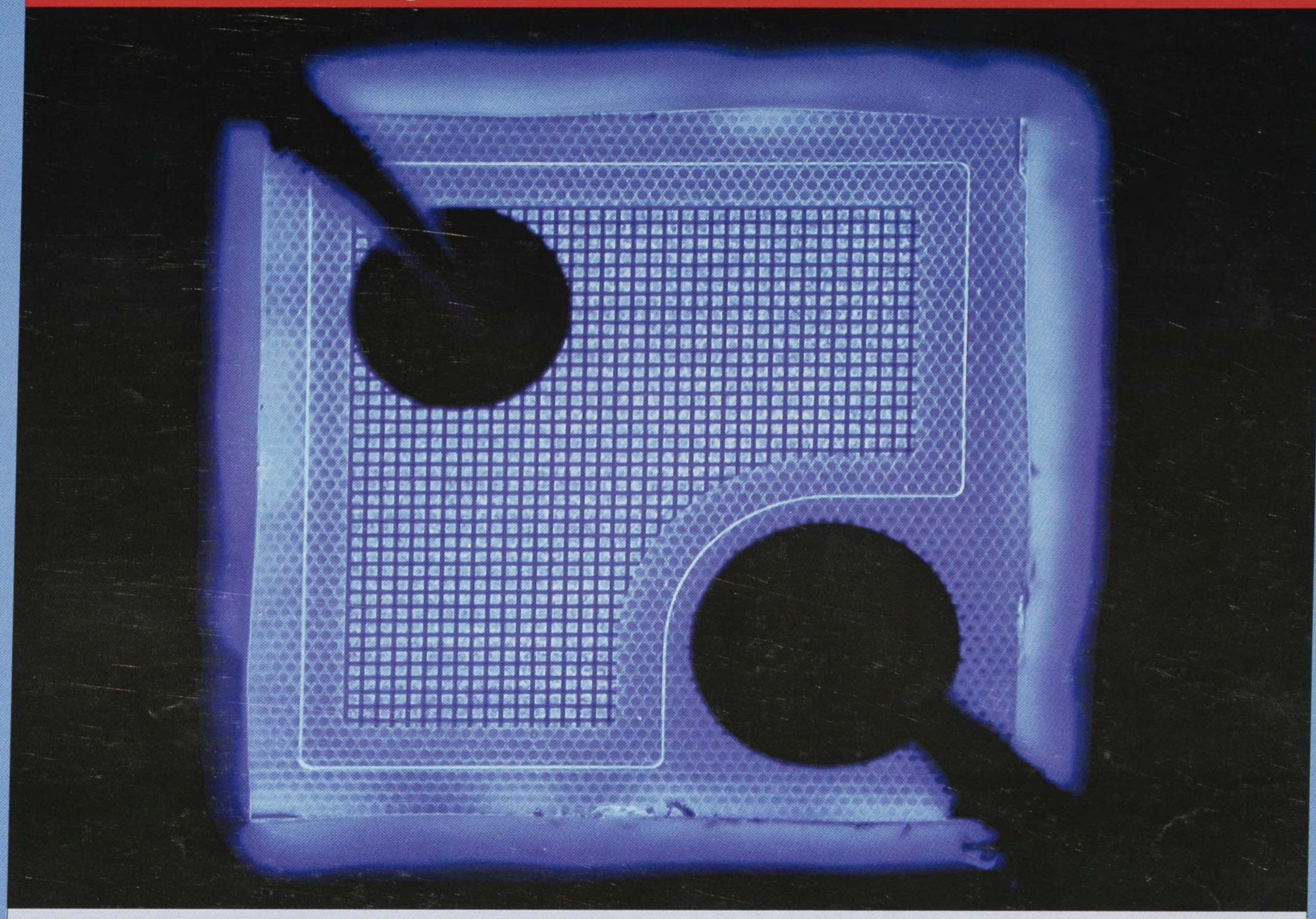
COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

August 2003 Volume 9 Number 7



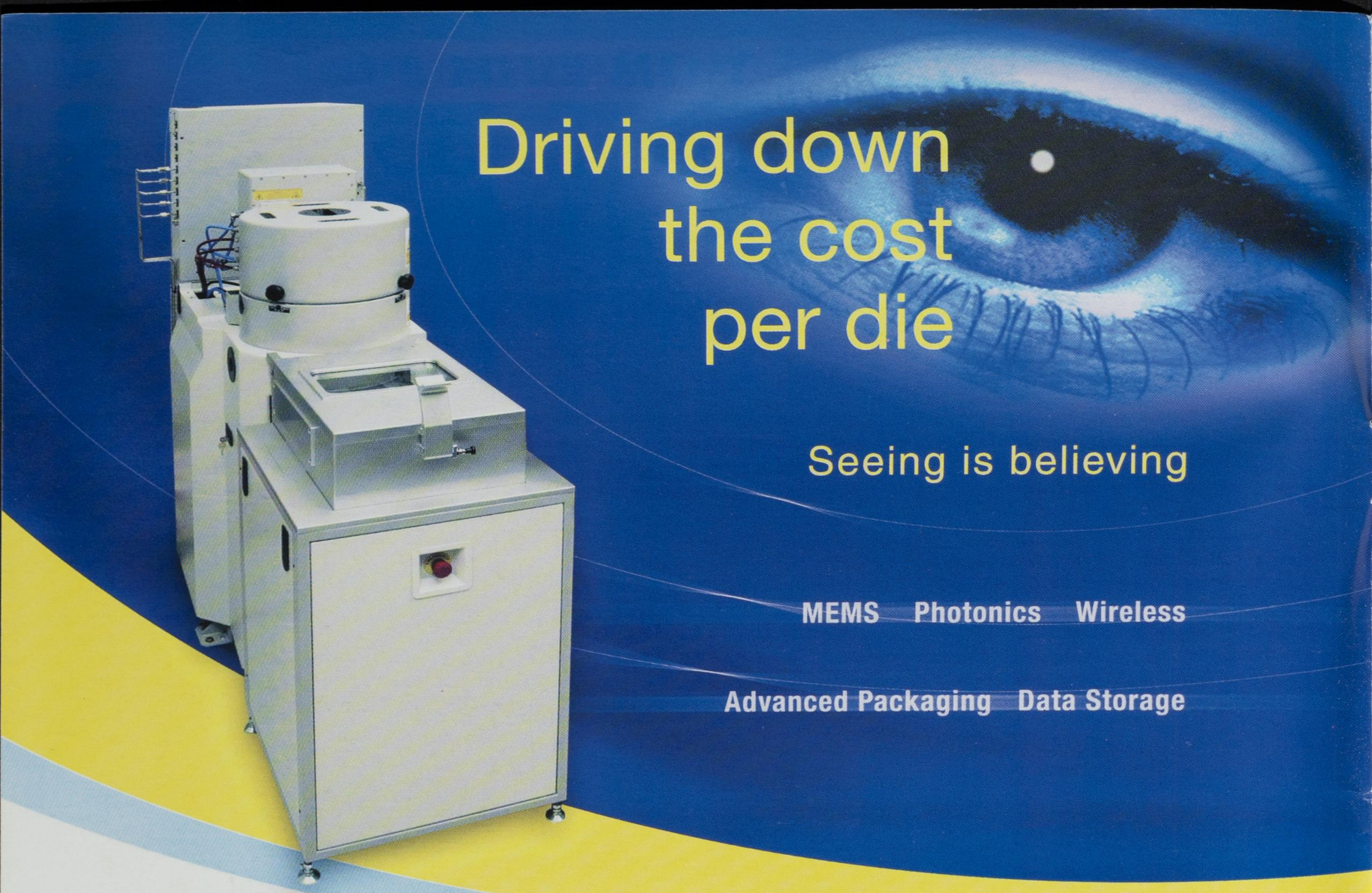
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Progress in AlGaN, HFETs on silicon and a report from ICNS

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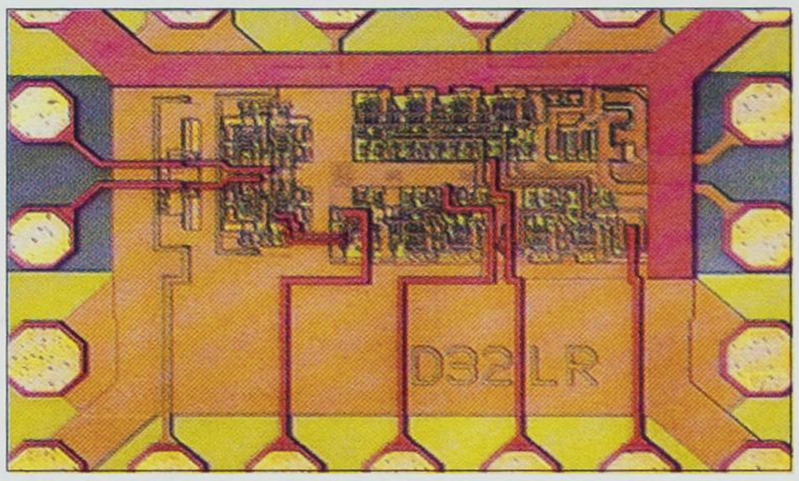
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Three-Fives and Silicon Heterostructures

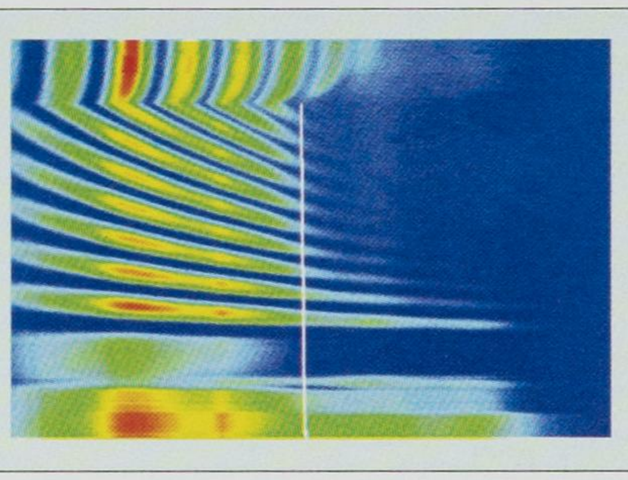
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On the cover: *Improvements to fabrication methods are raising the efficiency of GaN-based LEDs (image courtesy of Nichia) – see p19.*

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Vitesse wins InP development funds

The InP electronics market has received a boost with the news that Vitesse has won a $6 million DARPA contract to develop InP ICs for military communications, in collaboration with BAE Systems and the University of Illinois at Urbana-Champaign (UIUC).

Vitesse will work with BAE Systems and UIUC to develop advanced manufacturing processes and communication ICs using its sub-micron VIP-2 InP HBT technology. The initial 18 month contract contains option phases, which, if implemented, would bring the total value to more than $15 million.

The contract will allow Vitesse to further improve the capabilities of its VIP-2 process, which was selected for its ability to enhance speed, power, performance, circuit reliability and production-worthy manufacturing practices required for the DARPA specification. InP technology allows direct digital synthesis of high-frequency signals, thereby simplifying the system design and reducing the number of discrete components required in advanced satellite, aircraft and terrestrial communication systems.

"Being awarded the DARPA contract is a strong indicator to the industry regarding the capabilities of InP for building advanced communications ICs," said Ray Milano, VP of physical media devices at Vitesse.

Vitesse will collaborate with BAE Systems on the design of communications circuits; initially, these are for direct digital frequency synthesis for electronic warfare and radar applications. UIUC will focus on research for the next-generation transistor structures meant to further extend circuit performance and applications.

A two-fold improvement in critical performance parameters has already been attained in early VIP-2 experiments at 0.45 μm. Further scaling is planned, by incorporating UIUC's findings, with the ultimate goal of shrinking device geometry to 0.25 μm. This will result in static flip-flop toggle frequencies of 150 GHz.

"Military systems and our products are following a trend towards smaller, more highly integrated, and flexible solutions," said Frank Stroili, BAE Systems program manager for the Information and Electronic Warfare Systems unit. "To provide effective capabilities for these systems, a revolutionary jump is needed to increase speed and bandwidth, level of integration, and the efficiency of the payload electronics. The technology developed on this program plays a major role in achieving those goals."

The VIP-2 process is similar to the Vitesse VIP-1 process, which is currently in production at the company's fab in Camarillo, CA. Both processes use 4 inch diameter semi-insulating substrates, and are designed for high performance and high yield. The VIP-2 process utilizes a DHBT structure and has f_t and f_{max} values of 300 GHz, which is twice the speed of current VIP-1 transistors. It also has four layers of metal interconnect and includes resistors and capacitors.

Agilent to close UK fiber-optic component manufacturing plant

By Tim Whitaker

Agilent is to close its fiber-optic component manufacturing plant in Ipswich, UK, with the loss of 200 jobs. Production of DFB lasers and photodetectors will switch from the Ipswich site to a new Agilent facility in Singapore, opened earlier this year. Around 50 Agilent employees – mostly R&D and marketing staff – will be retained in Ipswich, but will be relocated to a smaller facility. The component fab will shut down by the end of July.

Hewlett-Packard, from which Agilent was spun out in 1999, acquired the Ipswich components operation in 1993 from BT&D Technologies. This company was established as a joint venture between British Telecom and DuPont in order to develop optoelectronic technologies.

Hewlett-Packard and Agilent invested more than $150 million in the Ipswich facility. This included an 80,000 sq. ft building built to house growing numbers of staff, which was completed in early 2002 at a cost of $20 million. However, staffing levels peaked at around 1100 in 2001, and have been falling ever since.

Agilent will now transfer the epitaxy and wafer processing activities for DFB lasers and photodetectors to its new $92 million facility in Yishun, Singapore, which was opened in February 2003. Some of the back-end processing activities for photodetector products had already been transferred to Singapore.

The vast majority of Agilent's optoelectronic devices, including optocouplers, standard-brightness LEDs, and emitters for IR transceivers, are already being fabricated in Singapore. Lumileds Lighting, the joint venture between Agilent and Philips Lighting, continues to manufacture high-brightness nitride and AlGaInP LEDs in San Jose, CA.

Agilent has also transferred its entire VCSEL component manufacturing business from California to Singapore. This means that, with the exception of Lumileds, Agilent has moved all optoelectronic device manufacturing out of the US.

For now, it appears that Agilent will continue to operate its R&D facility in Turin, Italy, acquired from Telecom Italia in early 2000. The 40,000 sq. ft facility contains a cleanroom for epitaxy and processing, as well as characterization and packaging laboratories.

Funding news in brief...

ASIP wins series C funding

ASIP, a developer of photonic integrated circuits for optical systems located in Somerset, NJ, has raised $16 million in the initial installment of its series C financing round. This brings the total investment in ASIP to $23.5 million.

ASIP is supplying high-speed, integrated lasers to companies developing the next generation of small form-factor transceivers. The company's products are built on its patented Asymmetric TwinGuide (ATG) technology platform (*Compound Semiconductor* November 2002 p29).

Nitronex secures $11.3m

Nitronex Corporation, which builds GaN-based RF power transistors for wireless applications on industry-standard 4 inch silicon wafers, has secured $11.3 million of series C financing.

Nitronex expects its first product, a 20 W device that will be released by the end of 2003, to challenge the incumbent silicon LDMOS technology (see p22).

Sandia uses quantum dot phosphors

Researchers at Sandia National Laboratories have fabricated what is claimed to be the first white LED using quantum dots in place of a conventional phosphor. The quantum dot material consists of CdS nanoparticles embedded in an epoxy or silicone encapsulant. The material is pumped by a near-UV LED, and emits light across the visible wavelength range.

The quantum dots strongly absorb light in the near-UV range and re-emit visible light with a color determined by both their size and surface chemistry. This provides two methods of tuning the optical properties in addition to the chemical composition of the quantum dot material itself.

Conventional bulk phosphor powders have poor absorption in the near-UV region, although a great deal of research is going on to identify new, more suitable phosphor materials. Also, the optical properties of the phosphor are determined solely by its chemical composition.



SANDIA NATIONAL LABS

Sandia's Lauren Rohwer with blue and white LEDs containing quantum dot phosphors.

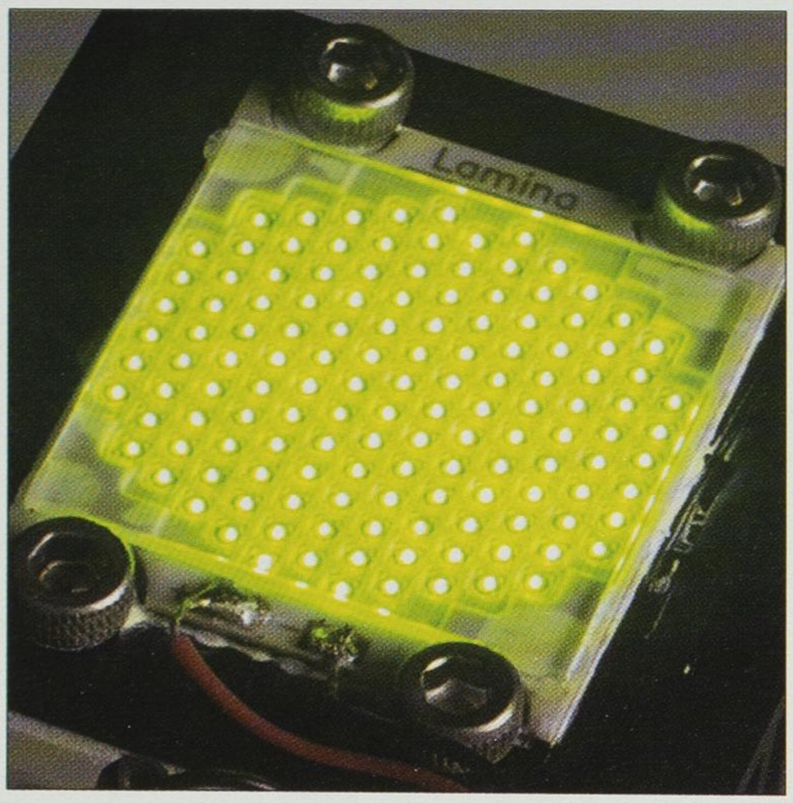
The nanometer-sized quantum dots are synthesized in a solvent containing soap-like molecules called surfactants as stabilizers. During encapsulation, the dots are attached to the "backbone" of the encapsulating polymer. This prevents the dots from clumping together (agglomerating), which would cause them to lose their light-emitting properties. The result is an increase in efficiency from 10–20 to 60%.

In the next year, the researchers will increase the concentration of the quantum dots in the encapsulant to obtain further increases in light output, while extending the understanding of quantum dot electronic interactions at high concentrations. The work at Sandia has been partly funded by the DOE Office of Building Technologies through a collaborative project with Lumileds Lighting.

Lamina Ceramics introduces new range of LED light engines

Lamina Ceramics has unveiled a family of LED light engines – highly engineered LED arrays combining super-bright LEDs with Lamina's proprietary low-temperature co-fired ceramic on metal (LTCC-M) technology. Target applications include road signs, automobiles and industrial lighting. The initial two light engines feature either a 7-element LED array (giving a luminous intensity of up to 840 lm, with 21 W power consumption) or a 134-element array (5360 lm, 134 W).

The LTCC-M technology allows LED dies to be attached directly to the package in a densely packed array configuration, and also allows operation up to 250 °C. Pricing is $40–100 (depending on die) in 1k volume for the 134-element array, and $10–30 in 1k volume for the 7-element array.



LAMINA CERAMICS

A light engine containing 134 LEDs with a maximum output of 5360 lm.

