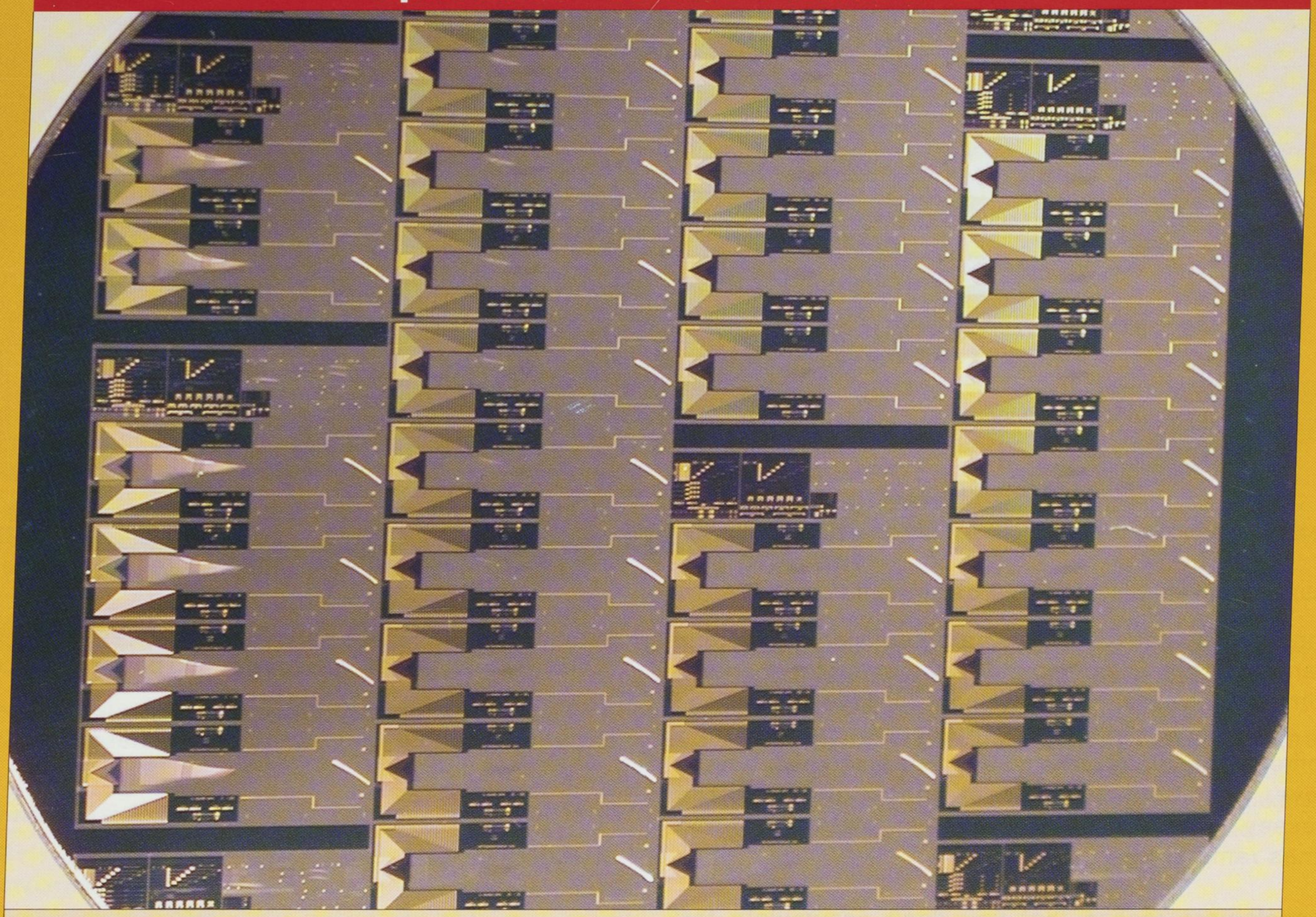
# COMPOUND SEMICONDUCTOR

## Three-Fives and Silicon Heterostructures

April 2003 Volume 9 Number 3



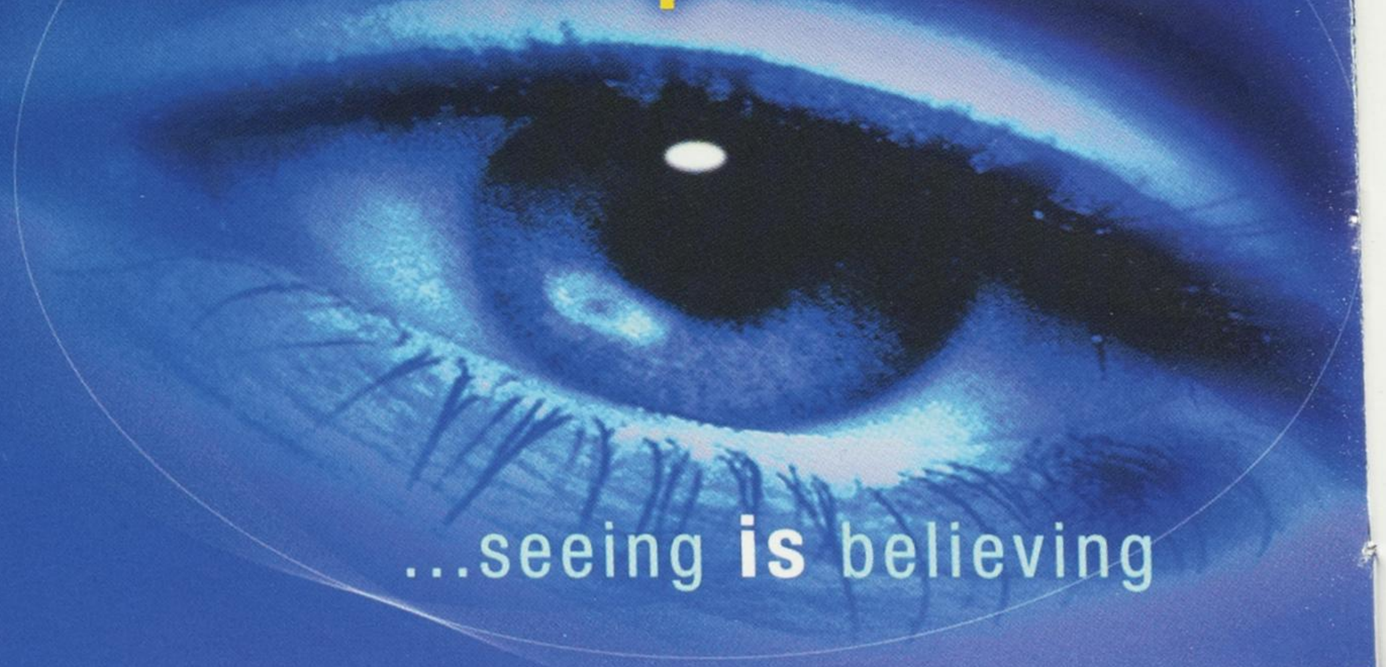
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# Monolithic integration on InP leads to novel functionality

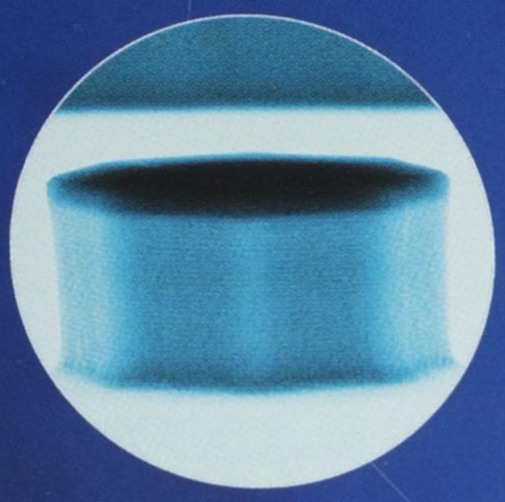
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| Market reports for lasers and LEDs | GaN PAs move closer to market | SSOI improves CMOS performance |

# There's no substitute for experience.

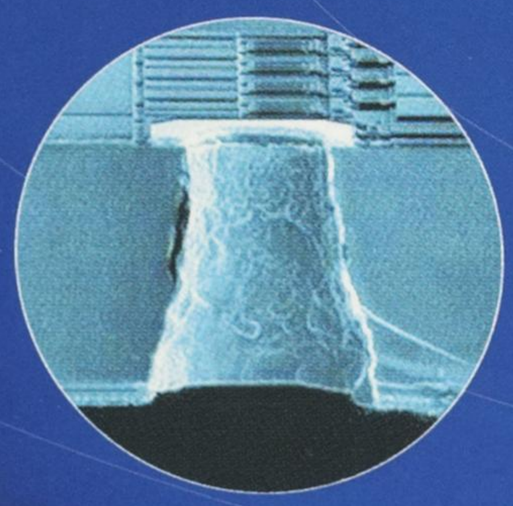


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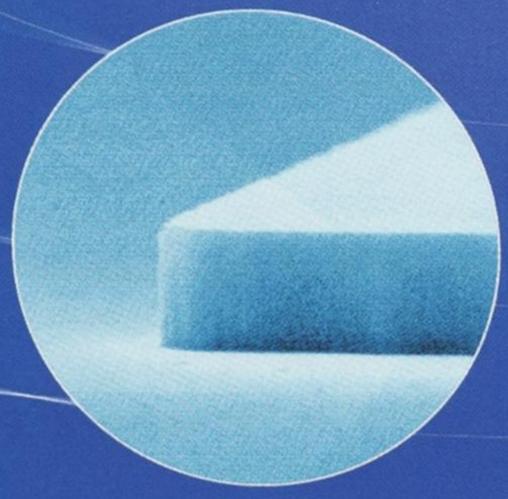


InP-based
VCSEL etch

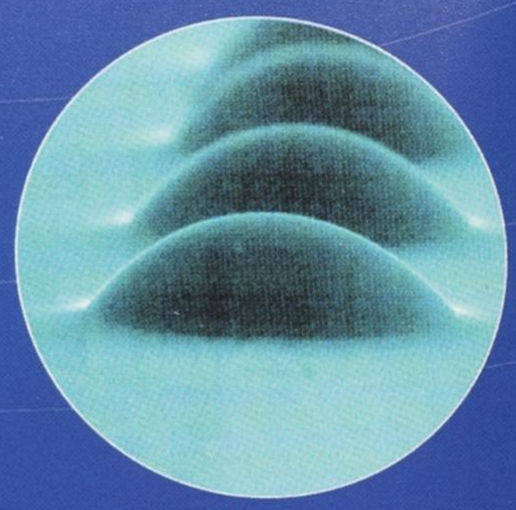
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GaAs
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GaN
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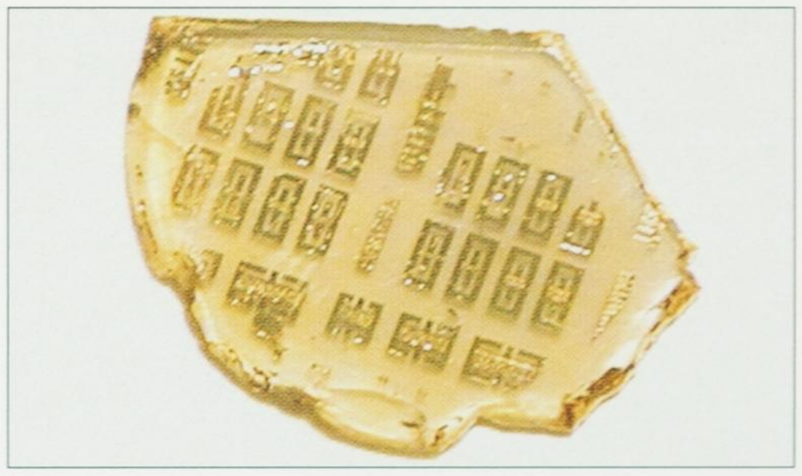
# COMPOUND SEMICONDUCTOR

## Three-Fives and Silicon Heterostructures

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AlGaN/GaN/AlN HFETS have been grown on bulk AlN substrates **p14**



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Everybody likes to see rising revenues and growing profits with each passing quarter, but it's worth taking a look at what else appears on financial statements.


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**On the cover:** *A fully processed 4 inch InP wafer containing 34 SurePath optical power monitor chips fabricated by MetroPhotonics – see p17.*

# COMPOUND SEMICONDUCTOR

**Three-Fives and Silicon Heterostructures**

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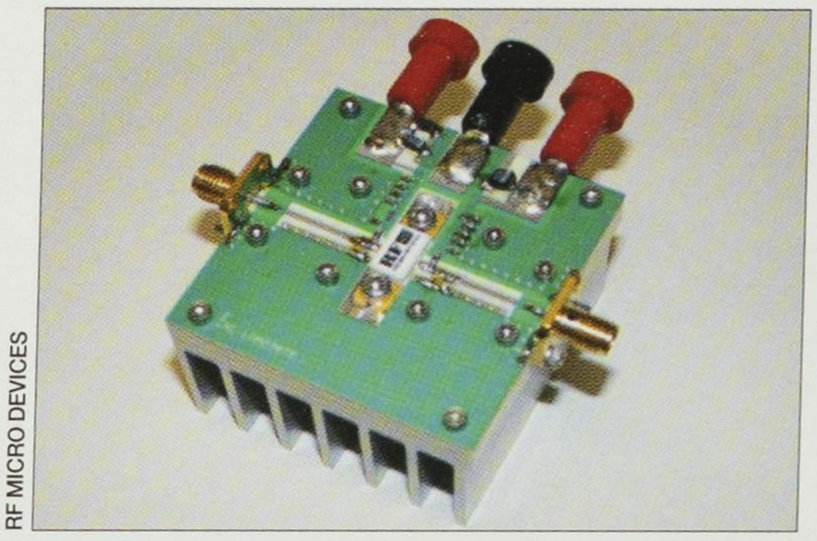
# RFMD moves GaN PAs closer to market

**By Jon Newey**

RFMD has achieved what it describes as a major milestone in the commercialization of GaN-based RF power technology for base-station applications. It has demonstrated 7 W wideband GaN PAs designed for DCS (1800–1880 MHz), PCS (1930–1990 MHz) and UMTS (2110–2170 MHz) wireless infrastructure applications. The PAs exhibit 11 dB of gain at 20 V operation, with gain slope of ±0.2 dB over the entire range and better than ±0.1 dB over the DCS and PCS bands. Engineering samples of the wideband GaN PAs are being evaluated by several infrastructure OEMs. The company expects to sample higher-power, higher-gain devices in the September quarter.

The devices are being fabricated at RFMD's facility in Charlotte, NC (formerly RF Nitro Communications), using its 0.9 μm gate-length HEMT process. SiC and sapphire substrates are being used in the development of the devices. Despite the performance advantages that can be gained when using SiC, sapphire substrates are relatively cheap, and 4 inch wafers are readily available. However, thermal management is an issue due to sapphire's inferior thermal conductivity. RFMD is investigating ways of taking the heat out of the top of the devices.

For some time now, GaN has been seen as a possible replacement for Si LDMOS PAs in wireless basestations. The power density possible in GaN devices is much larger than in LDMOS or GaAs PHEMT devices. "The gate periphery is smaller and impedance matching is therefore easier for the GaN device than for LDMOS," said Dave Grider, senior manager for GaN programs with RFMD. "Because the impedance mismatch is smaller, it is easier to match the device over a broader frequency range, giving better gain characteristics with frequency." Having smaller devices that require less cooling infrastructure not only lowers the overall cost of basestations, but also brings the advantage that the amplifiers can be located on the basestation tower, nearer to the antenna. The means that more air cooling can be used and losses in moving the signal from a ground-based amplifier up the tower to the antenna are eliminated.



RF MICRO DEVICES

RFMD's 7W tri-band (DCS/PCS/UMTS) GaN power amplifier mounted on a test board.

The Charlotte facility, although small compared with RFMD's GaAs operation in Greensboro, NC, has all of the processes required to manufacture GaN devices on 2 and 4 inch substrates, and is capable of handling the required GaN volumes for the foreseeable future. Grider concedes that as the technology takes off, a decision will need to be made as to how the company moves beyond the volumes that the Charlotte site is capable of. Options would include expanding in Charlotte or utilizing facilities elsewhere within RFMD, although Greensboro is currently working close to its full capacity (*Compound Semiconductor* December 2002 p10).

However, such issues lie some way ahead, and placing engineering samples with customers has been an important first move for RFMD. "There has been a lot of rhetoric about getting GaN devices into cell phone basestations," said Grider. "It was important to get something into the hands of a select set of customers, giving them access to some real technology that they could put on their test benches. Now we're anxious to get their feedback and hear about any issues that they see arising."

# Zia Laser and Emcore enter into manufacturing agreement

Quantum-dot laser pioneer Zia Laser has entered into a sublease and contract manufacturing agreement with Emcore. Under the agreement, Zia will sublease cleanroom space and supporting infrastructure within Emcore's Albuquerque facilities, where its PhotoVoltaic and Fiber Optics divisions are based. Zia will remain headquartered nearby at the University of New Mexico Science and Technology Park.

Zia will operate its own MBE reactor within Emcore's fab, and will receive technical support from Emcore in the areas of material characterization, wafer processing and device packaging. Having an MBE system in an Emcore facility may seem strange given that a large part of Emcore's business is in manufacturing MOCVD systems. However, Emcore has been expanding its fiber-optic components activities with some recent high-profile acquisitions, including Agere's west-coast optoelectronic operations and VCSEL transceiver supplier Alvesta (*Compound Semiconductor* March 2003 p5). But the deal with Zia is more than just renting out lab space.

"Emcore receives rent from us and there is a technology exchange occurring," Zia's Chris Wiggins told *Compound Semiconductor*. "It is a strategic partnership for both of us. We provide higher-performance, lower-cost solutions for uncooled optical communications while Emcore, post-acquisition of Agere's west-coast operations and the purchase of IP from Alvesta, has emerged as a leading provider in high-performance optical components. They are a potential customer [for QD lasers] as well as a potential vendor of their services and packaging capabilities."

At present there are no plans to move the MBE growth of quantum-dot laser material to Emcore's MOCVD platforms. The required high dot densities and control over dot size and distribution is not possible by MOCVD. "Our high-volume, high-throughput production MBE system will be able to provide the world's supply of quantum-dot solutions without having to transfer the process to MOCVD," explained Wiggins.

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# Sony unveils first violet-laser DVD recorder

Sony is to release a Blu-ray DVD recorder in April that utilizes a GaN/InGaN 405 nm violet laser to store up to 23 Gbyte of data. The recorder will use the format developed by the Blu-ray consortium, of which Sony is a founder member, and each disc has the capacity to store a 2 h high-definition TV program (*Compound Semiconductor* April 2002 p3). Last December, Sony formed an alliance with Nichia to develop nitride-based semiconductor lasers for the Blu-ray Disc recording format, with both companies planning to commence mass production by spring 2003.

Initially, Sony's new machine will only be available in Japan, and will be priced at ¥450,000 (about $3800), with discs retailing for ¥3500 each. Conventional DVD recorders using red lasers are priced at ¥50,000–70,000. With a growing number of households in Japan, the US and elsewhere now receiving high-definition TV from digital satellite broadcasts, Sony is aiming to gain a head start in this market.



SONY

Sony is the first company to launch a new generation of DVD recorders that use GaN/InGaN 405 nm violet lasers

Sony's Blu-ray machine will be able to play red-laser discs using the DVD-R and DVD-RW formats, but not those using the DVD-RAM or DVD+RW formats. A second industry group led by Toshiba is promoting an alternative to the Blu-ray format, which it says will be less expensive and more compatible with existing recorders. Toshiba hopes to have a violet-laser recorder on the market in about a year's time.

# Global handset sales grew 6% in 2002

Worldwide mobile handset sales totaled 423.4 million units in 2002, a 6% increase from 2001, according to Gartner Dataquest. Fourth-quarter mobile phone sales totaled 122.6 million units, an increase of 14% compared with the same period in 2001, and a rise of almost 15% sequentially. Worries that replacement handset sales would be affected by the delayed implementation of mobile data services were dispelled as the roll-out of models with color displays and cameras boosted replacements.

"This is an encouraging trend, because as carriers and manufacturers determine how to better align devices with applications and services, the market may prove stronger than expected during 2003," said Bryan Prohm, a senior analyst with Gartner Dataquest.

Nokia maintained its top position, cornering 35.8% of the global market, with product delays at Motorola keeping it a distant second at 15.2% market share. The most impressive growth came from Samsung, which grew its unit sales by 47.6% to 41.68 million units, giving it just under 10% of the market.

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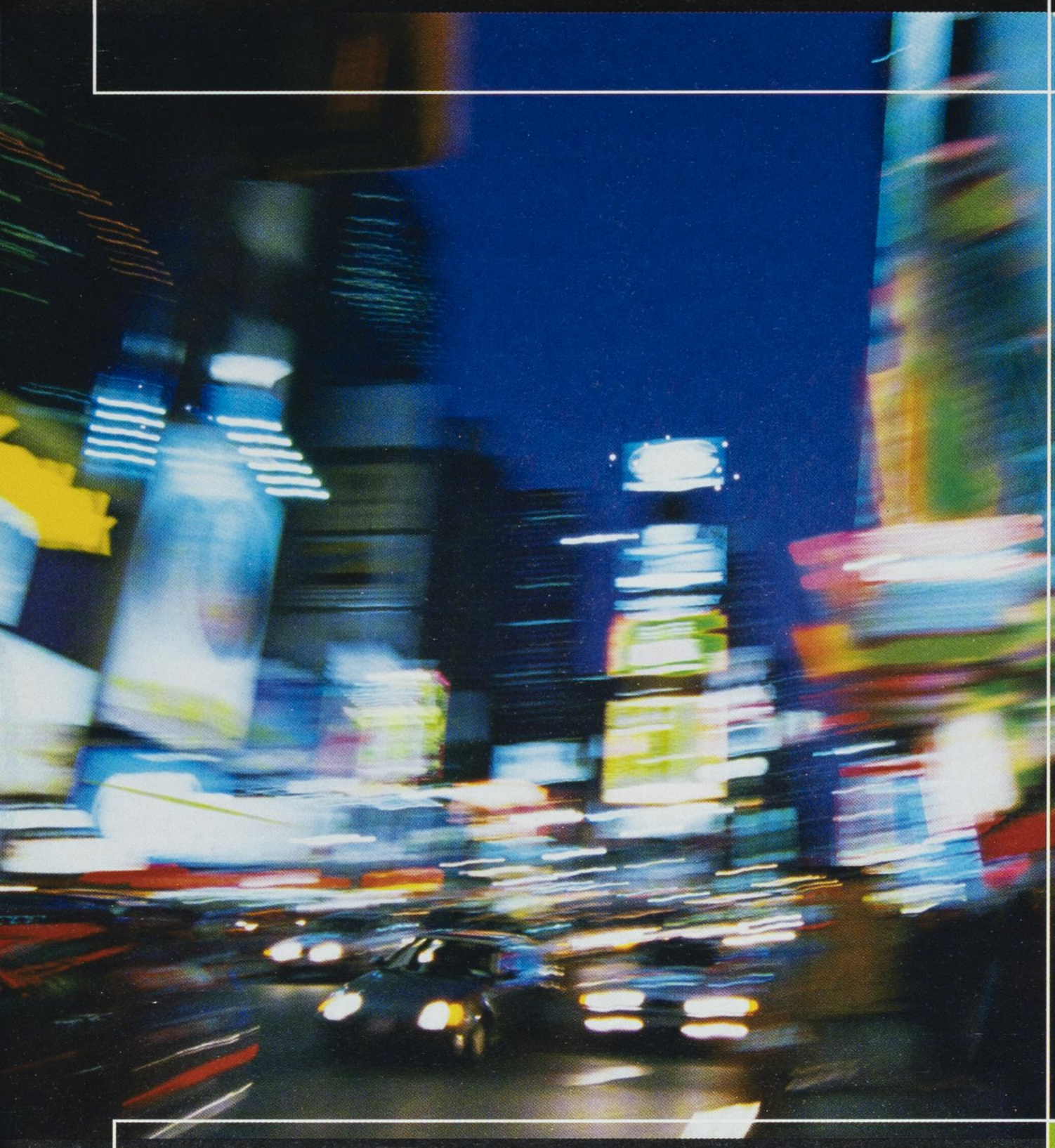
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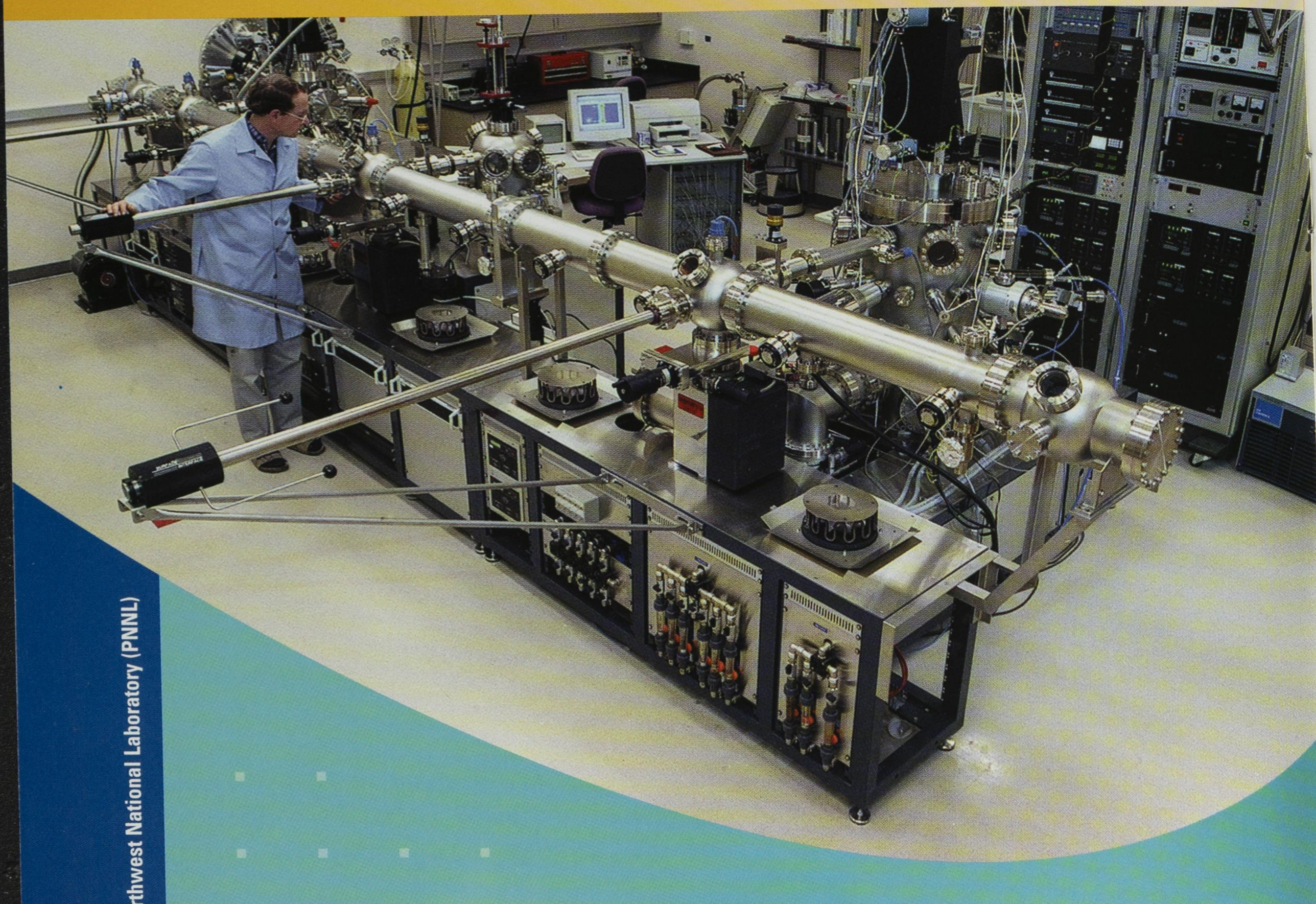
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INSTRUMENTS

# Skyworks and RFMD find compatibility

The rivalry between RFMD and Skyworks Solutions has continued with the further announcements that both companies are providing radio solutions for handsets that are compatible with GSM/GPRS baseband processors. Shortly after RFMD announced that its Polaris Total Radio was compatible with Intel's PXA800F cellular processor (*Compound Semiconductor* March 2003 p9), the same module was certified as being compatible with a baseband processor developed by National Semiconductor.

