditions. Instead, multicell testing under highly accelerated conditions is used to develop a statistically relevant device reliability model. Multicell tests generally probe the upper temperature and drive current ranges to deduce the sensitivity of diode reliability to each parameter. Analysis of the observed failure rates under high stress produces a model from which failure rates at normal operating conditions are extrapolated.

Diodes fail either suddenly (infant or random failure regimes) or through gradual degradation over an extended period of time (wear-out regime). Several root causes may contribute to failures within any regime.

Infant failure regime Infant failures occur early in a laser's working life. Such failures usually arise from damage or imperfections introduced during device fabrication or intrinsic semiconductor defects. A rigorous burn-in at high drive current and ambient temperature conditions is the accepted technique to screen out infant failures. The overstress must be severe enough to eliminate diodes subject to infant mortality over an economically viable burn-in period, but must not introduce any new failure modes. Therefore, only a robust diode laser technology can be effectively screened in production for infant mortality. For the lasers discussed below, routine screening, including a short burn-in, was performed prior to multicell testing to remove infant failures from the studied population.

Constant random failure rate regime

Sudden failures are the predominant failure mode in this regime. The root cause is randomly dispersed epitaxial defects. Therefore the failures are expected to be statistically ran-

While not shown in table 2, the multicell also predicts the reliability of the technology at heat-sink temperatures other than 25 °C. As a rule of thumb, $E_A = 0.43$ eV corresponds roughly to a tripling of the device failure rate with each 20 °C increase in T_j. These results are valuable to customers wishing to reduce their laser diode cooling power budget, but who still must know the resulting trade-off in laser reliability. To our knowledge, this is the only broad-area diode laser technology that has undergone a multicell test and demonstrated telecom reliability at any power level.

Non-telecom applications

As alluded to above, numerous industrial applications for broad-area laser diodes exist which tolerate sub-100,000 h MTBF. Medical and instrument applications with low duty cycles typically require only several thousand hours of diode life. Materials processing, diode-pumped solid-state lasers and printing set reliability requirement benchmarks in the 10,000–20,000 h range. To address whether yet higher output power levels are immediately available in the current 100 μm InGaAs-emitter technology, additional diodes were tested at 6 W operation. As summarized in Table 3, an MTBF value greater than 10,000 h was observed for 6 W, 35 °C operation – an acceptable level for many industrial applications. However, this value is considerably less than forecasted by equation 1, indicating that by 6 W, new failure modes not probed by the multicell test are emerging.

Conclusion

This paper presents the most detailed overview of broad-area laser reliability performed to date. The results indicate that extremely low failure rates at high output power are achievable for junction-side-down mounted broad-area lasers. Reliability studies like these allow customers to make system design trade-offs with full knowledge of how the diode lasers will perform under arbitrary output power and heat-sink temperatures. We believe that users of industrial lasers, who are adopting diode laser technology at an accelerating rate, will demand more studies of this sort.

Reliability at 6 W and 35 °C	
heat-sink temperature (°C)	35
junction temperature (°C)	75
current (A)	7.0
average power (W)	6.0
device hours	95,208
number of diodes	58
failures	8
MTBF (hours)	11,900

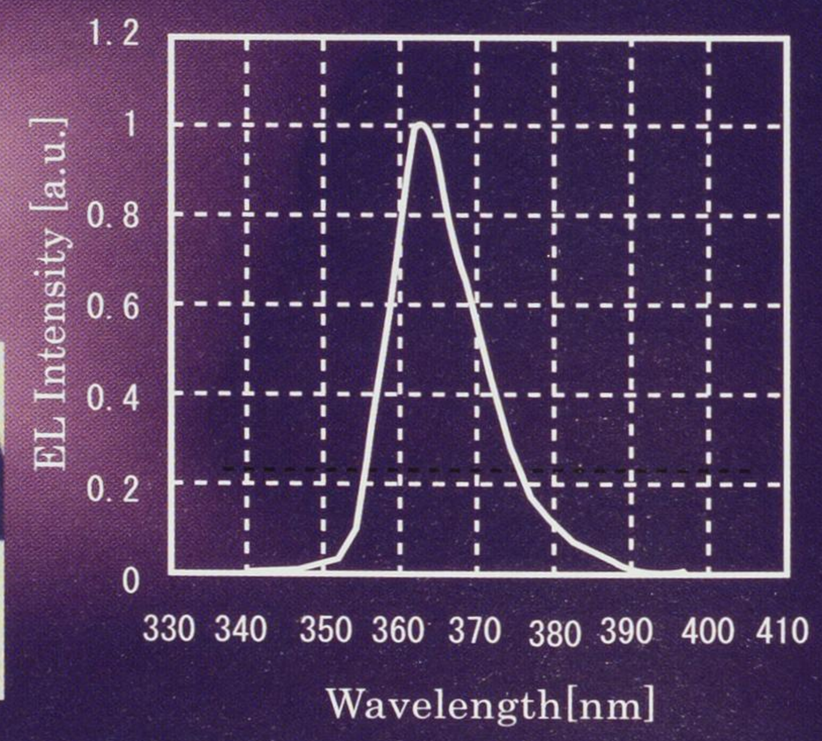
Table 3. Supplemental test results to establish AlGaInAs laser diode reliability.

Victor Rossin and Erik Zucker are chip development managers. Toby Strite (toby.strite@jdsu.com) is a businesss development manager for active components. Teh-Hua Ju is product engineering manager for pump modules and industrial diode products. The authors all work for JDS Uniphase. *The authors thank their colleagues Bruno Acklin, James Darchuk, Kevin Lascola, Gordon Mitchard, Matthew Peters and Deepika Ranaweera for their contributions to this article.*

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Near-IR focal-plane arrays improve camera performance

The recent improvement in performance of InGaAs-based detectors and cameras has opened up a wide range of applications, according to **Austin Richards** of Indigo Systems.

Advances in focal-plane array (FPA) design, along with the availability of higher quality III-V material, have enabled the fabrication of high-performance, commercial 2D arrays using InGaAs photovoltaic detectors. These advanced InGaAs FPAs have become instrumental in the creation of highly sensitive near-infrared (NIR) cameras that deliver excellent image quality, rivaling that associated with silicon CCD detectors, but with a spectral sensitivity that is shifted into the NIR band, from 900 to 1700 nm.