Korean LED maker admits copying Nichia designs

According to a company statement from Nichia, a rival LED manufacturer has admitted infringing on Nichia's intellectual property rights. Nichia says that the unnamed Korean company has been conducting the unauthorized manufacturing, selling and advertising of products based on Nichia's designs in a number of countries where these designs have been registered under the respective national laws.

The Korean LED maker admitted infringement in June 2003, and signed an agreement to accede to Nichia's demands. These included an immediate suspension of manufacturing, exportation of infringing products, and sales and promotional activities. The company also agreed to destroy the infringing products in its inventory, along with packaging materials and advertising materials.

Since the manufacturer agreed to an early settlement, a legal dispute was avoided. Nichia says that it will continue to vigorously enforce its intellectual property (IP) rights throughout the world. Several IP agreements between Nichia and its competitors were announced in 2002.

Despite intense speculation, the identity of the company has not been revealed. However, a source at Samsung indicated that Nichia has not made a claim against his company.

Tegal's sputter processes improve LED performance

Tegal has announced a new set of process applications for its Endeavor-AT PVD cluster tool that provide high-quality reactive sputtering capability in various applications, including LED manufacturing. Reactive sputter deposition of dielectric films has historically suffered from equipment and process anomalies, largely caused by chamber arcing.

Reactive sputter-deposited SiN is preferred in LED encapsulation applications, as it eliminates hydrogen contamination of the devices inherent in plasma-enhanced CVD of SiN films. The Endeavor-AT's DC-RF coupled S-Gun chamber eliminates electrical damage to the p–n junctions of the LED during SiN deposition, and creates high-density SiN films with near-zero intrinsic stress and good optical properties.

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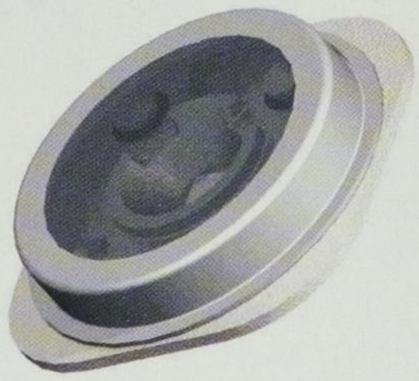
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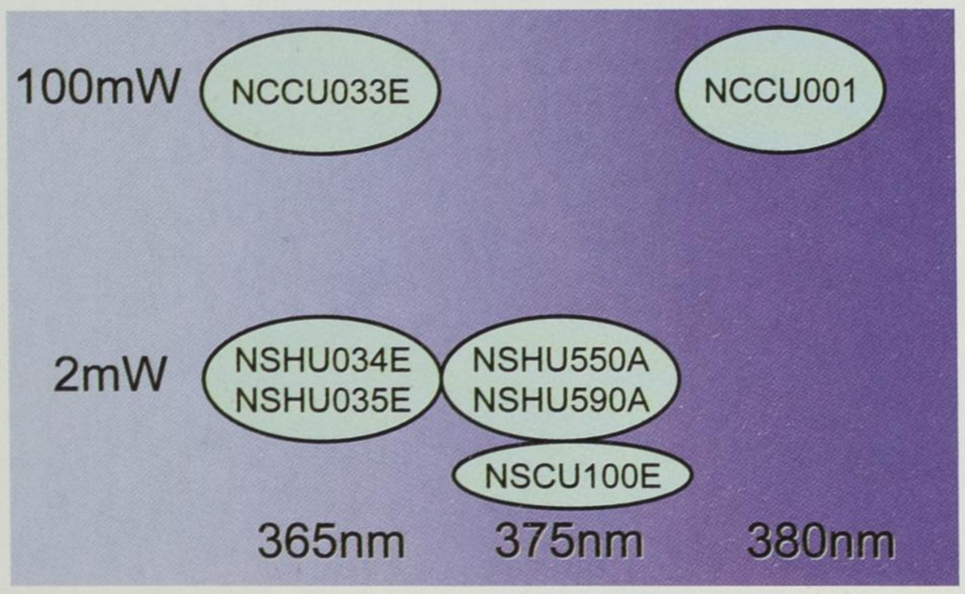
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Nichia UV-LED Products

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NSHU034E	365nm	*2.0mW	Flat	2004
NSHU035E	365nm	*1.4mW	Lens	2004
NSHU550A	375nm	2.0mW	Flat	Now
NSHU590A	375nm	1.4mW	Lens	Now
NSCU100E	375nm	*1.0mW	SMD	2003/11
NCCU001E	380nm	100mW	Flat	2003/12

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Ever Researching for a Brighter World

Seiwa Electric ramps up LED capacity to 10 million per month

Seiwa Electric, which began manufacturing blue LEDs in April 2002, is to increase its LED production capacity to 10 million units by September. So far, the company's limited capacity has meant turning away larger orders, but a ¥1 billion investment will allow it to meet current and future levels of demand.

The impact of the expansion on sales is expected to be significant, with Seiwa forecasting LED revenues of ¥2 billion for the year ending March 2004 (40 times the previous year's revenues). The LED business will also turn in its first profit, after losing ¥500 million in the year ending March 2003.

Samsung's 405 nm DVD lasers reach 10,000 hour milestone

As the momentum gathers for the next generation of high-density DVD players and recorders, the demand for 405 nm laser diodes will rise accordingly. So far, Sony and Nichia of Japan are the only companies to make such lasers commercially available, but others are set to join them in this market. One such company is Korea's Samsung, which discussed the performance of its 405 nm lasers at the recent ICNS-5 meeting (see p19).

The reported devices had 30 mW of output power with lifetimes exceeding 1000 h at 50 °C, which translates to 10,000 h at room temperature. The structures were grown on GaN deposited on sapphire substrates using epitaxial layer overgrowth to produce the low dislocation GaN necessary for subsequent high-quality AlInGaN growth.

News in brief

Supra delays ZnSe LED production switch-on

Supra, a Taiwan-based company jointly founded by Procomp of Taiwan and Japan's Sumitomo, has been forced to delay the start of mass production of its ZnSe-based white LEDs because of the SARS outbreak. Mass production has been delayed from June until late August. Supra is predicting that in the final quarter of 2003, monthly output will be 36 million units, rising to 100 million per month in 2004.

Mitsubishi raises DVD laser capacity

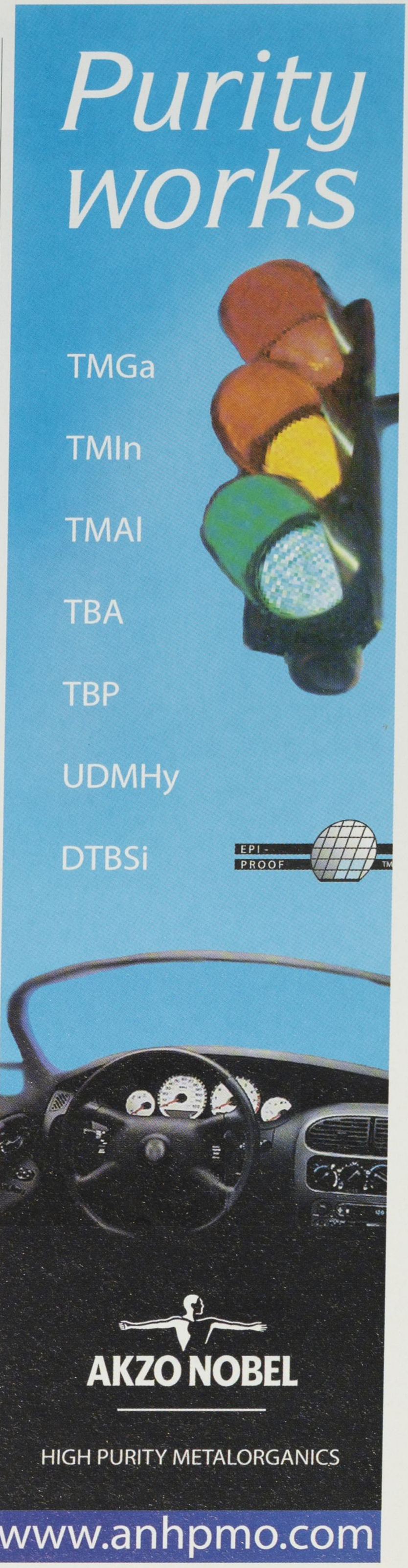
Mitsubishi Electric is to raise the output of its high-power red laser diodes. Since early 2002, when the company's monthly output of such lasers was 0.15 million, production capacity and output have steadily grown to the current level of 2.5 million units per month. The current expansion plan is for 3 million units per month by the end of September.

Aixtron Taiwan receives funding for new R&D center

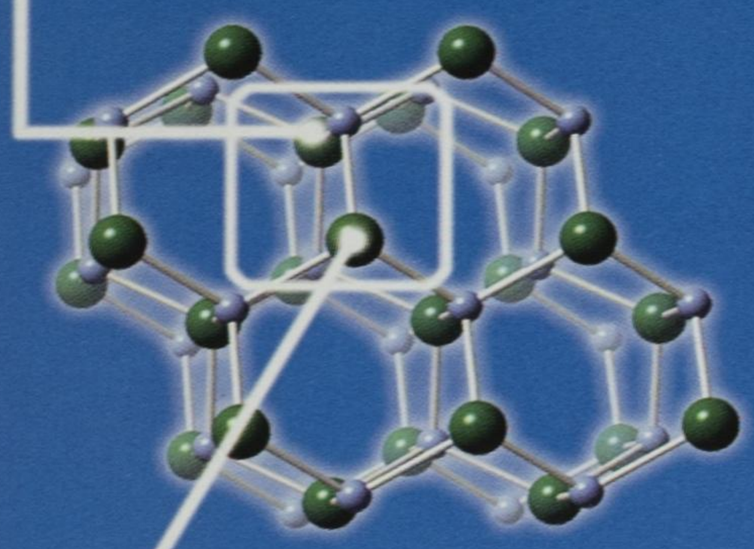
Aixtron has received funding for a three-year project from the Taiwanese government's Department of Industrial Technology (DoIT), to set up a new R&D center that will facilitate production-oriented technology transfer in Taiwan. Other companies that have also received funding from the DoIT for R&D centers include HP, Dell and Sony.

The DoIT stated that an important factor in selecting Aixtron Taiwan for the research center program is Aixtron's strong commitment to collaborate with the Taiwanese industry, universities and research organizations.

The common goals of the commercial production-related joint R&D projects include quality optimization and improved yield management of LED materials; increasing the throughput of high-power electronic devices; developing the production of key materials for high-k dielectrics; cost reduction and performance tuning of *in situ* process control, and developing organic vapor-phase deposition technology for advanced organic LED display production.



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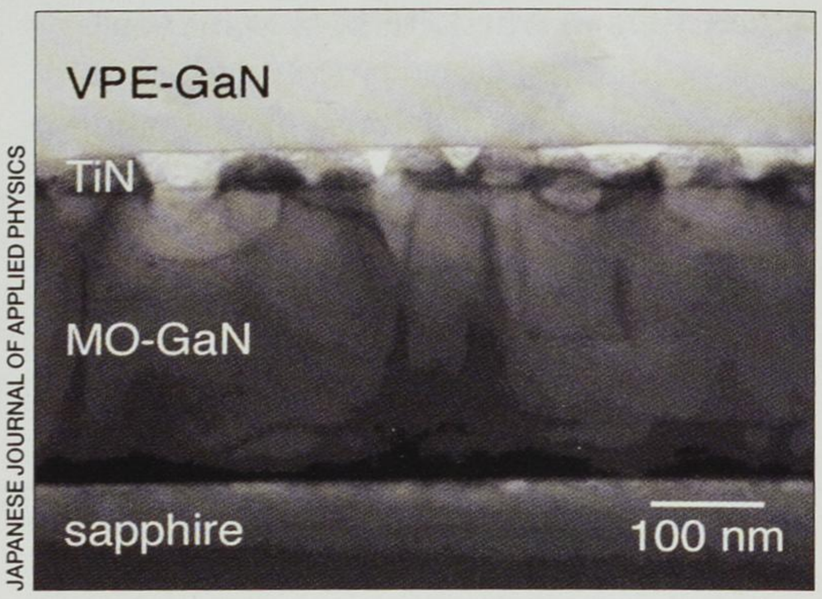
Progress in native GaN substrates continues

By Tim Whitaker

Commercial nitride-based devices are grown on sapphire, silicon carbide or silicon substrates, but GaN substrates remove the problems of mismatches between the epilayers and substrate in terms of lattice constants and thermal expansion coefficients. Many companies, ranging from giants like Samsung to specialists such as Kyma, Cermet and TDI, have joined the race to develop native substrates for GaN growth.

There are two main approaches to fabricating free-standing GaN wafers; one is the growth of GaN boules, while the other involves the epitaxial deposition of a thick GaN layer on a foreign substrate, after which the substrate is removed.

Extensive work on high-pressure growth of bulk GaN has been carried out by TopGaN, a spin-off from Unipress, the High Pressure Research Center operated by the Polish Academy of Sciences. Crystals with a very low dislocation density of less than 100/cm^2 are grown at a temperature of 1500–1800 °C under a high hydrostatic pressure of 10–20 kbar. The crystals are spontaneously nucleated from a nitrogen solution in gallium. The size of the crystals is about 1 cm^2 at present, explains Mike Leszczynski, VP of TopGaN. "We think that it is technically feasible to produce 1 inch wafers, and the first such crystals have been obtained," he said.



JAPANESE JOURNAL OF APPLIED PHYSICS

Fig. 1. Cross-sectional TEM of the layer structure used in void-assisted separation. The HVPE-grown GaN was separated from the TiN-coated GaN template after cooling.

Progress in Japan

Mitsubishi Chemical, Tokyo Denpa and Tohoku University have revealed that they have jointly developed basic technology to produce low-cost GaN single crystals as part of a collaboration dating back to mid-2002. The team grew GaN crystals at a temperature below 500 °C and a pressure of less than 1000 atm (about 1 kbar). These are the same conditions used to produce single-crystal quartz, an established mass-production technology.

The group says it should be possible to make a 2 inch GaN substrate for several hundred thousand yen (¥100,000 is about $850), and that commercial products should be available within 3 years. Mitsubishi Chemical has previously indicated that it plans to develop violet lasers using GaN substrates.

Last year, it was reported that Japan Energy and Yamaguchi University had grown 25 mm diameter GaN boules at a pressure of 1 GPa (10 kbar) and a temperature of 1475 °C (*Compound Semiconductor* July 2002 p45). Other Japanese companies are using epitaxial approaches. Hitachi Cable, in collaboration with NEC, is using void-assisted separation, in which a thin film of perforated titanium is deposited on a GaN-on-sapphire layer. This facilitates the growth of high-quality material, as well as separation of the GaN layer once the wafer is cooled (figure 1). The dislocation density of the GaN material was reported to be 5×10^6/cm^2.

Meanwhile, Sumitomo Electric is using a process called Dislocation Elimination by Epitaxial growth with inverse-pyramidal Pits (DEEP). As the GaN layer grows, dislocations are concentrated at the bottom of pits in the surface. The dislocation density on the surface is significantly reduced, although the usable area of material is limited to the areas around the pits.

200 mW lasers on GaN substrates

Commercially available lasers from Nichia are fabricated using lateral epitaxial overgrowth (ELOG). GaN is grown through a mask, and the areas above the mask stripes have a significantly lower dislocation density (typically around 10^7/cm^2) than the material that grows above the mask windows. As with the DEEP approach, the small usable area limits the size and hence the output power of laser diodes grown on these substrates.

Several manufacturers have made significant progress with lasers grown on GaN substrates. Sanyo Electric has achieved pulsed output powers of 100 mW, and 50 mW CW, from its lasers grown on GaN. These products, which are being sampled commercially, also use ion implantation for optical and electrical confinement (*Compound Semiconductor* May 2002 p10).

At the recent ICNS conference in Japan, both Sharp and Sony presented their latest results on lasers grown on GaN substrates. Sharp reported lasers with a threshold density of 2.9 kA/cm^2 and an output power of 30 mW at 50 mA and 5 V.

Sony reported 200 mW operation of laser diodes fabricated on GaN substrates from Sumitomo Electric. The substrates had a much lower dislocation density ($3–4 \times 10^5$/cm^2) than GaN grown by ELOG, and also allowed the fabrication of larger devices (see p20).

TopGaN has also grown lasers on its GaN substrates, and offers engineering samples of 50 mW pulsed-mode modules. "Our aim is to produce high-power lasers," said Leszczynski. "Our latest result of 2.6 W (1.3 W per facet) output power in the pulsed mode regime makes us feel optimistic."

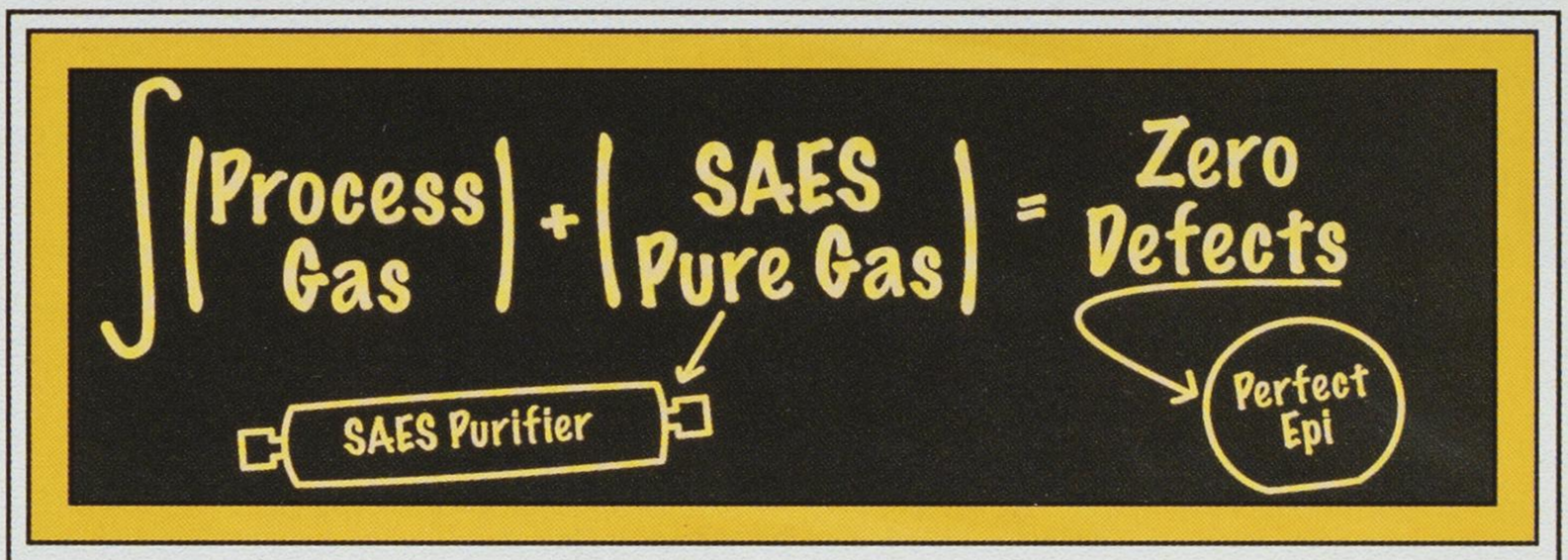
Cermet and TDI

Several small US companies, including TDI, Cermet and Kyma Technologies, are developing single-crystal GaN. TDI developed its True Bulk GaN technology, involving boule growth from a seed wafer, and demonstrated 1.5 inch substrates in 2001 (figure 2). Vladimir Dmitriev, TDI's president, says that TDI plans to start commercialization of 2 inch True Bulk GaN wafers in 2004.