Meanwhile, Skyworks announced that its GSM/GPRS direct conversion transceiver and PA module with integrated power control are also qualified to operate with the Intel PXA800F processor. A Korean handset manufacturer, Maxon Telecom, had previously announced that its new GSM/GPRS handset will combine the Skyworks and Intel products.

Maxon's new data-enabled MX-E320 "entertainment phone" will be available in late 2003, and will incorporate Skyworks' second-generation single-chip 8 × 8 mm CX74063 direct conversion transceiver and 8 × 10 mm CX77315 PA module with integrated power control functionality. The MX-E320 features two color LCD displays, a built-in digital camera, FM stereo radio, music/video players and Web browsing capability.

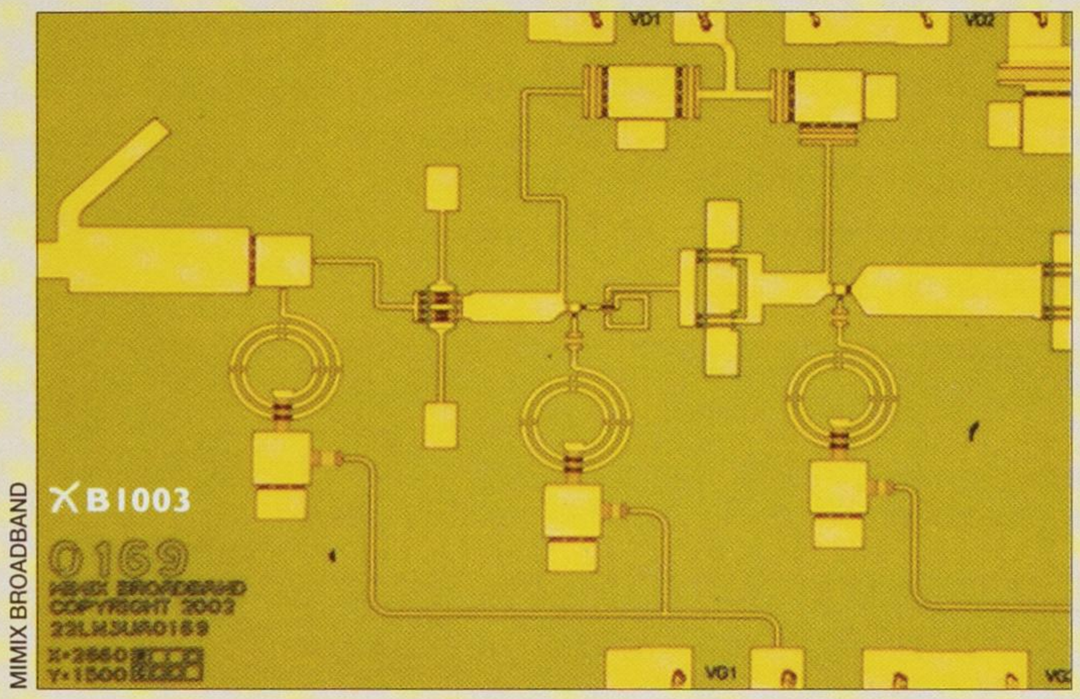
"Skyworks' RF and PA technologies, when coupled with Intel's baseband processor, enabled us to optimize our cellular phone architecture to create an entirely new class of entertainment-enabled phones that will allow consumers to experience a variety of emerging applications without sacrificing handset size or battery life," said Hyeon Kim, president and CEO of Maxon.

## New devices from Anadigics, Raytheon, Agilent and Mimix

● **Anadigics** has introduced two small quad-band PAs and a family of PHEMT switches. Developed using Anadigics' InGaP HBT technology, the AWT6123 is a low-cost, quad-band PA for GSM handsets in a 6 × 8 mm module package. The device provides manufacturers with 55% PAE in the GSM850/EGSM900 bands and 50% in the DCS/PCS bands. In addition, the AWT6123 provides +35 dBm GSM output power and +32.5 dBm DCS/PCS output power from a single 3.5 V supply.

The AWT6108 provides integrated power control in a 7 × 10 mm package. By integrating CMOS power control, the AWT6108 eliminates the need for couplers and other power-control circuitry, thereby reducing component count, simplifying handset design, and improving overall system efficiency.

Anadigics has also introduced four new PHEMT RF switches to deliver low insertion loss, high linearity and high isolation.




A new PHEMT-based three-stage buffer amplifier MMIC from Mimix operating in the 16–29 GHz band.

● The new RMPA2453-251 from **Raytheon RF Components** is an InGaP HBT linear WLAN PA for 802.11b/g applications. The low profile 16 pin 3 × 3 mm package with internal matching on both input and output to 50 Ω minimizes PCB space and allows for automated integration. The on-chip detector provides a power-sensing capability, while the logic control provides power-saving shutdown options. Small signal gain is 26 dB, output power is 26.5 dBm, and the device is operated from a 3.3 V single positive supply.

● **Agilent Technologies** has introduced a new series of enhancement-mode PHEMT (E-PHEMT) PA modules for CDMA and GSM mobile handsets. Two CDMA modules offer 40% PAE, while a GSM tri-band module offers up to 60% in the GSM band and 56% in both DCS and PCS bands. The module is also capable of Class 12 operation for 2.5G applications such as GPRS service. The devices, manufactured at Agilent's 6 inch fab in Fort Collins, CO, are being shipped to multiple customers in volumes exceeding 500,000 units per month.

# Size is everything for RFMD, Anadigics

As the manufacturers of modules for wireless handsets continue the struggle to pack more functions into a smaller package, RFMD and Anadigics have released modules that both carry the "world's smallest" tag.

RFMD has introduced the RF3133, the smallest available quad-band PA module with integrated power-control circuitry, extending the company's PowerStar family of PA modules. The 7 × 10 mm module is manufactured using GaAs HBT technology for the PA portion, with CMOS used to integrate the power-control circuitry. All PowerStar PA modules eliminate the need for directional couplers, detector diodes, power control ASICs and other power-control circuitry, giving handset manufacturers the benefits of reduced component count, improved production yield and simplified phone calibration.

"By integrating critical passive components onto our GaAs HBT process technology, we achieved not only a smaller footprint but also a highly precise PA matching network," said Joe Grzyb, general manager of PA products at RFMD. RFMD has sold more than 10 million PowerStar products to date, and the company anticipates the products will drive GSM/GPRS market share gains in 2003.

Anadigics is claiming that its new quad-band integrated RF transmit module is the world's smallest for GSM/GPRS and GPRS/UMTS handset applications. The AWT6201 PowerPlexer is housed in a 10.5 × 11 mm module, and combines Anadigics' InGaP HBT PAs, PHEMT antenna switches, integrated passive filters, and integrated CMOS power-control circuitry.

# Celeritek shareholders unite

The maneuvering between GaAs IC manufacturer Celeritek's board of directors and its shareholders is continuing. Some of Celeritek's shareholders, who collectively own 10.26% of the company's common stock, have formed a committee with the aim of encouraging the board of directors to improve Celeritek's corporate governance and to be more receptive to formal purchase offers. In September 2002, the company's board rejected a takeover bid from Anaren Microwave (*Compound Semiconductor* September 2002 p9).

A statement from the committee said: "The board appears to be uninterested in maximizing shareholder value...[and] apparently has rebuffed an indication of interest from a potential acquirer." The committee is also concerned by zero-interest company loans to certain employees.

Less than three weeks later, Celeritek announced that it had retained financial advisors and legal counsel, and planned to implement various measures. The company will appoint a lead independent director to liaise between the board and senior managers, as well as establishing a committee of independent directors to look into the corporate governance issues.

# Siemens selects Endwave transceivers

Endwave is to supply wireless transmitter/receiver (Tx/Rx) modules for the Siemens SRA L family of digital radios. The modules support continuous phase modulation and enable data rates from 8 to 32 Mbit/s. The SRA L family of digital radios operate at 7, 8, 11, 13, 18, 23, 26 and 38 GHz. Siemens will deploy the radios in certain markets within Europe in support of third-generation (3G) wireless networks.

# Anadigics, RFMD & Stratedge achieve ISO certification

Both Anadigics and packaging specialist Stratedge have received ISO 9001:2000 certification in recognition of their quality management systems. In 1993, Anadigics became the first GaAs IC maker to achieve ISO certification. The revised ISO 9000 standards include a greater emphasis on management practices, increased monitoring of continual quality improvement processes, and a greater focus on customer satisfaction levels. For Anadigics, the certification process involved an independent, in-depth review of all product development, manufacturing and customer support processes

RFMD has received ISO 14001:1996 certification covering its environmental management systems, indicating that its operations are conducted in a manner that minimizes potential environmental risks.

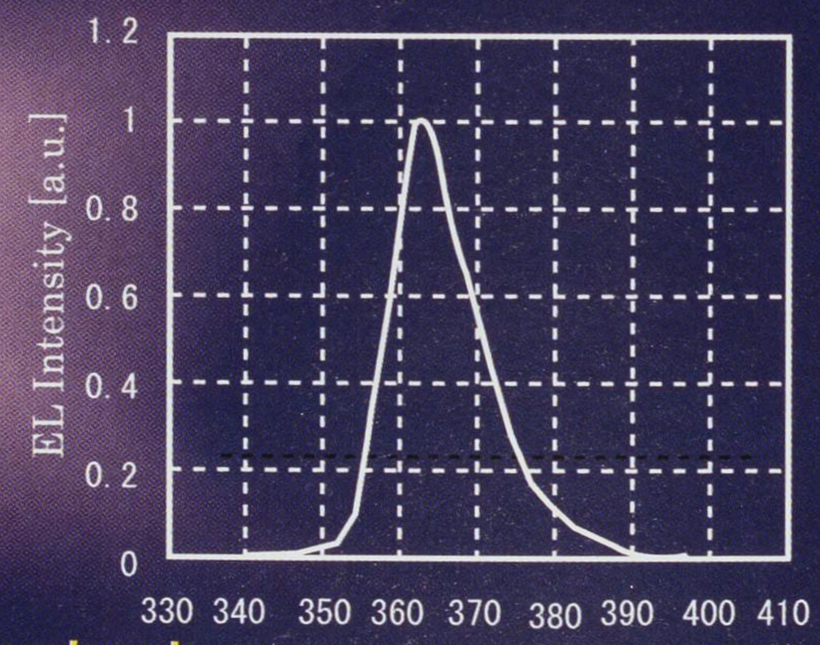

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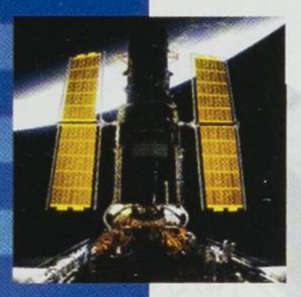
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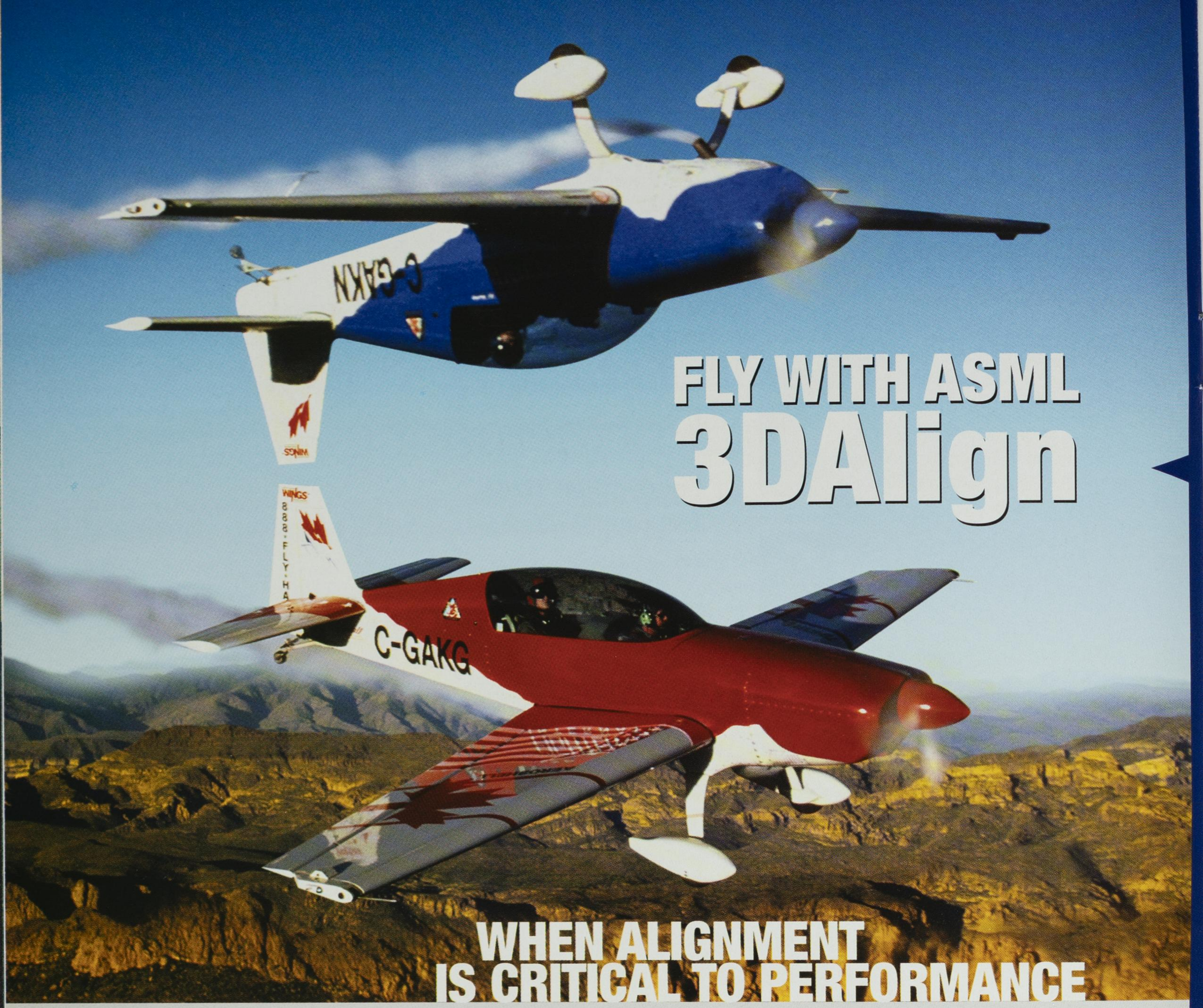

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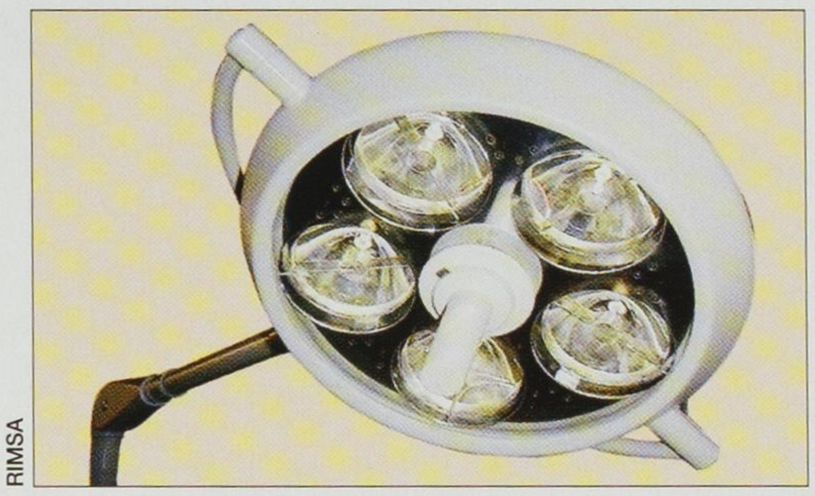
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# Surgical lamp uses LEDs

Rimsa, a medical and industrial lighting manufacturer based in Italy, is using Lumileds Lighting's Luxeon V LEDs to develop the world's first surgical lamp with 100% cold light and a 50,000 h life. The PentaLED lamp, scheduled for release in the third quarter of 2003, will equip surgeons with a cooler, longer-lasting and more energy-efficient alternative to conventional halogen-based lights. The Luxeon V is no stranger to medical applications, having been incorporated into a number of light sources for the curing of polymers used in dental surgery (*Compound Semiconductor* January/February 2003 p11).


RIMSA

Using only five LEDs in the surgical lamp, which consumes only 25 W of power, gives 600 lm of output and does not generate excessive heat in the operating theatre.

Rimsa selected the Luxeon V because it can generate sufficient light for a surgical environment with only five emitters. At 120 lm per emitter, the five-emitter configuration will give the PentaLED lamp a light output of 600 lm with 50,000 lux. The inherent energy efficiency of LEDs will allow the PentaLED lamp to operate with only 25 W of power, a third of that required by a comparable halogen lamp. The use of solid-state illumination will also allow the lamp to last up to 25 times longer than halogen products.

The cool LED light beam will increase physician comfort in the operating room and help prevent the open wound area from drying out, thereby eliminating the need to keep the area humid for the patient's safety.

# Golden Dragon may be popular with lighting designers

Osram Opto Semiconductors has launched its Golden Dragon series of high-brightness LEDs, which combine high output power chips with low-profile surface mount packaging. This combination is much in demand from the designers of lighting systems. The output power from the packaged devices is 1 W, and the 700 × 700 $\mu m^2$ die are housed in a 1.8 × 6 × 7 mm surface mount package. Although the packages occupy four times the surface area of Osram's established Power Topleds, achieving a similar lighting intensity as one Golden Dragon LED requires six Power Topleds. Optical efficiency is 20 lm/W, and lifetime is up to 20,000 h, depending on operating and ambient conditions.

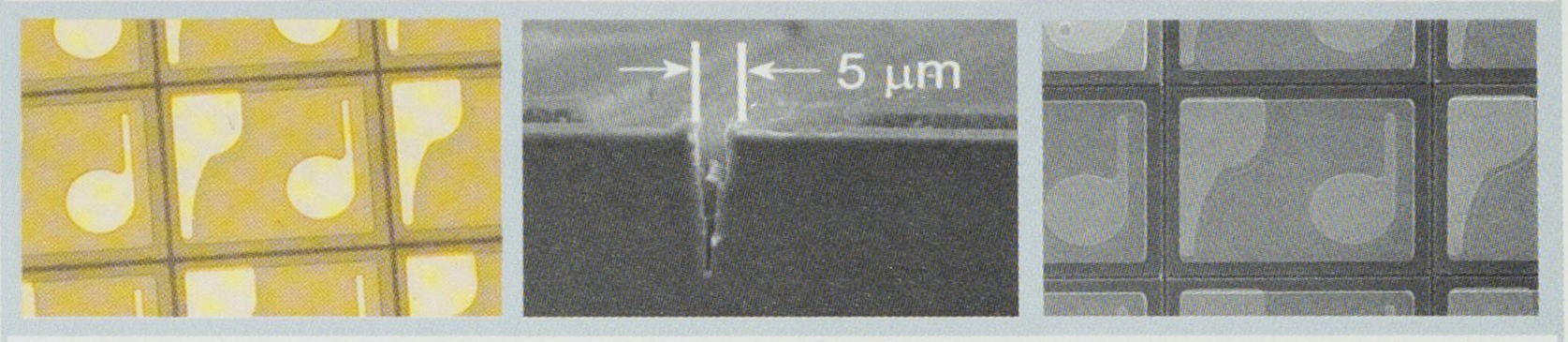
Osram is sampling red and yellow devices, with mass production scheduled for mid-2003. White versions are in development and will begin sampling in late 2003.

# Toyoda Gosei to boost LED capacity by 70% this year

According to a report in the *Nihon Keizai Shimbun*, a Japanese newspaper, Toyoda Gosei has embarked upon a ¥1.5 billion (about $13 million) program to boost its monthly production capacity for GaN-based LEDs by about 70% during 2003 to 150 million units. The company has been strengthening its LED operations since resolving its long-running patent dispute with Nichia last fall (*Compound Semiconductor* December 2002 p22). Toyoda Gosei expects sales from its LED operations to increase by 80% year-on-year to ¥25 billion ($208 million) for the year ending March 2003.

Toyoda Gosei is seeing the strongest demand for its LEDs from the mobile phone market, where they are used as backlights for keypads and liquid-crystal displays. The company is also enhancing its overseas sales operations for LEDs. In China, where the use of mobile phones is growing very rapidly, it is to set up a sales firm jointly with Mitsui. At present, Toyoda Gosei sells LEDs through local subsidiaries and sales agents in China and other countries.

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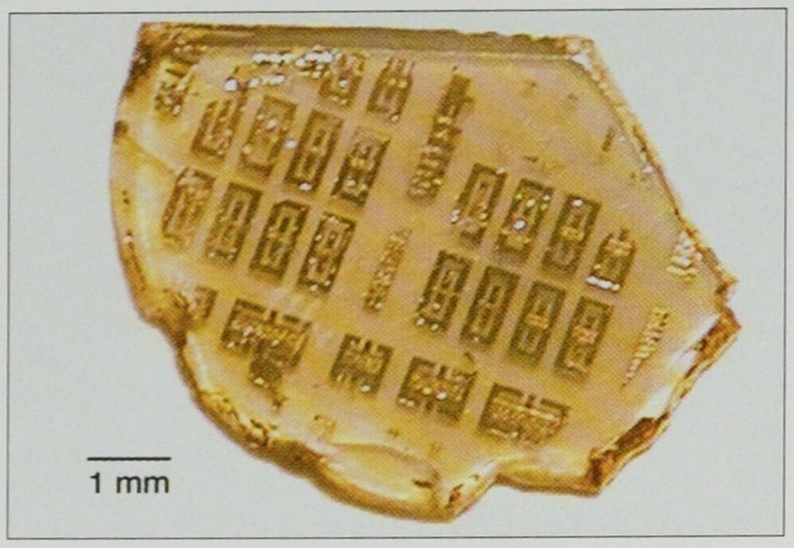
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# Researchers get to grips with bulk AlN

A collaborative effort between Sensor Electronic Technology (SET), Rensselaer Polytechnic Institute, the University of South Carolina and Crystal IS has resulted in AlGaN/GaN HFETs grown and processed on bulk AlN substrates. The group reported its results in the February 24 issue of *Applied Physics Letters*. Although steady progress is being made in the bulk growth of III-nitride substrates, the large-area substrates required for manufacturing lattice-matched III-nitride-based electronic and optoelectronic devices have yet to emerge. However, that is not stopping epitaxy and device development work being carried out on the small irregularly shaped substrates that are currently available.