The ability to produce high-quality images of objects in the 900–1700 nm waveband with high sensitivity opens up a range of applications, including laser-beam characterization, agricultural and petrochemical inspection, forensics, NIR imaging spectroscopy and astronomy. InGaAs detectors offer high quantum efficiencies (around 85%) in the 900–1680 nm band, unlike the competing technologies of lead-oxysulfide vidicons and coated CCD cameras. At wavelengths longer than 1100 nm silicon becomes transparent, making silicon-based cameras ineffective unless coated with a wavelength-shifting material. This coating results in a quantum efficiency of about 1–2% in the 1100–1700 nm band, which is useful in laser-beam profiling applications where intensities are high, but not in many other applications.

High sensitivity is important, since NIR scenes often span a wide dynamic range and light signals can be quite low in intensity, especially in NIR imaging spectroscopy where only a small portion of the InGaAs sensors' passband is admitted. InSb FPAs have high quantum efficiency in the NIR band, but require cooling to cryogenic temperatures using mechanical cryocoolers that cost about $10,000. Their spectral response is from 1 to 5.5 μm, so the sensor must be combined with a bandpass filter to make a camera that operates solely in the NIR band. Because the bandgap energy of InGaAs is much higher than InSb, InGaAs FPAs can operate at temperatures around ambient (25 °C) with noise performance comparable to InSb sensors at liquid-nitrogen temperatures. The thermoelectric coolers cost about $20, making the overall camera cost much lower.

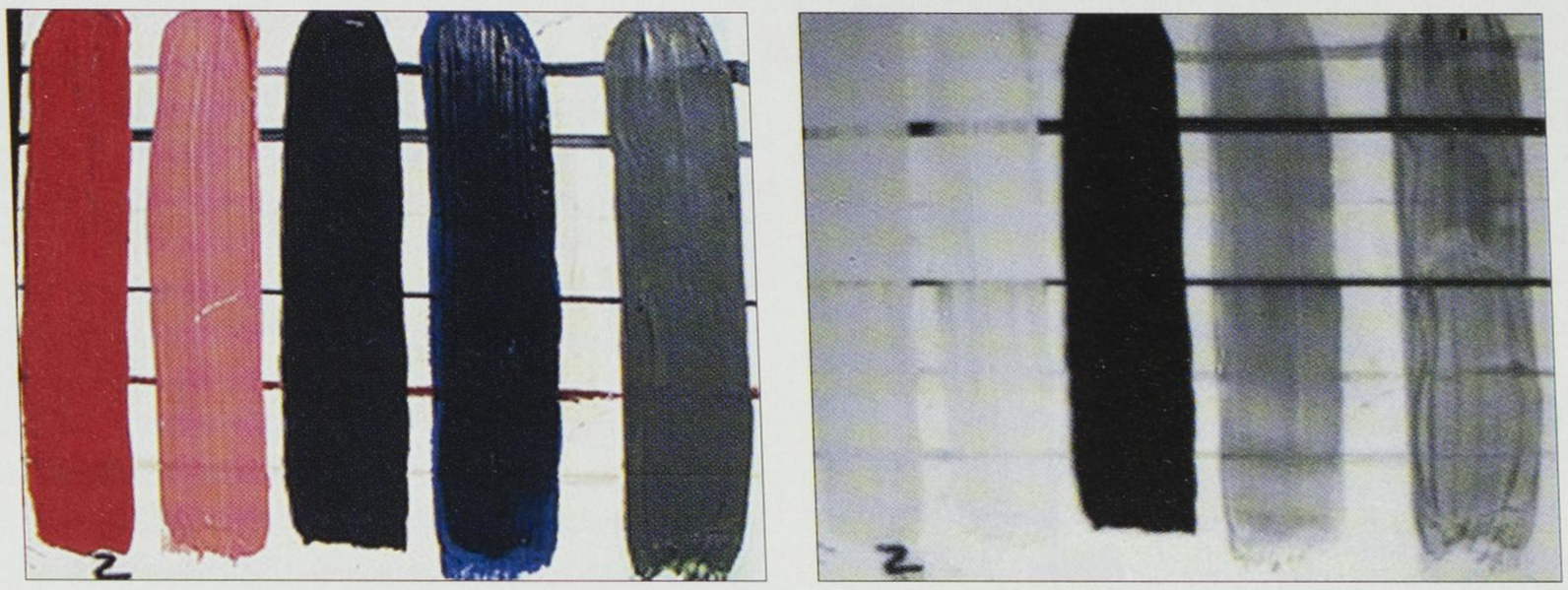


Fig. 1. An oil-paint test panel imaged with visible (left) and NIR (right) sensors. All the pigments except black show a degree of transparency in the NIR (900–1700 nm) band.

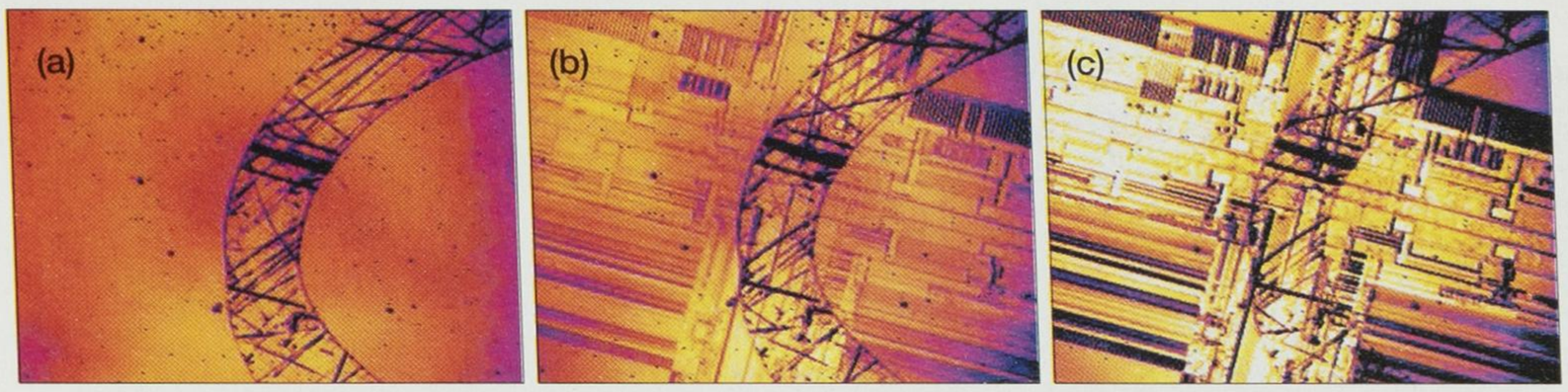


Fig. 2. Three images through the backside of a CMOS readout IC wafer taken with an InGaAs camera with filters at 1000 nm (a), 1050 nm (b) and 1100 nm (c).