Cermet is developing technology to grow bulk GaN single-crystal wafers in a research project sponsored by the Missile Defense Agency (MDA). The company is working on a novel, proprietary crystal-growth system that uses physical vapor transport. A stream of ammonia or nitrogen gas is introduced into the growth chamber to react with a vapor of gallium metal. The resulting GaN is epitaxially deposited on a seed such as sapphire, SiC or ZnO. ZnO seeds give the unique advantage of easy removal through chemical dissolution, and have the same crystal structure as GaN and only a 2% lattice mismatch.

"Crystals up to 50 mm in diameter have been grown using sapphire and SiC seeds," said Vicente Munne, principal research engineer at Cermet. "In addition, a GaN layer has been lifted from ZnO seeds by dissolving the





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ZnO seed using a hydrochloric acid solution. Growth rates of 30 μm/h are typical, while rates of up to 100 μm/h have been demonstrated. Crystals have been characterized with double crystal X-ray diffraction and a high degree of crystallinity has been found; peak widths in the sub-200 arcsec range are typical."

Kyma wins contracts

Kyma Technologies, a 1998 spin-off from North Carolina State University (NCSU), first shipped 2 inch GaN wafers in February 2002. The company recently received a series B funding round of $4 million (*Compound Semiconductor* July 2003 p8), bringing its total venture funding to more than $7 million. According to Ed Pupa, the company's CEO and president, the funding will allow Kyma to double its staff to more than 20 people by the end of this year.

As well as its second funding round, Kyma has also received a number of SBIR contracts, including one from the Department of Energy to develop GaN substrates for improved LEDs for solid-state lighting. Other awards from the



KYMA

Fig. 2. Kyma uses a physical vapor transport method to grow its GaN boules from which 2 inch wafers can be produced.

MDA will fund Kyma to develop doped GaN crystals, and to develop GaN-based FETs on semi-insulating GaN for use in X-band radar systems. Kyma is working with RF Micro Devices on the latter project.

Pupa says that most customer interest is for substrates for optoelectronic devices such as blue/violet/UV lasers and high-performance LED chips for solid-state lighting. On the basis of cost and performance, there will be no incentive for most current nitride LED products to be switched from sapphire or SiC substrates to GaN.

Although blue lasers are currently very expensive, substrate costs will be a major issue as laser ASPs drop sharply. "In general, blue laser manufacturers believe that in a three-year timeframe ASPs will drop to around the same cost as a red laser today – in the range of $15 for a packaged device," said Pupa. "We believe that with our high growth rate boule strategy we can reach the price points they need to be competitive."

Kyma uses a two-stage process to grow its boules; these are currently 2 inches in diameter, although 4 inch wafers are feasible. "We use a physical vapor transport technique, which was licensed from NCSU, and also a very fast vapor-phase technique developed at Kyma," said Pupa. As well as increasing both growth rate and boule thickness and reducing defect densities, Kyma is seeking to get the usable area for its substrates above 90%.

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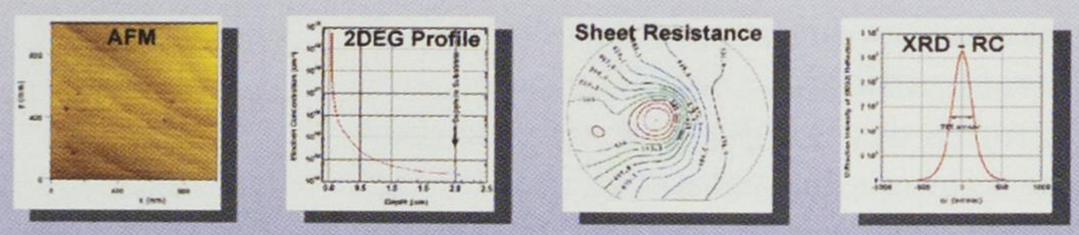
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XenICs and Sensors Unlimited receive funding to develop InGaAs sensors

XenICs, a developer and producer of InGaAs-based infrared image sensors located in Leuven, Belgium, has received €1.5 million ($1.75 million) in additional funding. The company, a spin-off from the Belgian research organization IMEC, was funded by investors including Fortis Private Equity and IMEC, as well as XenICs staff.

This second round of funding will allow the company to fully deploy new sales networks and attract international partners, while continuing to develop state-of-the-art IR image sensors. XenICs recently introduced a new InGaAs-based infrared focal plane camera, designated XEVA-USB. The imager has a resolution of 320 × 256 pixels and is sensitive between 0.9 and 1.7 μm, which is complementary to the sensitivity range of standard CCD cameras. Typical applications include hyper spectral imaging, laser beam profiling, semiconductor inspection, thermal imaging of hot objects and night vision.

In related news, Sensors Unlimited of Princeton, NJ, has received a number of contract awards to develop InGaAs-based detectors. DARPA has awarded the company a nine-month $890,000 contract to develop the first all-solid-state, 640 × 512 pixel, room-temperature InGaAs camera. The 0.9–1.7 μm camera will provide soldiers with night vision capability. The company has also received four separate small business innovation research contracts to explore new imaging opportunities using InGaAs-based photodiodes.

In June, Sensors Unlimited received a contract (worth $3.7 million if fully executed) from the US Air Force to develop a high-frame-rate, high-bandwidth, low-noise focal-plane array and camera. The system will allow active tracking, laser ranging and imaging, and will incorporate both *pin* photodiodes and APDs within each pixel of the array.

Comlase introduces passivation and facet-coating process

Comlase of Sweden has introduced a reactor for passivation and facet-coating of edge-emitting lasers that utilizes the company's proprietary Native Nitride Ion Beam Epitaxy (N^2IBE) process to increase damage threshold, improve output power and extend lifetime. The N^2IBE process utilizes nitrogen bombardment to remove surface oxides and impurities, and subsequently grows native nitrides that are non-absorptive due to their wide bandgaps. This prevents oxidation, and results in a substantial increase in the threshold for catastrophic optical mirror damage (COMD) and laser reliability.

Based in Stockholm, Comlase was founded in January 2001 with the aim of utilizing the N^2IBE process to make better and more cost-effective 980 nm telecom lasers. Market conditions caused a change of strategy, according to Peter Blixt, Comlase's VP of business development. "Comlase refocused its business in early 2003 to utilize its core competence, the N^2IBE process," he explained. "We are now offering this passivation process to manufacturers of most edge-emitting lasers, from blue InGaN devices to InGaAsP lasers at 1.55 μm. The current emphasis is on 8xx nm and 9xx nm pump lasers."

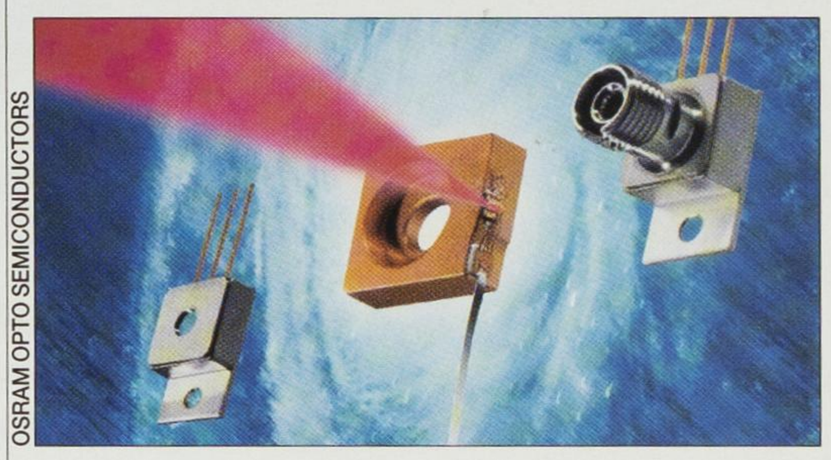
Comlase has three main strands to its business model: it offers passivation services and process development for customer-specific material and components; it licenses the technology, charging per bar or per chip; and it offers technology transfer by selling complete N^2IBE reactors and optimized process parameters.

Blixt says that Comlase is focusing on developing more applications for the N^2IBE process and improving yields. "The current system can load 200 bars, giving 4000–8000 chips per 4–6 h run," he said. "The process is very uniform and can benefit all edge-emitting lasers, with the exception of very low-cost devices for CD players. Removing oxides and other impurities from transmitter lasers will normalize the wavelength and power over the whole lifetime."

Comlase also recently announced that its 980 nm lasers have passed 5000 h Telcordia qualification. "The qualification was initialized when the company had the intention to sell 980 nm pump modules," said Blixt. "Now we are using this to prove that the native nitrides are very stable, giving telecom reliability for all laser structures that form nitrides on their facets."

The 980 nm lasers showed very low degradation in accelerated aging tests at 80 °C and 300 mA. Neither sudden, random failures nor COMD were observed. The lifetime of the devices was extrapolated as 82 years at a heatsink temperature of 25 °C. The CW facet intensities were greater than 10 MW/cm^2 for an output power of 200 mW.

Osram offers AlGaInP red laser diodes



OSRAM OPTO SEMICONDUCTORS

Osram Opto has added 0.5 W red AlGaInP devices to its range of high-power lasers.

Osram Opto Semiconductors has added the first AlGaInP-based laser diodes to its range of high-power lasers. The 650 nm devices have an optical output power of 0.5 W, and were made possible by modifications to the fabrication process, chip design and layer structure of longer-wavelength devices. High-power laser diodes with a wavelength of 650 nm are used in medicine, for example in ophthalmology, skin treatment, and photodynamic therapy for cancer treatment. Osram says that red lasers will also be used in laser projection systems once suitable blue and green devices are also developed.

In further news, Osram has increased the power of its existing near-IR products operating at 808, 940 and 980 nm to 2 W. It has also increased the pulse-proof characteristics of its laser diodes by more than one order of magnitude, allowing them to cope much better with thermomechanical stress.

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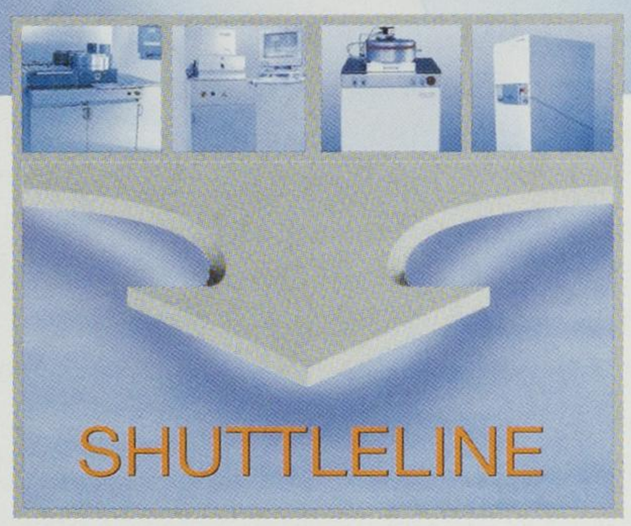


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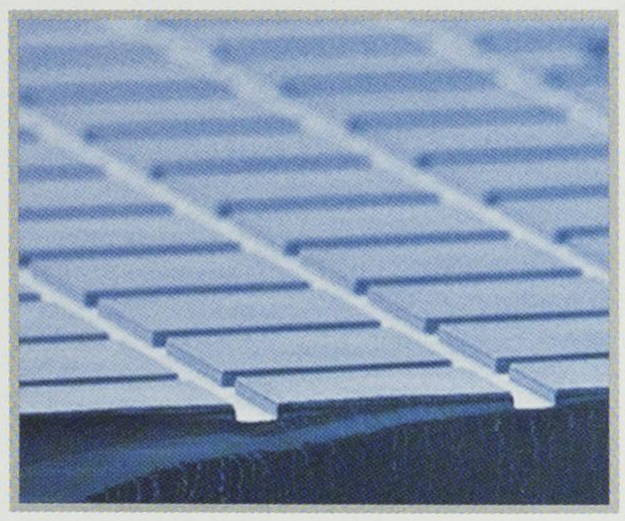
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Infineon demonstrates world-record SiGe ICs

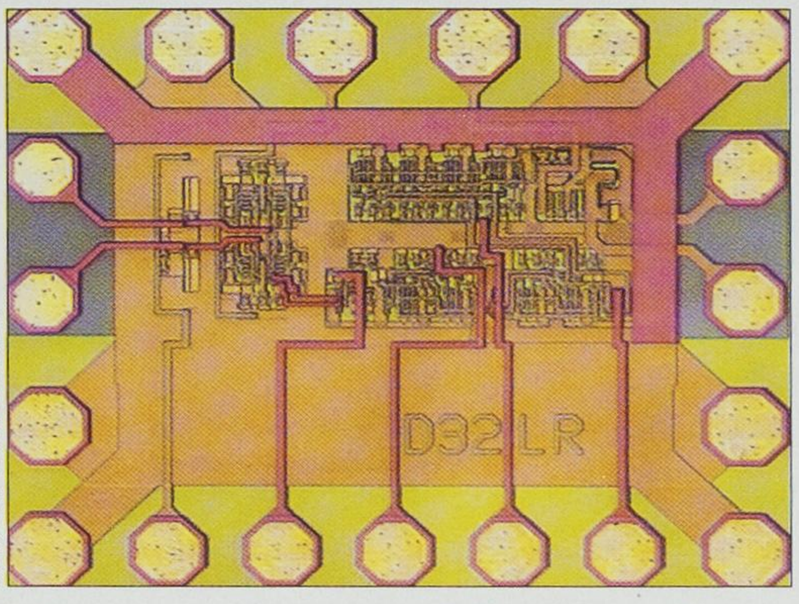
Infineon Technologies has demonstrated new peak performance values in high-frequency ICs at its research laboratories in Munich, Germany. The world records in speed were accomplished using the company's SiGe:C bipolar technology, which reaches a cut-off frequency of more than 200 GHz and has a demonstrated record ring oscillator gate delay time of 3.7 ps.

Using this process technology, the researchers fabricated and demonstrated three record-setting ICs:

- a dynamic frequency divider with a divide ratio of 2 and a measured maximum input frequency of more than 110 GHz. The IC had a current consumption of 62 mA operating from a 5 V supply voltage.
- a static frequency divider (divide ratio of 32) with a maximum input frequency of 86 GHz. This circuit works with a 5 V supply voltage and consumes only 180 mA.
- a voltage-controlled oscillator operating in the 95–98 GHz frequency range with a phase noise of only –97 dBc/Hz at 1 MHz carrier offset frequency. The output power is –6 dBm. At 5 V supply voltage the circuit shows a very low current consumption of 12 mA.

Devices and products benefiting from these research results in the short term will include 40 Gbit/s low-power fiber-optic communication systems, high-speed microwave radio links and ultra-wide-band communication systems up to 60 GHz. Infineon also demonstrated that an integrated 77 GHz automotive radar transceiver in SiGe, based on these building blocks, is now feasible.

Infineon already has several products in mass production using a 70 GHz f_t SiGe process, including RF transistors, low-noise amplifiers, and base-station MMICs.



INFINEON TECHNOLOGIES

Infineon has developed SiGe-based ICs operating at up to 110 GHz, as well as a 77 GHz automotive radar transceiver.

European researchers join forces to develop GeOI technology

Three European organizations are joining forces to develop germanium-on-insulator (GeOI) wafers to meet the challenges posed by process dimensions of less than 45 nm. IMEC, a Belgian research center, has joined with French SOI wafer specialist Soitec and Belgian materials company Umicore to explore the development of substrates from which Ge-based devices can be fabricated.

Ge has a higher carrier mobility than Si for both electrons and holes, and it is expected to be compatible with high-k materials. It also requires much lower dopant activation temperatures than Si, facilitating the formation of shallow junctions. These features make Ge an excellent candidate from which to fabricate high-performance CMOS devices.

As part of the collaboration, Umicore will be responsible for the development and production of 200 and 300 mm Ge wafers. Soitec will apply its proprietary Smart Cut process to transfer thin Ge layers onto Si wafers with a surface oxide, creating GeOI wafers.

IMEC will develop a high-k layer deposition technique for GeOI substrates, as well as defect inspection techniques. It will also fabricate devices to demonstrate the potential of GeOI substrates for the sub-45 nm node.

"It's clear that innovative solutions are required to overcome the scaling challenges for sub-45 nm devices," said Gilbert Declerck, president and CEO of IMEC. "To solve the channel mobility and gate leakage current problems in scaled Si devices, alternative concepts such as the combination of high-k dielectrics with Ge need to be examined."

AmberWave to qualify tools for SS

Strained Si (SS) specialist AmberWave Systems and ADE, a supplier of production metrology and inspection systems for semiconductor wafer manufacturing, have announced that ADE's line of inspection and metrology tools will be qualified to measure strained Si wafers.

"Standard metrology recipes do not work with SS wafers," said Mitch Tyson, AmberWave's CEO. "We are working with ADE and other inspection and metrology partners to qualify their tools to measure such wafers."

So far, ADE's Film Inspection Tool for surface particle inspection and defect classification, AcuMap high-speed film thickness mapping system, and UltraGage 9900 for wafer dimensional certification have been qualified. Other tools will be qualified in the future.

Soitec and ASM produce SGOI wafers

Soitec and ASM International have reached a milestone in their strained SOI partnership program by producing samples of 200 mm fully relaxed SiGe-on-insulator (SGOI) substrates incorporating 20% Ge with and without the final strained Si layer.

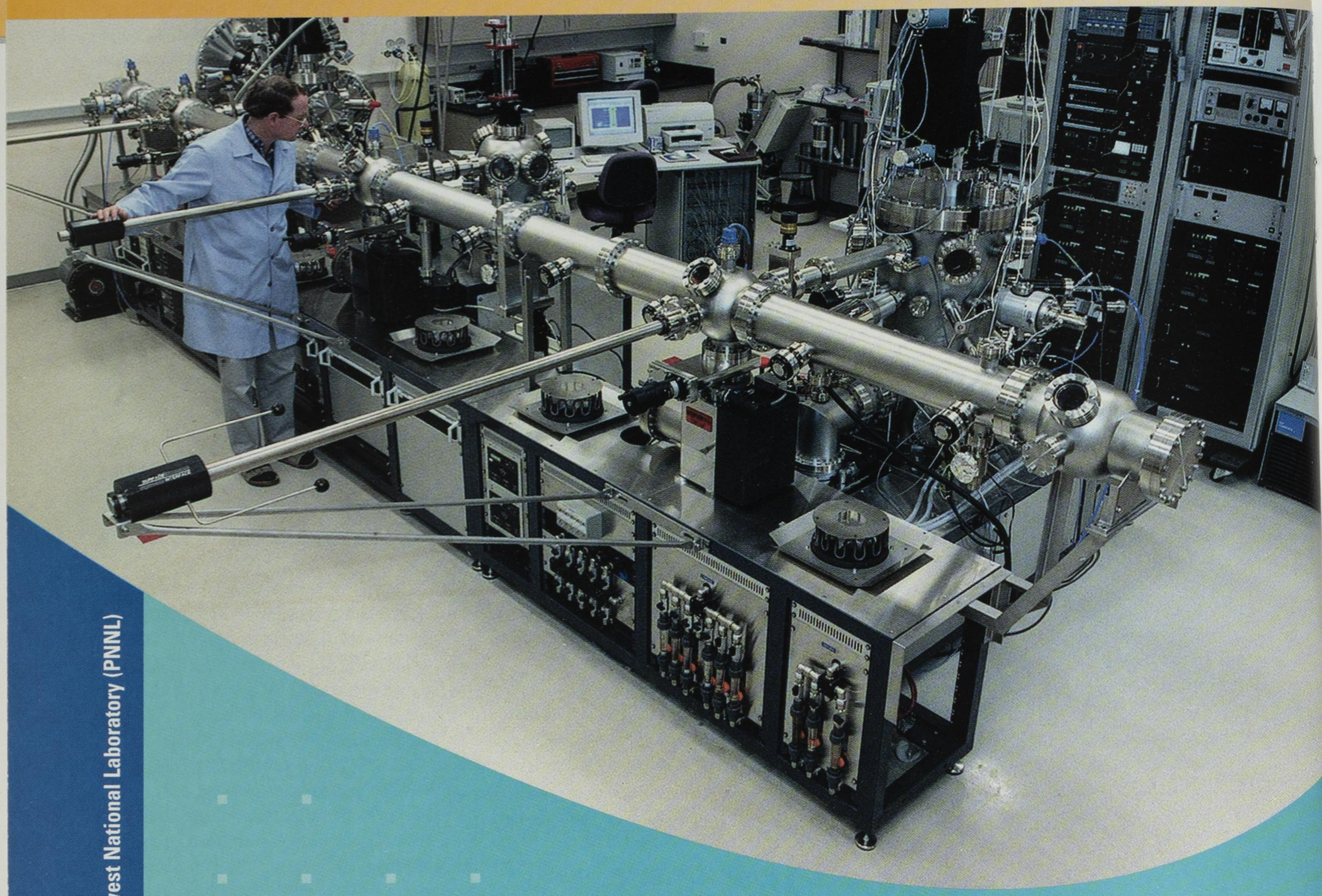
The partnership combines Soitec's Smart Cut technology for fabricating SOI wafers with ASM's epitaxial growth technology (*Compound Semiconductor* June 2003 p15). Soitec's subsequent generations of strained Si solutions will include SGOI with higher Ge content and strained Si without the SiGe template layer.