To date, the best-performing high-power devices have been fabricated on SiC substrates, because they offer a better lattice match than Si or sapphire, and have a high thermal conductivity. AlN substrates have a higher thermal conductivity than SiC, and provide a very good lattice match to GaN and AlGaN. AlN is also highly resistive, an important consideration in reducing parasitic losses for devices intended for RF operation. The group's HFET epilayers were deposited by MOCVD onto substrates measuring approximately 8 × 8 mm and polished 10° off the c-axis. The structure comprised a 0.3 μm AlN homoepitaxial layer followed by an undoped 0.1 μm GaN layer capped with 25 nm of $Al_{0.2}Ga_{0.8}N$. The same device layers were grown onto SiC substrates so that direct comparisons could be made. Thanks to the excellent lattice match to AlN, the epilayers had dislocation densities of $10^4$–$10^5$ $cm^{-2}$, about four orders of magnitude lower than is achievable on SiC. The sheet carrier densities and mobilities were $10^{13}$ $cm^{-2}$ and 1100 $cm^2$/Vs for the layers on AlN, and $1.7 \times 10^{13}$ $cm^{-2}$ and 1200 $cm^2$/Vs for layers on SiC.



SENSOR ELECTRONIC TECHNOLOGY

AlGaN/GaN/AlN double HFETs grown and processed on a bulk AlN substrate.

HFETs 200 μm wide with 1.5 μm gate lengths were fabricated with Ni/Au Schottky gates. The forward turn-on voltage was 1.2 V and the reverse bias leakage current was 5 μA at a gate bias of –10 V. The maximum saturation current was higher in the devices on SiC, at 650 mA/mm, compared with 600 mA/mm for devices on AlN. The difference is likely to be the result of the larger sheet carrier density of the devices on SiC. The devices showed $f_t$ and $f_{max}$ values of 5 and 13 GHz respectively.

While the results may not look hugely impressive, they represent important early steps on the path to high-performance, manufacturable devices on AlN substrates. "At this stage of transistor-on-AlN development, a key obstacle in obtaining high RF powers is the small size of the available substrates," said co-author of the paper, Remis Gaska of SET. "It makes processing of the devices very difficult, especially lithography due to sample edge effects. We believe that power numbers will catch up pretty fast once the size of the workable area of the substrate becomes more than 10 × 10 mm."

## Hitachi Cable to mass-produce GaN substrates using VAS

Hitachi Cable, a Japanese substrate and epiwafer manufacturer, plans to mass-produce GaN substrates for blue laser diodes, according to the *Nikkei Business Daily*. The company is building a production line in Ibaraki Prefecture to produce 2 inch GaN substrates. It is now marketing the substrates, and initially intends to produce 300 units per month.

Hitachi is using a newly developed growth method called void-assisted separation (VAS) that allows it to mass-produce GaN with high uniformity and with 10,000 times fewer crystal defects than other methods. The technique was described in a paper in the *Japanese Journal of Applied Physics* (2003 **Pt.2 (1A/B)** L1) and also in *Compound Semiconductor* (March 2003 p23). It involves the deposition of a thin film of perforated titanium on the sapphire, which facilitates the growth of high-quality GaN. When cooled, the GaN is easily removed from the titanium-coated sapphire.

## Sirenza Microdevices awarded its first SiSiC technology patent

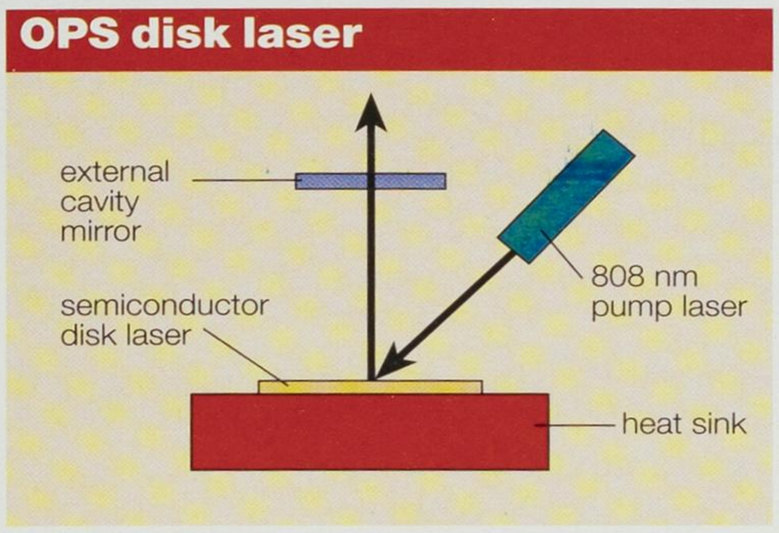
Sirenza Microdevices, a fabless RFIC supplier based in Sunnyvale, CA, is aiming to challenge the emergence of GaN for high-power applications by using Si LDMOS-type devices fabricated on SiC substrates. The company has been issued US Patent 6,521,923 entitled "Microwave field effect transistor structure on silicon carbide". This is Sirenza's first patent concerning its Si-on-SiC, or SiSiC, technology.

The patent describes a Si-based FET structure grown or bonded onto a SiC substrate for devices operating at 1–4 GHz. The structure allows the relatively low cost of Si LDMOS to be combined with SiC's superior thermal properties. GaN-based devices are widely thought of as eventual replacements for Si LDMOS in many applications, because of GaN's ability to maintain RF performance at high powers and high temperatures. Sirenza thinks that its SiSiC approach could significantly raise the bar for competing high-power technologies such as GaN. A major advantage of the SiSiC approach is that it uses standard, low-cost silicon processing technology. Sirenza says that its SiSiC structure offers high-power microwave performance beyond that currently available from any other semiconductor technology. The patented device structure, coupled with other device improvements, will be integrated into the company's future power amplifier module products targeting the wireless infrastructure market.

"This innovation makes possible a new class of semiconductors demonstrating significant improvement in saturated output power, in power-added efficiency and in power gain over current state-of-the-art LDMOS devices," said Pablo D'Anna, director of LDMOS technology for Sirenza. "Additionally, this technology can lead to major reductions in thermal resistance, resulting in lower junction temperatures and enhanced long-term device reliability."

# Osram's disk laser sets a new record for power

Researchers at Osram Opto Semiconductors in Regensburg, Germany, have achieved record output powers from an optically pumped semiconductor (OPS) disk laser. An output power of 8 W at 980 nm was recorded for an optical pump power of 19 W, setting a new record for both power and efficiency.




The basic set up for an OPS disk laser.

OPS disk lasers, also referred to as vertical external cavity surface-emitting lasers (VECSELs), combine the advantages of diode-pumped solid-state (DPSS) disk lasers and VCSELs to give high output powers with round beam shapes. DPSS disk lasers use a thin (100–200 μm) disk of laser gain medium, such as Nd:YAG, bonded to a heat sink with a high reflection coating between the disk and heat sink. The disk is optically pumped by a diode laser and because the disk is thin, laser reabsorption is limited, resulting in a low lasing threshold and high efficiency, while heat is easily dissipated into the sink. As no electrical connections are involved, heat originating from contacts is not a consideration for this type of laser and the output power is adjusted by controlling the size of the pump laser spot.

Osram Opto's OPS disk laser uses a GaAs-based epitaxial structure bonded epi-side down to a copper heat sink using soft solder. After bonding, the substrate is removed. An 808 nm pump beam impinges upon the epitaxial structure at 45°, and the emitted light enters an external cavity with a partially transparent laser mirror at the opposite end to reflect light back into the cavity and couple a portion of the light out of the cavity (see figure). Osram fabricates the pump laser chips and sends them to Dilas in Mainz, Germany, for packaging. The OPS disk lasers reported by Osram and others operate in the 900–1300 nm range depending on the epitaxial structure. However, placing a nonlinear optical crystal in the cavity to frequency-double the output shifts the emission to visible wavelengths.

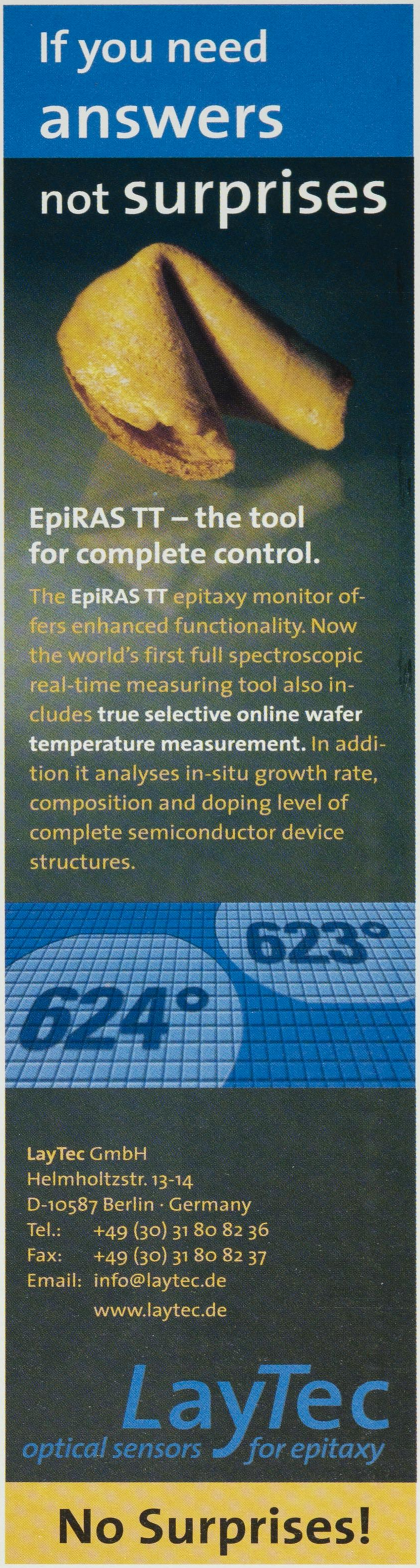
The work at Osram Opto on OPS disk lasers has been running since June 2000 and is partially funded by the German government. The company says that its record breaking output powers are the result of its wide experience in the manufacture of high-power semiconductor lasers and VCSELs combined with refinements of the epitaxial layers and good thermal management.

The first commercial applications for such lasers are likely to be in materials processing, where they would be a cheaper, more compact replacement for solid-state alternatives. The ultimate application may lie in laser TV. Here, colors are produced and projected by mixing the output from red, green and blue OPS disk lasers. Excellent picture definition would be possible because of the round beam shape.

## University of Tampere wins further funding

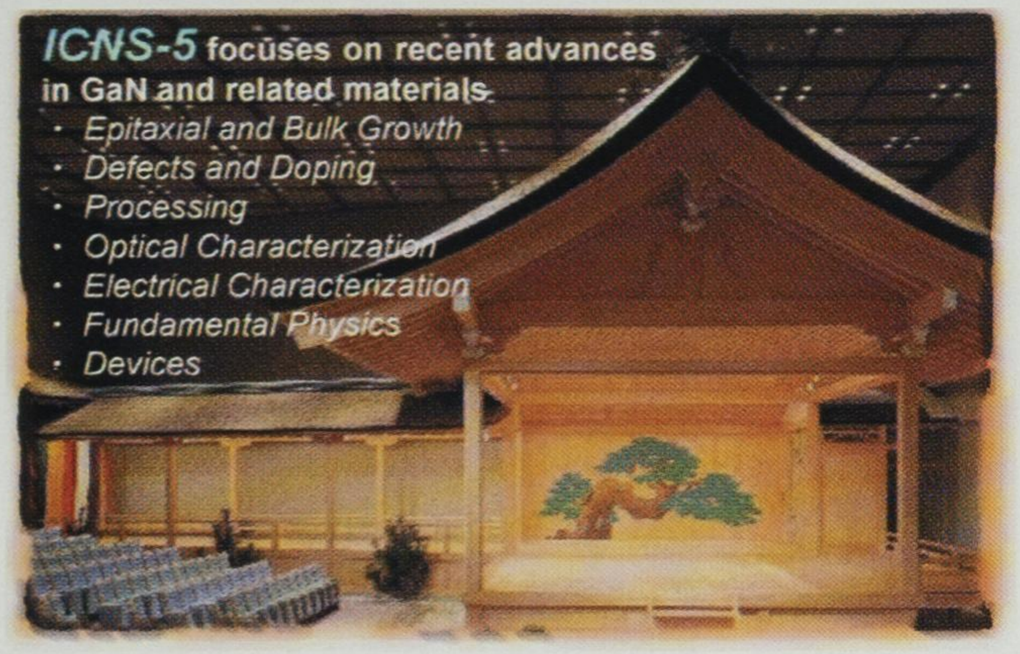
The Optoelectronics Research Centre (ORC) at Tampere University of Technology in Finland has received a two-year grant worth €1.08 million ($1.14 million) from the Finnish National Technology Agency. The funds will be used in a project called "Towards Lighter Technologies", or TORCH, which will explore ways to achieve femtosecond-regime optical pulses from fiber lasers integrated with semiconductor saturable absorber mirrors. Another aspect of the project is the further development of dilute nitride edge-emitting lasers and VCSELs operating at 1300 nm, an area in which the ORC has considerable experience.

Facilities at the ORC include five MBE systems and an optoelectronic device fabrication area. A new ORC building is nearly complete, and an additional €1.4 million worth of new equipment has been installed in the new facility. ORC also plans to hire more researchers using the new funds.



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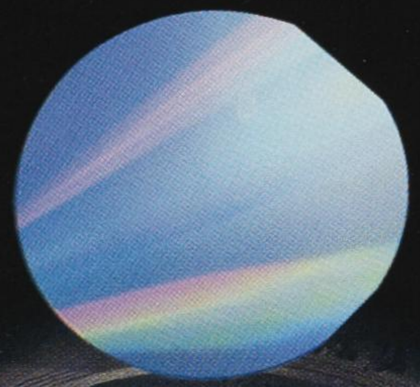
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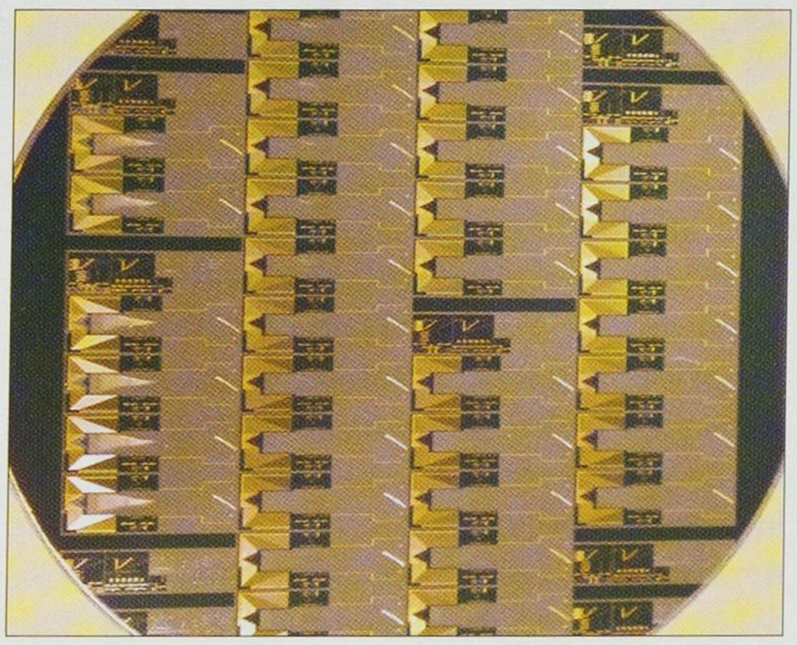
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# MetroPhotonics moves up to 4 inch InP

MetroPhotonics has announced the successful upgrading of its fabrication line in Ottawa, Canada, to process 4 inch InP wafers. This makes MetroPhotonics' fab the world's first 4 inch InP line dedicated to the manufacture of photonic integrated circuits. Upgrading from 3 to 4 inch gives almost double the number of chips per wafer at only a minimal increase in substrate, epitaxy and processing costs, giving an overall drastic reduction in costs per unit.

"Price is ultimately the main industry driver at present," said David Clark, CEO of MetroPhotonics. "We know our chips have the functionality that our customers are looking for. The 4 inch wafer line will ensure that we can supply those chips at a price that makes realistic business sense."



METROPHOTONICS

A fully processed 4 inch wafer, showing 34 complete SurePath monitor chips.

The company has also completed the evaluation of its prototype SurePath monitor with key telecom module and system-level manufacturers. The product is a 100 GHz optical power monitor that monolithically integrates MetroPhotonics echelle grating technology with unique waveguide-based *pin* detectors. The company says that the devices represent the highest level of monolithic integration in WDM components to date, and replaces 91 discrete components that would be required to fulfill the same function.

# CyOptics acquires manufacturing facility and core staff from Cenix

CyOptics, a developer of InP-based optical components, has acquired the optoelectronic component packaging capabilities of Cenix in Allentown, PA. The purchase gives CyOptics immediate access to the expertise and capital equipment required for package design and automated manufacturing of its optical modulators and other products. Cenix was founded in June 2000, and developed a proprietary state-of-the-art automated manufacturing facility capable of low-cost and uniform production of more than 10,000 components per month.

The financial terms of the acquisition have not been disclosed, but the purchase includes all capital equipment, inventory and intellectual property in Cenix's Allentown facility. CyOptics has also hired the core manufacturing technical staff at the site. The optoelectonic subsystem design and intellectual property associated with Cenix's Irvine, CA, operations were not included in the deal.

"We believe that in order to turbo-charge this industry, our customers require large-scale device integration and 2× cost reductions from current prices in their overall supply chain. This consolidation of two best-in-breed players gives us the technology and low cost structure to meet our customers' needs," said John Pilitsis, president and CEO of CyOptics.

In acquiring the new factory, CyOptics gains the ability to provide a wider selection of components. It will also be able to offer customized parts for high-volume applications, including lasers and detectors for small form factor transponders and transceivers.

# Companies establish tunable laser MSA

Iolon, Intel, Bookham Technology and Santur have joined forces to form a multisource agreement (MSA) for tunable lasers. This is the second such agreement that Bookham has put its weight behind; in November 2002, it entered into an MSA for tunable lasers with Alcatel and Agility. Bookham's involvement with both MSAs is part of its strategy to accelerate the uptake of tunable sources.

"Bookham made the decision to be involved in both MSAs because they have the potential to move forward the use of tunable laser technology," said Tim Simmons, Bookham's representative on both MSA groups. "The major investment in building optical modules like these is the cost of the optics, which can be common to both MSAs. The control electronics and the external mechanics are relatively low-cost."

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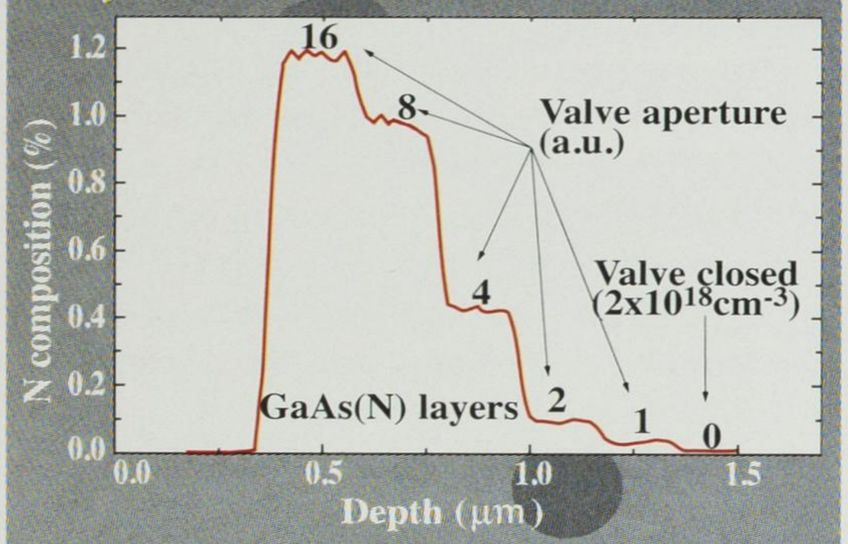




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# Picolight and Pemstar join forces for manufacturing

Picolight of Boulder, CO, has entered into a manufacturing partnership with Pemstar, a provider of engineering and manufacturing services to OEMs. The partnership will enable Picolight to seamlessly expand the manufacturing capacity for its Accelar and Extensus fiber-optic transceivers for enterprise and metro/access markets.

Picolight is one of a number of optical component manufacturers who have recognized the need to be able to quickly meet any increases in demand from customers, and to manufacture additional products as required. A number of options are available to companies with limited capacity, including partnerships with established contract manufacturers and the purchase of existing plants with the required facilities (for example CyOptics' acquisition of Cenix's facility; see p17).

Picolight continues to manufacture key optical subcomponents in Boulder. These optical elements are assembled by Pemstar and tested to Picolight's standards. Picolight says that a number of its customers have already completed audits of the combined Picolight and Pemstar supply chain, and have reported results of outstanding quality. Manufacturing for a number of its transceiver products has already been transferred to Pemstar's facilities in Bangkok, Thailand.

Picolight has also added eight products to its family of 1310 nm SFF and SFP fiber-optic transceivers for access and metro networks, and has released its first products for the synchronous optical network market. These new products range in speed from 100 Mbit/s to 2.488 Gbit/s over distances of 2–15 km, and support features such as digital diagnostics. Picolight's Extensus family of transceivers now supports the majority of high-volume 1310 nm applications.

"Picolight was founded on the premise that enterprise optics concepts would ultimately expand to dominate the transceiver market," said Stan Swirhun, Picolight's CEO. "The same high-volume, high-performance product approach we developed in the enterprise and storage-network markets is now available for access and metropolitan transport applications."

# Consolidation beckons for the 1310 nm transceiver market

Suppliers of 1310 nm transceivers are being threatened by excess supply to the market and continuing developments such as competitively priced 1550 nm transceivers, commercialized long-wavelength VCSELs and quantum-dot lasers, according to a new report from Strategies Unlimited. Most of the leading suppliers of 1310 nm transceivers are North American companies, while Japanese and Chinese companies dominate the merchant laser subcomponent markets. There is an excess supply of 1310 nm transceivers, but start-up companies are generating many of the most intriguing innovations.

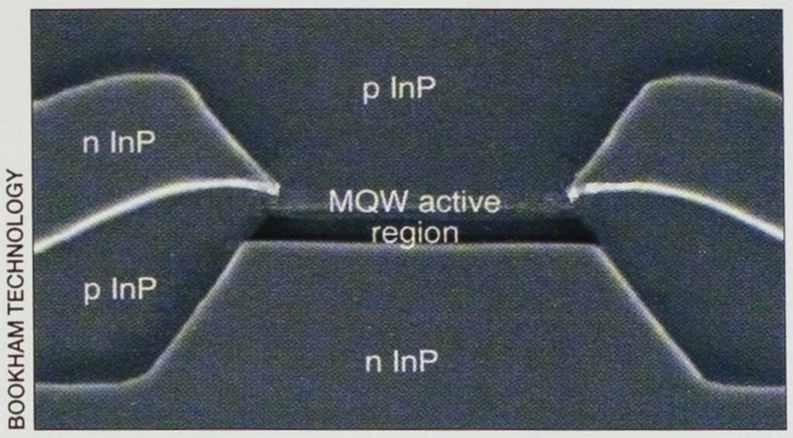
While the market is currently depressed by slack demand and lingering inventories, the report predicts that by 2007, annual transceiver sales will exceed $500 million. However, this will come as little relief to the current crop of suppliers to this market, unless there is more consolidation among them.

Datacom and telecom components converge in the 1310 nm laser market, making the market dynamics very interesting. In datacom applications, where 850 nm VCSELs are widely deployed, there is a strong demand for lower costs and conformation to standards. The telecom world places a high priority on performance, and is dominated by Fabry–Perot and DFB lasers. The convergence of these laser technologies at 1310 nm makes the battleground especially interesting.

Strategies Unlimited suggests that the outcome will depend on the ability of suppliers to deliver price reductions. The adoption of long-wavelength VCSELs still awaits a breakthrough in performance and manufacturing cost to beat Fabry–Perot lasers.