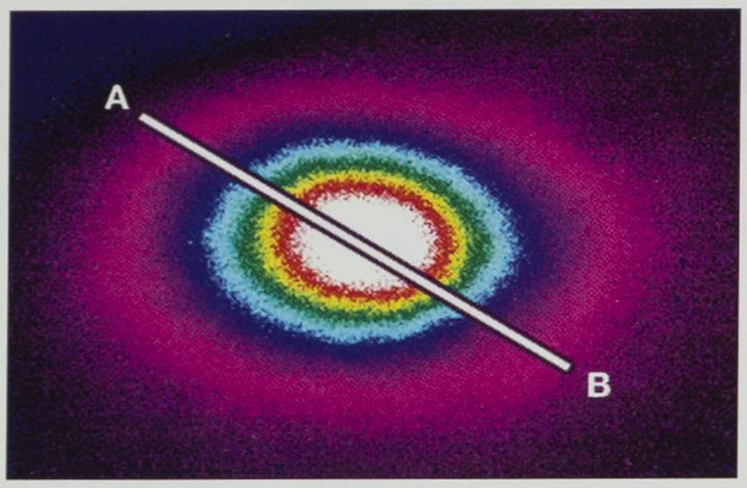
The FPA sandwich

The FPAs are made from InGaAs photodiode arrays fabricated on 3 inch, MOCVD-grown InGaAs-on-InP epiwafers. The 30 × 30 μm^2 detectors are made by diffusing zinc (a p-type dopant) through a diffusion mask and into an n-type (S- or Si-doped) InGaAs epilayer. After forming ohmic contacts, a total of 82,000 truncated-cone-shaped bumps of indium are deposited onto the contact metal pads to make a 320 × 256 pixel array. The same number of indium bumps are deposited onto a silicon mixed-signal IC die, which Indigo Systems designs and offers as a standard readout IC (ROIC) product.

After a proprietary cleaning process, the indium bumps on the InGaAs detector dies are fused to the bumps on the ROIC wafer under pressure in a cold-forming process. The technicians probe the ROIC bond pads and check for operational hybrid interconnection, before wire-bonding the FPA to a motherboard inside a dewar package.

The combination of an anti-reflection (AR) coating on the BK-7 glass or quartz window of the package, and an AR coating deposited directly on the detectors, results in extremely high transmissivity in the 1300–1550 nm range. The vacuum package also incorporates thermoelectric cooling to stabilize the FPA at an appropriate operating temperature, typically between 0 and 20 °C.

The FPAs that are incorporated into cameras have 99.5% operability and few cluster defects. In addition, algorithms have been



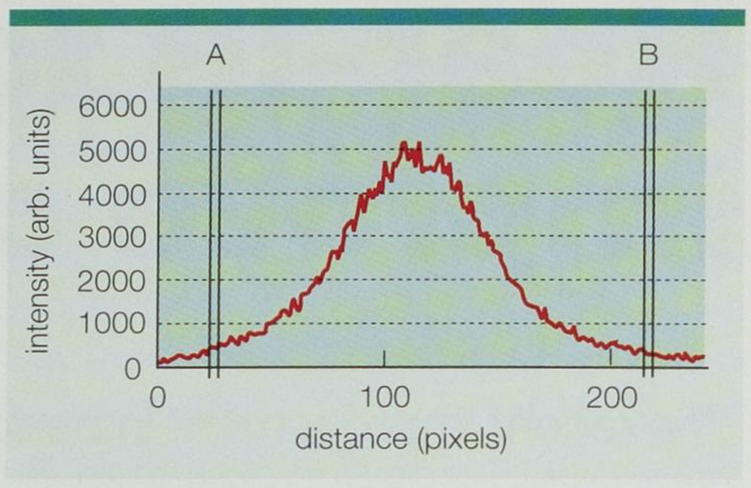


Fig. 3. Cross-sectional image of a 1550 nm laser beam (left), along with an intensity profile that corresponds to the diagonal line over the beam spot (right).



Fig. 4. Image from an InGaAs camera with a 900–1000 nm filter (a) and a 1400–1600 nm filter (b). The third image (c) shows the difference between the other two images, false-colored in red and overlaid onto (a). Exposed skin and vegetation are clearly apparent.

developed that substitute neighboring good pixels for the few isolated bad pixels. These semiconductor and software advancements result in an image quality that competes favorably with silicon CCD detectors.