Bede sells high-volume X-ray metrology tools

A leading Si semiconductor company has taken delivery of five Fab200/300 (now rebranded BedeMetrix-F) X-ray metrology tools from Bede. One tool is located in the customer's research lab while the other four are in separate 300 mm production fabs. Bede says that it is the first company to qualify X-ray diffraction and reflectivity metrology tools for Si fabrication lines. The tools are needed for new materials such as SiGe and low- and high-k dielectrics.

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

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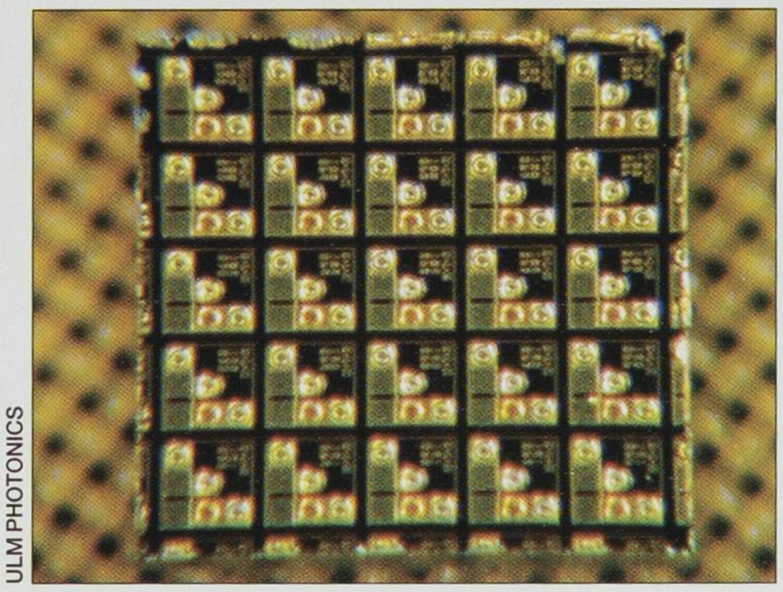
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INSTRUMENTS

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Ulm Photonics samples glass substrate VCSEL

VCSEL vendor Ulm Photonics, based in Ulm, Germany, is now sampling its new 850 nm Trans-sub VCSEL operating at 3.125 Gbit/s. The GaAs-based VCSEL is grown as a bottom-emitting structure with topside p and n contacts, and emits 850 nm light in the direction of the substrate. Using a wafer-scale process, the GaAs substrate is removed and replaced with a 100–300 μm thick transparent glass substrate.

The technology offers a VCSEL for direct flip-chip mounting, which has a mechanically robust surface on the emitting side and contacts on the opposite side. This allows for easy assembly of single devices and arrays. Fibers or connectors may touch the glass surface of the VCSEL without influencing the performance and lifetime, making assembly easier and cheaper. Two years ago the cost ratio of the VCSEL chip to the package was in the range of 1:1, while it is now approaching 1:4.



ULM PHOTONICS

Ulm's transferred substrate VCSEL is designed to make fiber attachment easier.

Northlight moves to former ADC laser site

Northlight Optronics, which bought Ericsson's optoelectronics business at the start of this year, plans to move to a new, purpose-built facility. The company has a carefully scheduled relocation plan taking place in phases between June and December, ensuring no interruption of production.

The new site is the former ADC pump-laser manufacturing facility in Järfälla, Sweden. It consists of 1200 m^2 of cleanroom space and 1600 m^2 of office, labs and production space, and allows for expansion when required.

ThreeFive Photonics files for bankruptcy protection

ThreeFive Photonics, a fabless developer and supplier of monolithically integrated InP-based optoelectronic chips based in the Netherlands, has filed a "suspension of payments" request with the Dutch court. The measure, equivalent to a Chapter 11 filing in the US, has been taken in order to explore alternative financing strategies for the company.

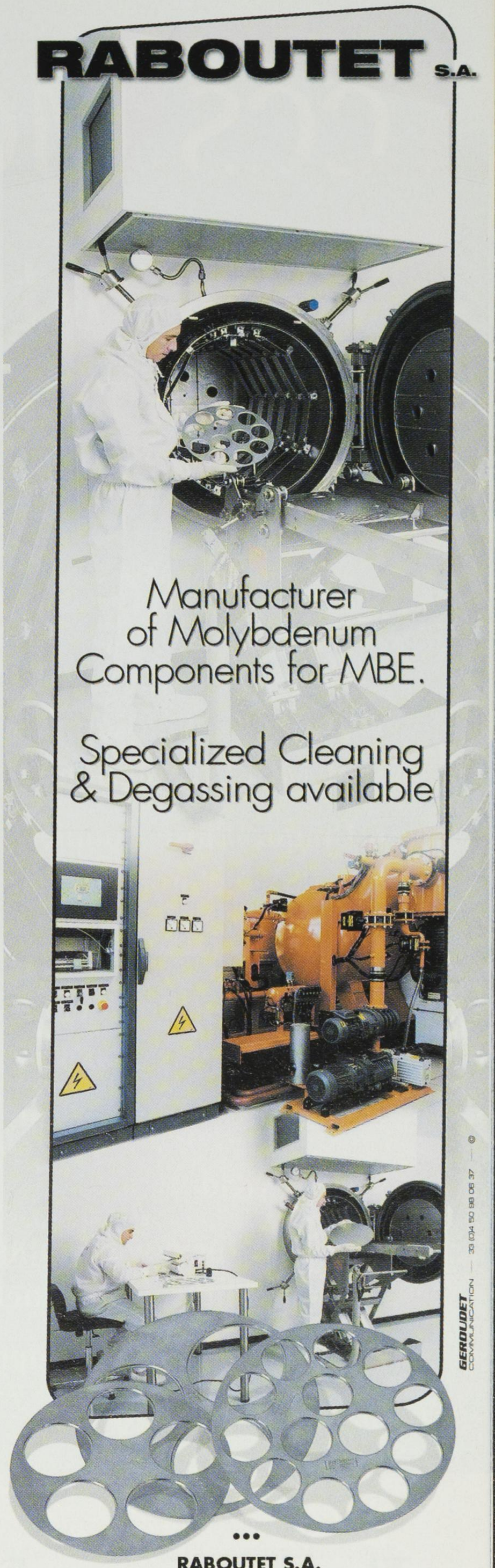
"Our existing financing situation does not allow us to sit through the current telecom winter," said Wouter Deelman, ThreeFive's CEO. "While our current investors Atlas Venture and Gilde are willing to contribute a significant amount to the series B round, we have not been able to complete the round with new investors yet. At this point we are evaluating all possible alternatives, including the sale of the company as a going business."

Nortel Networks halves its stake in Bookham Technology

Nortel Networks is reducing its stake in fiber-optic component maker Bookham Technology. Nortel is disposing of about 30 million shares (half of its holding) at £0.67 each, valuing the sale at £20 million ($32 million).

Nortel was Bookham's biggest shareholder with a 29.7% stake acquired when Bookham took over Nortel's optical components group. Bookham issued its 61 million shares to Nortel in October 2002 at £0.47 each.

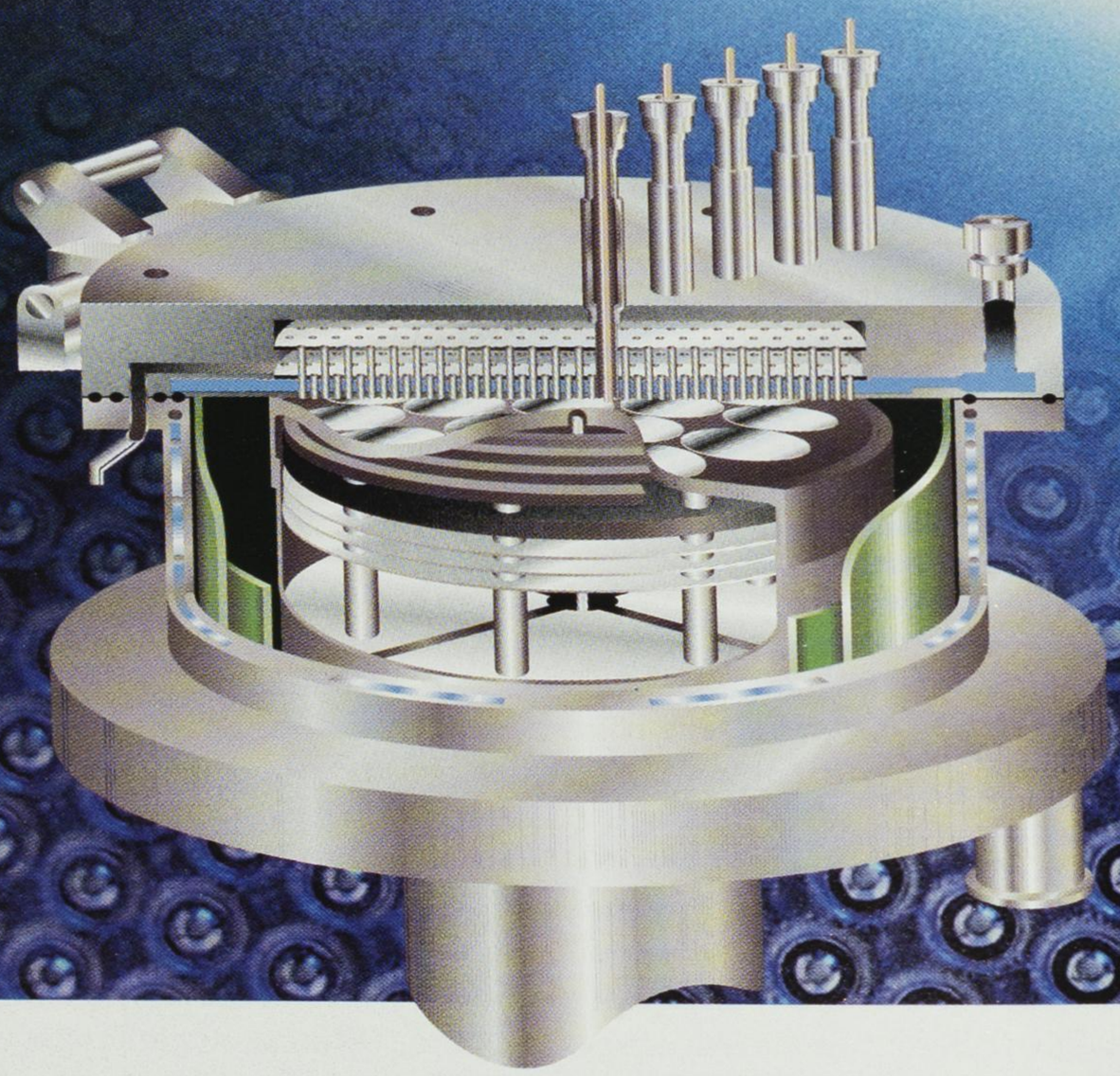
In the week following Nortel's decision, Bookham entered into an agreement to acquire substantially all of the business and assets of Cierra Photonics in a share-based deal worth about £2.25 million. Cierra, based in Santa Rosa, CA, designs and manufactures thin-film filters and other components for the fiber-optic telecommunications industry.



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NITRIDE MATERIALS AND DEVICES

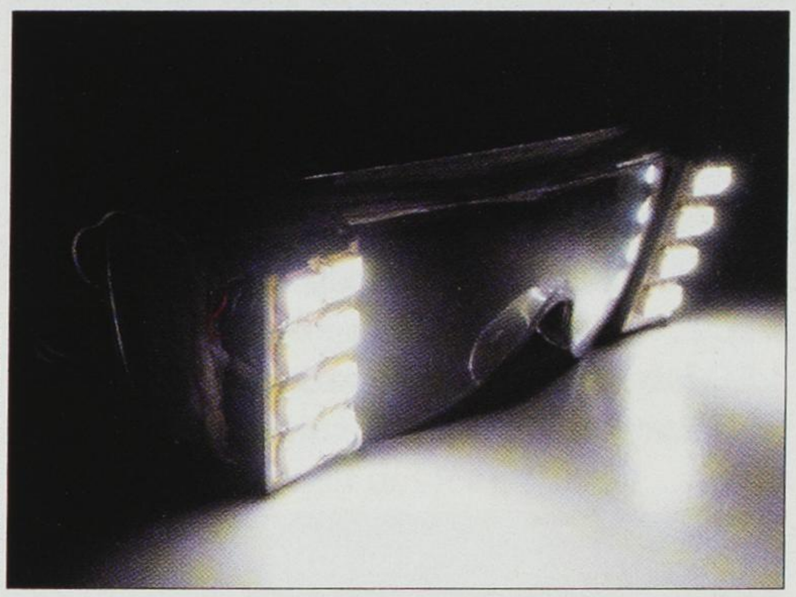
Nitrides leap ahead at ICNS-5

The III-nitrides are a growth area for compound semiconductors, and recently there has been rapid progress in performance and the variety of devices available. **Richard Balmer** reports from Nara.

The 5th International Conference on Nitride Semiconductors (ICNS-5) was held in the ancient Japanese city of Nara on May 26–30, 2003. The majority of the 649 delegates were from Asia, including 405 from Japan and 63 from South Korea. However, the attendance from elsewhere was also strong, with 78 US and 63 European delegates. A total of 406 papers were presented, although sadly 23 presentations were withdrawn by researchers from China, Taiwan and Singapore due to the SARS outbreak.

The number of presentations demonstrated not only the continued growth of activity in this field but also the tremendously rapid progress that has been made since ICNS-4 in 2001. There was a much more commercial feel at this meeting, which stems from the emergence of spin-off and start-up companies that are taking processes and devices to market, as well as the ever-present large corporations which are continually adding new products and improving existing ones. Some of the areas of significant progress included UV-LEDs with increased quantum efficiency, white LEDs with better color rendering, and HEMTs with significant improvements in breakdown voltage, current collapse and gate leakage.

The conference was opened with a series of plenary lectures, including one by Fernando Ponce from Arizona State University, who summarized the current status and identified the important issues for the growth of InGaN alloys, and one by Hiroshi Ogawa from Sony Corporation, who discussed the impact of nitride laser diodes on the evolution of optical data storage.



NICHIA/KYOTO UNIVERSITY

Fig. 1. Surgeon's goggles with 16 power LED modules, each providing 23 lm from a 1 mm² die driven at 350 mA.

Bulk nitride substrates

The development of large-area III-nitride substrates for lattice-matched growth of GaN and related alloys is gathering momentum. As a result there was much discussion of recent progress, with most of the commercial developers represented at the meeting. R Vaudo from ATMI in Danbury, CT, described an investigation of free-standing semi-insulating Fe-doped GaN substrates grown by HVPE. Fe concentrations up to $2 \times 10^{17}/cm^3$ were achieved, but the highest resistivity observed was 2×10^9 Ωcm at room temperature for an Fe concentration of $4 \times 10^{16}/cm^3$.

Leo Schowalter of Crystal IS in Latham, NY, described the company's AlN bulk growth technology from which it produces substrates with a variety of orientations (*Compound Semiconductor* July 2003 p8). Vladimir Dmitriev from TDI in Silver Spring, MD, described the development of freestanding AlGaN substrates fabricated using HVPE growth onto SiC with subsequent removal of the SiC. Dmitriev also presented work by TDI and co-workers on AlN substrates grown by vapor phase techniques, which have so far resulted in 35 mm diameter substrates, with 50 mm material expected by the end of 2003. Mike Leszczynski from Polish company TopGaN described the progress made with the company's high-pressure growth technique for bulk GaN substrates. Although the current samples are only about 12 mm in diameter, they show excellent low dislocation densities of about $100/cm^2$ and have been used to fabricate blue lasers (see also p10).

The bandgap of indium nitride

In the two sessions devoted to InN, the fundamental bandgap of this material was a hot topic, with many researchers supporting the recent reports of a narrower bandgap than the previously accepted 1.9 eV. Deposition of high-quality (as determined by XRD) InN films on sapphire and Si(111) by RF-MBE was reported by Y Nanishi representing a group of researchers from Ritsumeikan University and Sony Corporation, Japan. A carrier concentration of $4.9 \times 10^{18}/cm^3$ and a room temperature mobility of 1130 cm^2/Vs were measured. Absorption and PL measurements observed sharp luminescence at 0.8 eV and no peak at 1.9 eV.

A Yamamoto from Fukui University, Japan, and co-workers at the Ioffe Institute in Russia reported MOVPE growth of InN films with absorption between 0.7 and 2 eV. XPS studies indicate that oxygen contamination of the films is the mechanism for the absorption at 2 eV.

New processes yield better LEDs

The topic of LEDs was initiated with a well attended and stimulating discussion session on general lighting using white LEDs. Many of the critical issues were covered including lowering costs, raising the luminous efficiency and total flux per lamp, improving color rendering, and phosphor conversion versus multichip RGB LEDs. One of the highlights was a presentation by H Shimada, a surgeon at Kyoto University, and Takashi Mukai from Nichia on shadowless lighting during surgery using goggles mounted with high-power white LEDs (figure 1). The minimum luminance required for surgery is 20,000 lm/m^2, and the local area of illumination is 15×15 cm^2, so a total luminous flux of 450 lm is necessary.

The current-generation goggles contain 16 power LED modules mounted on an AlN plate, supplied by packaging specialist Kyocera, and a heat sink, which is cooled with microfans. Each module gives 23 lm at 350 mA from a 1 mm^2 die, allowing a head-to-patient distance of 52 cm. The drawbacks are that the heat generated from non-radiative processes prevents the use of the goggles for more than 15 minutes before they are too hot to wear, and poor color rendering in the red band makes muscle tissue appear blue, making it difficult to distinguish between arteries and veins. The next-generation goggles will incorporate the latest white LED modules, which achieve superior color rendering by uti-

lizing improved phosphor technology.