● The report, *High Data Rate 1310 nm Lasers: Datacom and Telecom 2003*, is available from the Strategies Unlimited website. See www. strategies-u.com.

# Bookham sets higher performance standards




BOOKHAM TECHNOLOGY

SEM image of an InP buried-heterostructure laser fabricated with the new *in situ* process.

At the Optical Fiber Communication Conference and Exposition (OFC), held on March 25–28 in Atlanta, GA, Bookham Technology revealed some new developments in its portfolio of device and manufacturing technologies that will be seen in its products in the near future. In a technical paper, Bookham introduced a 40 Gbit/s electroabsorption modulator (EAM) with the lowest unamplified insertion loss, the lowest polarization-dependent loss over a wide range of wavelengths, and the highest bandwidth yet reported for this type of modulator. All of these performance parameters were achieved simultaneously in a manufacturable design, while maintaining the practical requirement of more than 10 dB extinction with a voltage swing of less than 2.5 V.

"We now have the technology to build the world's best EAM for high-speed systems, and this is a complete, single package integrating all the necessary 40 Gbit/s RF functions," said Kelvin Prosyk, senior researcher at Bookham Technology. The EAM also gives the near-zero chirp needed for the dispersion compensation of 40 Gbit/s signals on standard single-mode fiber links with spans of more than about 8 km. Zero chirp is also important in applications such as the data gating of a train of pulses, as pulse clipping occurs if gate signals are not square.

## *In situ* etch for lasers

Bookham also reported a novel *in situ* etch and regrowth process for manufacturing uncooled InP-based buried-heterostructure lasers. The resulting devices showed 50% lower rates of burn-in degradation and 20% lower threshold currents than are obtained by current standard processes. The process is also compatible with the newer AlGaInAs material system, which is being investigated by Bookham and others, and which promises significant reliability gains for lasers.

The etching and regrowth required to make buried heterostructures can leave defects or introduce surface contamination on the mesa sidewalls during transfer from the etching tool back to the epitaxial growth reactor. Any etch damage or impurities remaining at the surface affect the quality of the regrown material, causing higher leakage currents that increase the laser threshold during device operation and reduce its lifetime. Unfortunately, AlGaInAs is highly vulnerable to damage and contamination. Bookham's reported *in situ* etching process eliminates the problem of post-etching surface damage or contamination by performing the etching step within the MOCVD reactor itself. Overgrowth is performed immediately on the clean, freshly etched surface, thereby preventing surface contamination from the air.

## New laser saves power and space

Bookham has also been developing uncooled directly modulated DFB lasers in joint research with a group at Cambridge University in the UK, which is focusing on developing new techniques allowing full RF transmission over multimode fiber using uncooled lasers. Such lasers are crucial to the realization of the direct transport of analog microwave/RF signals over fiber between the nodes in wireless networks.

Uncooled directly modulated lasers are attractive because they are cheaper, more compact and consume less power than externally modulated sources. "Typically, you can reduce power consumption by up to 1 W, and in terms of packaging, there is a factor of two in area reduction in removing the cooler," said Bookham's Kenton White. "This would really help optics to move into the wireless area, for example, by solving the big problem of providing low-cost fiber-fed radio access points."

A paper presented on the lasers described an InP-based compressively strained MQW DFB laser, which incorporated a unique semi-insulating buried heterostructure for enhanced thermal performance, allowing operation at temperatures above 100 °C.

linn High Therm

Crystal growing



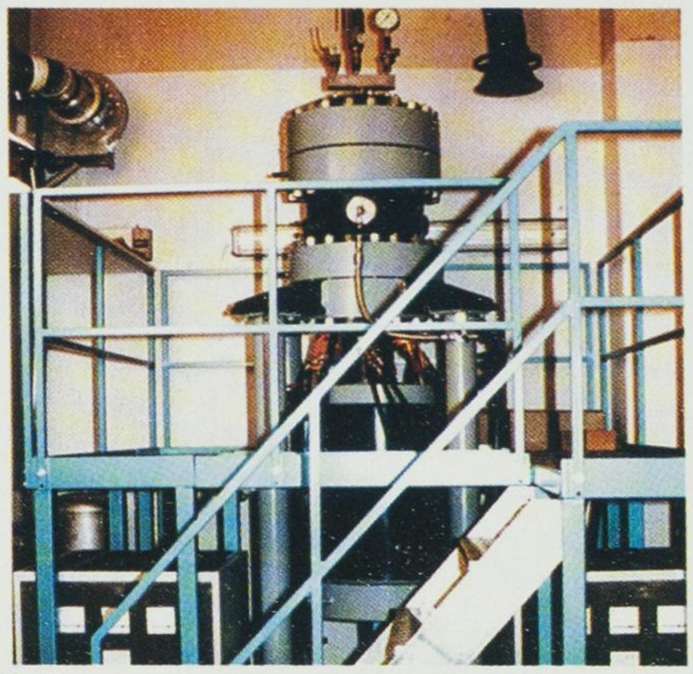
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# IMEC, National develop SiGe BiCMOS process

IMEC, an independent European microelectronics R&D center, and National Semiconductor, a leading US semiconductor manufacturer, are developing SiGe-based BiCMOS processes optimized for low-power applications. The project will enable National Semiconductor to offer a 0.18 μm SiGe-based BiCMOS process by December 2003 for its manufacturing facility in South Portland, ME. In the second phase of the four-year contract, the companies plan to develop next-generation (0.13 μm) SiGe-based BiCMOS technology by the first half of 2005.

IMEC and National have been jointly developing a 0.18 μm SiGe HBT module since January 2002 for integration into National's existing high-speed BiCMOS process family. Under the terms of the non-exclusive agreement, IMEC will license its 0.18 μm SiGe HBT module to National along with the test chip structures and bipolar model.

The present version of the integrated 0.18 μm HBT module under development has an $f_t \times BV_{ceo}$ product exceeding 200, with 40% increase of $f_t$ at low-current densities. The peak $f_{max}$ exceeds 100 GHz. The process is being further optimized to achieve the best trade-off between peak $f_t$, low-current $f_t$ and minimum noise figure.

National will integrate the SiGe HBT module into its existing 0.18 μm CMOS process without changes to the CMOS performance. A suite of radiofrequency (RF) passive components such as spiral inductor, varactor, metal–insulator–metal (MIM) capacitor and polysilicon resistors will also be fully integrated into the process, giving National an enhanced process capability for RF designs.

## RFMD ships SiGe CDMA front end to TCL Mobile

RFMD has commenced production shipments of the RF2461 LNA/mixer front end to TCL Mobile for use in several handsets for the Chinese domestic market. The product is a single-band SiGe-based front end designed for the receive section of dual-mode CDMA/FM handsets.

## Seika to distribute Soitec's Smart Cut products in China

French silicon-on-insulator (SOI) wafer manufacturer Soitec has appointed Seika as its exclusive distributor in China for products based on Soitec's proprietary Smart Cut technology. The new agreement builds on a successful 10 year distribution partnership between the two companies.



# ATMI finds a buyer for its GaAs epiwafer business

ATMI seems to have found a buyer for part of its GaAs epiwafer business, although the buyer's identity has not been disclosed. ATMI's annual report states: "Effective January 31, 2003, certain assets of this business have been sold under an asset purchase agreement. The lease of the related facility in Phoenix, AZ, has been assumed by the buyer."

In September 2002, ATMI announced that it planned to exit the GaAs epiwafer business and transfer its operation to a joint venture company, although it would continue its activities related to GaN and silicon epiwafers (*Compound Semiconductor* November 2002 p6). The company recorded a $31.5 million charge to recognize the impairment of assets in the GaAs epitaxial services business, and an additional $3.1 million charge related to a write-down of GaAs inventories was included on its balance sheet.

# JPSA Laser plans to expand its facilities

Excimer laser specialist JPSA Laser is to expand its facilities in Hollis, NH, in a multi-phase plan that will immediately double its existing floor space to 12,500 sq. ft and then later increase that to 20,000 sq. ft. The expansion is being driven by increasing demand for the company's products, which include excimer laser refurbishing services and UV laser scribing systems for separating LED chips fabricated on sapphire and SiC substrates (*Compound Semiconductor* December 2002 p29).

# Veeco opens development facility and China office

Veeco has opened a new facility for MBE process development. The 15,000 sq. ft epitaxial Process Integration Center (PIC) has been set up adjacent to Veeco's MBE manufacturing operations in St Paul, MN. It will develop compound semiconductor epitaxial processes for customers' material systems and device structures before transferring those processes to the customer's own systems.

PIC users will have access to Veeco R&D and production MBE systems, as well as a comprehensive set of optical, electrical and structural characterization tools.

"The PIC will enable our advanced wireless and optoelectronic device customers to lower the risks and costs of their process development, improve their product quality, ramp up to production faster, and receive expert training for their staff," said Marlin Braun, general manager of Veeco's MBE group.

Veeco Instruments has also opened an office in Shanghai to support recent customer orders and develop new sales prospects in the fast-growing China market. Veeco expects that 20% of its sales, worth about $45 million, will go to China by 2006. The company has received orders for atomic force microscopes from Semiconductor Manufacturing International Corp, and for a GEN II MBE system from the Chinese Academy of Sciences. The new Shanghai office will have more than 10 employees by the end of 2003.

"We see a broad and increasing demand for our products in technology and research sectors across China. The Shanghai office will provide comprehensive product support and 24 hour service," said Michael Weiss, vice-president and general manager of Veeco's Asian operations.

## Equipment sales

● **Emcore** has sold a second E300 GaNzilla production tool to **South Epitaxy Corporation** of Taiwan for the production of GaN-based high-brightness blue and green LEDs.

● **Aixtron** has received a further order from LED manufacturer **Epistar** for two AIX 2600G3 HT multiwafer mass-production MOCVD reactors. The systems will be located in Epistar's fab in the Science-based Industrial Park in Hsin-Chu, Taiwan. Aixtron has also reported the sale of a 24 × 2 inch wafer MOCVD system to **Uni Light Technology** for the mass production of InGaN-based LEDs. The system will be installed in Uni Light's facility in Taoyuan, Taiwan.

● A **Thomas Swan Scientific Equipment** 3 × 2 inch close coupled showerhead MOCVD reactor has been successfully commissioned for the III-V Integrated Devices and Circuits Group at the **University of Michigan**. The new reactor will be used for the R&D of high-power and high-temperature GaN-based HEMT devices and MMICs, as well as sensors and two terminal devices for signal generation, amplification, mixing and multiplication.

● Following its sale of a GEN2000 MBE system to RF Micro Devices in January, **Veeco Instruments** has announced another GEN2000 sale to an undisclosed customer. The 7 × 6 inch system will be used to produce epiwafers for manufacturing ICs for wireless applications.

● **Riber** has announced a number of shipments of MBE systems made over the past several months. A dual MBE 49 production machine has been delivered to **Sharp**'s new plant in Mihara, Japan, for the manufacture of 650 nm AlGaInP/GaAs DVD lasers. **ULM Photonics** has recently qualified a Riber MBE 49 (multi 4 inch) production MBE system at its new VCSEL manufacturing facility in Ulm, Germany. **IntelliEPI**, a manufacturer of GaAs and InP epiwafers based in Richardson, TX, has installed the industry's first Riber MBE 7000 system. The company already operates two MBE 49 (4 × 4 inch) and two MBE 6000 production systems. The MBE 7000 allows the growth of seven 6 inch or four 8 inch wafers. Riber has received several orders for its Compact 21 series of MBE growth systems from corporate and independent research centers, as well as academic institutions. The company has now sold 13 of its Compact 21 systems.

# Bringing a fresh approach

A novel approach to monolithically integrating electronic and optoelectronic functions is yielding higher-performance and lower-cost fiber-optic components, writes **Simon Hicks**.

InP is now established as the material of choice for a range of long-wavelength (1300–1600 nm) optoelectronic devices, and it has also been used to realize extremely high-frequency electronic circuits. However, the InP epitaxial layer structures and the fabrication processes employed for the two applications differ significantly, limiting the commercial success of attempts to utilize InP's inherent optoelectronic and high-frequency electronic properties in a single chip form.

A new approach to InP integration overcomes many of these issues, and allows a significant degree of electronic and optoelectronic functionality to be integrated in a single chip form suitable for high-volume manufacturing.

## InP monolithic integration

The crystal properties of InP and its associated alloys allow structures to be grown with optical band edges covering the range of wavelengths relevant to fiber-based telecommunication applications (1300–1600 nm). For this reason, InP has been used to realize a wide range of commercially available optoelectronic devices, such as lasers, modulators, detectors and semiconductor optical amplifiers.

At the same time, InP has also been used to realize high-frequency electronic circuits. Typically, variations of HBT or HEMT structures are employed to achieve $f_t$ values well in excess of 200 GHz. Some companies have enjoyed commercial success in supplying InP-based electronic circuits, but only in applications where Si-, SiGe- or (to a lesser extent) GaAs-based devices cannot compete on performance. For example, the performance of current-generation 0.13 μm CMOS technology means that manufacturers can implement 10 Gbit/s serializer and deserializer circuits without the need for III-V technologies.

There is now significant activity in the InP community to integrate InP-based optoelectronic and electronic functions on the same substrate. An example of this is the integration of an InP waveguide detector with an InP TIA. The main advantages of this approach are that it reduces chip count, with the potential of incrementally lower packaging costs and improved efficiency between the elements.

## Current monolithic limitations

Critical disadvantages arise with standard monolithic approaches to integration because the epitaxial layer structure and, greater still, the die fabrication processes, differ between the electronic and the optoelectronic elements, making processing complicated. Typically, the epitaxial layers are grown for the optoelectronic functions, followed by die processing. Epitaxial regrowth is then employed to grow the layers for the electronic functions. A significantly different set of fabrication techniques is used to realize transistors, resistors, capacitors and other devices.

Merging these manufacturing techniques into a unified process for monolithic device production inevitably compromises device performance. One must carefully weigh the gains in reduced real estate and packaging costs against the resultant decrease in the level of performance.

Product cost is the chief casualty of the aforementioned technique. First, the merging of separate manufacturing processes often results in reduced yield of the monolithic part, compared with that of the discretes. At lower volumes, the unit cost of the monolithic product is not able to compete with that of the discrete approach, and often does not become competitive until higher-volume break points are achieved. The investment required to achieve this longer-term gain may outweigh the perceived benefits of integration.

Second, packaging costs are negatively affected. A key driver for the integration of optoelectronic elements on the same chip is to avoid costly optical alignment processes during packaging. However, these alignment stages are not avoided by integrating electronic functionality, thus negating any significant cost reductions.

In addition to product and packaging costs, reliability is affected. As discussed earlier, the process of monolithic integration results in a trade-off in device performance compared with the performance of the discrete devices. The cost of engineering a monolithically integrated part with comparable reliability to that of the established discrete parts may be prohibitive. It is necessary to give careful consideration to the factors affecting reliability as a result of monolithic integration, and the resultant changes to burn-in, environmental stress screening and other testing that may detrimentally affect unit costs.

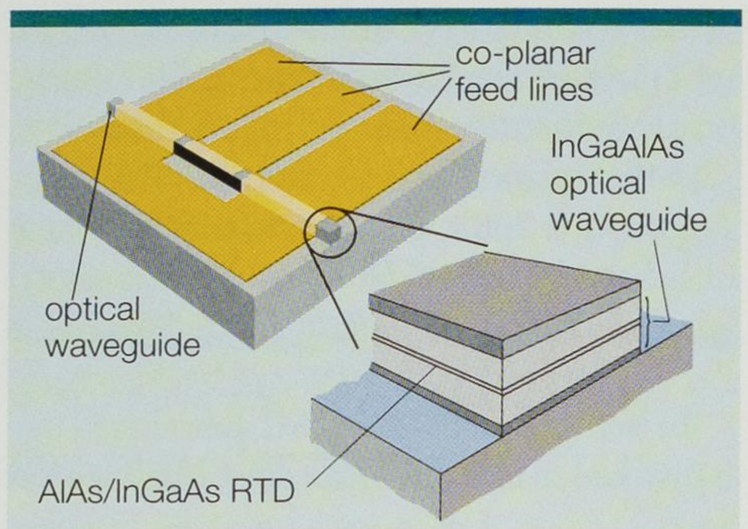



**Fig. 1. Schematic diagram of an EAM with an AlAs/InGaAs RTD integrated into an InGaAlAs optical waveguide. The chip is approximately 0.5 × 0.5 mm in size.**

For these reasons, the commercial success of devices employing high-frequency electronic and optoelectronic functionality monolithically integrated onto a single InP chip has been severely limited.

## Moving beyond convention

Essient Photonics has taken an innovative approach to InP integration that conquers many of the above issues, and enables a significant degree of electronic functionality to be integrated with optoelectronic functionality, all in a single chip form suitable for high-volume manufacturing. This is achieved by integrating InP-based resonant tunneling diode (RTD) technology with more traditional InP optoelectronic technology.

For a number of years, RTDs have been investigated for use in the electronics sector, sometimes being employed as high-frequency oscillators and logic circuit elements. Many of their useful electronic properties arise from the fact that they exhibit at least one region of

# to monolithic integration

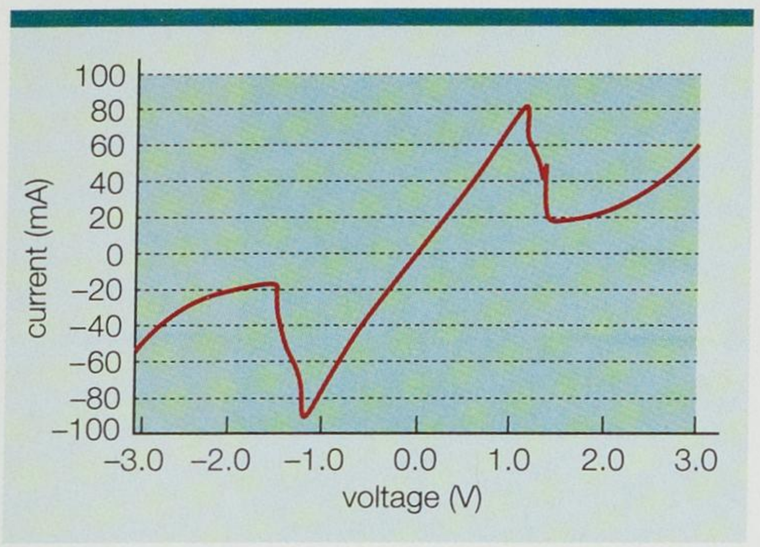



Fig. 2. Typical I-V characteristic of an electroabsorption modulator (EAM) with a resonant tunneling diode (RTD) integrated into the optical waveguide.

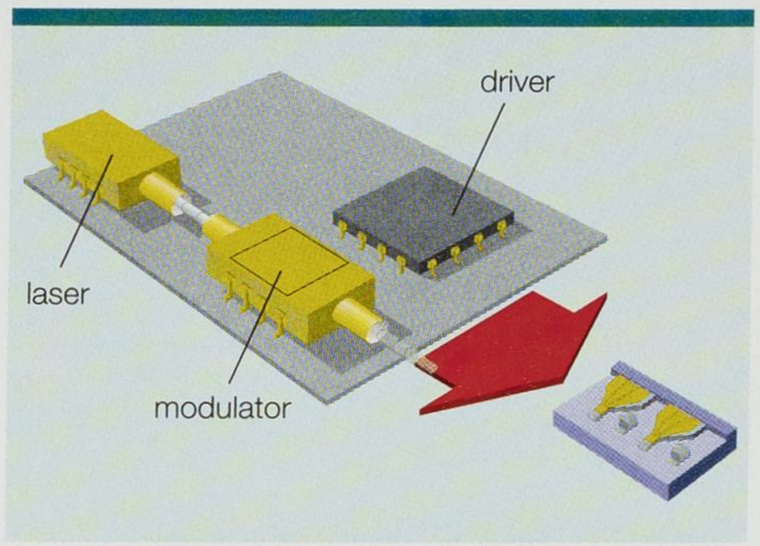



Fig. 3. The application of an RTD-EAM technology to transceiver design. The large device shows a traditional implementation using discrete packaged components (laser and modulator) and high-power driver circuitry. The smaller implementation uses a single optical submount for the laser and modulator assemblies. The high-power driver circuitry and associated heat sinking is eliminated.

negative differential resistance (NDR), giving the potential for devices that provide electronic gain and high-frequency switching.

Essient's RTDs consist of two 2 nm thick AlAs barriers surrounding a 6 nm thick InGaAs quantum well, embedded within a unipolar InGaAlAs waveguide (figure 1). MBE is used to grow the structures, giving the required layer thickness control and uniformity.

The RTD introduces a non-uniform distribution of the electric field across the waveguide core. The electric field strength becomes strongly dependent upon the bias voltage due to accumulation and depletion of electrons in the emitter and collector sides of the RTD respectively. Depending on the DC bias point (approximately 1 V in figure 2), a small high-frequency AC signal (typically 100 mV) can induce high-speed switching of the electric field. This produces substantial high-speed modulation of the optical absorption coefficient within the waveguide at a given wavelength near the material band-edge via the Franz–Keldysh effect; therefore, it modulates light at photon energies lower than the waveguide core bandgap energy.

In this mode, the device operates as an extremely low drive voltage (~100 mV) EAM, achieving DC optical extinction ratios of greater than 20 dB. This must be compared with the electrical drive voltage of >2 V required for a conventional InP-based EAM with comparable optical properties. Essentially, integrating electronic functionality into the EAM structure reduces the input power requirements of the optoelectronic interface from the power amplifier level, making it compatible with standard CMOS signals.

There are several important advantages to this electronic–optoelectronic integration strategy. One benefit is that the die fabrication process does not require an epitaxial regrowth step, as the optoelectronic and electronic layer structures are spatially identical. The complete structure is therefore grown in a single run that can potentially simplify the process and enhance yield.

Another benefit is that the die fabrication process does not require separate processing stages for the optoelectronic and electronic functions; both are realized through a single set of fabrication stages that in many ways are similar to those employed to realize traditional commercially available III-V modulator devices. All of the stages employ standard III-V optoelectronic device manufacturing techniques, including optical lithography, etching and metallization, which results in a small die size and a high-yield fabrication process.

It is also possible to obtain the electronic functionality without the fabrication of complex HEMT or HBT-based circuitry. This significantly impacts die size and complexity and, in conjunction with the far simpler fabrication process, leads to a significant yield enhancement.

## Datacom and telecom applications

Further significant advantages of this integration strategy are realized when it is applied to telecom and datacom transceiver modules. For the transmission of information at 10 Gbit/s, the transceiver design will depend on the required performance specification, yet some important general points can be made:

- Bringing the optoelectronic interface drive voltage requirements down from >2 V to ~100 mV eliminates the need for high-frequency, high-power driver amplifier circuitry. Essentially, the signal levels are compatible with the output signals coming directly from the CMOS aggregation electronics, typically in the form of serializer/deserializer chips.
- The driver circuitry is a significant source of heating within a module. The driver circuits typically employ bulky heat sinks to dissipate heat. Elimination of the driver circuitry reduces these thermal management issues.
- Furthermore, eliminating the driver circuitry results in a transceiver power requirement of less than one-third, and a board space of less than two-thirds, of that of a traditional transceiver.

The above module power and size reductions aggressively address the demanding design constraints that today's module and system designers face, offering a higher degree of flexibility as opposed to modules incorporating conventional optoelectronic technologies. Because of its ability to provide ultra-low power with a reduced footprint while maintaining high levels of performance, this technological approach could have important applications to Ethernet solutions, such as XFP, XPAK and X2 as shown in figure 3.

By combining electronic and optoelectronic functions on a single InP-based chip through the integration of RTDs with optoelectronic waveguide structures, the power level requirements of the optoelectronic interface in telecom and datacom applications can be addressed. In addition, it is possible to significantly enhance module performance and economics, making it an approach worthy of further consideration.

*Simon Hicks is the CTO of Essient Photonics, an optical components company based in Scotland, UK. E-mail simon.hicks@essient.com.*




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# Strained Si-on-insulator development accelerates

With strained Si now on the CMOS roadmap and wafer bonding accepted as a method for producing SOI substrates, **Gianni Taraschi** looks at the ongoing efforts to combine the two technologies.

Recently, a number of semiconductor manufacturers have announced plans to incorporate strained Si into future CMOS technologies, yielding enhanced performance for minimal additional cost. Typically, the strain in a thin Si surface layer is induced by a SiGe graded buffer deposited onto a Si substrate. Tensile strain significantly increases carrier mobility, thereby improving performance (*Compound Semiconductor* September 2002 p39). Another material that has been used for some time now in CMOS fabrication is Si-on-insulator (SOI). In SOI, a buried insulating oxide layer reduces parasitic junction capacitance, thereby increasing drive currents while decreasing noise and power dissipation.

There has been rapid progress in the development of process technologies that merge both strained Si and SOI. To achieve this end, processes typically involve the creation of engineered substrates consisting of relaxed SiGe-on-insulator (SGOI), which serve as templates for thin strained Si layers. Due to the presence of the surface strained Si and the underlying buried oxide, the final structure is sometimes referred to as strained Si-on-insulator (SSOI).