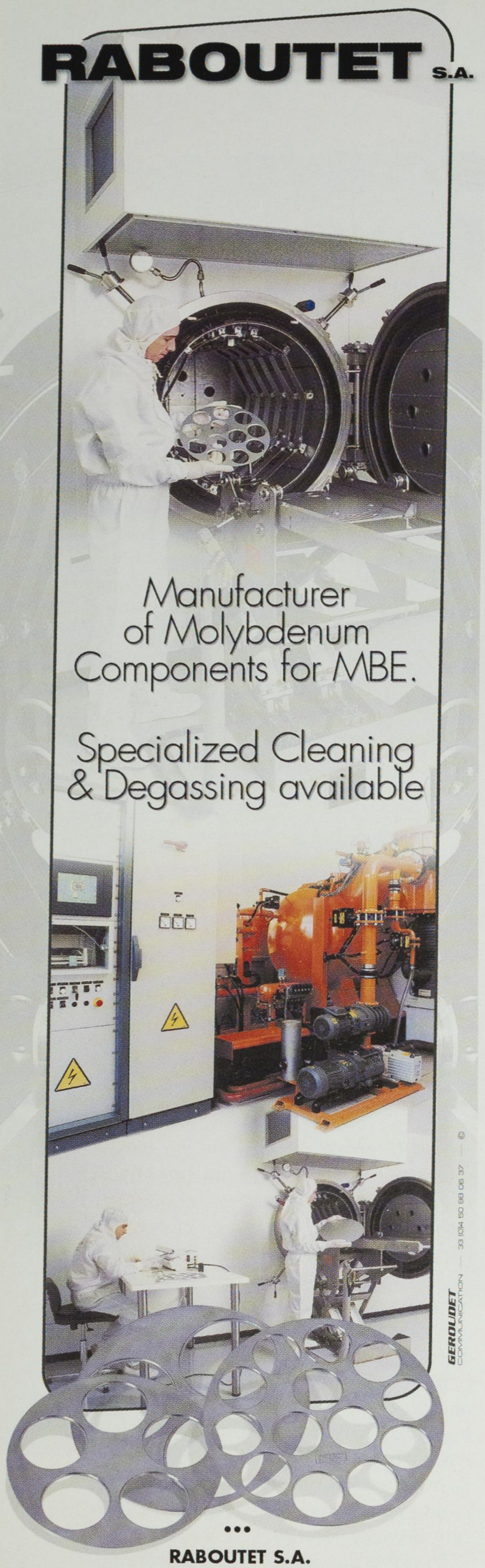
InGaAs camera performance

Because Indigo Systems designs and fabricates its own ROICs and detectors, and then integrates them into its line of cameras, the company controls the supply chain, assuring that the FPAs have an ROIC optimized for use with InGaAs detectors. One of the ROIC chips used with InGaAs detectors – the ISC9809 – is designed for ultra-low-noise operation in very-low-background applications, i.e. environments in which there is a very weak signal from the target object. The ISC9809 has the additional feature that the integration capacitor used in each unit cell on the focal plane is selectable, enabling 20 times gain changes without appreciable noise increases. Indigo Systems manufactures three varieties of InGaAs cameras. The highest performance camera is the Phoenix, which has a 14-bit dynamic range in its A/D converter. This enables the user to select exposure times as short as several microseconds and as long as 660 ms – a change in sensitivity of approximately five orders of magnitude. The on-chip gain can also be switched by a factor of 20. The tremendous operational range of camera sensitivity means that the camera can be used both for the extremely low light levels typical of applications in astronomy, and for the high-brightness conditions encountered in laser-beam measurement.

The ISC9809 FPA has four separate outputs, and can stream image data at rates up to 40 megapixels per second into a computer. This corresponds to frame rates of 346 Hz at the full 320 × 256 array size, enabling high-time-resolution recording of very dynamic events such as missile launches and explosions. In one embodiment of the Phoenix camera system, two serial data links transmit image data from the camera to a PC equipped with a special frame grabber board and 1 gigabyte of RAM, allowing large data bursts to be acquired. A new version of the Phoenix camera contains a 640 × 512 pixel InGaAs array for applications needing higher sensor resolution.

Unmasking art forgeries

Art dealers, museums and collectors now have a new tool to protect themselves from multi-million dollar liabilities caused by elaborate forgeries. Works of art can be authenticated by imaging through surface pigments to detect the presence of any "underdrawings" beneath the top layer. The art conservator can thus verify that the style of the underdrawing matches that of the artist's other works, and can also detect the possible existence of another painting beneath. Silicon CCD detectors have historically been used to image through art



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materials such as dirty varnish that can obscure the painting, but standard silicon detectors begin to lose their effectiveness at about 1000 nm, and cut off completely at 1100 nm. In contrast, InGaAs sensors can be used to view through traditional paint pigments, which exhibit a high degree of transparency at wavelengths longer than 1100 nm.

Figure 1 shows an oil pigment test panel imaged with visible and NIR sensors. The horizontal black lines are made by a variety of media, including pencil and charcoal. All the pigments show some degree of transparency in the 900–1680 nm band, with the exception of the black pigment, which contains carbon particles that are highly absorbing across the NIR band. Imaging through black pigment requires X-ray techniques.

Semiconductor wafer inspection

NIR cameras using InGaAs FPAs are also proving useful for inspecting semiconductor wafers because the cameras deliver accurate images of wafer surface features, even though the images are taken looking at the backside of the wafer. The underside is opaque to visible light, but the silicon becomes transparent at wavelengths longer than 1100 nm. The transition from opacity to transparency is fairly gradual for some silicon wafers bearing CMOS circuits, occurring over a span of 100 nm in wavelength. Figure 2 shows three images of a silicon wafer with CMOS readout ICs fabricated onto it. The images are taken through the wafer's backside. The InGaAs camera is fitted with one of three bandpass filters (20 nm FWHM), having center wavelengths of 1000 nm, 1050 nm and 1100 nm, respectively.

The black line in the 1000 nm image is an ink mark made on the wafer's surface. The circuitry is barely visible through the silicon at this wavelength. But at 1050 nm and 1100 nm, progressively deeper layers of circuitry are exposed. The selective use of bandpass filters, coupled with an optical system with small depths of field, helps to enable the construction of a 3D characterization of a wafer, which has potential applications in the wafer inspection field. Voids and cracks within the wafer's volume can be detected and their position in X, Y and Z co-ordinates can be determined.

Optical device characterization

Manufacturing 1300 and 1550 nm lasers requires precise measurements of the spatial distribution of the laser energy in order to efficiently couple that energy into a fiber, waveguide or other optical device.