S Kamiyama from Meijo University, in collaboration with Kyocera Corporation and the Advanced Materials Laboratory in Tsukuba, Japan, reported violet LEDs grown on a zirconium diboride (ZrB_2) substrate. This material is reported to have excellent electrical and thermal conductivities (130 W/mK) as well as a perfect lattice match for $Al_{0.26}Ga_{0.74}N$. On-wafer measurements yielded an operating voltage of 3.5 V and an L-I curve with excellent linearity compared with equivalent devices on sapphire, attributed to reduced output power saturation due to self heating.

Nichia's Mukai also gave an invited talk covering the status of LED and laser technology at Nichia and the efforts to improve the devices. In particular he described the advances in LED efficiency through the use of a patterned sapphire substrate, which scatters some of the downward-directed emission back into the structure that would otherwise be lost through the substrate. He also discussed the further enhancement to extraction efficiency through the use of a Rh metal mesh top electrode (figure 2).

Mukai's colleague Daisuke Morita reported a GaN-free 365 nm UV LED, which incorporates the mesh electrode and exhibits a peak output power of more than 200 mW. Removing the GaN reduces the losses due to UV photon absorption. The LEDs are initially grown on a sapphire substrate with a GaN buffer layer. Absorption in the GaN layer is avoided by transferring the device to a CuW substrate bonded to the top surface using AuSn solder. The sapphire and the GaN buffer layer are then removed, leaving a GaN-free device. A 50% increase in the extraction efficiency was obtained by replacing the NiAu with a Rh mesh electrode, taking the extraction efficiency above 10% for both pulsed and DC operation of a 365 nm LED for the first time.

Other groups also reported impressive efficiency gains using patterned sapphire substrates, including Mitsubishi Cable and Stanley Electric, which together have developed 405 nm LEDs grown on grooved sapphire. Mitsubishi's Hiromitsu Kudo described a systematic study to investigate how the groove depth influenced the photoluminescence of the LED structure. Increasing the depths of the grooves increased the PL intensity and removed unwanted interference fringes from the spectrum. The 405 nm devices had an output power of 26.1 mW and an impressive external quantum efficiency of 43%, the highest to date for violet LEDs.

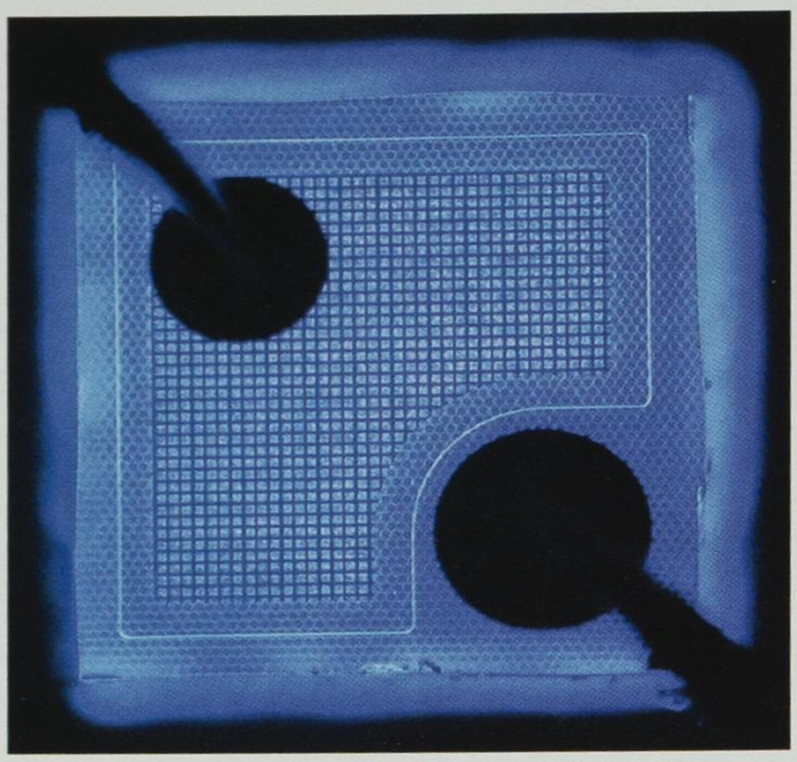
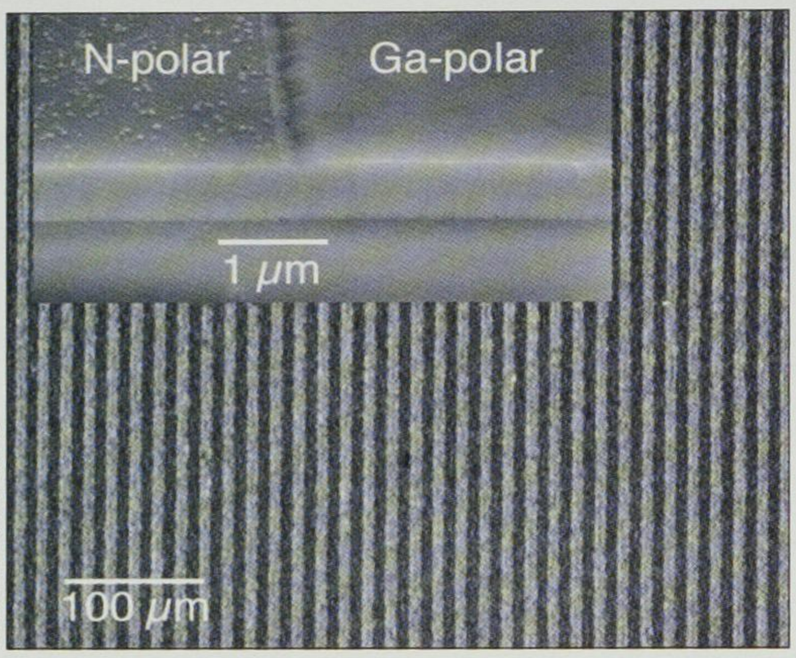

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Fig. 2. Top view of a high-efficiency blue LED fabricated using a patterned sapphire substrate and a Rh mesh top contact.



BELL LABORATORIES

Fig. 3. An SEM image of the PPGaN with the inset showing a higher magnification image of the N- and Ga-polar regions.

Lasers

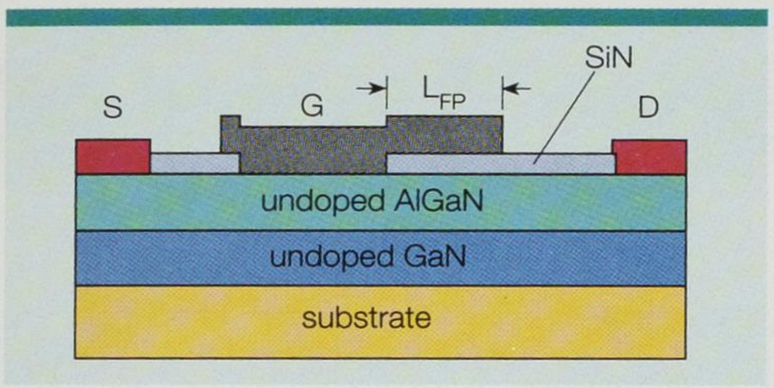
Michael Kneissl from Palo Alto Research Center reported on the design and performance characteristics of InGaN/InAlGaN MQW UV laser diodes. The x-value in the $In_xGa_{1-x}N$ QWs was systematically varied from 0.027 to 0.002, which gave room-temperature laser emission of 378–363.2 nm. Pulsed threshold current densities around 5 kA/cm^2 were achieved for emission between 368 and 378 nm. Furthermore, a light output of 400 mW and differential quantum efficiency of 4.8% was achieved under pulsed current injection conditions (emission at 369 nm, a pulse duration of 500 ns and repetition frequency of 1 kHz).

The role of threading dislocations in determining the lifetime of nitride-based lasers was a topic of significant interest. Shu Goto from Sony Shiroishi Semiconductor reported the characteristics of high-power AlGaInN-based laser diodes fabricated on low dislocation density GaN substrates to improve device lifetimes. Devices were fabricated on regions with a dislocation density of 3–4 × 10^5/cm^2, which implies the presence of only 18–24 dislocations in a laser stripe with an area ~6 × 10^{-5} cm^2. The laser's wavelength was about 405 nm and threshold current densities for stripe widths of 10, 50 and 100 μm were 2.0, 1.8 and 1.4 kA/cm^2 respectively. Preliminary lifetime results performed under 0.2 W CW operation at 25 °C were presented for a device with a 10 μm stripe width, showing stable output current for 100 h operation. In contrast to this, work presented by S Tomiya from Sony presented a TEM and cathodoluminescence investigation of degraded GaN-based lasers. No dislocation multiplication due to threading dislocations was observed despite threading dislocations being present in the stripe regions, calling into question whether dislocations play an important role in determining the lifetime of laser diodes. However, pyramidal defects were observed in the p-type layers and it was proposed that these might be detrimental to the device lifetime.

The transparency window of GaN covers ~0.365–13.6 μm, giving the potential of generating wavelengths in the far infrared or near-UV by sum- or difference-frequency generation. Aref Chowdhury from Bell Labs reported the first experimental demonstration of second harmonic generation in periodically poled GaN (PPGaN) by first-order quasi-phase matching. PPGaN samples were prepared using plasma-MBE to grow a thin GaN film on an AlN nucleation layer on a sapphire substrate. The GaN/AlN was then lithographically patterned and etched to form 17.2 μm stripes separated by exposed sapphire. Further growth of GaN resulted in Ga-polar GaN on the AlN stripes and N-polar GaN on the sapphire (figure 3). Samples were prepared by mechanical polishing then pumped with a femtosecond laser at a wavelength of 1658.6 nm. For an input power of 7 mW, 9 μW of second harmonic power from the PPGaN was observed.

Breakdown voltages on the rise

Akira Endoh and co-workers at Fujitsu Labs are well known for their work on InP HEMTs, but are also applying their expertise to GaN HEMTs. In collaboration with Osaka University, the group has investigated the dependence of f_t on the gate length for devices fabricated using T-gate technology. The highest f_t measured was 102 GHz for a gate length L_g of 35 nm. Also from Fujitsu, T Kikkawa



NEC CORPORATION

Fig. 4. An AlGaN/GaN power HFET with the field plate structure.

reported improved linearity and high reliability from AlGaN/GaN HEMT devices for wireless basestation applications incorporating a thin n-GaN cap and SiN passivation to control the polarization-induced surface charge. The n-doped ($\sim 10^{18}/cm^3$) cap is included to obtain a flat band to the surface and reduce high fields at the gate. A 70 W CW saturation power (48.43 dBm) at a V_{ds} of 55 V was obtained under power-matched conditions near class-B operation for a 24 mm gate periphery device. Under efficiency-matched conditions, 51 W (47.08 dBm) with a maximum PAE of 40.8% at a V_{ds} of 55 V was obtained. The two-tone characteristics at 8 dB backed-off power from P_{sat} were studied and state-of-the-art intermodulation distortion figures of IM3 = –35.7 dBc with a PAE of 26.8% at a V_{ds} of 30 V were reported.

The use of deposited Al_2O_3 films as a gate dielectric for insulated gate FETs was reported by a number of groups. The advantages of Al_2O_3 over more commonly used materials such as SiN are a large conduction band offset with AlGaN to suppress gate leakage, a high dielectric constant to minimize reduction of transconductance due to series capacitance under the gate, and surface passivation to minimize current collapse. T Hashizume from Hokkaido University reported a process involving an ECR-N_2 plasma treatment of the AlGaN surface followed by deposition of 3 nm of Al at room temperature in an MBE chamber. The Al layer is oxidized by exposure to an ECR-O_2 plasma followed by a UHV anneal at 700 °C. Angle-resolved XPS analysis revealed the successful formation of a 3.5 nm Al_2O_3 layer without disordering the topmost AlGaN layer. A conduction band offset of 2.1 eV with respect to the AlGaN was determined. Hashizume claims the highest reported value of g_m for an AlGaN/GaN IG-FET of 120 mS/mm and no current collapse was observed.

For conventional HEMT structures, there is a trade-off between on-resistance and breakdown voltage because the electric field becomes concentrated at the edge of the gate electrode on the drain side. Two groups reported the use of field-plate (FP) technology to relax the electric field at the gate electrode to improve the breakdown voltage and also suppress current collapse. In an invited presentation, Masaaki Kuzuhara from NEC Corporation discussed L-and Ka-band devices fabricated using an FP deposited over SiN on SI-SiC substrates (figure 4). By introducing the FP electrode for a 0.9 μm gate-length device, the breakdown voltage was increased from 50 to 160 V. With a drain voltage of 32 V, a 5-cell FP-FET power chip with a gate periphery of 20 mm delivered a CW output power of 75 W (3.7 W/mm) with a PAE of 50% and a linear gain of 9.3 dB at 2 GHz. A 0.25 μm short channel FP-FET was fabricated for Ka-band applications. For a gate width of 2 × 50 μm (2-finger device), f_t and f_{max} were 50 and 120 GHz, respectively, and P_{out} was 2.3 W (6.4 W/mm), with a PAE of 38% and a linear gain of 8.8 dB at 30 GHz for a 6-finger device. Moreover, extremely high breakdown voltages of up to 594 V for an FP-HEMT were reported by Y Takada from Toshiba Corporation. These devices showed ultra-low on-state resistance of 3.3 $m\Omega cm^2$ and a switching current density of 850 A/cm^2 at V_{dc} of 300 V and no current collapse was observed.

A number of groups including UCSB and the University of South Carolina reported the use of thin AlN layers between the AlGaN barrier layer and the GaN buffer layer to obtain improved mobility in the 2DEG. Thickness optimization and electrical assessment of these carrier exclusion layers was reported by Richard Balmer from QinetiQ, UK. The room-temperature drift mobility as a function of carrier number density was determined by combined I-V and C-V measurements for large-area devices with and without the exclusion layer. At low number density (near class B operating point), the drift mobilities are comparable, but with increasing number density, the mobility stays more or less constant with the exclusion layer but reduces without the exclusion layer. In the open channel condition, the drift mobility was 2177 cm^2/Vs and 1308 cm^2/Vs with and without the exclusion layer, respectively. It was demonstrated that the observed degradation in mobility was due to increased alloy disorder scattering due to greater penetration of the electron wavefunction into the AlGaN.

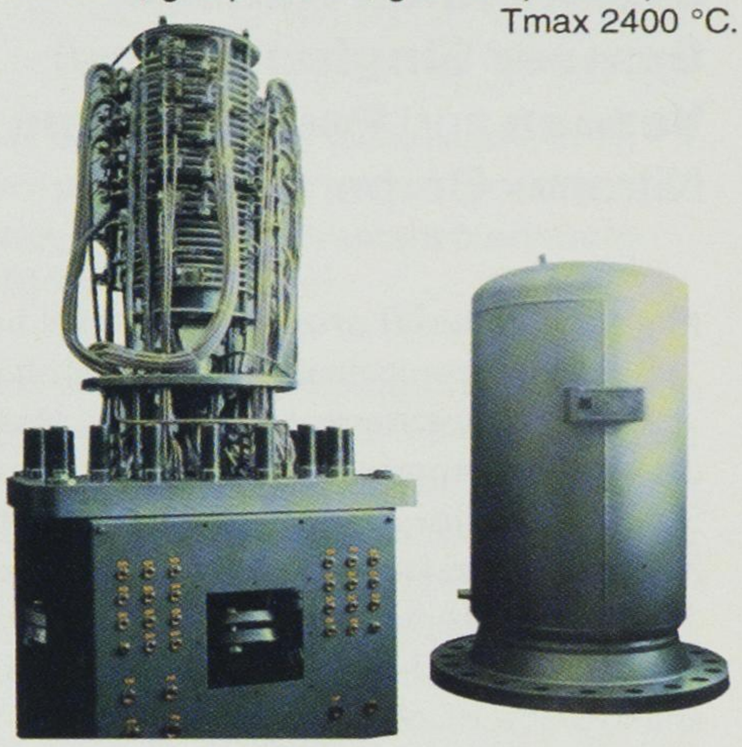
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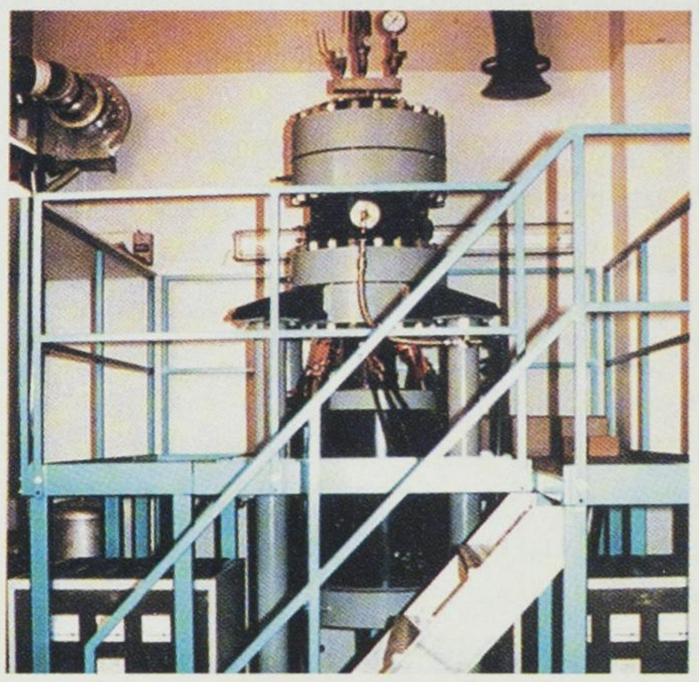
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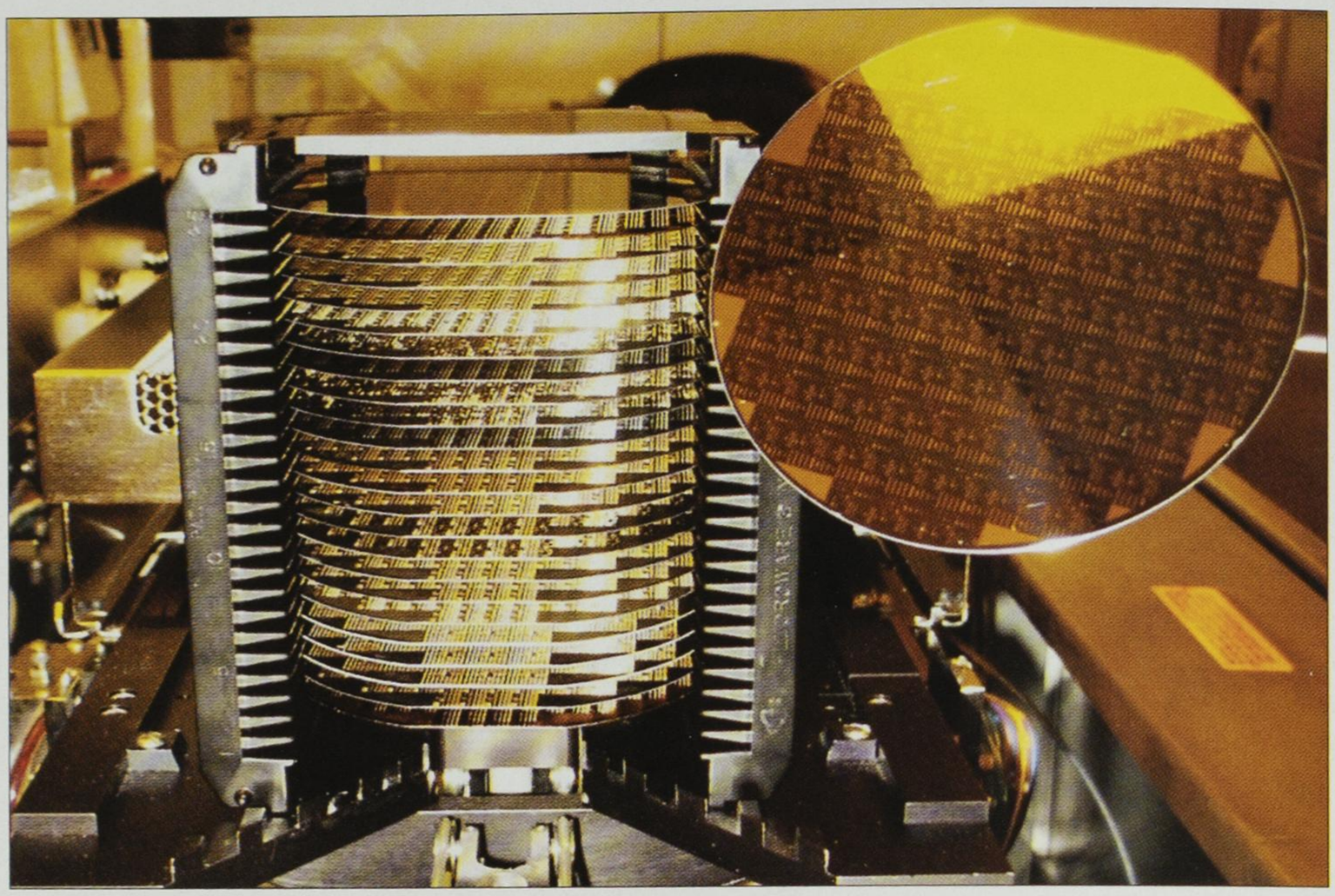
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GaN HFETs on silicon target w

The high breakdown voltages inherent in GaN HFET technology make it well suited to high-voltage operation in wireless infrastructure applications, according to **Ricardo Borges**, **Jeff Brown**, **Allen Hanson**, **Sameer Singhal**, **Andrei Vescan** and **Paul Williams** of Nitronex Corporation.