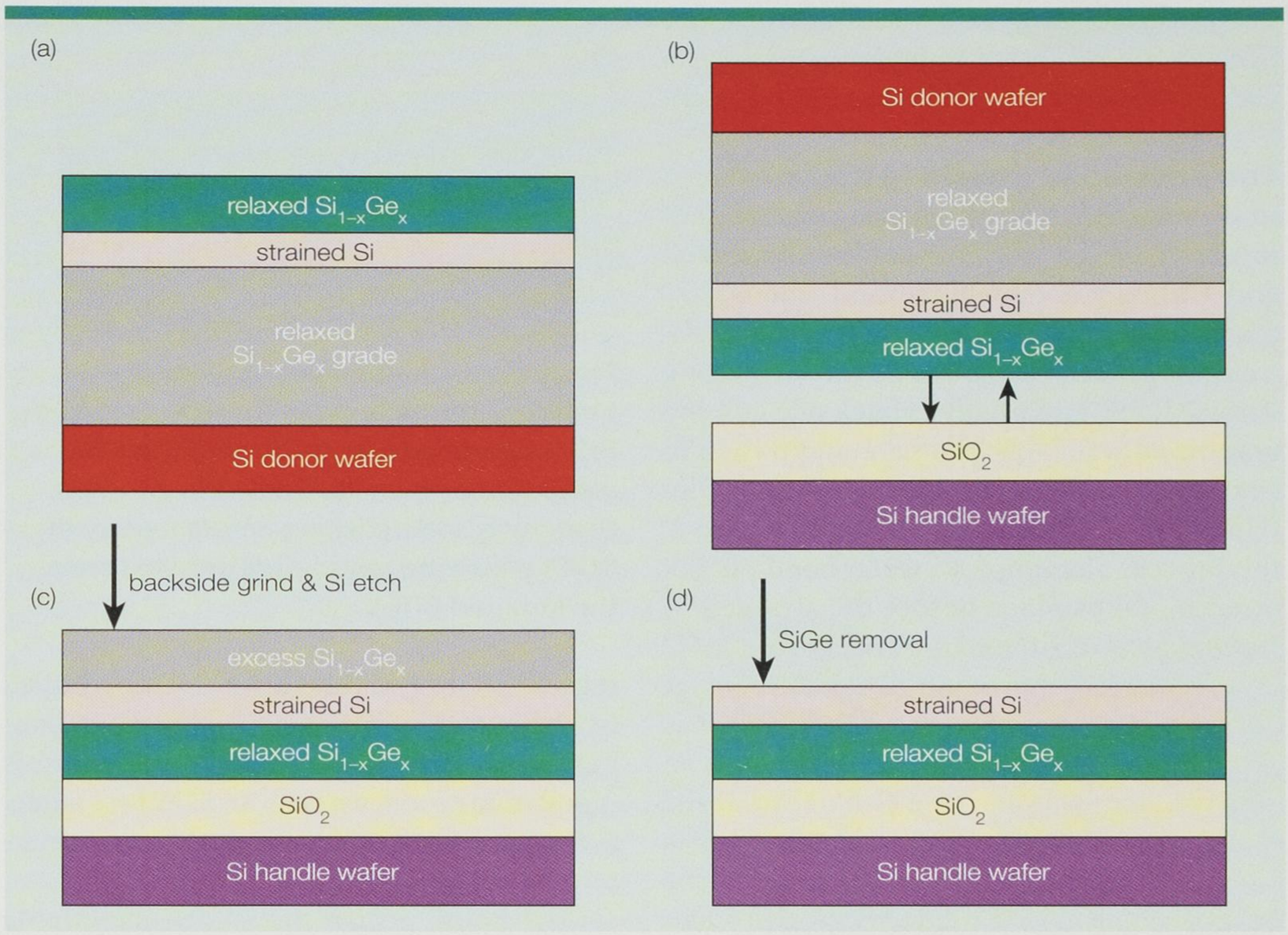



**Fig. 1. The process flow for substrate fabrication using a strained Si etch stop layer. The starting substrate consists of a relaxed SiGe bonding layer with strained Si underneath (a). After bonding to a Si wafer with an oxide surface (b), the backside is thinned using grinding and a Si etch (c). A final SiGe etch removes excess material and stops on the strained Si (d).**

Separation by implanted oxygen (SIMOX) and wafer bonding are popular approaches for the fabrication of a buried oxide. SIMOX involves the implantation of oxygen ions into the wafer surface, followed by a high-temperature anneal to remove implant damage from the crystalline layer and form the buried oxide layer. Although ideal for bulk Si, SIMOX has been unsuccessful when applied to SiGe with Ge contents above 30%, due to thermal instability during high-temperature post-implant annealing (*Compound Semiconductor* November 2002 p37).

In contrast, wafer-bonding approaches do not suffer from this limitation, and allow for SGOI substrate fabrication with any Ge content, in addition to strained Si directly on oxide. For this reason, a number of groups in both industry and academia have developed high-quality SGOI and SSOI substrate fabrication based on wafer bonding. All of these methods begin with the growth of a relaxed SiGe graded buffer on a Si substrate, which minimizes the density of dislocations in the surface film. The SiGe graded buffer then serves as the donor for the bonding process, but each method employs different techniques to achieve smooth transferred layers.

## The Si stop-layer approach

A first demonstration of SGOI fabrication using wafer bonding was presented at the 2000 Electronic Materials Conference (Taraschi *et al.* 2002a). Via the use of a strained Si etch stop layer, the process ensures that the final structure possesses a smooth and uniform SiGe film, with a RMS roughness of about 1 nm. Figure 1 shows the process flow, beginning with the growth of a relaxed SiGe buffer, graded up to the desired surface Ge content. Due to the influence of dislocation strain fields during growth, the surface of the SiGe buffer is considerably roughened and requires polishing to provide a flat surface for subsequent growth steps and wafer bonding. After polishing, a strained Si etch-stop layer followed by about 100 nm of SiGe is deposited onto the graded buffer (figure 1a). The wafer is then bonded to an oxidized Si handle wafer (figure 1b), the backside of the original wafer is ground away, and a selective etch (KOH or TMAH) removes excess Si while stopping in

the SiGe graded buffer (figure 1c). KOH and TMAH solutions have been shown to quickly etch Si while effectively stopping on SiGe with Ge content greater than 20%, making these etchants ideal for a backside removal process.

Next, excess SiGe is removed using one of the many selective SiGe etchants that stop on the strained Si layer (figure 1d). Numerous chemical etchants containing hydrogen peroxide, nitric acid or ammonia can be tailored to etch SiGe at a much faster rate than Si, and are therefore ideal for selective etching. Once the process is complete, the final structure consists of a strained Si layer on a uniform thickness SiGe layer bonded to a buried oxide.

## The post-bond polishing approach

In standard SOI fabrication using wafer bonding, transferred layers are often planarized and thinned using post-bond chemical–mechanical polishing (CMP). An SGOI fabrication process has been developed along similar lines, and involves backside etching combined with a final post-bond polish to smooth the surface of the transferred SiGe film (Cheng *et al.* 2001a). As shown in figure 2, this process also employs wafer bonding, but bonding takes place before the strained Si layer is grown (figure 2a). The relaxed SiGe layer is bonded to an oxidized Si handle wafer before the backside of the donor wafer is removed using grinding combined with an etch that stops in the 20% Ge region of the graded layer. After the backside etch, CMP is used to polish the surface and remove the excess portion of the graded buffer, producing a smooth SGOI substrate. A final growth then deposits a relaxed SiGe layer with a Ge content matching that of the SiGe remaining after the CMP step, followed by the strained Si device layer (figure 2b).

Researchers at IBM and the Massachusetts Institute of Technology (MIT) (Huang *et al.* 2001; Cheng *et al.* 2001b) have also independently demonstrated a SGOI fabrication approach using post-bond polishing, but have combined it with delamination via implantation to achieve layer transfer (figure 3). The process flow involves implanting hydrogen ions into the SiGe surface prior to bonding to an oxidized Si wafer (figure 3a). The implanted surface is bonded to the oxidized Si handle wafer and annealed at a low temperature of 250–350 °C to strengthen the bond. Annealing at a slightly higher temperature (400–500 °C) induces delamination at the depth of the hydrogen implant (figure 3b). The resulting handle wafer then consists of a relaxed SiGe layer (about 500 nm) on a buried oxide layer. Unfortunately, since the delaminated surface is quite rough, polishing is required to produce a smooth SGOI substrate. A final growth then produces the same structure depicted in figure 2b.

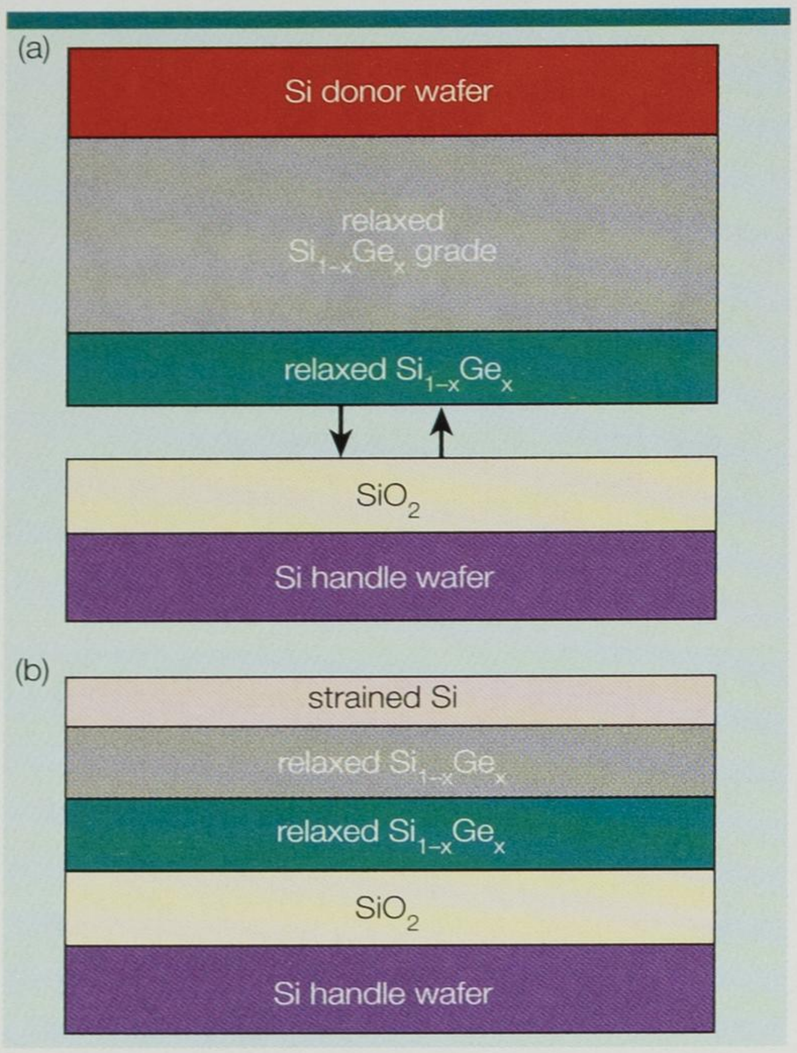



Fig. 2. Post-bond polishing with a backside etching approach. After growth of relaxed SiGe, bonding to an oxidized Si handle wafer takes place (a). Backside grinding, Si etching and polishing create a smooth SGOI substrate, and a final growth forms the strained Si (b).

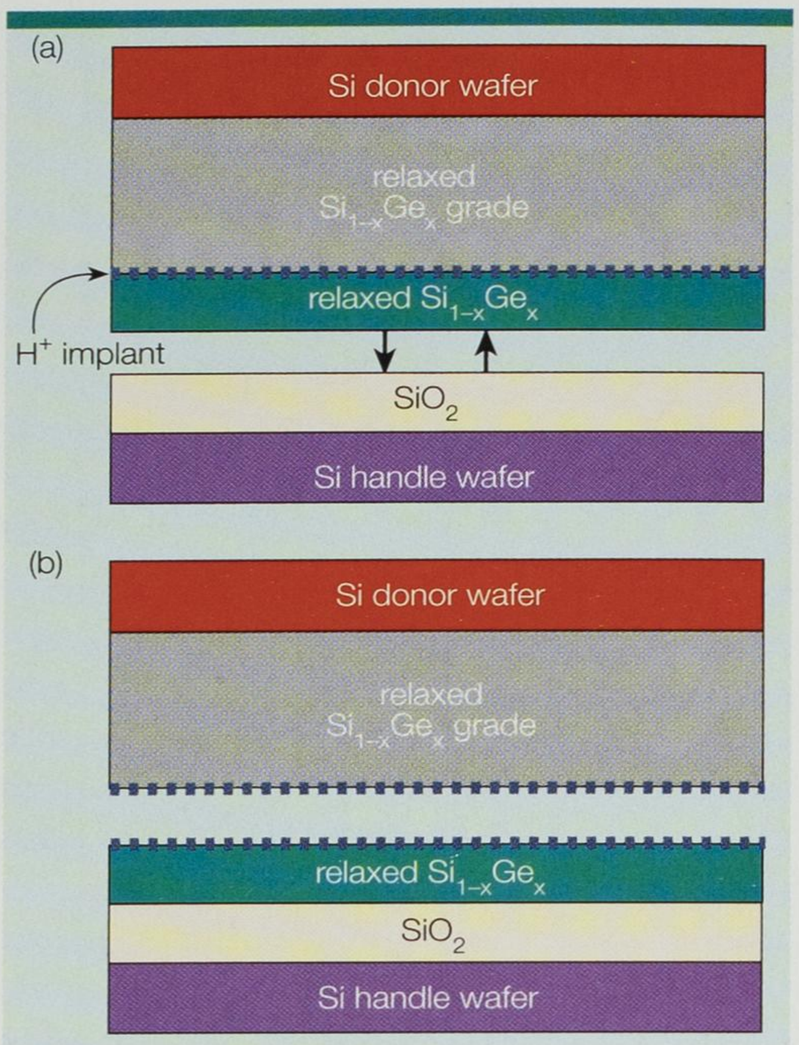



Fig. 3. Post-bond polishing with delamination via implantation approach. After relaxed SiGe growth, followed by hydrogen ion implantation, the wafer is bonded to an oxidized handle wafer (a). Annealing causes delamination at the implant peak (b).

Post-bond polishing is an acceptable approach for creating smooth SiGe layers on oxide, with thicknesses of about 300 nm or more, and hence is a viable fabrication avenue for partially depleted substrates. Unfortunately, the method cannot be easily adapted to the fabrication of fully depleted devices. Such structures require ultra-thin transferred layers with thicknesses less than 50 nm, and post-bond polishing is plagued by wafer-scale non-uniformity in the removal rate, which makes the creation of ultra-thin layers impractical, if not impossible.

## Ultra-thin SSOI

To address the demand for ultra-thin SSOI, MIT researchers have demonstrated an ultra-thin transferred layer process using a strained Si etch stop method combined with an ultra-thin SiGe bonding layer and delamination via implantation (Taraschi *et al.* 2002b). After wafer bonding to an oxidized Si handle substrate, layer transfer proceeds through delamination by implantation and annealing instead of backside etching. This transfers the strained Si b layer, the SiGe bonding layer, and an excess thickness of SiGe. As described in the original stop layer process (figure 1), excess SiGe is then removed with a selective etch which stops on the strained Si layer, producing the final substrate.

Figure 4 shows a cross-sectional TEM image of an ultra-thin SSOI structure, fabricated using a strained Si stop process and a nitric-based SiGe selective etch. The process also introduced novel improvements including metastable strained layers and low-temperature wafer bonding. Metastable layers grown and bonded at very low temperatures result in high-quality strained layers that can be thicker than their equilibrium counterparts.

Stop layers eliminate the need for post-bond polishing, enabling the fabrication of ultra-thin transferred layers. The MIT group has demonstrated the fabrication of ultra-thin SSOI, with a 30 nm SiGe bonding layer between the strained Si and the oxide. Although this SiGe layer underneath the strained Si surface channel could be useful for enhanced dual-channel devices, it is not necessary from the standpoint of maintaining the strain in the Si layer.

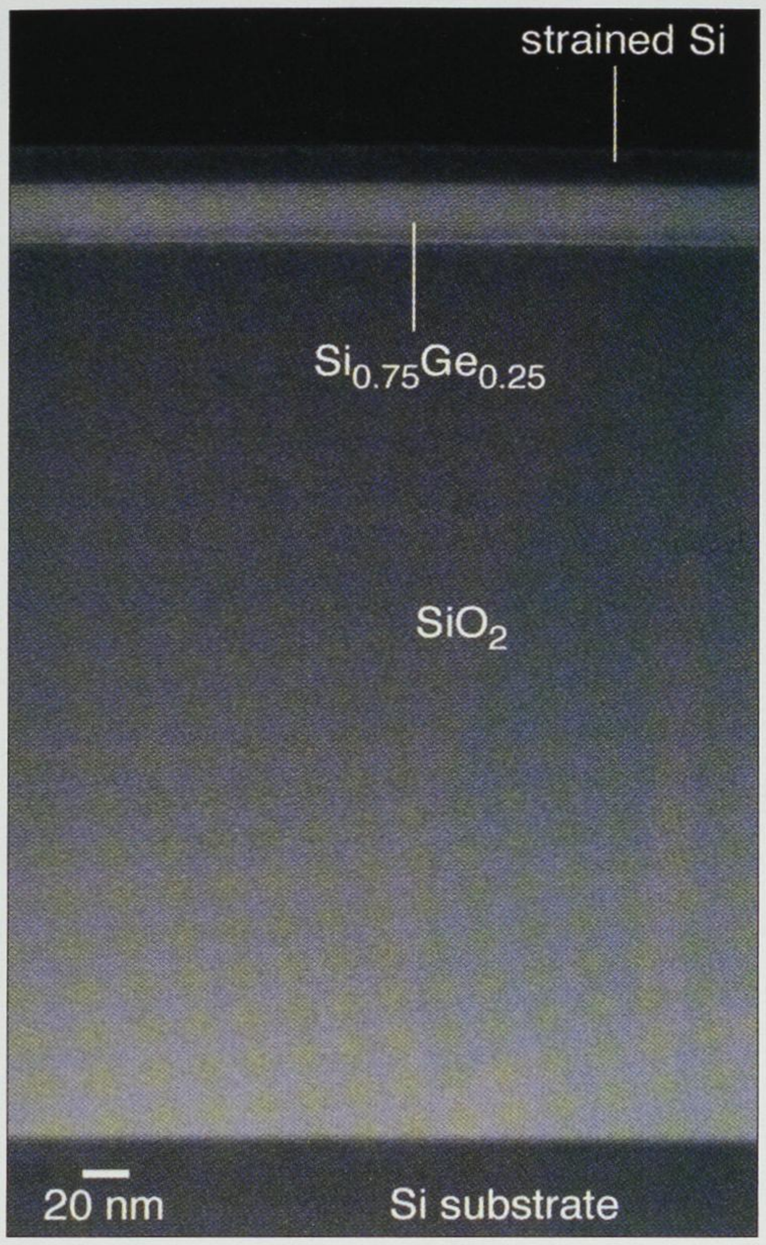



Fig. 4. A cross-section TEM image showing an ultra-thin SSOI structure fabricated using wafer bonding with a strained Si stop layer.

## Strained Si directly on insulator

The next step in the evolution of SSOI has arisen from the proof that strained Si directly bonded to an oxide can retain strain originally imparted by the relaxed SiGe buffer. As demonstrated by researchers at AmberWave Systems (Langdo *et al.* 2002), a strong bond between a strained Si layer and a buried oxide is more than sufficient to maintain strain in the Si film, even after annealing at an elevated temperature of 1100 °C.

The process employed by the AmberWave researchers was similar to the stop layer approach, except that the strained Si was bonded directly to the $SiO_2$. Another difference was the use of a novel SiGe removal process to strip any excess SiGe present on the surface after delamination. Instead of using a wet chemical etch to selectively remove SiGe and stop on strained Si, their approach used selective, low-temperature steam oxidation, followed by a wet oxide strip. Other similar SSOI fabrication approaches have been developed by researchers at MIT, IBM and the University of Virginia, and were presented at the International Conference on Si-based Epitaxy and Heterostructures in March this year.

Irrespective of the particular SiGe removal method employed, the final structure produced with this wafer-bonding process is an SSOI structure consisting of a strained Si film directly on an oxide layer. The resulting SiGe-free SSOI substrate is ideally suited to endure the high temperatures experienced during standard CMOS processing.

## Other novel approaches

Although this article has focused on substrates fabricated via wafer bonding, a novel technique developed by researchers at Toshiba uses high-temperature oxidation of a low-Ge content SiGe film on a thinned SOI substrate. High-temperature oxidation of the SiGe expels Ge from the oxide, which in turn diffuses into the underlying Si layer, forming a relaxed, Ge-rich, ultra-thin SiGe layer on oxide. In addition, it is thought that the high temperature allows the buried oxide to flow, thereby allowing the Ge-rich SiGe film to relax via lattice expansion and not dislocation nucleation. This technique may be useful for Ge-rich SGOI fabrication. Although low dislocation densities have been observed when using micron-sized mesas, wafer-scale application of the technique requires further characterization of defect densities.

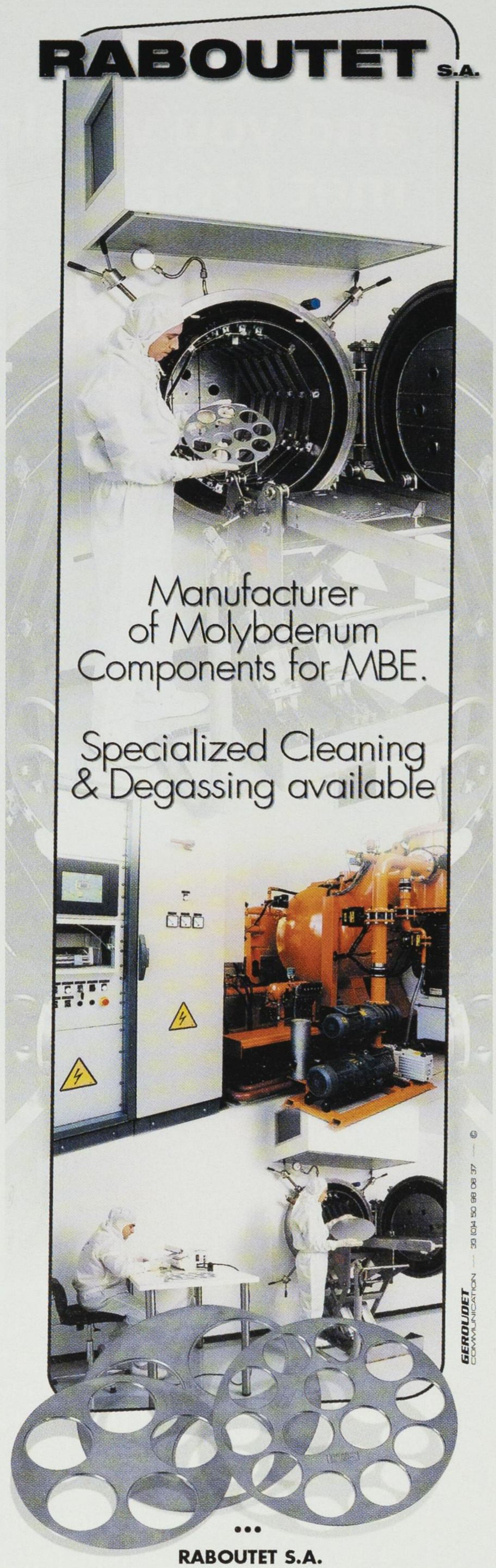
## The future of SSOI

The feasibility of high-quality SSOI and SGOI substrate fabrication has been clearly demonstrated by a number of researchers, and further developments are in the pipeline. Such substrates may serve as ideal platforms for high-performance, low-power CMOS, but for that to happen, fabrication processes must move out of research and into development. SSOI may very well become a future technology on the evolving CMOS roadmap, but for the near term, strained Si or SOI on their own will endure as cost-effective options. ●

## Further reading

Cheng *et al.* 2001a *Elec. Dev. Lett.* **22(7)** 321.
Cheng *et al.* 2001b *J. Elec. Mat.* **30(12)** L37.
Huang *et al.* 2001 *Appl. Phys. Lett.* **78(9)** 1267.
Langdo *et al.* 2002 *IEEE SOI Conf. Proc.* (in press).
Taraschi *et al.* 2002a *J. Vac. Sci. Technol. B* **20(2)** 725.
Taraschi *et al.* 2002b *Mat. Res. Soc. Fall Proc.* (in press).

*Gianni Taraschi is a researcher at the Massachusetts Institute of Technology, Cambridge, MA. E-mail giannit@mit.edu.*



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# Mobile applications prompt strong growth in LED market

The high-brightness LED market was the star performer of the compound semiconductor industry in 2002. **Tim Whitaker** reports from the annual Strategies in Light conference.