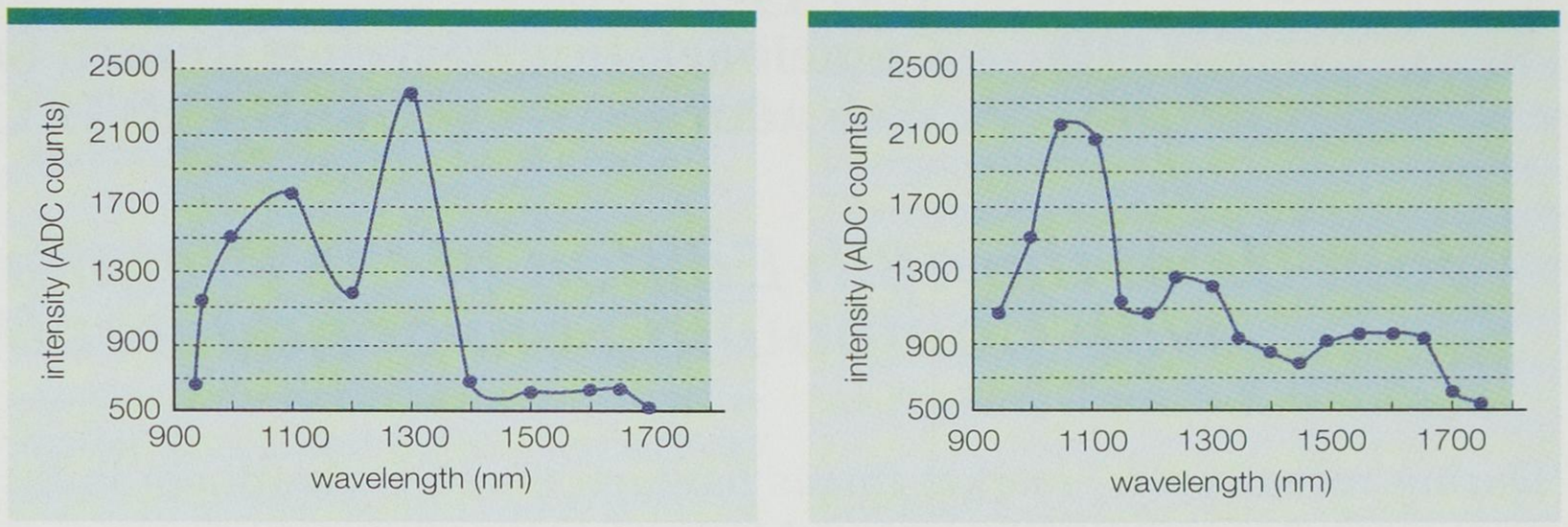
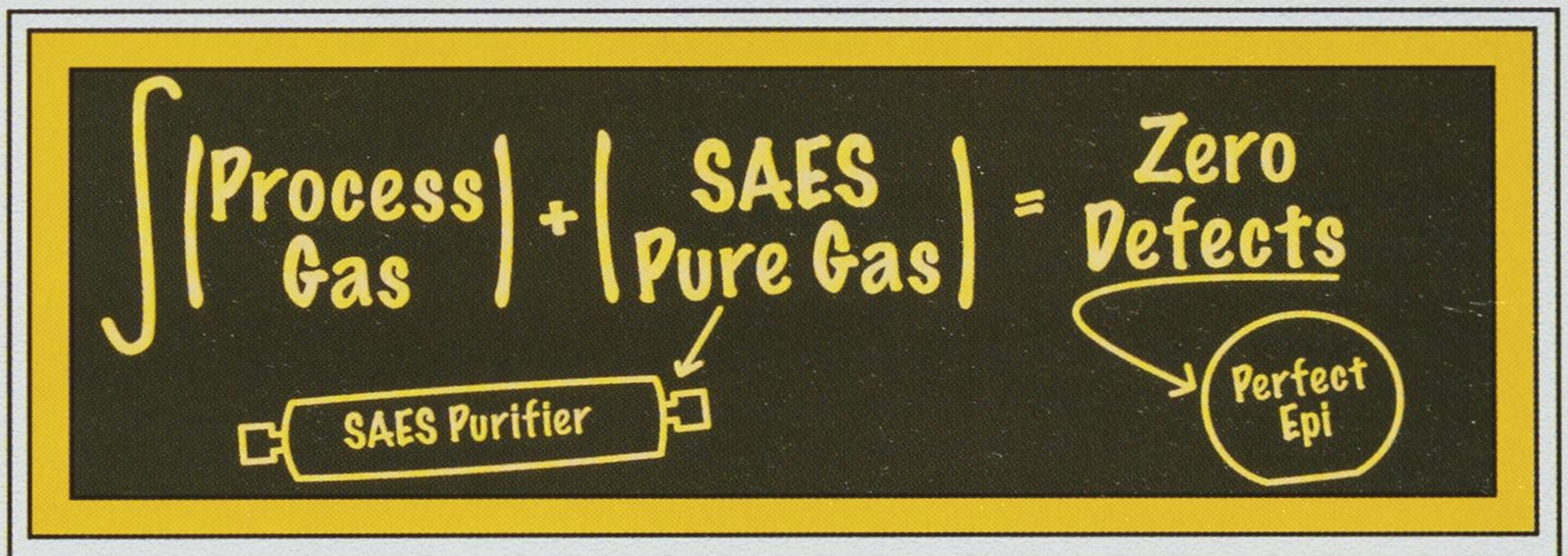


Fig. 5. Near-infrared transmission spectra of methanol (left) and water (right).

InGaAs sensors outperform other materials in this so-called beam-profiling application, which is best done using a 2D detector array that is directly illuminated by the laser light. Uncoated silicon CCD detectors cannot be used for profiling 1300–1550 nm laser light, while lead-oxysulfide vidicon cameras suffer from various drawbacks, including high nonlinearity, limited dynamic range, image retention and a low damage threshold. In contrast, InGaAs sensors offer high resistance to damage – typically 1 W/cm^2 – which is two orders of magnitude greater than is possible with lead-oxysulfide, and do not suffer from image retention.

Related applications are in the area of laser designators used for targeting guided munitions that operate at 1064 and 1540 nm, and laser range-finders operating at 1570 nm. InGaAs cameras are used to image the laser designator or range-finder spot on a target at varying distances during system development and as a way of calibrating and focusing field systems.

The 14-bit dynamic range of the Phoenix camera enables laser beams to be characterized from the intense center region out



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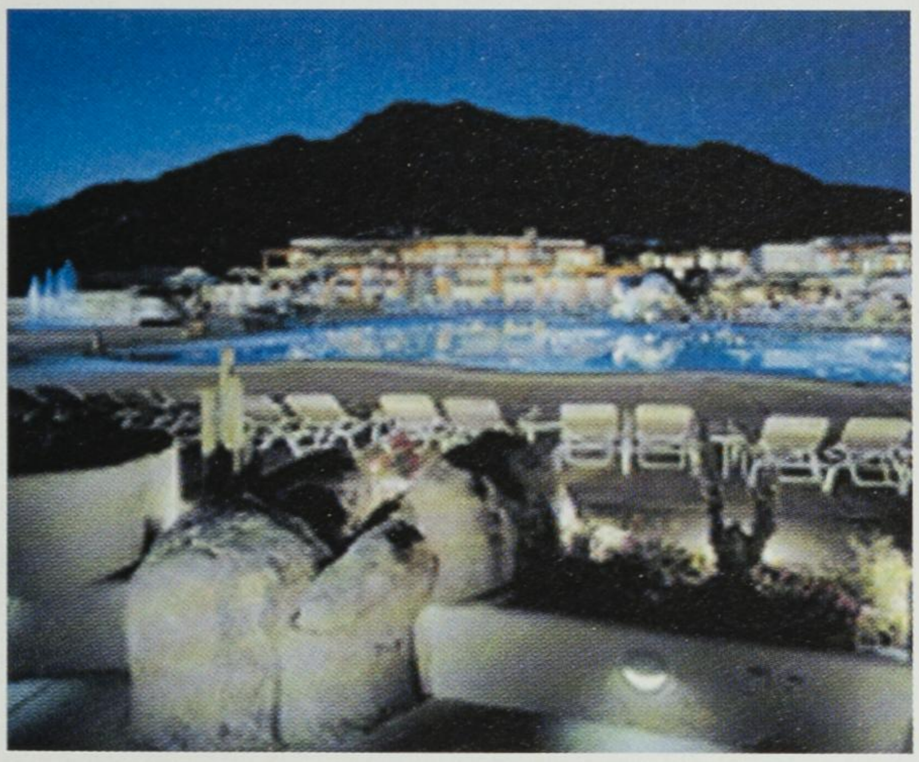
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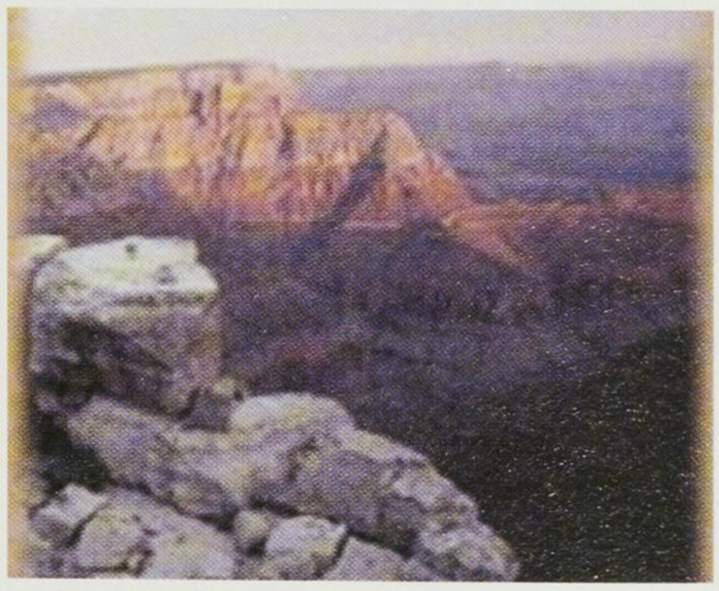
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❑ **Ugly Picture Contest:** This is a very entertaining and informative contest. It gives everyone a chance to benefit from their problems by winning a prize for the most photogenic example of a manufacturing problem and its solution.