Nitronex's GaN-based HFETs, fabricated on 100 mm silicon wafers, target 3G markets.

The material properties of GaN have long been considered ideal for high-power microwave applications. Having developed a proprietary process, designated SIGANTIC, for growing GaN on silicon, Nitronex has created the opportunity to exploit the material properties of GaN while benefiting from the wide availability, high quality and low cost of silicon substrates.

However, the real proof of a semiconductor's capability is seen in its application to a commercial situation, prompting Nitronex to consider a number of markets in its search for a match for the properties of GaN. This has led to the development of a prototype power transistor for the UMTS or third-generation (3G) power-amplifier market.

RF power transistors for 3G

Wireless infrastructure RF power-transistor technology has evolved as new air-interface standards demand increasingly higher performance. Second-generation cellular networks based on the GSM standard use constant envelope modulation. The amplifiers needed to boost these signals can be effectively built with current silicon and GaAs technologies. Capitalizing on its lower substrate and overall process cost, silicon-based technologies gained the lion's share of the market, with the more recent LDMOS process surpassing the older BJT technology. Only in Japan did GaAs MESFETs and HFETs manage to keep a stronghold in the market.

Emerging 3G standards such as W-CDMA use variable-amplitude envelope modulation, which places much stricter constraints on the linearity of the power amplifier (PA) to minimize distortion. This in turn demands a more linear power transistor, so LDMOS manufacturers continue to upgrade their transistors, with the leading vendor now working on a fifth-generation process. The emphasis is on maximizing efficiency at a given level of linearity. In the race to squeeze more performance from existing technologies, process development teams are beginning to encounter the limits posed by the fundamental properties of the underlying semiconductor material.

Transistor requirements

The transistor linearity is commonly expressed in terms of the adjacent channel power ratio (ACPR). As the name implies, the ACPR is a measure of the amount of power spilling into the adjacent channels referenced to the power in the transmit channel. A typical set of RF power transistor requirements addressing the 3G power-amplifier market is shown in table 1.

To achieve the required linearity, W-CDMA transistors must operate with the power backed off to well below their peak capability. For example, a state-of-the-art LDMOS transistor with a P1dB rating of 180 W is capable of producing about 38 W (~80 mW/mm) of linear power under W-CDMA modulation, at 28 V operation. Constrained by a device technology of moderate power density, LDMOS manufacturers must utilize very large gate peripheries and correspondingly very low die impedances to keep scaling up the power. As that happens, the bandwidth of the matching circuit is reduced. With lower operating voltages (12–15 V), higher operating currents and lower thermal conductivity than silicon, GaAs HFET manufacturers face an even more challenging task than their silicon counterparts.

These issues can be circumvented by a higher power density technology, which enables higher total output power and increased bandwidth resulting from a more compact layout. In the case of GaN HFETs, their high-frequency response can also address higher-frequency bands, as future generations of wireless systems push up in frequency, while their inherent higher-voltage capability can open up new PA architecture and system options. Certainly, these attributes should not come at the expense of the superior linearity and efficiency demanded from present and future RF power transistors, as will be discussed in the following sections.

wireless infrastructure market

RF power transistors	
Property	
WCDMA output power (W)	10 to 40
ACPR linearity (dBc)	–45 to –39
drain efficiency at	
linear operation (%)	22 to 30
gain (dB)	12 to 15

Table 1. Typical set of RF power transistor requirements addressing the 3G power-amplifier market.

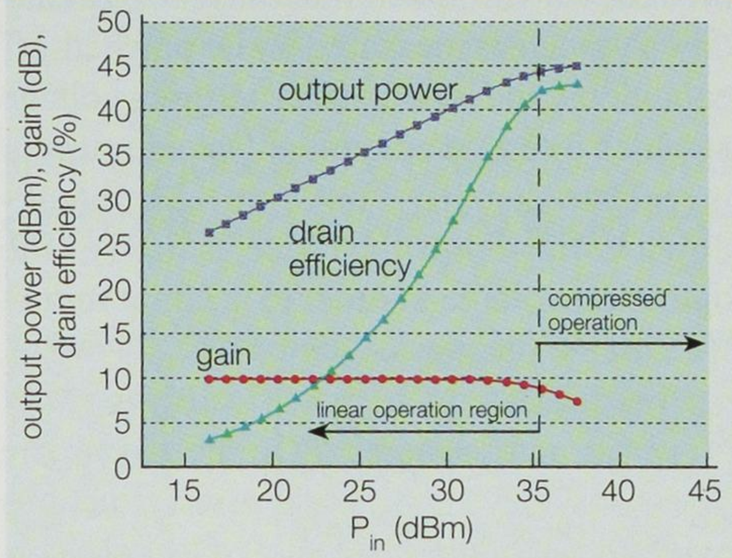


Fig. 1. Power sweep at a drain voltage of 28 V showing 30 W of saturated output power, 10 dB gain and 43% peak drain efficiency.

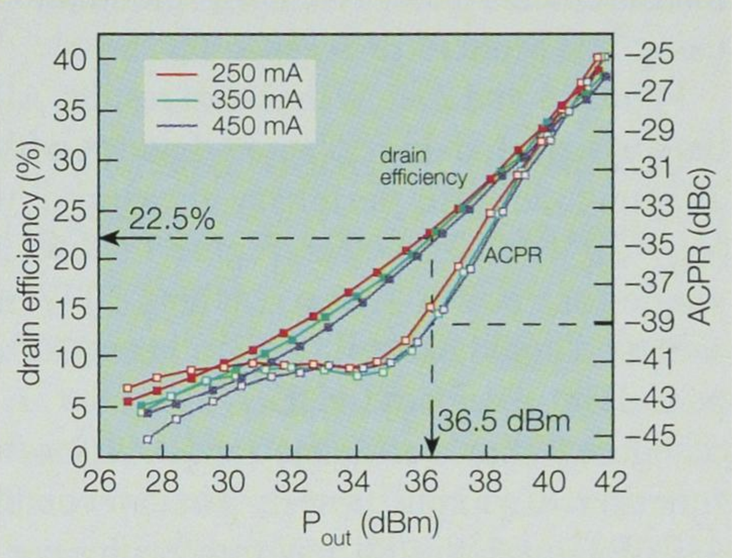


Fig. 2. Drain efficiency (solid) and ACPR (open) plotted against output for a drain voltage of 28 V and quiescent currents in the 250–450 mA range.

GaN on silicon

One of the major challenges of GaN technology is the material growth, and intrinsically linked to it is the choice of the substrate material. For the foreseeable future, bulk GaN will not be available in practical sizes, or at a reasonable price. Therefore, the focus is still on the more conventional substrates – sapphire, SiC and silicon. Of these, silicon has been shown to be the most difficult substrate to grow on, especially due to its more than 50% lower thermal expansion coefficient.

The tensile stress upon cooling down from growth temperature presents a significant challenge towards achieving high-quality epitaxial layers. However, several groups (Krost and Dadgar 2002) have developed transition layers or stress-compensating buffer layers, enabling the growth of thick, crack-free GaN layers on silicon. In particular, Nitronex's SIGANTIC process, employing a proprietary (Al,Ga)N transition layer, has demonstrated the ability to reproducibly grow thick, crack-free GaN layers on silicon with excellent electrical transport properties (Rajagopal *et al.* 2002). This process was initially developed on a 2 inch platform, and then successfully transferred to a 100 mm GaN HFET pilot line in the fourth quarter of 2001.

It is true that the issues related to growing good-quality material in spite of the significant lattice and thermal expansion coefficient mismatch have been addressed, and workable solutions are available for each of the mentioned substrates. The final choice of substrate is not a question of feasibility, but rather of the targeted application, in conjunction with economical aspects such as volume and cost.

Sapphire substrates, although available at moderate costs and large substrate sizes, present a challenge in the thermal design of power devices given their low thermal conductivity. Process steps intended to mitigate the thermal limitations, such as aggressive thinning or flip-chip mounting, increase cost and complexity. On the other hand, while SiC has excellent thermal conductivity, large-area substrates with low defect density are not yet commercially available. It remains to be seen whether these highly priced substrates will be competitive for commercial applications.

Using silicon as a substrate material enables a variety of commercial applications and manufacturing technologies. On a 100 mm platform, standard silicon packaging techniques, as one example, can be used to bring this state-of-the-art compound semiconductor to production volumes.

Design and operation

GaN HFETs may be treated like power devices in any other device technology from the perspective of design and operation. The primary factors that drive the device design beyond other technologies are the characteristics that make these devices attractive for high-power applications. These are the high breakdown fields, typically exceeding 50–100 V/μm of gate-drain spacing; and the high RF power density, which can be as high as 4–5 W/mm of saturated power on large periphery devices (Kikkawa *et al.* 2003). High breakdown fields enable high operating voltages, and the high power density allows for a reduction of the total device area.

We have described the application-specific performance requirements for these devices, but there are requirements beyond the performance metrics. The devices must be able to operate at the expected ambient conditions without experiencing excessive junction temperatures that could degrade the operational lifetime. Amplifier design requires that the devices have input and output characteristics that make it possible to present readily achievable source and load impedances. The junction temperature and device impedance are largely affected by the high power density and the ability to minimize any parallel equivalent capacitance of the device. By careful design of the gate pitch and unit gate width, an optimal combination of device capacitance and junction temperature can be achieved.

A well-designed device exhibits a range of performance capability depending on the conditions under which it is operated. Devices intended for use in W-CDMA amplifiers would typically be operated in a condition that is backed off from the onset of compressed operation shown in figure 1. Since efficiency is a key metric of this application, devices are operated in a condition that yields the best efficiency without sacrificing other critical attributes such as gain and linearity. The operating condition commonly used to satisfy these requirements is deep class AB and as near to maximum linear power as possible, so as to improve the efficiency while maintaining sufficient linearity and maximizing gain to meet the system specifications.

Prototype performance

Power transistors used in 3G base stations require a minimum level of linearity, defined by an ACPR of –39 dBc, with the efficiency and power being optimized at this level. In this work we report linearity in terms of ACPR measurements under W-CDMA modulation using Test Model 1 of 3G spec TS 25.141.

Figures 1 and 2 show the latest results. All data is reported on packaged devices with 16 mm total gate periphery measured at V_{ds} = 28 V and 2.14 GHz. Figure 1 shows a single-tone power-sweep reaching 30 W of saturated output power, 10 dB gain and 43% peak drain efficiency.

Figure 2 shows efficiency and ACPR as a function of output power. The power at –39 dBc is 4.5 W (280 mW/mm) with a corresponding drain efficiency of 22.5%.

The shape of the curves in figure 2 also reveals two interesting features. First, the curve is very insensitive to the quiescent current (I_{dq}) in the 250–450 mA range (deep Class AB bias). Second, the ACPR curve exhibits a plateau around –41 dBc for a wide range of efficiency/power. These characteristics are desirable to a PA designer, since they provide additional freedom in the circuit design and operation.

Currently, amplifiers run with typical operating voltages of 28 V, which is limited by the breakdown voltage of the transistor. Breakdown voltage is measured under pinched-off conditions, and is defined as the drain voltage at which a certain amount of leakage current is reached (usually 1 mA/mm). The breakdown voltage must be twice as high as the operating voltage in order to account for the RF voltage swing.

Breakdown measurements were carried out on test structures adjacent to the 16 mm die shown in figures 1 and 2. These test structures exhibited less than 1 mA/mm of leakage current with 150 V on the drain. This high breakdown voltage allows higher operating voltages. The higher operating voltage results in higher power densities, better linearity performance, and increased device impedance and bandwidth, making it easier for the PA designer to match the device.

Conclusions

As discussed, GaN transistor technology is proving to be well suited to wireless infrastructure applications. Given the high breakdown voltages inherent in this technology, it is expected to prove enabling to the development of PAs operating at higher DC supply voltages with obvious benefits. These include increased power density, the ability to take advantage of design techniques that optimize efficiency, and reduced loss associated with DC power distribution.

While the focus is on 3G frequency bands, GaN transistor technology has also been shown to be capable of operating at much higher frequencies beyond the reach of current silicon technologies. ●

Further reading

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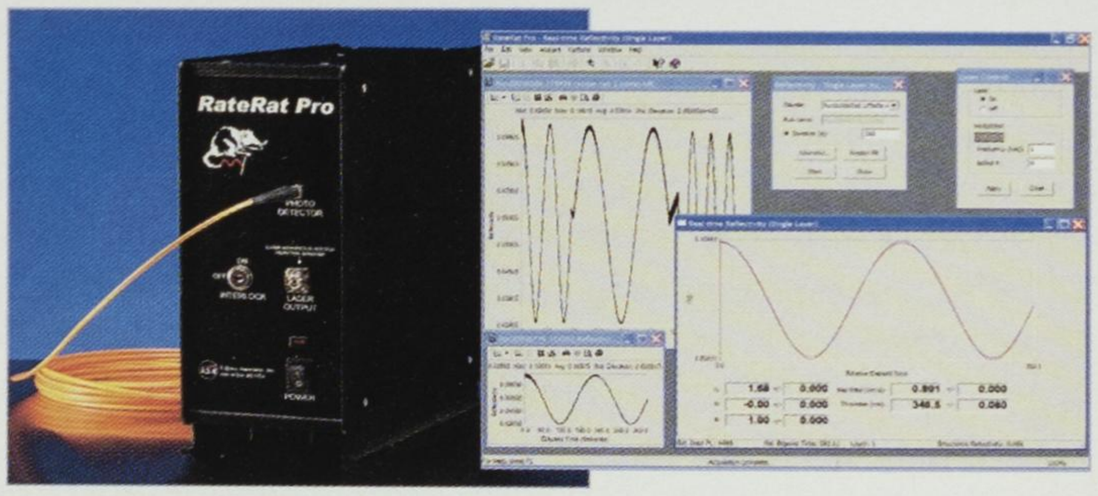


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NITRIDE MATERIALS AND DEVICES

Bringing AlGaN from research to high-volume production

Recent AlGaN development work in the laboratory will help to shape the future market for a variety of devices, according to **David Gotthold** and **Shiping Guo** from Emcore.

With new applications rapidly emerging for AlGaN-based devices such as HEMTs and UV LEDs, the seamless move to growth on 3 inch (75 mm) and 4 inch (100 mm) substrates has become a key objective in the compound semiconductor industry. Current research and engineering for epitaxial structures requiring high aluminum content layers (25–60%) is laying the foundation for high-volume, low-cost growth of these advanced materials. To this end, the challenges associated with transferring such sensitive processes to a production platform are steadily being overcome through innovative equipment design combined with a flexible approach to deposition. As in the silicon industry, it is falling to equipment manufacturers to develop and transfer growth techniques that enable end users to smoothly ramp up to mass production.

Taking AlGaN HEMTs into production

Due to their promise as high-performance RF devices and their ability to operate at extreme temperatures, AlGaN/GaN HEMTs have attracted considerable attention from a number of industries. For high-frequency (10 GHz) applications, devices have been produced that can operate at power densities in excess of 11 W/mm (Eastman *et al.*). In addition, there has been a more immediate commercial interest in these devices from the telecommunication and automotive industries, for high-voltage and high-temperature applications. In order to successfully move these devices from the university laboratory to a full production environment, high-volume and cost-effective growth technologies must be developed.

Scaling the growth of AlGaN HEMTs to a true production-ready multiwafer growth platform requires focusing on a range of issues. These include the repeatability of the epitaxial structure, the process yield (especially given the high cost of semi-insulating SiC substrates), and the ability to transfer a laboratory-developed 2 inch process to 3 and 4 inch substrates. In particular, strict wafer temperature control during deposition is a major concern, as the thermal drift associated with high Al-content AlGaN growth can significantly affect run-to-run repeatability. Once a reliable and cost-effective production process is established that does not sacrifice the high performance levels indicated by earlier low-volume prototype devices, AlGaN/GaN HEMTs can be effectively commercialized.



Fig. 1. The GaNzilla tool used for development of production processes for AlGaN devices such as UV emitters.

Two different sizes of reactors are currently used for HEMT development in the Emcore laboratory: a research-scale D180GaN tool, used for basic structure and process development on 2 and 3 inch substrates; and a production scale E300GaN tool, for growth of up to five 4 inch substrates in a single run (figure 1). In both systems, a proprietary *in situ* temperature-monitoring instrument utilizing emissivity-compensated pyrometry and developed specifically for GaN growth is used to enhance process control. A range of HEMT structures can be grown, depending on the specific application and customer preferences. The structures consist of a 15–30 nm thick 25–35% AlGaN barrier layer on 1–3 μm of semi-insulating GaN, and a substrate-specific nucleation layer.

Approaches to different substrates

As advanced AlGaN-based structures move from the laboratory to production, reducing the overall cost of manufacturing these devices becomes necessary. In the case of AlGaN HEMTs, it is important to incorporate the use of larger, lower-cost substrates, both for process development and for final devices. When using low-cost substrates for process development, it is imperative to prove process transferability between sapphire and SiC. Through careful control of defect density, strain and surface morphology, it is possible to achieve essentially identical results on both sapphire and 4H-SiC substrates when using identical growth recipes for the semi-insulating GaN and the AlGaN barrier layer. On a test pair of 2 inch substrates, sheet charge and mobility results are found to be similar, with a carrier density (N_s) for both wafers of ~8×10^{12}/cm^2, and mobility (μ) of ~1550 cm^2/Vs with equivalent uniformities. For low-cost 100 mm growth, silicon substrates are ideal – however, cracking of the epilayer can be a severe problem due to mismatches in the coefficients of thermal expansion between Si and GaN-based material. With adjustments to improve strain control, a crack-free surface was obtained, yielding an XRD (0002) reflection with a FWHM of 334 arcsec. Typical AlGaN HEMT characteristics were sheet resistance (R_s) = 360–380 Ω/sq, R_s uniformity <3%, μ>1500 cm^2/Vs, N_s >8×10^{12}/cm^2.