While other segments of the compound semiconductor industry continued to struggle in 2002, the high-brightness (HB) LED market enjoyed a bumper year. After experiencing zero net growth in 2001 (a good performance relative to the markets for fiber-optic components and GaAs ICs), the HB-LED market grew by 50% in 2002, reaching $1.8 billion.

These outstanding figures were presented by Strategies Unlimited's Bob Steele at February's Strategies in Light conference. According to Steele's estimates, mobile appliances made up the largest market segment in 2002 with a 40% share of the total, followed by signs (23%), automotive (18%), illumination (5%), signals (2%) and other (12%).

Steele predicted steady growth in the HB-LED market of around 20% per year for the next five years, assuming that normal growth takes place in the general economy (figure 1). Continued recession and/or the impact of war with Iraq could reduce capital spending on trucks and large video screens; consumer spending on cars and mobile appliances; and government spending on highway signs and traffic signals, for example. Steele predicted that the HB-LED market will reach $4.4 billion by 2007. Mobile appliances will continue to be the largest segment with a value of around $2 billion, while the illumination market will grow to around $500 million.

In terms of materials, the market continues to be dominated by InGaN-based devices. Spurred by the use of blue, green and white LEDs in mobile handsets, InGaN LED shipments grew by 72% in 2002, reaching a value of $1.22 billion. This exceeds the value of the entire HB-LED market in 2001. While InGaN devices accounted for 68% of the market in 2002, AlGaInP and AlGaAs devices had shares of 24% and 4%, respectively. The remaining 4% was accounted for by multichip devices, which contain red, green and blue chips for making white light (figure 2).

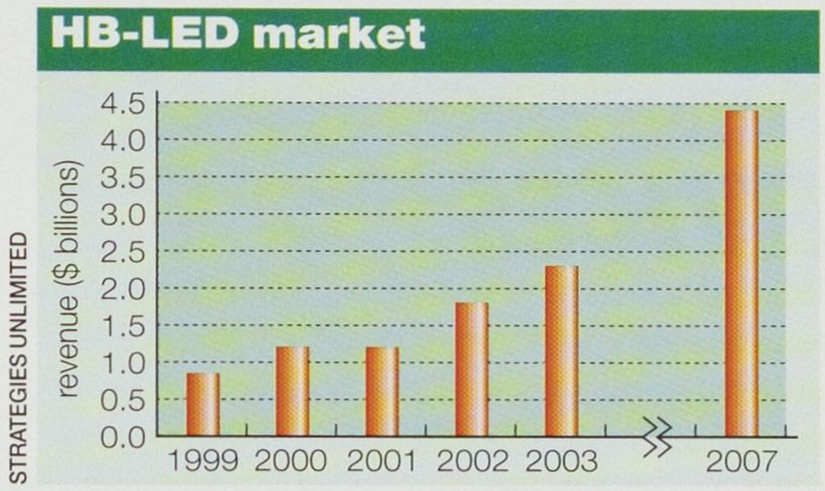



Fig. 1. After growing by 50% in 2002, the HB-LED market is predicted to grow by around 20% through 2007. Figures refer to packaged devices.

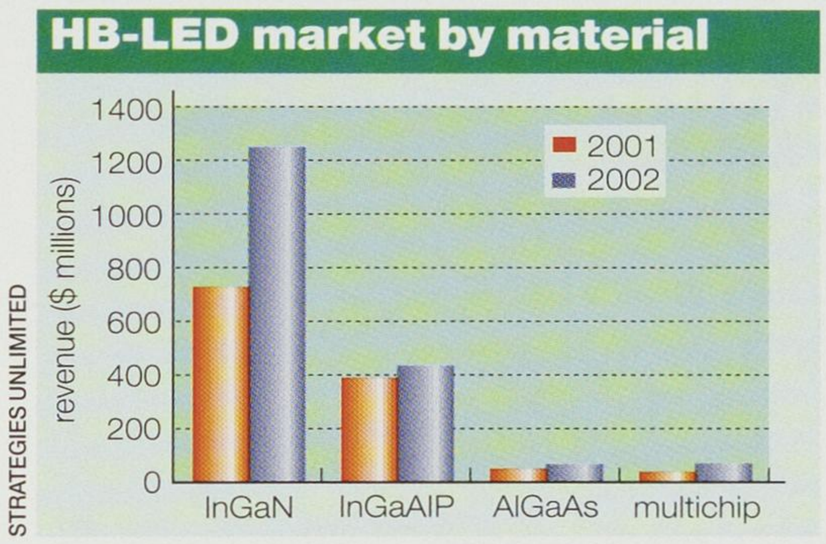



Fig. 2. InGaN LEDs accounted for 72% of HB-LED market revenue in 2002.

## Mobile appliances

Steele explained that growth in the HB-LED market during 2002 was mainly due to demand from mobile appliances. This market segment, which now accounts for 40% of the overall HB-LED market, includes mobile phone screen and keypad backlights, as well as LEDs used for similar functions in PDAs and digital cameras.

Despite very little growth in shipments of mobile phone handsets during 2002, the consumption of HB-LEDs in handsets grew a massive 114% compared with the previous year. Several factors influenced this growth, including the proliferation of blue and full-color screens, the latter requiring white LED backlights. Full-color screens are now found in almost all phones sold in Japan, and are also very popular in Korea. Larger screens (requiring more or brighter LEDs), secondary screens and keypad backlights all added to the demand for HB-LEDs, as did functions such as multicolor ringer lights that can be programmed to match a different caller with a different color.

Sen Yang from Motorola's display design center described technology for full-color displays in mobile handsets. Early color displays used reflective technology, in which ambient light passes through the LCD and is reflected back out again. These work well outdoors and in sunlight, but can be difficult to read in office environments. For this reason, LED frontlights are usually used, but this creates other problems. Transmissive technology, which is also used in laptops, relies entirely on backlighting, and provides the richest colors in an indoor environment. However, such displays are virtually unreadable in strong sunlight. The third technology is transreflective; such displays have a backlight and also reflect ambient light. They perform less well than transmissive displays indoors, but are better in sunlight.

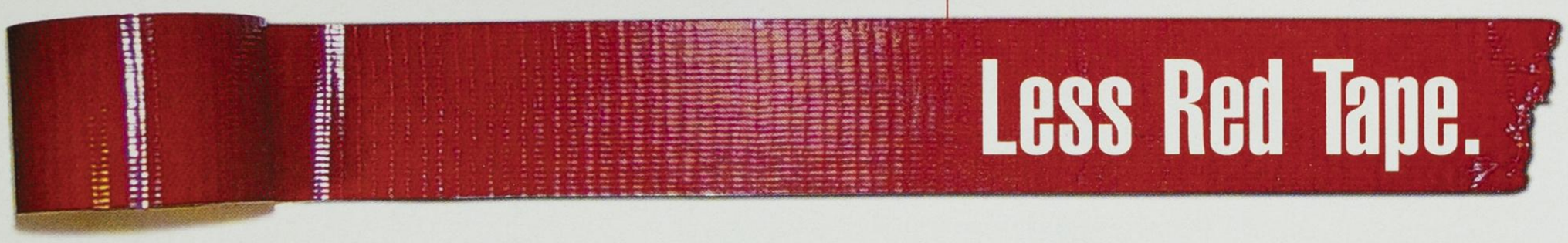
Backlights continue to improve, and are becoming thinner, brighter and more uniform. "Backlights for today's full-color displays almost all use white LEDs together with a plastic lightguide," said Yang. Making further improvements to the brightness of backlights will require brighter LEDs, as well as smaller variations in brightness and color. Handset designers are also looking for thinner lightguides, thinner LEDs and narrower display borders for mechanical, cosmetic and ergonomic reasons.

Yang described organic LEDs (OLEDs) as offering high brightness, video rates and good saturated color. "OLEDs will continue making inroads," he said. "However, issues with cost, lifetime and readability in sunlight remain to be solved."

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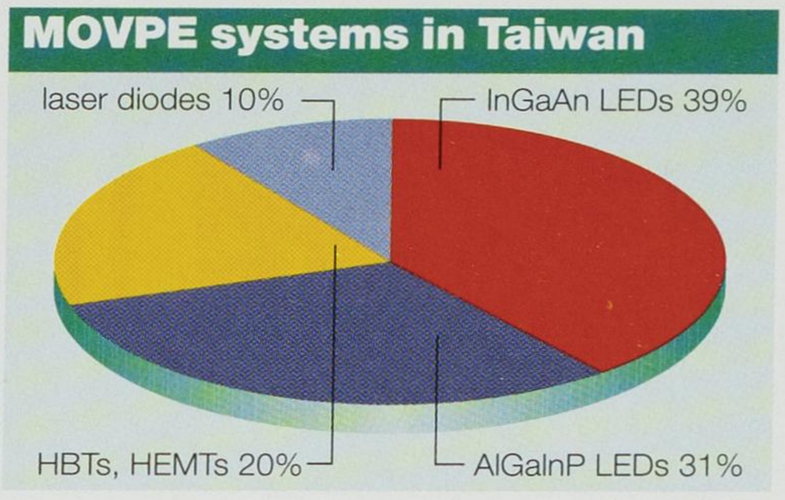
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Fig. 3. The 2003 Honda Accord is one of a number of automobiles that uses white LEDs to backlight the instrument panel. The interior automotive lighting market was worth about $250 million in 2002.




OPTOTECH/EPISTAR

Fig. 4. The number of MOVPE systems for LED growth is equivalent to a production capacity of 200 million InGaN chips and 800 million AlGaInP chips per month (NB actual production levels are much lower).

## Signs and displays

The second largest market for HB-LEDs in 2002 was the signs segment, with a 23% share. Signs using LEDs range from single-color moving message panels to full-color video screens. Although there was an increase in the overall surface area of LED-based signs deployed during 2002, price declines meant that the net revenue growth was only around 3%. Large companies such as Barco, Daktronics and Lighthouse selling full-color video screens for sports stadia, concerts and casinos continued to prosper, although advertising signs suffered due to the recession. Traffic variable message signs were a major market for single-color signs.

According to Paul Semenza of Stanford Resources, the market for large LED video signs will more than double from 30,000 $m^2$ in 2002 to over 60,000 $m^2$ in 2007. Meanwhile, the market for LED text signs is already at 60,000 $m^2$ and will increase to 100,000 $m^2$ by 2007. Prices are higher for indoor displays and small pixel pitches – as high as $60,000 per $m^2$ for indoor displays with a 5 mm pitch.

## Automotive lighting

The automotive segment had an 18% share of the total HB-LED market ($324 million) in 2002, and grew by around 30% compared with the previous year, said Bob Steele. Most of this growth came from interior applications, where LEDs are used as to illuminate instrument clusters and control functions (figure 3). Around 80% of European cars now have LED lights in their instrument panels. There is very little activity among US car makers, while Japan seems set to be the next growth area. Exterior lighting showed a small amount of growth, mainly for center high-mounted stop lights. Rear stop/turn/tail lights are limited to high-end cars, in modest production volumes, while LED-based headlights are still several years away. The truck and bus market is growing rapidly, driven by the benefits of reduced maintenance when standard bulbs are replaced by LEDs. Most new US trucks, and all buses, are being built with LED signals and markers.

Expanding on the exterior automotive lighting market, Jianzhong Jiao of North American Lighting explained the appeal of LEDs to car makers. In the US, car makers are interested in styling and design flexibility, while Japanese and European manufacturers tend to value longer lifetimes and power consumption savings. "A power reduction of 100 W is equivalent to 2% improvement in fuel economy," said Jiao. Negative impacts of LEDs include a higher initial cost, and increased lamp design complexity.

The challenges for LED suppliers, said Jiao, are to reduce cost while increasing quality and performance. Targets for the latter include higher lumen output, meaning fewer LEDs, and higher brightness (defined as the number of lumens per unit area). For headlamps, brightness is more important than total lumen output, and there are strict requirements for high brightness gradients within the beam.

## Signals and illumination

According to Steele, around 1.5 million LED traffic signals (including arrows and pedestrian signals) were installed in 2002. Most of these are in the US, where around 39% of red signals are LED-based, while China is the second largest market. Road traffic signals dominate the signals segment, which



accounted for around 2% of the total HB-LED market in 2002.

In the aviation industry, LEDs have a number of potential uses for interior and exterior lighting in aircraft, according to John Petrick of TWR Lighting. Also, airports have a huge number of lights to mark out runways, taxiways and boundaries, and to mark obstructions such as towers. "Runway centerline LED lights are already in place, although no navigational lights have been deployed yet," said Petrick.

Illumination accounted for 5% of the total HB-LED market in 2002, and was made up of a number of niche applications such as architectural lighting, machine vision, emergency lighting and flashlights. Most applications use colored lights, and LEDs are not yet competing in the general illumination market, although rapid improvements are being made.

According to Liam Kelly of StockerYale, there are a wide variety of machine vision applications: "These include separating green apples from red, or detecting defects in semiconductor packaging, or paint quality analysis. LEDs are gradually displacing other forms of illumination." Machine vision illuminators

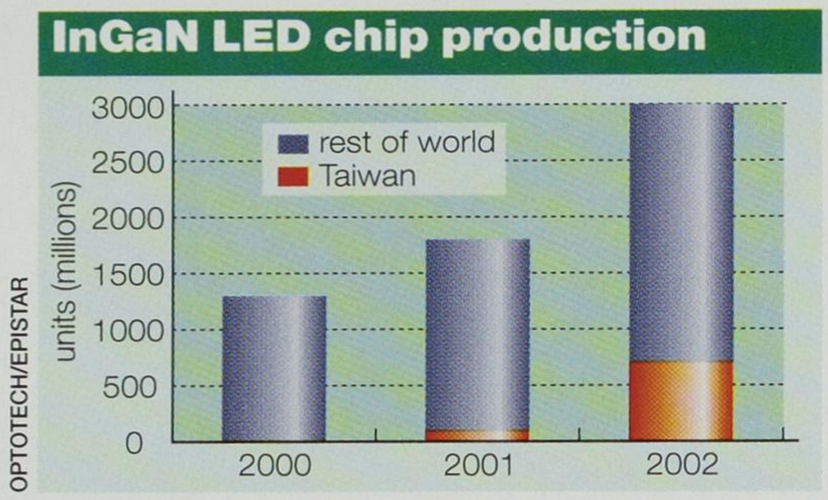



**Fig. 5. Taiwan produced 700 million InGaN LED chips in 2002, equating to 23% of the worldwide total.**

come in a variety of standard formats, including lines, area lights and ring lights.

## Next generation lighting initiative

The Next Generation Lighting Initiative (NGLI), a US program to accelerate the development of solid-state lighting, is still waiting to be approved by Congress. According to Pamela Farrell of GE Global Research, who handles technology policy for GE in Washington DC, the proposal has bipartisan support, but at the present time security issues tend to grab the attention.

"We have been assured that the NGLI will be included in any energy legislation put forward in 2003," said Farrell. "Unfortunately, it will be combined with more contentious issues such as oil drilling in Alaska."

The US Department of Energy requires legislation in order to fund a consortium of industry, academia and national laboratories, which will conduct fundamental research and produce technology demonstrators.

## Taiwan

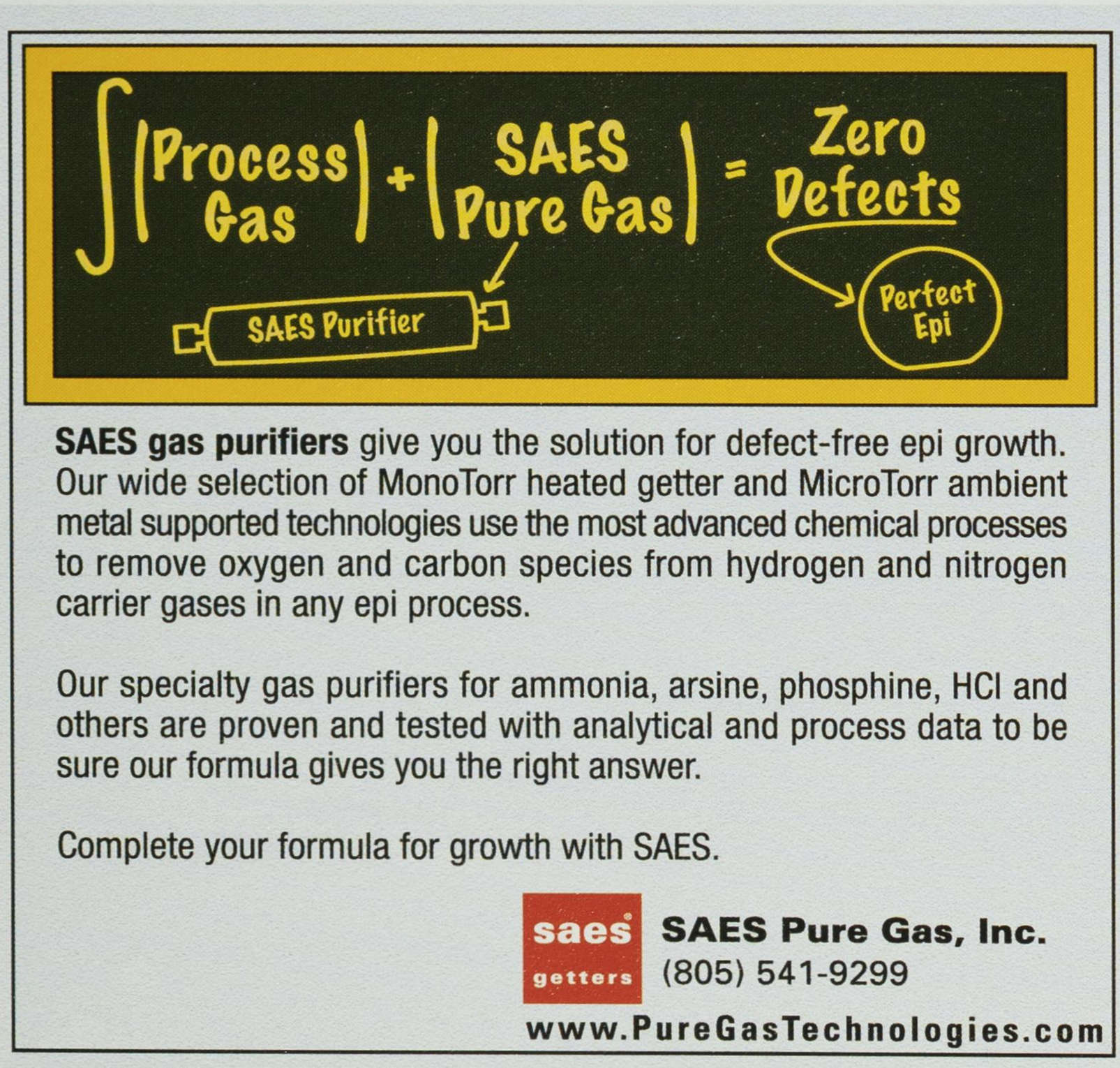
Already the dominant producer of AlGaInP LEDs, Taiwan is rapidly emerging as a leading supplier of InGaN-based LEDs. The country has a number of manufacturers shipping chips, of which UEC, Epistar, Arima and Formosa Epitaxy are the largest, and at least 10 other companies at various stages of development. Steele estimated that there are more than 80 InGaN MOCVD reactors in Taiwan, while the total chip-making capacity exceeds 250 million dice per month (however, actual production levels are not that high). Mostly, these are moderate-quality blue LEDs which are largely used for keypad lighting of mobile phones.

Later in the conference, Schiu Sche of Opto Tech, a leading Taiwanese LED maker, provided some more detail on Taiwan's optoelectronics industry, which grew from $8.5 billion in 1999 to $14 billion in 2002. Compared with the rest of the world, Taiwan is very strong in IT and display products, but is relatively weak in applications related to communications.

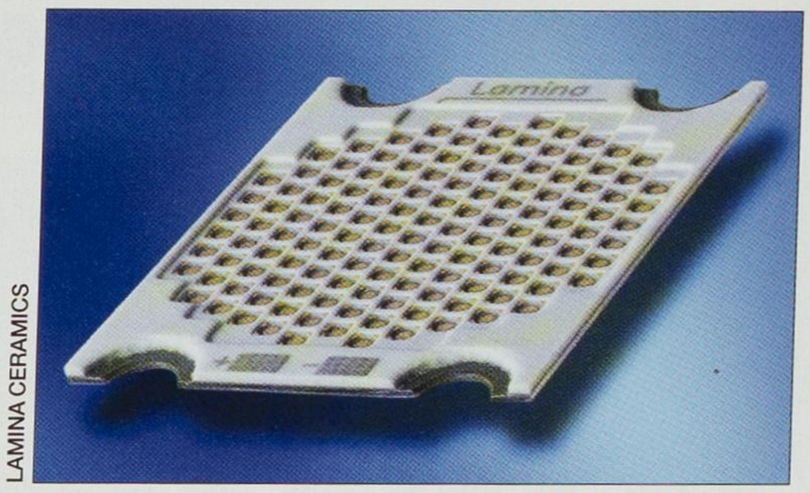
Sche claimed that Taiwan now accounts for 64% of LED chip production worldwide, and that there are close to 200 MOVPE reactors installed throughout the country, operated by at least 17 different companies. As shown in figure 4, more than two-thirds of MOVPE capacity in Taiwan is for LED production, while other companies are producing HBT and HEMT epiwafers, and developing laser diodes (mainly VCSELs).

Sche estimated that worldwide InGaN chip production reached 3 billion units in 2002, up from 1.8 billion units in 2001. The figures do not include low-quality, out-of-specification chips, many of which are shipped to China for use in toys. Taiwan achieved more than a seven times increase in InGaN chip output during 2002 (figure 5), and accounted for 23% of worldwide shipments. This number seems certain to continue to increase.

Sche also described the activities of the Taiwan semiconductor lighting industrial



association, an R&D consortium aiming to develop next-generation light sources using LEDs. Phase one of the project aims to organize the R&D activities of Taiwan's LED industry, while at the same time assessing its capabilities. Phase two, which will take place from 2003 to 2005, aims to develop production capability for 50 lm/W white LEDs, and to demonstrate 100 lm/W devices.




LAMINA CERAMICS

Fig. 6. A low temperature co-fired ceramic on metal (LTCC-M) package capable of holding up to 134 LEDs. The package has a thermal conductivity of 170 W/mK, and can operate up to 250 °C.

## Illumination challenges

Nadarajah Narendran of the Lighting Research Center (LRC), based at Rensselaer Polytechnic Institute, described some of the challenges facing the adoption of LEDs for general illumination: "Initially, LEDs are more suitable for direction lighting. As the total lumen count increases, LEDs become suitable for general lighting."

A possible roadblock to the acceptance of LED lighting is the use of the certain metrics such as luminous efficacy, measured in lumens per watt (lm/W) and color rendering index (CRI). Lumens per watt is appropriate for characterizing the light source, said Narendran, but a better metric is needed for energy use in system applications. For example, the efficacy of a source can be significantly different in directional applications.

Narendran also said that there is a common misconception that high CRI equates to a more pleasing appearance. The LRC conducted a series of human factor experiments to compare white light sources. LED-based reading lamps were generally preferred to halogen and incandescent sources. However, in comparing skin-tone preferences, multichip RGB white LEDs did much better than other types of device, notably those combining blue chips with yellow phosphors, due to the low red component in the spectrum of the latter devices.

Rather than being an absolute scale of color rendering, CRI measures the degree to which the colors of an object illuminated by a test source match the same colors illuminated by a standard source. This standard is often an incandescent bulb, which is not perfect and has a low blue spectral content. Therefore, a better metric is required for quantifying color rendering properties.

Narendran also explained that traditional light sources define lifetime as the time taken for 50% of the samples to burn out. However, since LEDs do not fail catastrophically, life should relate to lumen maintenance. He suggested that lifetime could be defined as the time taken for light output to fall to 70% of its initial value.

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# Data storage keeps laser diode market buoyant

The laser diode market has undergone drastic changes in size and shape since the heady days of 2000, when telecom lasers were in high demand. Data storage is now the dominant application, as **Jon Newey** finds out when looking at the latest figures from Strategies Unlimited.

The market for laser diodes in 2002 presented a mixture of good and bad news, depending on the application. According to research from Strategies Unlimited, the overall market contracted by 16% in 2002 to $2.4 billion due to a steep drop in demand for telecommunications lasers. However, that figure masked impressive growth in the market for lasers for optical data storage. At the Lasers and Optoelectronics Marketplace Seminar in San Jose, CA, in January, Robert Steele, Strategies Unlimited's director of optoelectronics, revealed that revenue from lasers for optical storage grew by 82% to $1.4 billion in 2002. Optical data storage applications accounted for 58% of the total laser diode market, driven by consumer acceptance of the DVD format. This growth meant that sales of lasers for optical storage surpassed those of telecom lasers, and are forecast to maintain the leading position in 2003.

Other application sectors, which include pump lasers for diode-pumped solid-state lasers (DPSSLs), barcode scanners, laser pointers, and medical and printing applications, accounted for 14% of the market with revenues of $348 million in 2002. This was a decline of 8% compared with the 2001 figure, although the market for pump lasers in DPSSLs showed healthy growth.