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

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to the much less intense edges of the power pattern. Figure 3 shows a 1550 nm laser-beam cross-sectional image and a line profile that corresponds to the diagonal line over the beam spot.

Water detection

Another application of NIR imaging uses the wavelength-dependent reflectance of materials containing water to detect the materials' presence in a scene. Water is strongly absorbing at and above 1350 nm, but not nearly as absorbing at shorter wavelengths. This behavior causes certain objects imaged at wavelengths around 1100 nm to be quite reflective, while the same objects imaged at 1350 nm or higher can appear quite dark.

Figure 4a shows a person imaged with an InGaAs camera through a filter that passes 900–1000 nm light. The skin is quite reflective. In 4b, which shows the same scene imaged through a filter that passes 1400–1600 nm light, the exposed skin appears quite dark. Figure 4c shows the difference between the other two images, false-colored in red and overlaid onto the 900–1000 nm image. Exposed skin is readily apparent because of its water content, as is the background vegetation for the same reason. The difference in contrast between water-filled objects and "dry" objects can also be used to detect the absence of water in a scene.

NIR spectroscopy

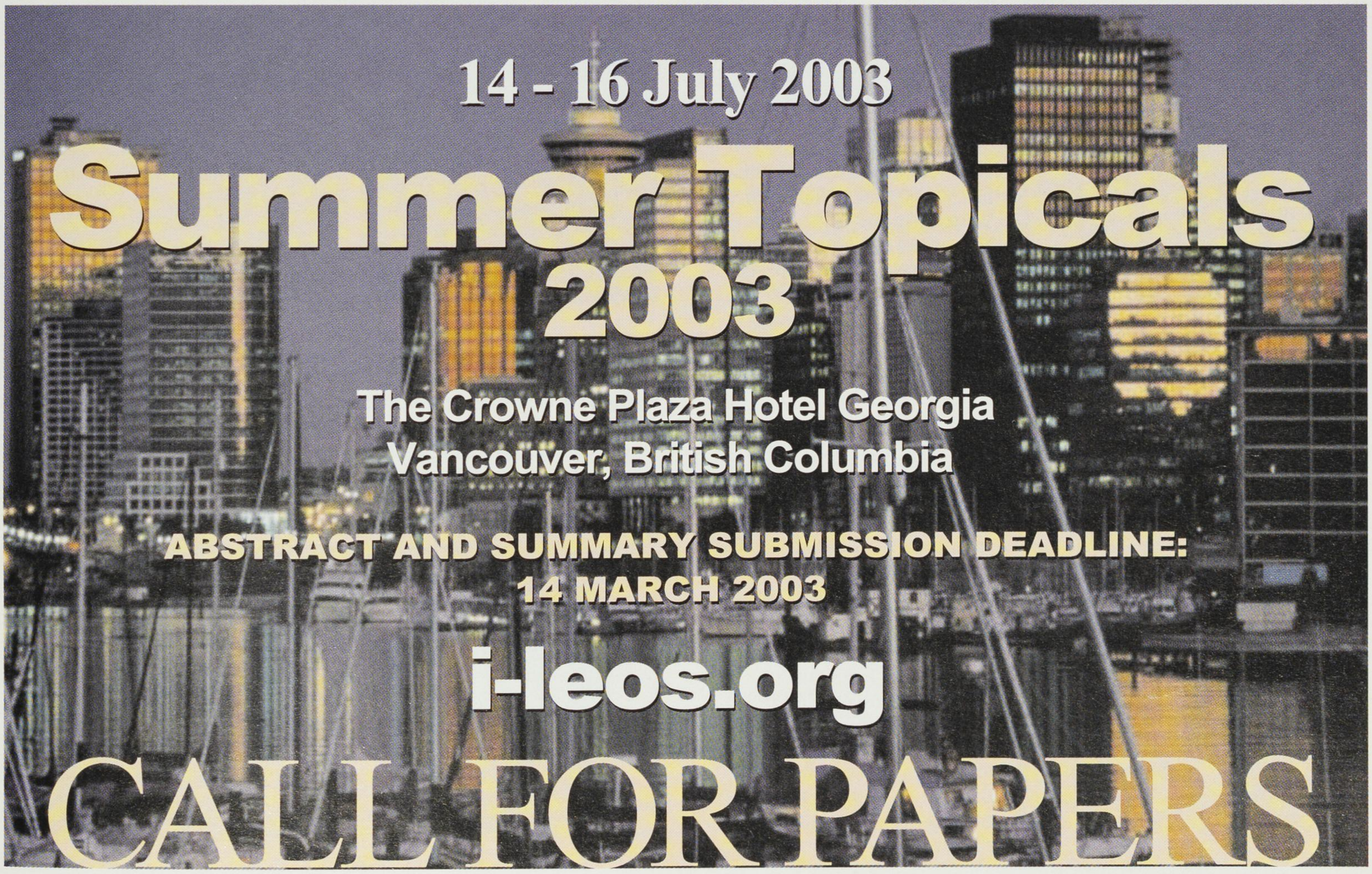
NIR spectroscopy is often called the most rapid non-destructive method of analyzing the chemical composition of a material. It involves measuring the intensity of NIR light reflected or transmitted through a material as a function of wavelength. The resulting intensity versus wavelength curves are called NIR spectra, and the shapes of the curves convey information about the chemical species in the material.