Due to a build up of deposits on the platter, drift in the Al composition over time has presented a challenge for AlGaN HEMT repeatability in a production environment. Using the proprietary GaN RealTemp 200 to correct for drift in wafer temperature, it is possible to maintain a steady temperature over multiple runs. Using the research reactor over three consecutive runs (AlGaN HEMT on 2 inch SiC), an average R_s of 367.4 Ω/sq was achieved with a run-to-run standard deviation (σ) of 1.8% and an average thickness of

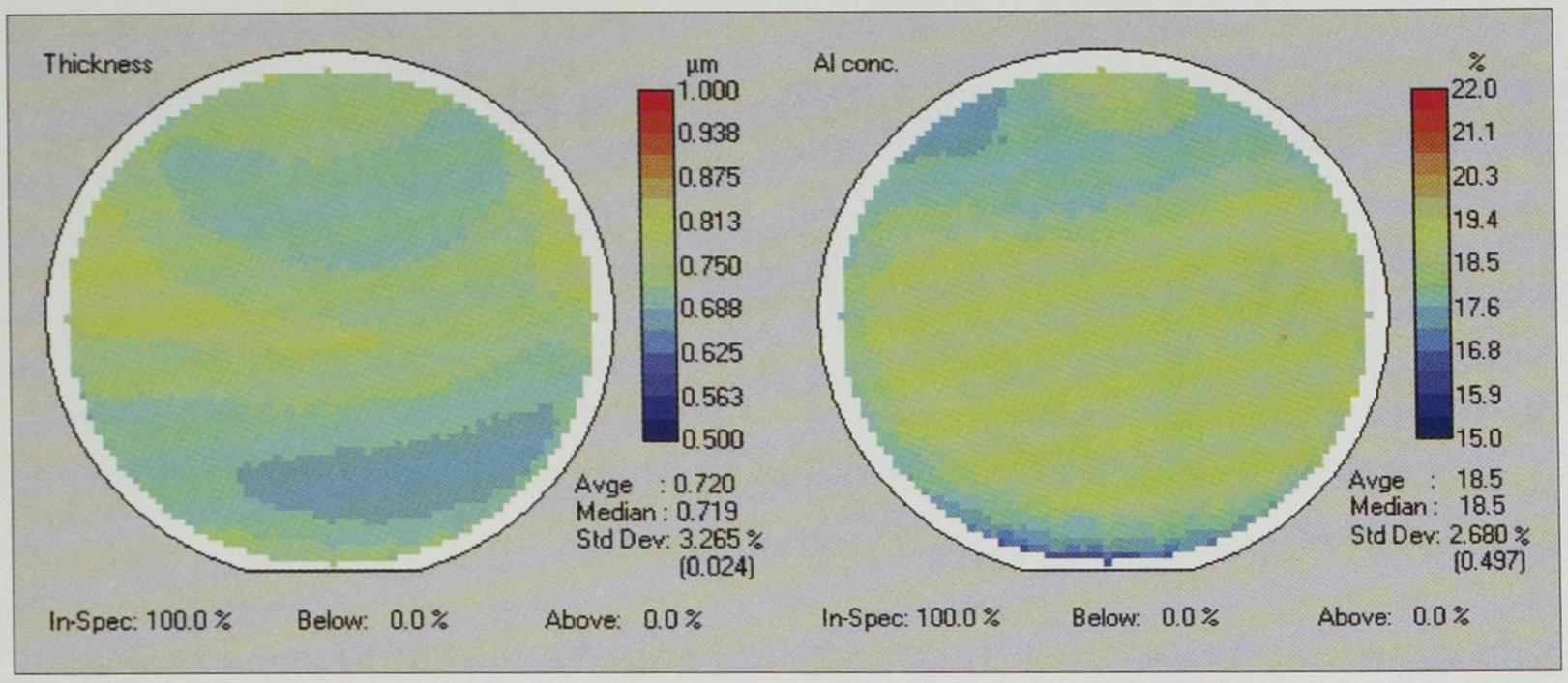


Fig. 2. Thickness and composition maps for AlGaN on 3 inch sapphire.

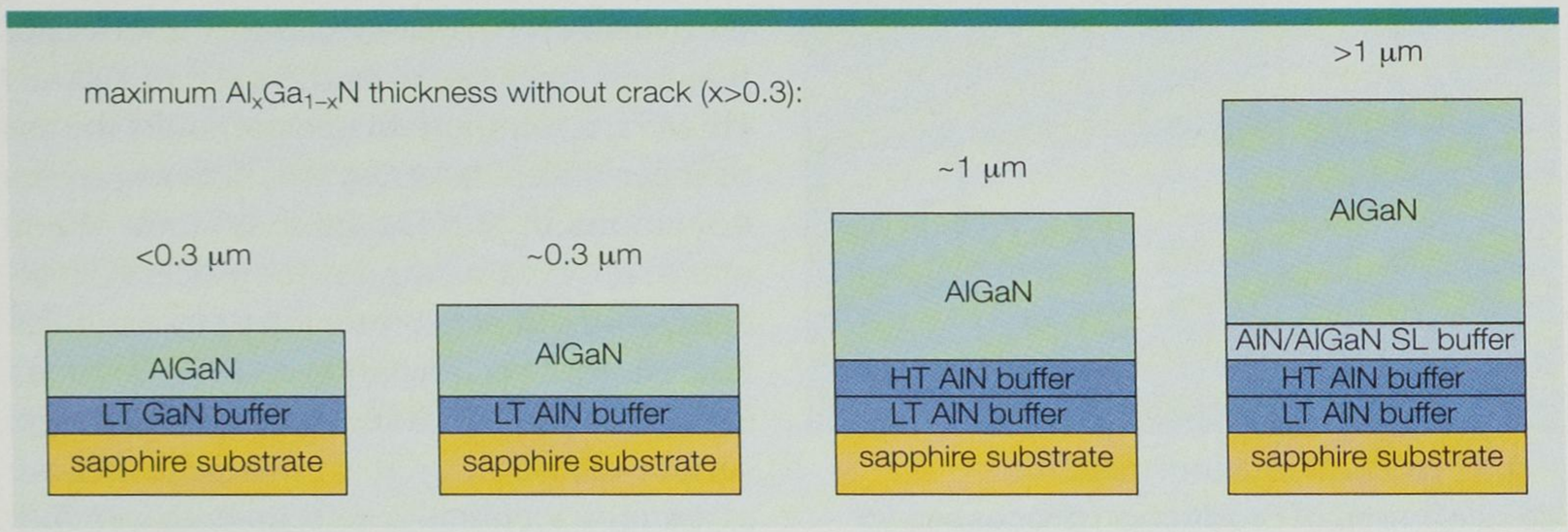


Fig. 3. Crack-free thicknesses for AlGaN films grown with various buffer layers.

1.48 µm (σ=0.46%). Over longer timeframes (~45 runs over 6 weeks), AlGaN composition for a set of basic HEMT runs was maintained at 30% with σ=0.5%. In addition, the uniformity and repeatability of both the composition and thickness of the AlGaN barrier layer is critical for creating constant HEMT performance. Figure 2 shows composition and thickness maps of a reference, quasi-bulk AlGaN layer grown on a sapphire substrate.

To further the development of HEMTs, Emcore has entered a partnership with Cornell University, wherein Cornell processes submitted epiwafers into complete HEMT devices for evaluation. Through this collaboration, GaN HEMT device results on SiC (0.2 µm gates) show excellent DC and RF characteristics, with I_{max} >1 A/mm, P_{out} >7 W/mm at ~50% PAE (10 GHz), f_t >80 GHz, f_{max} >110 GHz. Devices on silicon also show encouraging DC results, with early devices having I_{max} >600 mA/mm and a breakdown voltage >–50 V, with good pinch-off characteristics.

The challenge of UV optoelectronics

In addition to HEMTs, significant work is being carried out on two different sets of AlGaN-based UV optoelectronic devices: UV LEDs and solar-blind/visible-blind detectors. Based on the results of these studies, insight into the growth of high Al-content materials is being transferred to production-scale reactors, as with the HEMT examples described previously. This parallels the development path of HB-LEDs, which are already in true mass production. In this discipline, GELcore (a joint venture between Emcore and GE Lighting) has developed 405 nm LEDs for solid-state lighting, with current results showing output power of 110 mW at 350 mA for packaged 1 × 1 mm^2 flip-chip die. For the purposes of this article, the focus will remain on higher Al-content materials, which is the more challenging area of research.

UV emitters over a range of wavelengths have attracted great interest for bio-applications and solid-state lighting products. High Al concentrations are critical for practical device applications in the UV spectrum, with increasing levels of Al required as the emission wavelength is pushed down. Surface cracking is a serious obstacle for AlGaN growth on traditional low-temperature (LT) GaN nucleation layers. A buffer engineering technique is used to achieve bulk crack-free AlGaN with high Al composition. The layer sequence required to produce the maximum crack-free thickness of AlGaN using various buffers is shown in figure 3. A cracked surface was observed using optical microscopy for 0.3 µm $Al_xGa_{1-x}N$ grown on an LT GaN nucleation layer when x>0.3. However, $Al_xGa_{1-x}N$ grown on an LT AlN nucleation layer has smooth, crack-free surfaces with thickness up to 0.3 µm and x as high as 0.6. Introducing an additional HT AlN buffer layer on the LT AlN nucleation layer, the crack-free thickness for AlGaN film was increased up to 1 µm for high Al mole fractions. By adding an additional short period AlGaN/AlN superlattice buffer, the crack-free thickness for AlGaN films can be more than 1 µm.

For UV LEDs emitting at 340 nm and visible-blind photodetector applications, a highly Si-doped AlGaN layer with approximately 30–40% Al is required, and for UV LEDs at 280 nm and solar-blind detector applications, up to 60% Al is required. Due to the increase of the ionization energy with the increase of Al concentration and the solubility limit of the Si dopant, it is difficult to achieve highly conductive n-type AlGaN with an Al concentration higher than 40%. Using a Si and In co-doping technique combined with buffer engineering technology, highly conductive n-type doped AlGaN with a high Al concentration has been achieved. Figure 4 shows the dependence of room temperature Hall carrier concentration and mobility of Si-doped AlGaN on Al concentration for AlGaN samples. A high n-type doping level of ~3 × 10^{18}/cm^3 can be achieved for $Al_xGa_{1-x}N$ with an x of up to 0.6. The mobility decreases with the increase of Al composition due to the increase of electron effective mass and scattering center density. For AlGaN with x~0.6, a carrier concentration of ~3 × 10^{18}/cm^3 with a high mobility of ~25cm^2/Vs was observed.

UV photodetectors have numerous potential applications, including flame detection, biological sensing and missile tracking. Since solar-blind detectors operate at wavelengths of 260–280 nm, a structure consisting of a conductive window layer of 60% n-AlGaN and an absorption layer of 45% AlGaN is appropriate. Using a production-level MOCVD tool, Emcore has successfully grown *pin* solar-blind detector structures achieving an external quantum efficiency of 25% at zero bias and 38% at –5 V bias in a truly solar-blind spectrum range of 255–280 nm. Visible-blind AlGaN-based *pin* photodetectors consist of AlN-based buffer layers, an n-type doped $Al_{0.4}Ga_{0.6}N$ conductive window layer, an undoped $Al_{0.25}Ga_{0.75}N$ absorber layer, p-type doped $Al_{0.25}Ga_{0.75}N$,

and GaN layers. Good I-V curves with very low reverse-bias leakage currents and high zero-bias resistances were measured for all *pin* structures. The dark current is constant up to –10 V at low 10^{-12} A. The zero-bias resistance (R_0) is greater than $1 \times 10^{14}\ \Omega$ for a junction area of ~0.05 mm^2, giving an R_0A product of $>5 \times 10^{10}\ \Omega cm^2$. The photocurrent is nearly independent of bias voltage around V = 0. The external quantum efficiency of the device at a peak wavelength of ~310 nm is ~27% at zero bias and 51% at –10 V bias. These results are similar to the best reported values for AlGaN-based photodiodes (Lambert *et al.*).

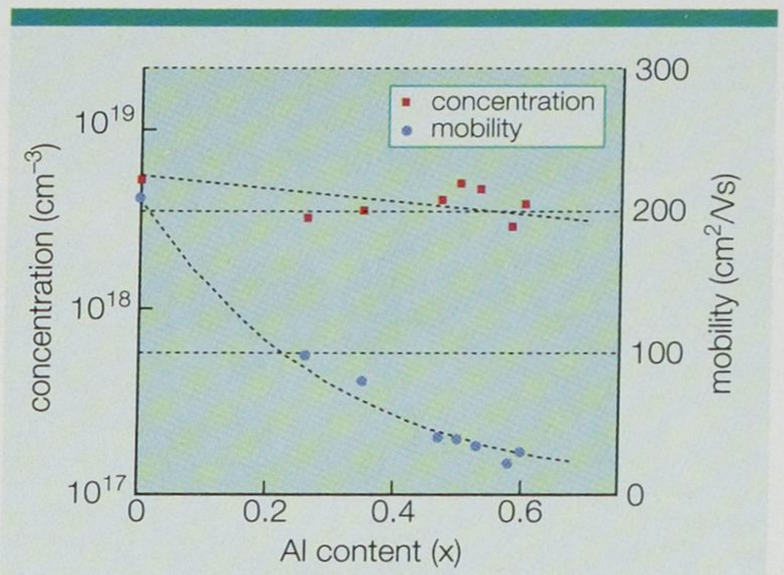


Fig. 4. High carrier concentration and mobility of Si-doped AlGaN as a function of Al concentration at room temperature.

Conclusions

By exploiting the latest advances in high-volume MOCVD production technology, research teams are positioning the industry to fulfill future demands for complex AlGaN-based devices. Working in conjunction with equipment designers, scientists are perfecting deposition methods that will lower production costs to the range where viable products can be introduced to the market.

Preliminary work with high Al-content materials has produced encouraging results, including consistent repeatability for HEMTs at high volume, crack-free materials on large-area substrates, and the growth of highly doped n-type AlGaN at 60% Al.

Acknowledgments

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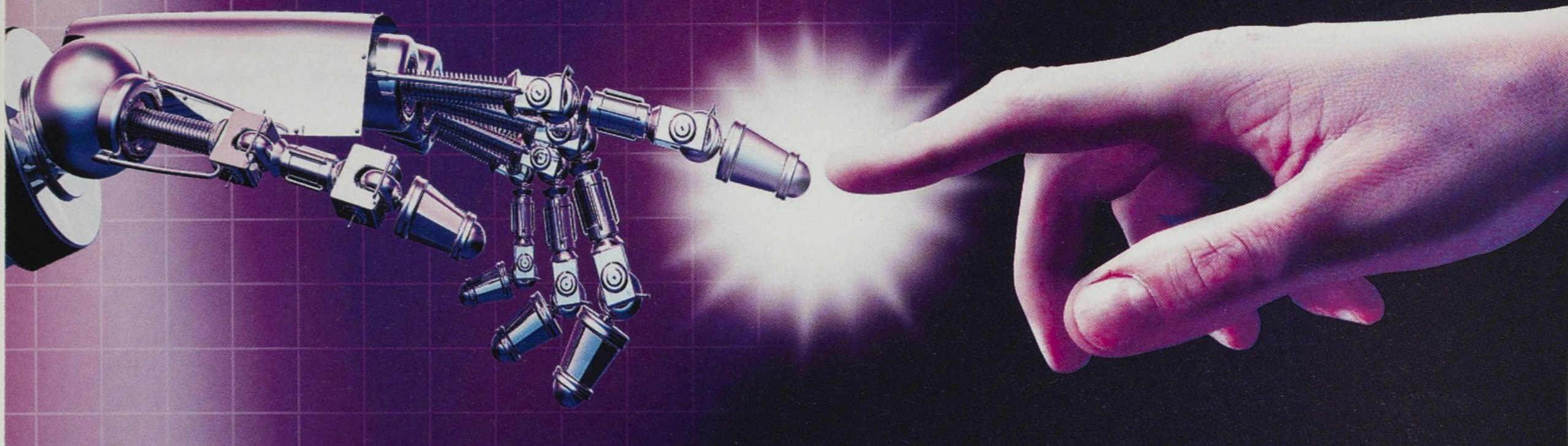
Further reading

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Pyrometry and reflectance techniques provide *in situ* control for GaN growth

Emissivity-corrected pyrometry in conjunction with spectroscopic reflectance can improve the reproducibility and efficiency of GaN epitaxy, according to **Kolja Haberland** and colleagues.

Even more so than conventional III-V epitaxy, the growth of GaN remains challenging. Several different techniques have been developed to cope with the massive lattice mismatch between the substrate – usually sapphire, SiC or silicon – and the epilayer; these include nitridation and nucleation, epitaxial lateral overgrowth, and masking with SiO_2.

In no other growth process does the quality of the final layers depend so much on the initial epitaxial steps. In addition, the nucleation step turns out to be extremely temperature-sensitive. In contrast to other material systems, optical *in situ* studies of GaN growth have been indispensable in improving material quality, optimizing surface roughness and obtaining run-to-run reproducibility.

One of the parameters most critical to control for all epitaxial growth processes is the temperature. However, measuring the susceptor temperature using only a thermocouple or light pipe from the backside is not sufficient, since there is usually a significant offset between wafer and susceptor temperature. Furthermore, the size of this offset is not a constant value but depends, for example, on wall or ceiling depositions, type of substrate wafer and susceptor coating. Thus, there is a strong need for tight control of the wafer temperature, which can only be done by emissivity-corrected pyrometry of the wafer.

In addition to pyrometry, single-wavelength or fully spectroscopic reflectance measurements are widely used for GaN growth in order to characterize the growing layers in real time (*Compound Semiconductor* June 2002 p41). The reflectance data also allows the determination of growth rates or layer thicknesses together with roughness and composition information.

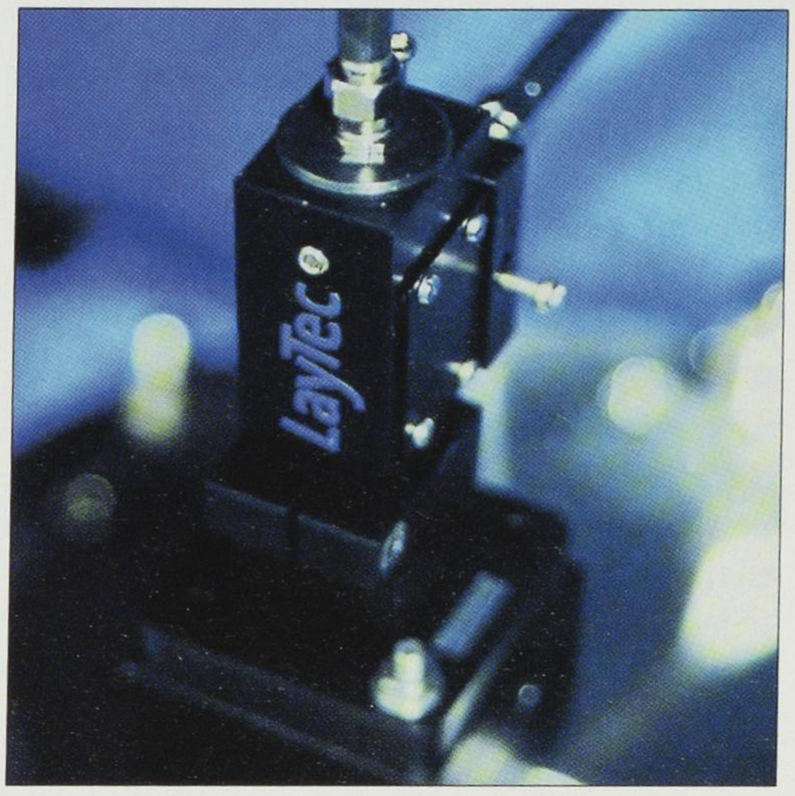


Fig. 1. Optical head of an EpiTT sensor.