With modest growth expected to return to the fiber-optic components market this year (*Compound Semiconductor* January/February 2003 p24), and the continued acceptance of DVD technologies, the overall laser diode market is predicted to grow by 17% in 2003 to $2.81 billion.

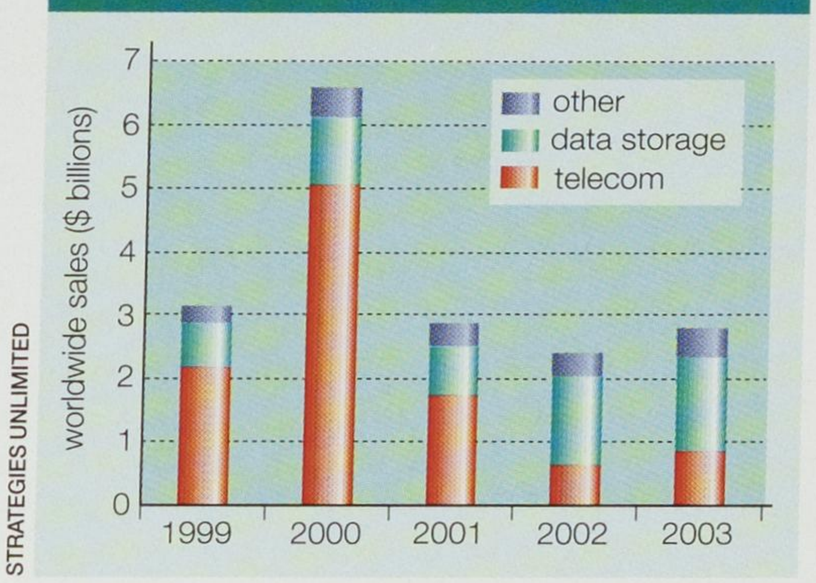
## Telecommunications

The telecom laser market fell by 61% from $1.72 billion in 2001 to $665 million in 2002. In 2002, telecom lasers accounted for 28% of the total diode laser market, while in 2000, that figure was 83%. Transmission lasers fared slightly better than pump lasers for optical amplifiers in 2002. Revenue from transmission sources fell by 50% to $600 million, while pump source revenue fell by 87.5% to $65 million.

The differences in performance arise because optical amplifiers are deployed in long-haul systems, an area in which there was very little build activity in 2002. Transmission sources have benefited from demand in the more active short-haul area, and also from modifications to increase the capacity of existing links by adding channels.

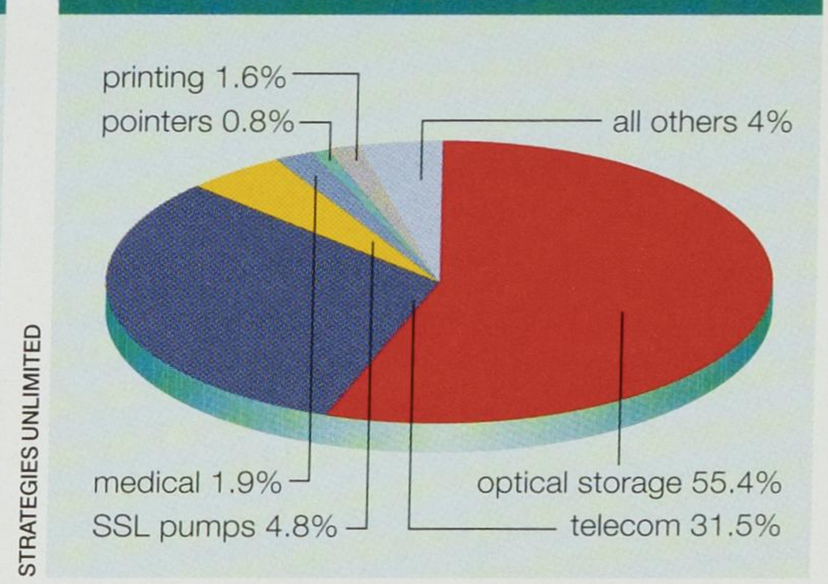
The forecast for telecom lasers in 2003 is for 33% growth to $885 million, still below 1996 levels. Revenue from transmission sources will grow by 30% to $780 million,

**Worldwide laser diode market**




Data storage is now the dominant application as growth returns in 2003.

**2003 market by revenue**




Strengthening telecoms will help the total market to reach $2.81 billion in 2003.

**Total sales of lasers for optical storage applications in 2002 were $1.42 billion, an increase in revenue of 82% on unit growth of 38%.**

with pump laser revenue growing by 62% to $105 million.

A related area that is included in the "other" category is lasers for short-reach optical communications such as local-area networks (LANs). The market for LANs and storage-area networks (SANs) has not suffered as badly from the over-investment and high inventory levels that the telecom market is now paying for. However, capital spending among the corporations that use SANs and LANs has been put on hold due to falling corporate profits. The impact on the laser diode market has been a reduction in sales of transceivers that use 850 nm VCSELs and 1310 nm edge-emitting lasers. Revenues from such lasers fell by 35% to $79 million in 2002, and continued economic uncertainty means that the market is expected to remain flat in 2003.

## Optical storage

Just as the CD-based optical storage market saturated and began to decline, along came DVD to lift volumes again. Total sales of lasers for optical storage applications (780 nm for CD and 650 nm for DVD) in 2002 were $1.42 billion, an increase in revenue of 82% on unit growth of 38%, compared with the

2001 figures. More modest growth is expected in 2003, with revenues forecast to reach $1.56 billion from 487 million unit shipments, although Steele suggests that this figure may have more to do with suppliers' conservative estimates than with market realities.

Sales of DVD players for movies, DVD-based games units and also PCs with DVD drives snowballed in 2002, helped by falling prices and the increasing number of movies, games and software titles available in DVD format. Sales of 650 nm DVD lasers grew to 148 million units in 2002, bringing in revenue of $448 million. Nearly a third of these were monolithically integrated dual-wavelength (650 and 780 nm) lasers that were introduced in 2001 to enable DVD players to also read CDs. Prior to 2001, this need was met by two co-packaged discrete lasers.

The lack of a clear winner amongst the different standards for recordable DVDs has failed to dent enthusiasm for rewritable DVD drives. These use higher-power (30 mW) 650 nm lasers, of which 7.5 million were sold in 2002. Increasing numbers of PCs are being shipped with CD-RW drives for backing up data, storing digital images from cameras and writing music files. This pushed sales of 40 mW 780 nm lasers to 89 million units valued at $615 million in 2002.

**Unit shipments in 2003**

| *Application* | *Units (millions)* |
|---|---|
| optical data storage | 487.3 |
| telecommunications | 2.5 |
| SSL pumps | 0.144 |
| medical | 0.271 |
| laser pointers | 43 |
| printing | 7.6 |
| all others | 9.6 |
| total | 550.415 |

### Other applications

There is a large spread in the price per unit across the applications outside of telecom and data storage. High-power diode lasers used to pump DPSSLs make up the next most valuable category, and are also showing healthy growth. Unit sales of DPSSLs grew by 38% in 2002, helping the unit sales of pump lasers rise to 123,000. Total revenue increased by 19% to $119 million. Much of the growth came from an increase in US military spending, which will help pump laser revenues to grow to $135 million in 2003.

At the other end of the unit price range is the category of lasers for entertainment and display applications, which mostly comprises laser pointers. This is a relatively mature application, and most of the lasers are manufactured in Taiwan before being packaged in China. Although unit sales are expected to be flat in 2003 at 43 million, the unit price will decline. Total revenue will drop from $25.3 million in 2002 to $22.9 million in 2003, due to low-cost packaging methods for this relatively undemanding application.

Lasers for medical equipment sit between DPSSLs and laser pointers in the price per unit range. After suffering a two-year decline in sales, the forecast for 2003 is somewhat better. Unit shipments will reach 270,000 units valued at $53 million, still below the 364,000 units and $82 million in 2000.


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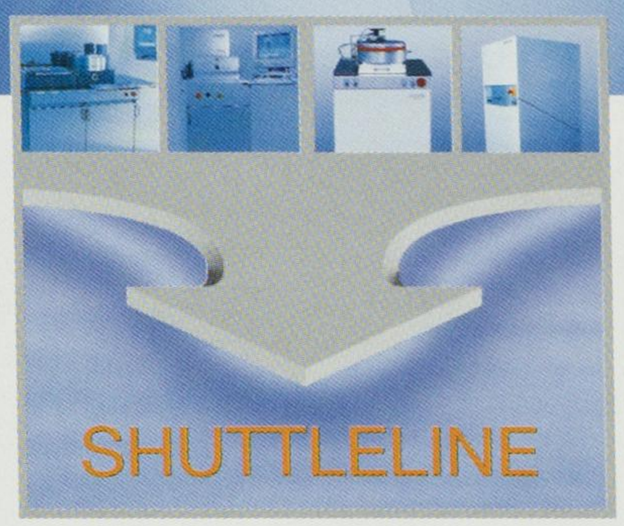



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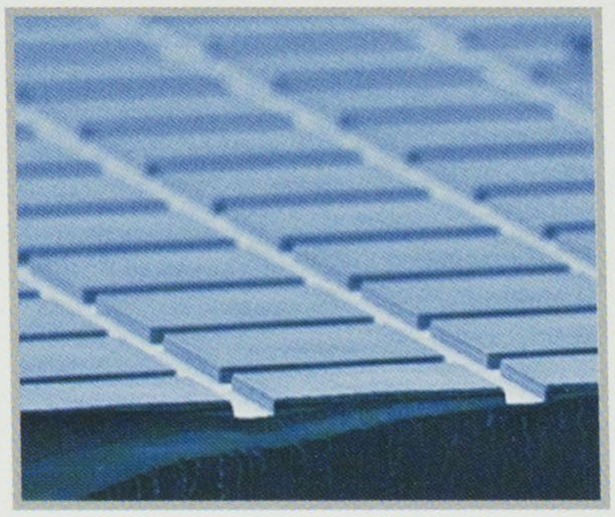
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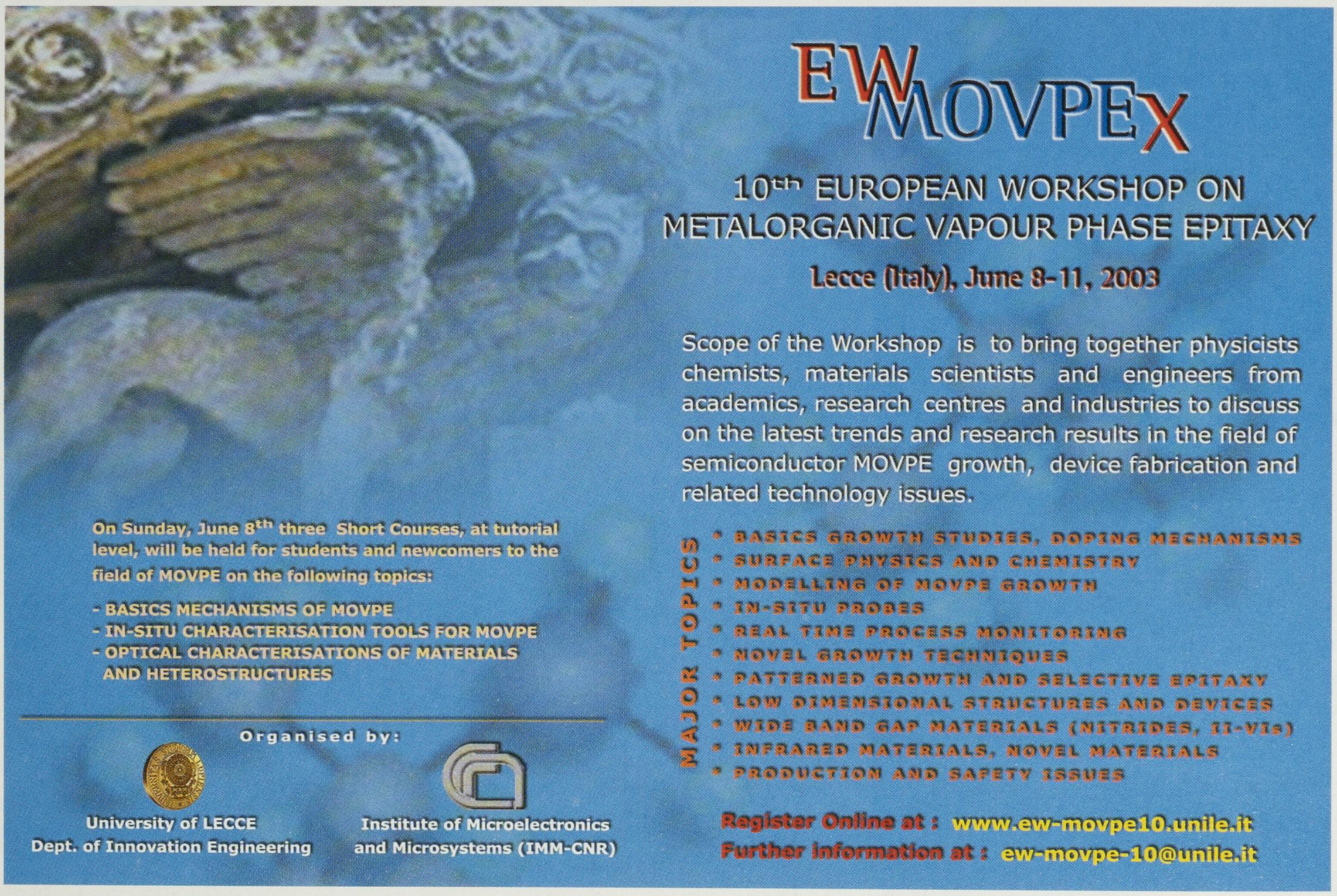
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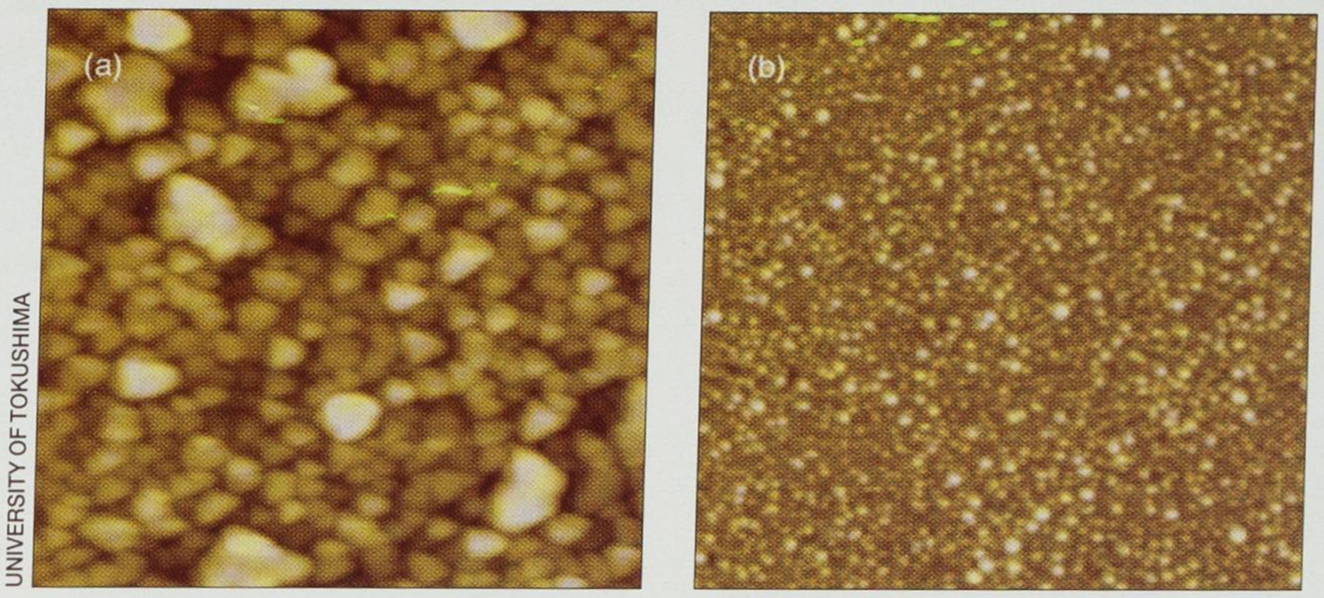
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# Phosphorus gives better GaN buffers

The reduction of dislocation density in GaN and related materials is an ongoing battle for those growing GaN-based devices. The deposition of low-temperature (LT) buffer layers, such as LT-GaN or LT-AlN, has become an indispensable procedure for growing commercially available GaN-based epiwafers with reasonably low dislocation densities. A team from the University of Tokushima in Japan has demonstrated that a new buffer layer, GaN-rich GaNP, can significantly reduce dislocation density in the subsequently grown GaN epilayers (*Appl. Phys. Lett.* 2003 **82(6)** 919).



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AFM images of an annealed (a) LT-GaN buffer (maximum AFM image height 30 nm) and (b) LT-GaNP buffer (maximum AFM height 20 nm).

The LT-GaNP buffers were deposited under conditions identical to those for LT-GaN buffers, except for the introduction of a phosphorus source gas, $PH_3$. The dislocation density in a 2.4 μm GaN layer grown using LT-GaNP as a buffer was as low as $5 \times 10^8$ cm$^{-2}$, and the FWHM of the (0002) and (10$\bar{1}$2) X-ray rocking curves were 190 and 300 arcsecs, respectively.

The morphology differences between AFM images of the annealed GaNP and GaN buffer were compared to analyze the dislocation reduction mechanism caused by the introduction of P into the LT-GaN buffer layer. A conventional LT-GaN layer is partly evaporated during heating, and the resulting islands enlarge and coalesce before a flat GaN layer is obtained during the growth of GaN at high temperatures. The coalescence boundaries remain as dislocations. The introduction of P into LT-GaN results in a less dense GaNP compound, and islands are larger with a pronounced c-axis face; thus the dislocation density is lower. The group is now further optimizing the growth conditions for the LT-GaNP buffer layer and succeeding high-temperature GaN layers for the growth of device structures.

# Virtual substrates for crack-free AlGaN/GaN mirrors

InGaN/GaN quantum well heterostructures have become the standard active medium in violet, blue and green LEDs and violet-blue edge emitting lasers, which are now commercially available. LED performance can be improved by placing the emitting active zone inside a resonant cavity (*Compound Semiconductor* January/February 2002 p49). The development of efficient resonant cavity LEDs and VCSELs necessitates the growth of high-quality DBRs. In the case of III-nitride reflectors, the mirror performance has been limited by the low index contrast ratio between the stacked layers of GaN and AlGaN, with an Al composition in the range 0.08–0.34, that constitute the Bragg mirror. The large lattice mismatch between GaN and AlN of ~2.5% induces cracks into the layers.

A research group from the Centre National de la Recherche Scientifique in Valbonne, France, has shown that these limitations can be overcome by strain-balance engineering through the growth of a lattice-matched DBR on a virtual $Al_yGa_{1-y}N$ substrate (*Appl. Phys. Lett.* 2003 **82(4)** 499). The $Al_yGa_{1-y}N$ composition of this virtual substrate layer is chosen in order to have the same lattice parameter as that of the average lattice parameter of the $Al_xGa_{1-x}N$/GaN Bragg mirror. Before the $Al_yGa_{1-y}N$ layer is grown, a high-temperature AlN interlayer is grown which avoids crack formation inside the $Al_yGa_{1-y}N$ strain-mediating layer. Using this procedure, $Al_xGa_{1-x}N$/GaN Bragg mirrors with Al compositions of 0.2 and 0.5 were grown by MBE onto 2 inch sapphire substrates. The resulting epiwafer surfaces were totally free of cracks. The $Al_{0.5}Ga_{0.5}N$/GaN Bragg mirror with just eight periods exhibited a peak reflectivity of 69% centered around 450 nm with a large FWHM stopband of 49 nm. This approach opens the way to the fabrication of high Al-content crack-free AlGaN/GaN Bragg mirrors, having the high numbers of periods required for vertical cavity structures at UV and visible wavelengths.

# Facet controlled buffers yield high-quality AlGaN

A group from Meijo University in Nagoya, Japan, has demonstrated a high-efficiency UV-LED grown using a novel variant on the epitaxial layer overgrowth techniques that are used to reduce dislocation densities in material grown onto sapphire (*Jpn. J. Appl. Phys.* 2003 **42 (Pt.1/2A)** 400).

The MOVPE growth technique involved the deposition of a 20 nm low-temperature AlN buffer layer followed by a 3 μm GaN layer. An $SiO_2$ stripe mask was deposited onto the GaN, and facet-controlled GaN seed crystals were grown into the mask windows. This facet-controlled GaN substrate was then covered with a low-temperature AlN interlayer onto which crack-free AlGaN with a dislocation density as low as $2 \times 10^7$ cm$^{-2}$ was grown over the entire wafer. This value of dislocation density is two orders of magnitude lower than that of conventional AlGaN growth – an important consideration, as dislocations act as nonradiative recombination centers that diminish device efficiency.

The device structure was also optimized to improve the light-extraction efficiency, resulting in a high-efficiency UV-LED with a peak wavelength of 363 nm and a FWHM as narrow as 4.8 nm. The output power was 4.7 mW at an injection current of 100 mA. Although the external quantum efficiency is still below that of violet and blue LEDs with InGaN/GaN active regions, the team believes that further refinements to the growth and structure of the device will yield more efficient devices. The group is now using the technique to develop a UV laser with a GaN/AlGaN MQW active layer.

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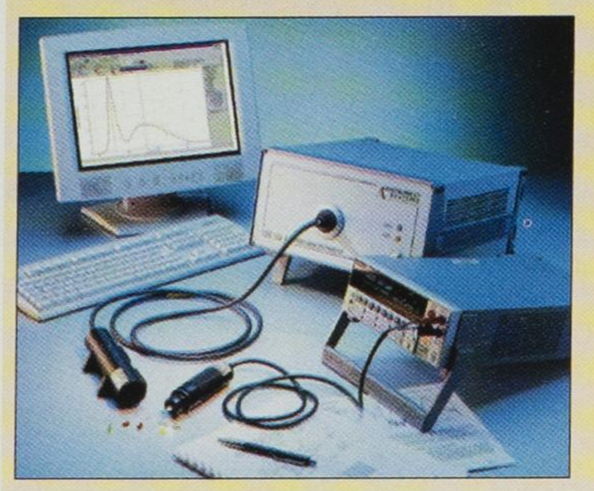


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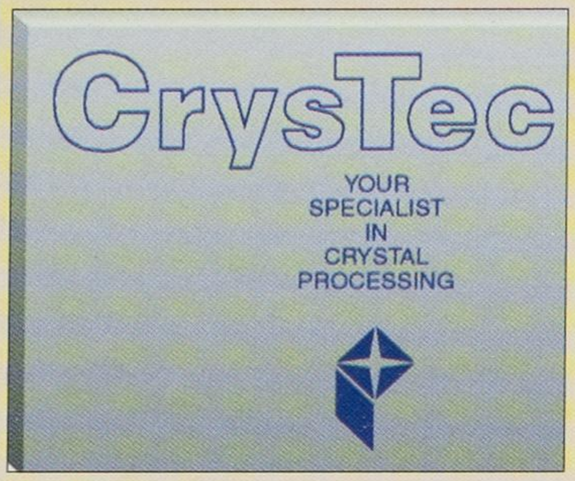


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# Magdeburg team grows buffers for GaN-on-Si

The growth of high-quality GaN on Si, which is being developed for the mass production of low-cost LEDs and FETs, is difficult due to the high thermal mismatch of these materials, which leads to the cracking of layers in excess of 1 μm thick. A method to reduce tensile stress for GaN growth on Si has been developed by Armin Dadgar and coworkers from Otto-von-Guericke University, Magdeburg, Germany (*Appl. Phys. Lett.* 2003 **82(1)** 28).

In addition to the unavoidable thermal stress, intrinsic tensile stress is usually induced at the coalescence boundaries of GaN islands originating at the nucleation layer for typical GaN growth processes on Si. This intrinsic stress, which can be significantly higher than the thermal stress, can be greatly reduced by growing larger-sized GaN islands, using for example an *in situ* deposited SiN mask. Additionally, by applying such a mask the dislocation density is reduced by about a factor of three, and the PL intensity increases about an order of magnitude for a 700 nm thick GaN layer. This method can also be applied for GaN growth onto SiC, where tensile stress is also an issue.

The Magdeburg team grew 7 μm thick, high-quality, crack-free GaN layers on Si using SiN masks and low-temperature AlN interlayers for stress reduction. First results on the properties of these thick layers were presented at the 2002 MRS Fall Meeting.