An imaging spectrometer is an instrument that can generate NIR spectra for each pixel in the scene being imaged. The spectrometer uses a variable filter or diffractive optic for spectral selection. The dataset generated by an imaging spectrometer is known as an image cube because there are three dimensions to the data set: X and Y spatial co-ordinates and the center wavelength of the filter passband of the pixel along the Z axis. Imaging spectrometers are used in agricultural inspection, remote sensing, exhaust-gas analysis and pharmaceutical formulation analysis. Figure 5 shows the NIR transmission spectra of two liquids, methanol and water, which have transmission curves with very different shapes. These shapes, known as signatures, can uniquely identify compounds within a scene. One possible application is the detection of spilled chemicals, such as gasoline, by an unmanned aerial vehicle with an InGaAs camera.

Summary

Commercially available InGaAs cameras are enabling many new applications in NIR imaging, making high-performance imaging in an important region of the electromagnetic spectrum possible at a cost that is lower than cooled sensor technology. The FPAs in these cameras are made with techniques developed for the semiconductor industry, which are inherently scalable to high-volume production and lend themselves to automation, enabling further cost reduction and the penetration of new markets with this imaging technology. ●

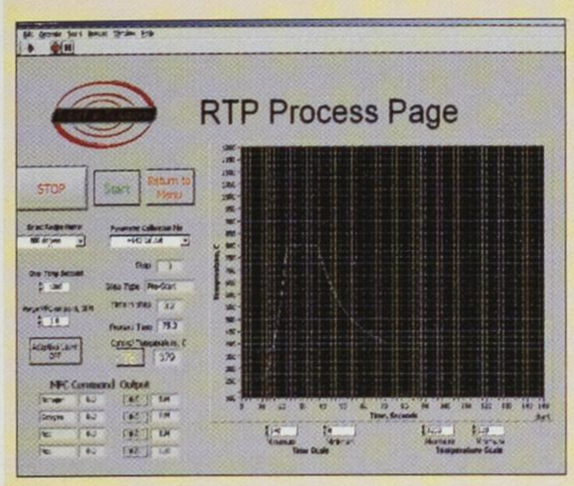
Austin Richards is a senior applications engineer with Indigo Systems Corporation of Goleta, CA. Web www.indigosystems.com.



Heatpulse 610 Software

Total Fab Solutions

Total Fab Solutions announces the release of an advanced process controller for the Heatpulse 610 Rapid Thermal Anneal system. The new GUI process controller replaces the PCAT and Rockwell control systems. New features included in the GUI process controller include: adaptive PID control, graphic time/temperature display, data logging and automated calibrations and troubleshooting. The new software also allows MFC control as an option.

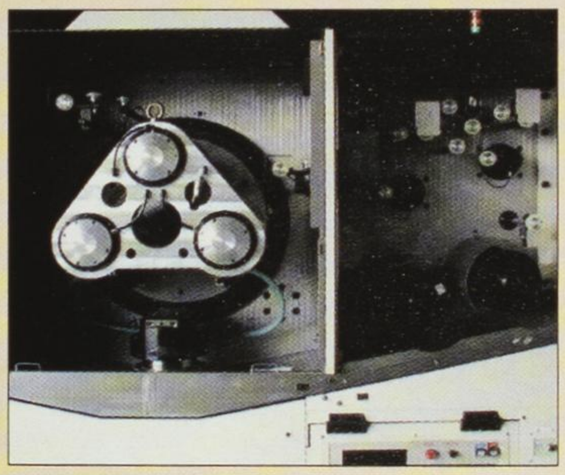


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RFIC makers enjoy handset boom

While fiber-optic component makers and companies supplying materials and equipment continued to struggle, RFIC and LED manufacturers generally performed well in the final quarter of 2002.



After a blockbuster performance by Cree in the December 2002 quarter, when the LED maker recorded a 16% sequential increase in revenue, RF Micro Devices did even better. The RFIC supplier had quarterly sales of $145.8 m, soaring past analysts' expectations of $131.9 m. The revenue figure compared with $119.7 m in the September 2002 quarter and $100.6 m in the year-ago period. The company attributed its success to strong growth in PA sales in response to demand from handset manufacturers. RFMD expects to see sequential revenue growth throughout 2003, combined with pressure on its gross margins due to a decline in average selling prices and a continued shift from MMICs to modules (modules now account for 62% of RFMD's revenue). Plans to mitigate against this decline include converting RFMD's second fab to 6 inch operation.

Market overview

Company	*Symbol*	*Closing price on Feb 18*	*52-week low–high*	*Market cap**
GaAs IC companies				
Anadigics	ANAD	1.88	1.59–14.09	57.5 m
Celeritek	CLTK	6.95	5.01–11.16	85.8 m
Endwave	ENWV	1.02	0.32–4.60	9.1 m
RF Micro Devices	RFMD	6.45	5.159–22.19	1.181 bn
Sirenza Microdevices	SMDI	1.45	1.10–6.55	43.2 m
Skyworks Solutions	SWKS	6.55	2.89–21.60	904.4 m
TriQuint	TQNT	3.00	2.55–13.09	397.5 m
Vitesse	VTSS	2.02	0.62–10.47	409.4 m
Opto companies				
Agilent	A	12.49	10.50–37.99	5.833 bn
Alcatel Optronics	ALAO	7.35	1.50–7.55	121.3 m
Cree	CREE	16.14	8.989–25.42	1.182 bn
JDS Uniphase	JDSU	2.81	1.58–6.90	3.977 bn
Semiconductor materials and equipment companies				
ATMI	ATMI	18.55	11.75–37.10	568.4 m
AXT	AXTI	1.08	0.94–12.00	24.3 m
Emcore	EMKR	2.24	0.98–10.48	82.5 m
Kopin	KOPN	4.5	1.93–10.93	312.2 m
Tegal	TGAL	0.55	0.13–1.53	8.4 m
Trikon	TRKN	4.73	3.25–15.90	66.3 m
Veeco	VECO	13.88	9.14–38.80	404.5 m
European companies (currency data in €)				
Aixtron	AIXG.F	3.17	3.15–23.53	199 m
Bede	BED.L	0.29	0.23–3.19	8.2 m
Bookham	BHM.L	1.23	0.60–2.76	252.7 m
Filtronic	FTC.L	1.33	0.39–6.73	94.76 m
IQE	IQE.L	0.04	0.01–2.93	8.64 m
Picogiga	PGIG.LN	0.35	0.3–5.62	2.3 m
Riber	RIBE.LN	0.8	0.55–5.66	15.1 m
STS	SRTS.L	0.13	0.07–2.58	4.17 m