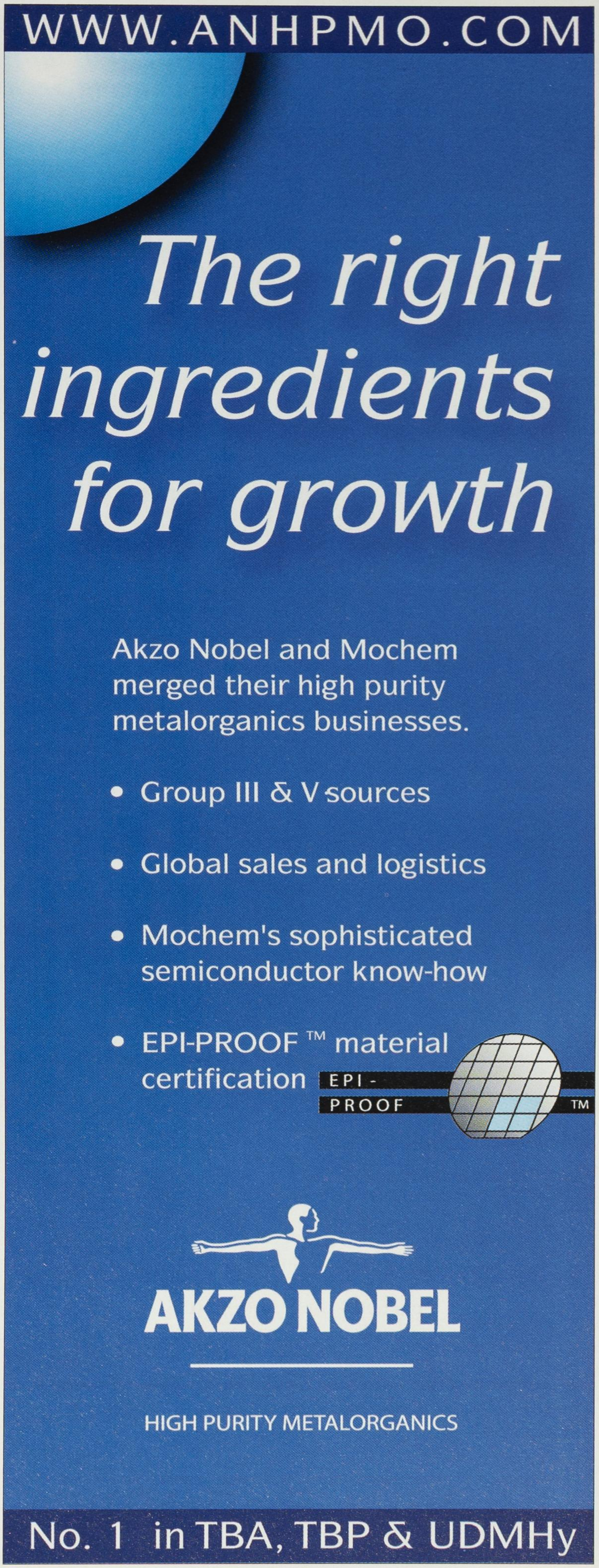
# GaAs/GaN HBTs formed by wafer bonding

AlGaN/GaN HEMTs have been widely reported, but AlGaN/GaN HBTs are another class of device being actively developed. The performance of such HBTs is limited by large acceptor ionization energies and low hole mobilities. One solution is to use an AlGaAs emitter, GaAs base and GaN for the collector, although a large lattice mismatch between GaAs and GaN prevents epitaxial formation of this structure. A group from the University of California, Santa Barbara, has reported device results from an HBT using this structure and formed by wafer bonding (*Appl. Phys. Lett.* 2003 **82(5)** 820).

The AlGaAs/GaAs emitter/base structure was grown onto a GaAs wafer by MBE after deposition of an AlAs etch-stop layer. The GaN collector was grown onto a sapphire wafer by MOCVD. The GaAs and GaN epiwafers were then cleaved into rectangles measuring 5 × 10 mm before being placed in contact and annealed at 750 °C for 60 min in an $N_2$ ambient to form a bond. The GaAs substrate and AlAs etch-stop layer were then removed by selective wet chemical etching.

The I-V characteristics of the GaAs/AlGaAs junction formed by MBE were tested before and after periods at high temperatures and found to be almost identical, indicating that the bonding anneal step did not degrade the junction's characteristics. However, the same junction exhibited a degradation of its I-V properties after bonding to the GaN wafer, probably as a result of diffusion of defects and dopants during the bonding anneal.

The current gain (β) was expected to be similar to that of AlGaAs/GaAs HBTs, but was found to be low for the bonded HBT. Again this was attributed to the diffusion of dopants across interfaces during periods at elevated temperatures. Work is underway to investigate the effects of the annealing temperature on the device.

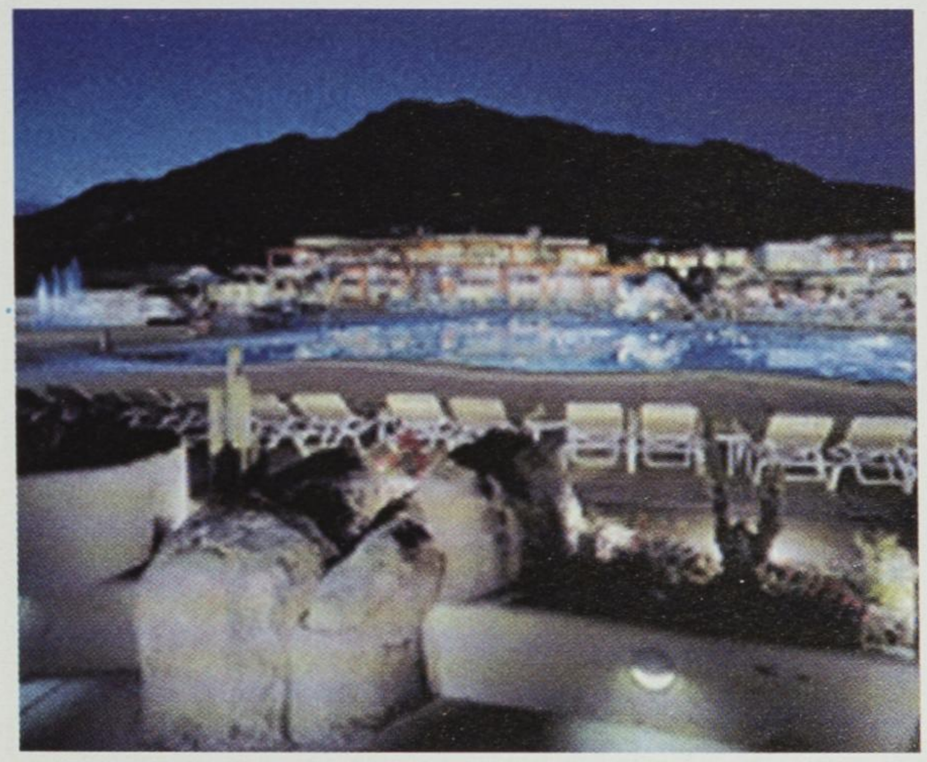


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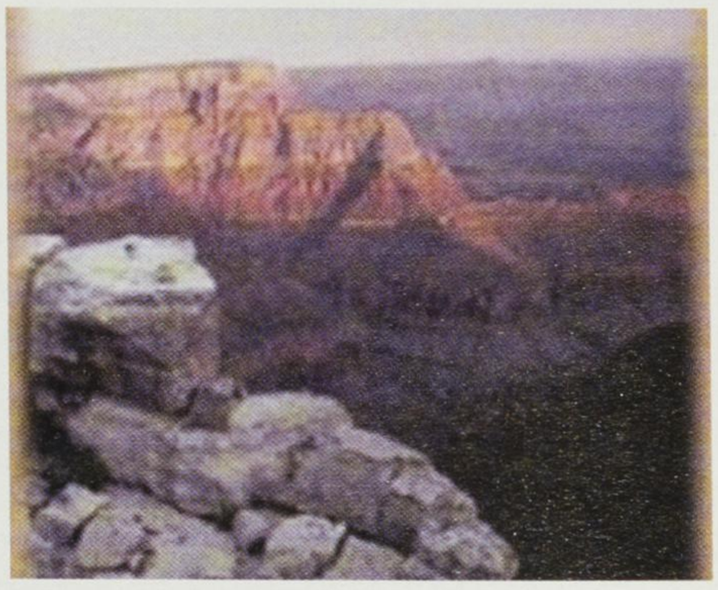
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- Power Amps for Wireless Applications
- GaN
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- MEMS
- Advanced Interconnect for Compound Semiconductors

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

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

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



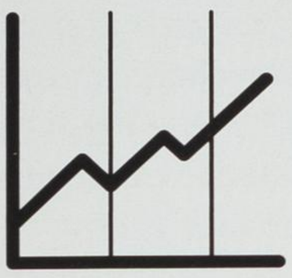
❑ **Ugly Picture Contest:** This is a very entertaining and informative contest. It gives everyone a chance to benefit from their problems by winning a prize for the most photogenic example of a manufacturing problem and its solution.

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

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# What lies behind the figures?

Everybody likes to see rising revenues and growing profits (or narrowing losses) with each passing set of quarterly results, but it's worth taking a look to see what else is on the income statements.



Recent quarters have seen a number of companies involved in compound semiconductors report increasing revenues and increasing profits (or narrowing losses). While some of this is undoubtedly due to an upturn in business, higher profits do not necessarily have to come from increased revenue. With the December 2002 quarter earnings announcements behind us and the March quarter figures eagerly anticipated, it is perhaps a good time to take a look at what lies behind the headline figures.

Taking HBT epiwafer and display manufacturer Kopin as an example, its total revenue increased by $6.5 m over the four quarters up to September 28, 2002. Over the same period there was a steady fall in operating loss, which turned into a $0.6 m operating profit in the September 2002 quarter. The company also cut its operating expenses (R&D and the cost of sales and administration) from about $8 m to $5.9 m in the year to September 28, 2002. Without this cut in expenses, Kopin would have made an operating loss in the September 2002 quarter. The ideal scenario would be rising profits from increasing revenues, especially if the profits come with higher margins.

**Market overview**

| *Company* | *Symbol* | *Closing price on Mar 25* | *52-week low–high* | *Market cap** |
|---|---|---|---|---|
| **GaAs IC companies** | | | | |
| Anadigics | ANAD | 2.19 | 1.59–13.61 | 67.2 m |
| Celeritek | CLTK | 7.4 | 5.01–11.16 | 91.3 m |
| Endwave | ENWV | 1.06 | 0.32–3.80 | 9.5 m |
| RF Micro Devices | RFMD | 6.58 | 5.159–21.90 | 1.204 bn |
| Sirenza Microdevices | SMDI | 1.35 | 1.05–6.17 | 40.2 m |
| Skyworks Solutions | SWKS | 6.67 | 2.89–17.68 | 921.0 m |
| TriQuint | TQNT | 3.15 | 2.55–13.09 | 417.3 m |
| Vitesse | VTSS | 2.42 | 0.62–10.253 | 494.9 m |
| **Opto companies** | | | | |
| Agilent | A | 14.26 | 10.50–36.95 | 6.720 bn |
| Alcatel Optronics | ALAO | 6.76 | 1.50–8.10 | 734.1 m |
| Cree | CREE | 18.73 | 8.989–25.42 | 1.372 bn |
| JDS Uniphase | JDSU | 2.83 | 1.58–6.20 | 4.005 bn |
| **Semiconductor materials and equipment companies** | | | | |
| ATMI | ATMI | 20.6 | 11.75–37.10 | 633.0 m |
| AXT | AXTI | 0.8 | 0.69–12.00 | 18.0 m |
| Emcore | EMKR | 1.86 | 0.98–10.48 | 68.7 m |
| Kopin | KOPN | 4.74 | 1.93–9.89 | 328.9 m |
| Tegal | TGAL | 0.4 | 0.13–1.42 | 6.4 m |
| Trikon | TRKN | 3.46 | 3.05–15.45 | 48.5 m |
| Veeco | VECO | 16.55 | 9.14–38.80 | 482.3 m |
| **European companies (currency data in €)** | | | | |
| Aixtron | AIXG.F | 2.62 | 2.06–21.30 | 172 m |
| Bede | BED.L | 0.17 | 0.16–3.15 | 4.85 m |
| Bookham | BHM.L | 1.15 | 0.59–2.72 | 245.34 m |
| Filtronic | FTC.L | 1.50 | 0.38–6.64 | 108.49 m |
| IQE | IQE.L | 0.04 | 0.02–2.89 | 6.62 m |
| Picogiga | PGIG.LN | 0.28 | 0.21–5.62 | 1.8 m |
| Riber | RIBE.LN | 0.69 | 0.55–5.66 | 13.0 m |
| STS | SRTS.L | 0.13 | 0.08–2.54 | 4.12 m |

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

### Research set to pay dividends for Kopin

Cost control is important to an efficiently run business, but aggressive cost-cutting when profits are being squeezed should be seen as a short-term measure to be taken before longer-term sustained profitability can be achieved. In Kopin's case, the R&D spend has been largely unaffected, with most of the savings coming from cuts to the cost of its sales and administration. Cuts to R&D spending can be bad news for a company's long-term prospects, and for companies deeply rooted in science and technology the results could be fatal. In fact, the December 2002 quarter saw a marked increase in Kopin's R&D costs to $5.1 m, compared with $3.7 m in the preceding quarter.

The epiwafer business (which accounts for about 45% of Kopin's annual revenues) is particularly cut-throat right now. Epiwafer vendors are competing on price, which helps them to maintain market share, but forces them to exist on smaller margins (*Compound Semiconductor* December 2002 p41). Kopin's results for the December 2002 quarter showed direct evidence of this pressure. Revenue from its III-V business was down 30% over the year-ago period, at $5.6 m compared with $8 m.

Kopin seems to be coping better than many of its competitors, mainly because of its strength in HBTs for the wireless industry, and its lack of exposure to the crippling downturn in optical communications. The company has no significant debt to service, and is sitting on about $118 m in cash and equivalents. One of the reasons for maintaining its R&D spend has been the development of its CyberLite blue LEDs; these are now being sampled, and have been qualified by a packaging customer in Taiwan. Blue LEDs are one of the growth areas in compound semiconductors at present, and Kopin could do well here.

Another result of the R&D effort is its dilute nitride HBT technology, which promises further performance gains over standard InGaP HBTs. At the Key

**RFMD's 2002 revenues and operating expenses**

| *Quarter ending* | *Dec 31* | *Sep 30* | *Jun 30* | *Mar 31* |
|---|---|---|---|---|
| total revenue ($m) | 145.8 | 119.7 | 103.9 | 100.4 |
| R&D expenses ($m) | 24.4 | 22.6 | 23.1 | 22.4 |
| selling, general & admin expenses ($m) | 24.2 | 14.1 | 13.4 | 12.3 |
| operating income ($m) | 5.78 | 9.31 | 5.03 | 6.26 |

**Kopin's 2002 revenues and operating expenses**

| *Quarter ending* | *Dec 31* | *Sep 28* | *Jun 29* | *Mar 30* |
|---|---|---|---|---|
| total revenue ($m) | 16.5 | 21.9 | 20.8 | 17.6 |
| R&D expenses ($m) | 5.1 | 3.7 | 4.1 | 3.3 |
| selling, general & admin expenses ($m) | 1.8 | 2.2 | 2.9 | 3.3 |
| operating income (loss) ($m) | (2.53) | 0.63 | (1.61) | (3.66) |

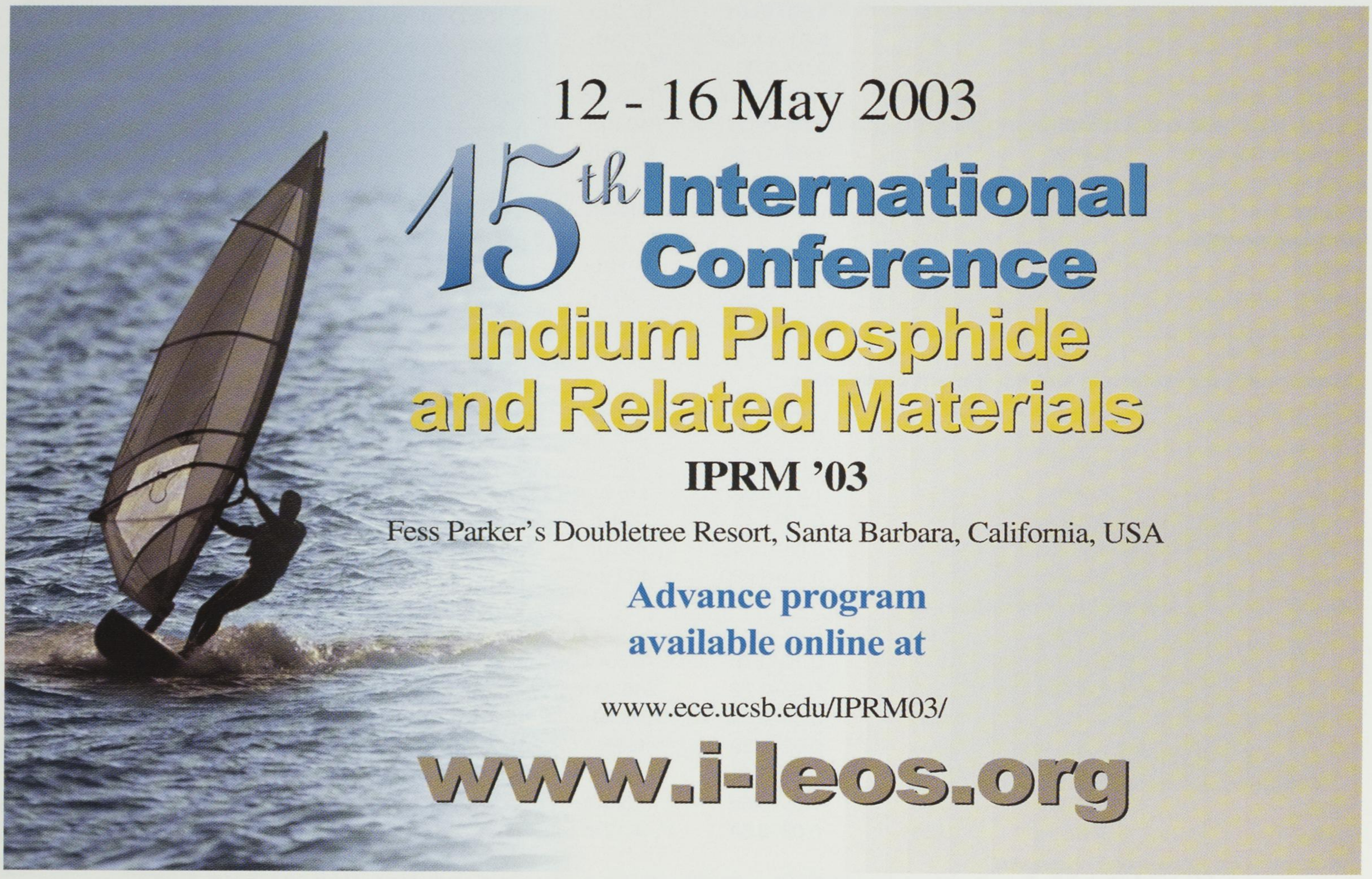
Conference on Compound Semiconductors in March, Kopin's Dave Davito said that the company's new HBT material was now being evaluated by customers, and that announcements concerning its adoption were likely later this year.

### Profits flow from revenue at RFMD

In 2002, RFMD reported accelerating revenue growth with each quarter. For the first three quarters, operating expenses remained flat as revenue climbed. Operating and net income went up during the year, generating healthy rising profits from rising revenues – a rare scenario in the semiconductor industry lately.

However, the December quarter provided an upset to that scenario, which should be temporary. While revenue growth continued apace during the quarter, the balance sheet was spooked by costs and charges related to RFMD's acquisition of Resonext, a provider of CMOS wireless LAN chipsets. A $10.9 m charge meant the company recorded a net loss of $5.2 m. Ongoing expenses in the March 2003 quarter related to the acquisition are expected to total $8.1 m. The race is now on to fully integrate Resonext and its technology for WLAN chips into RFMD so that it adds to the bottom line. The company already occupies the number two spot in the WLAN transceiver market, and growth plans depend on further progress here.

Revenue in the March quarter is predicted to be $135 m, about $10 m down on the December 2002 figures. However, from the June quarter onwards, RFMD is expecting sequential revenue growth as its aggressive push into the market for wireless LAN chipsets continues to bear fruit, and it attempts to increase its market share in wireless handset PA modules. ●



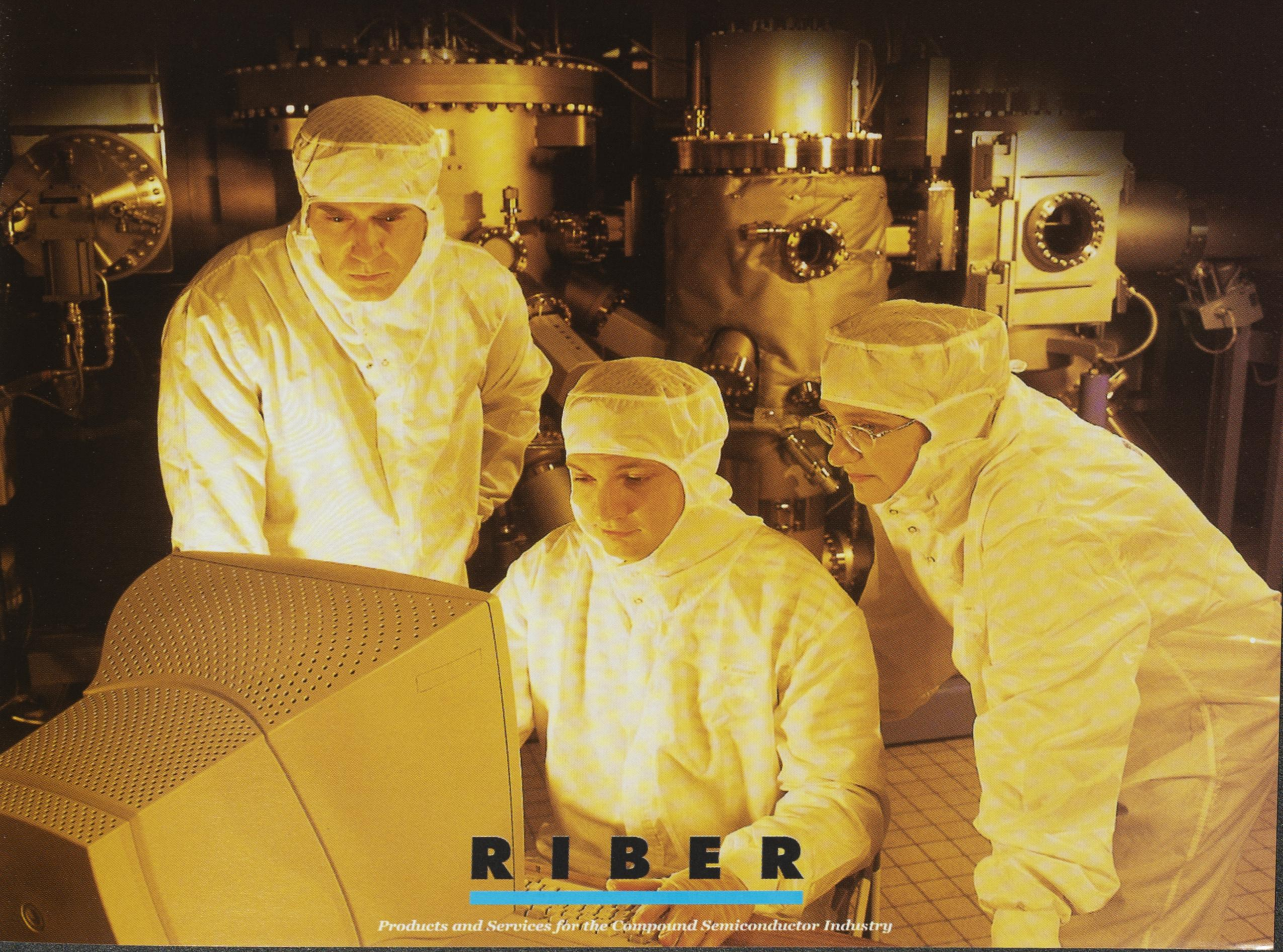
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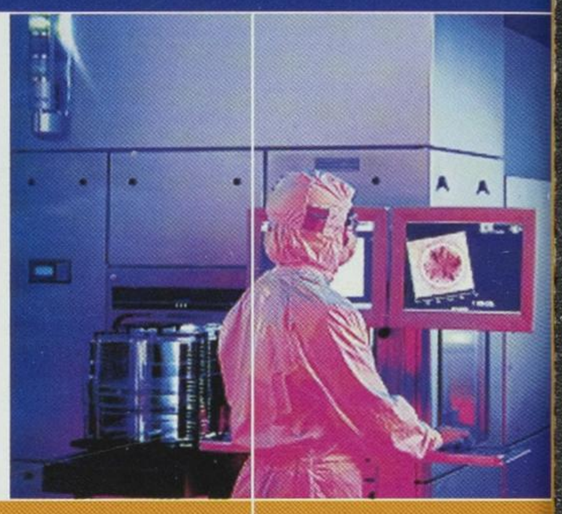
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