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

Skyworks and TriQuint

Skyworks Solutions reported $160.2 m in revenue together with an operating profit of $6.4 m and a net loss after deductions of $1.93 m. The December period marked Skyworks' sixth consecutive quarter of revenue growth with improving operating results. The company expects sequential revenue growth in the seasonally weak March quarter, driven by the ramp-up of recent design wins and increasing market share.

TriQuint's revenue grew slightly in the December 2002 quarter to $72.7 m, but the company took several charges and adjustments that contributed to a large loss of $149.6 m. The charges included $49 m relating to excess capacity and facility space in TriQuint's Oregon operation; $15.7 m relating to investments in non-public companies, which are continuing to struggle with the downturn in the technology sector; and $39.9 m for certain intangible assets and goodwill associated with acquisitions. Without the charges and adjustments, TriQuint would have reported a loss of $2 m. TriQuint's annual revenue for 2002 was $267.3 m, a drop of 20% compared with $335 m in fiscal 2001. The company believes that its revenue in 2003 could be in the $340 m to $375 m range, helped by growth in the wireless market and $50 m to $75 m in revenue from the former Agere optoelectronics business.

Celeritek and Sirenza

Celeritek's revenue was $10.5 m, down 32% compared with $15.5 m in the previous quarter. The company expects sales of $8 m to $9 m in the March quarter. Celeritek's semiconductor revenue was $5.5 m compared with $11.4 m in the previous quarter. This drop reflects the previously announced decision of Motorola, a primary buyer of Celeritek's PA modules, to discontinue its strategy of dual-sourcing PA modules. Subsystem revenue in the December 2002 quarter grew to $5.0 m compared with $4.1 m in the previous quarter, and was all from defense customers.

Sirenza Microdevices reported December quarter revenue of $5.8 m, along with a net loss of $5.1 m after charges relating to a 7% reduction in force and consolidation of its facilities. Sirenza also recorded an impairment charge of $2.9 m to reduce the fair market value of its investment in GaAs and InP foundry Global Communication Semiconductors.

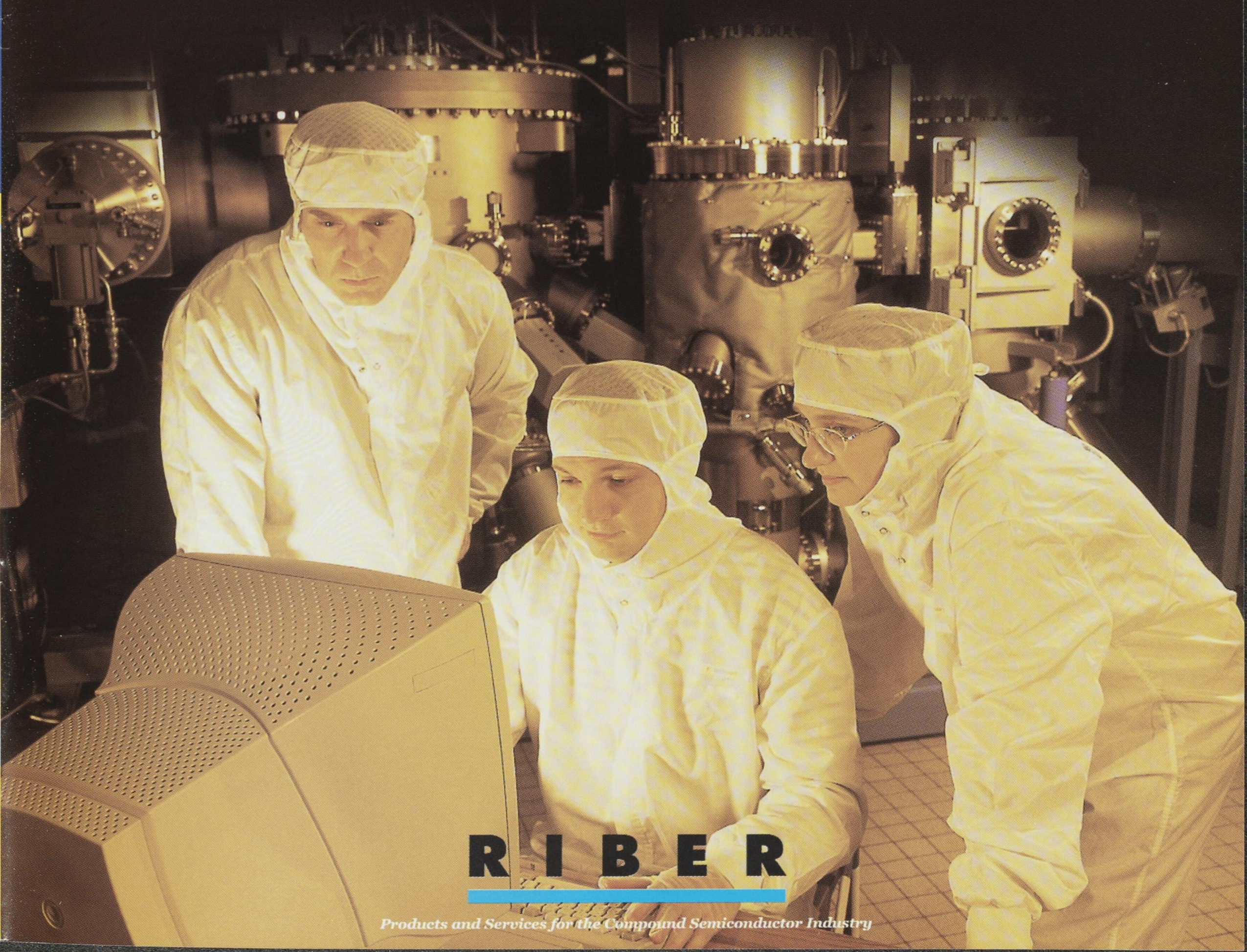
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