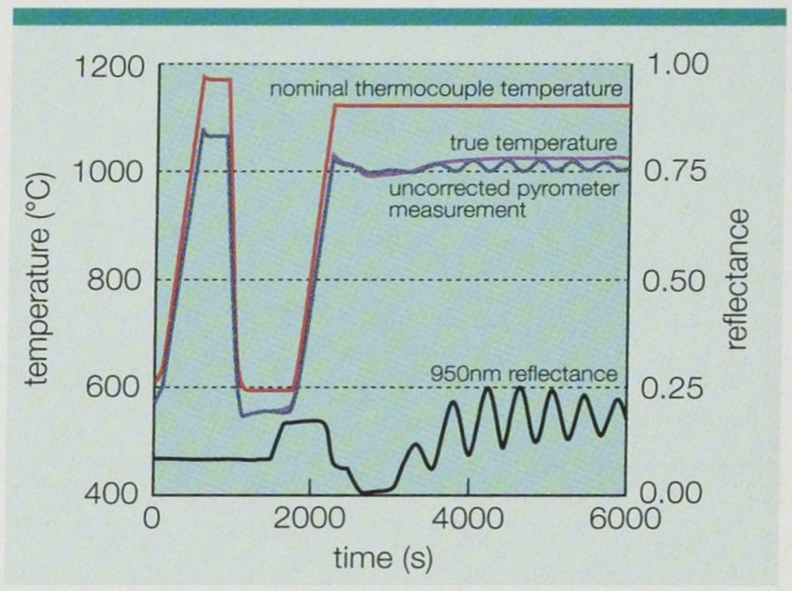


Fig. 2. Temperature measurement during GaN buffer layer growth. The offset between the nominal thermocouple temperature and the non-oscillating true temperature can be clearly seen.

Emissivity-corrected pyrometry

Direct pyrometry of the wafer from the top is the method of choice in determining the true wafer temperature. This can easily be applied when, for instance, GaN is grown on an opaque substrate such as silicon. For transparent substrates such as sapphire or SiC, at least the temperature of the susceptor surface directly beneath the wafer can be measured.

Calibrated sensors such as LayTec's EpiTT (figure 1) or EpiR TT systems can measure the temperature with an accuracy of better than 1 K and an r.m.s. noise of less than 0.2 K. With a special (patent pending) calibration procedure, the true wafer temperature can also be determined on transparent substrates.

Things get more complicated during heteroepitaxy when the emissivity of the material changes with time during growth. In consequence, the measured pyrometry signal starts to oscillate with the same period as the Fabry–Perot oscillations of the simultaneous reflectance measurement (figure 2). Maintaining high accuracy of the temperature measurement during heteroepitaxy requires compensation for changes in reflectivity, using emissivity-corrected pyrometry. EpiTT or comparable systems can perform a simultaneous reflectance measurement at the pyrometry wavelength. By detecting the changing reflectance, the emissivity of the growing material can be determined in real time and thus the temperature measurement can be corrected to its true value. In figure 2, the offset between true temperature and nominal temperature at 1200 °C is around 100 K. Depending on the viewport geometry of the MOCVD reactor, the temperature range of 400–1400 °C can be assessed with a typical accuracy of better than 1 K.

Wafer-selective measurements

In multiwafer systems the true wafer temperature is measured for each wafer separately. This allows wafer-to-wafer reproducibility checks and can also be used to optimize sus-

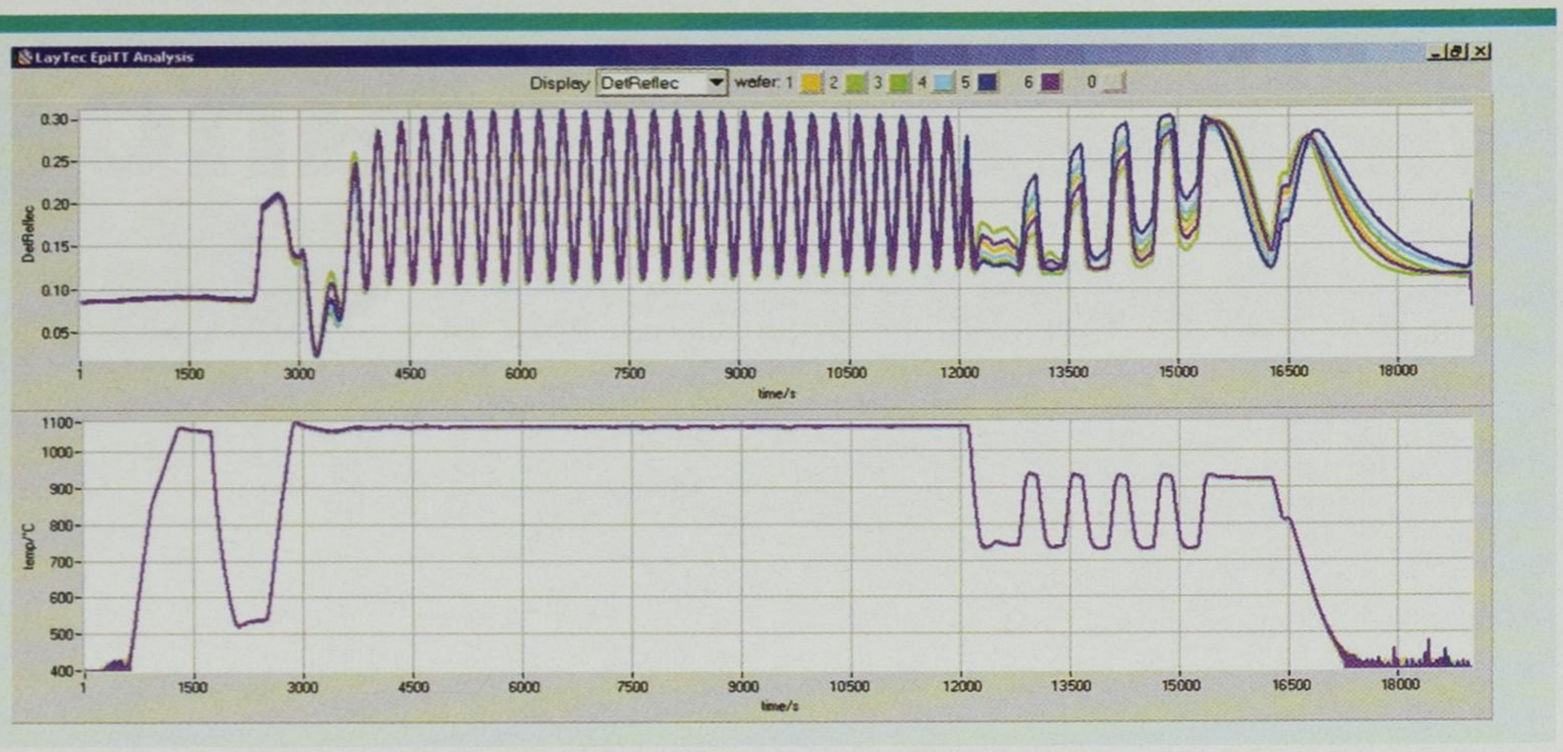


Fig. 3. Reflectance measurements at 635 nm (top) and true temperature (bottom) on six wafers during growth of GaN buffer layers and quantum wells.

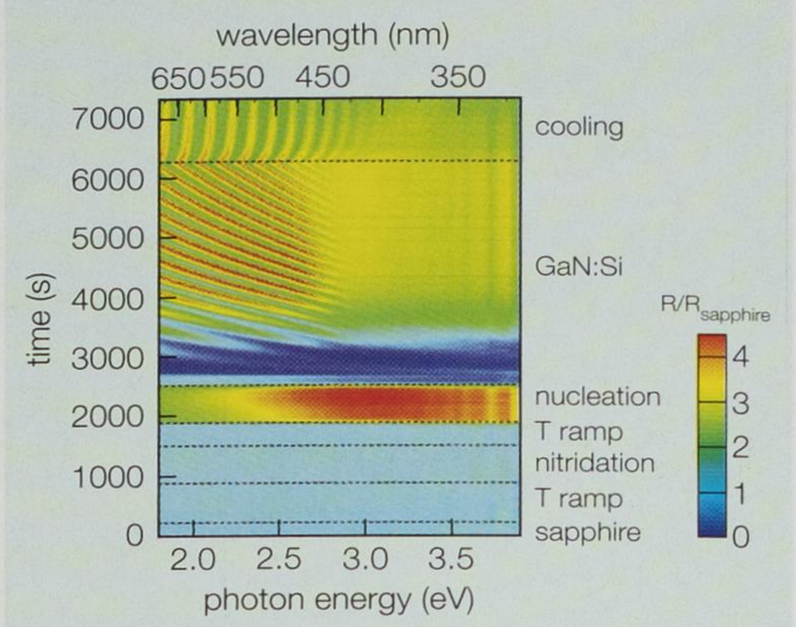


Fig. 4. Color plot of GaN buffer growth showing the nucleation phase and subsequent Fabry–Perot oscillations.

ceptor temperature uniformity. Monitoring pocket-to-pocket temperature differences is also essential for assessing compositional variations in quantum well (QW) growth.

Much more can be learned about the growth if, in addition to infrared pyrometry, reflectance measurements are performed at a shorter wavelength, for example 635 nm. Shorter wavelengths are far more suitable with respect to the band edge of the material and the penetration depth of the light. A shorter wavelength also leads to a shorter period of the Fabry–Perot oscillations during growth, which enhances the accuracy of any growth-rate fit.

Figure 3 shows data recorded during the growth of a GaN buffer and five subsequent InGaN QWs on a set of six wafers in a Thomas Swan Scientific Equipment CCS reactor. The wafer-to-wafer temperature variations (bottom graph) are very small (< 1K) and only small wafer-to-wafer differences in the reflectance signal (top graph) can be seen. These variations are due to slightly different nucleation processes.

The measurements shown in figure 3 are perfectly suited for easy run-to-run and wafer-to-wafer comparison in device production. The reflectance trace allows precise determination of the growth rate. More advanced analysis of the growing layers is possible in multiwafer reactors, when the optical tool allows detection of highly time-resolved data as performed by EpiTT. These data can be used to characterize the reflectance and temperature uniformity of the wafers during all stages of the growth.

Spectroscopic reflectance

For monitoring and optimizing complex multilayered structures such as LEDs, lasers or electronic devices, fully spectroscopic measurements offer significant opportunities. Reflectance spectra covering the whole spectral range from near UV to visible IR (280–750 nm) taken with high temporal resolution during the entire growth process allow simultaneous data analysis at different wavelengths. Taking advantage of the spectroscopic information, it is possible to determine roughness, composition and layer thickness in addition to the growth rate.

Since the data is dependent on time and wavelength, a false-color-coded pseudo-3D display is the most intuitive method of presentation (figure 4). The color plot serves as an overview of the complete growth. In addition, it allows the extraction of time-resolved and spectroscopic data (sections through the color plot) at any time and wavelength. These extracted data can then be used for quantitative analysis and for fitting purposes.

Growth rate

Applying the optical sensors for growth rate calibration purposes is one of their easiest and most useful applications. With advanced virtual layer-fit algorithms, the growth rate of any growing material can be determined, even with unknown compositions or optical properties. The refractive index n and the absorption coefficient k can also be determined in one single fitting procedure using only the substrate properties from an included database.

If the optical constants of the layer to be fitted are known, n and k can be excluded from the fit. A growth rate fit can be performed with high accuracy (usually better than 1%) as soon as one period of oscillations has been measured. As an example, the upper part of figure 6 shows the result of an even more complex fit and illustrates the excellent agreement between measured data and fit result that can be achieved. Surface roughness effects can lead to an attenuation of the Fabry–Perot oscillations. When using LayTec's high-temperature database for the optical constants of GaN, and its advanced post-growth fitting routines, this attenuation can be utilized to determine the roughness of the growing layer. Real-time fits of the growth rate are possible as well if the optical constants of the growing layer are known.

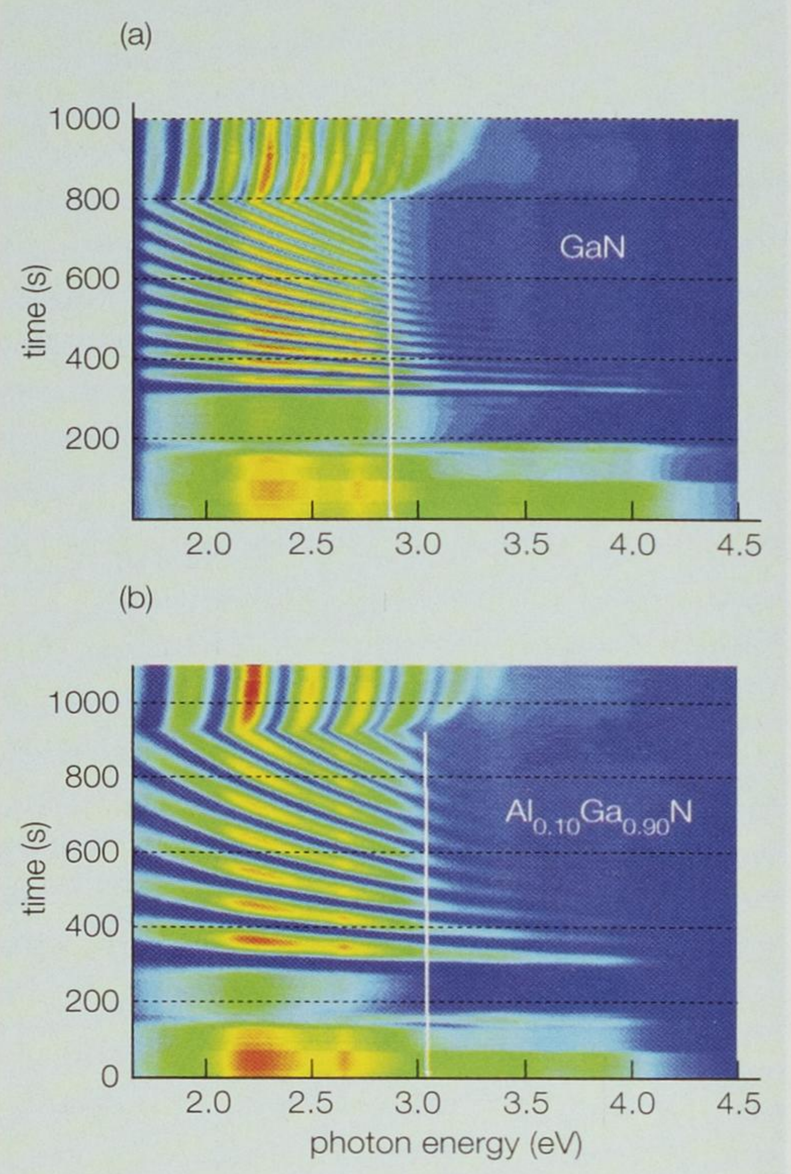


Fig. 5. Color plots of (a) GaN and (b) AlGaN buffer layers, showing composition-related differences in bandgap wavelength.

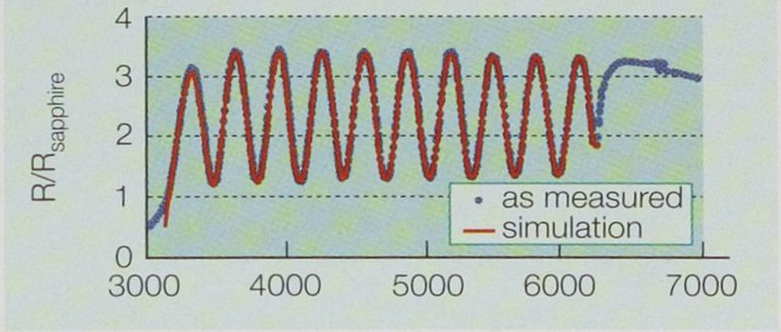


Fig. 6. Time-resolved reflectance measurement at 635 nm extracted from the color plot in figure 4.

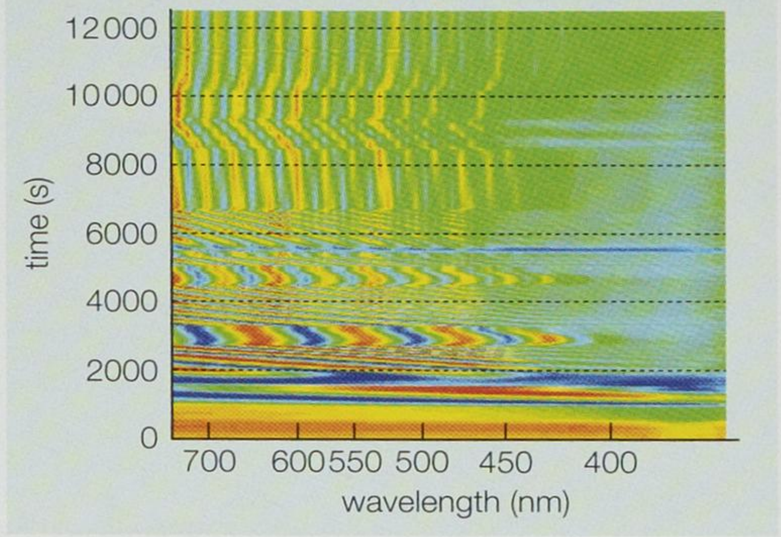


Fig. 7. Color plot of a complete LED structure grown on a silicon substrate.

Composition

The spectroscopic data of the color plots also contain information about the composition of ternary material, as shown in figure 5. The spectral position of the bandgap can be clearly seen by the attenuation of the Fabry–Perot oscillations.

The spectral position of the bandgap for GaN is indicated by the white line in figure 5a, while figure 5b shows the higher bandgap of $Al_{0.1}Ga_{0.9}N$. Hence, the position of the bandgap can be used to determine the composition.

Alternatively, the refractive index determined by the *n-k-r* fit procedure can be correlated with the composition using a spectroscopic and temperature-dependent database. For this, of course, exact knowledge of the true wafer temperature is needed again.

Roughness analysis

For GaN growth the measurement and subsequent optimization of roughness is one of the key issues. In addition to a microscopic roughness in the nanometer range, statistical variations in the optical thickness of the material with domain sizes in the order of microns (so called "waviness") can occur.

From a time-resolved measurement at 635 nm, the growth rate and the roughness and waviness profiles can be determined by a post-growth analysis of the measured data (figure 6).

Device fingerprint measurements

With the knowledge gained from systematic investigations as described above, it is also possible to monitor and analyze even very complex layer structures like optoelectronic devices. In this case the color plot is the optimum way of visualization, since it allows a very simple run-to-run comparison of the whole structure. As an example, figure 7 shows a GaN LED structure grown on a silicon substrate at the University of Magdeburg. Each layer and each temperature ramp can be recognized in the color plot, and deviations between different runs can be easily spotted. In multiwafer systems, a color plot can be generated for each wafer, allowing wafer-to-wafer comparisons.

Summary

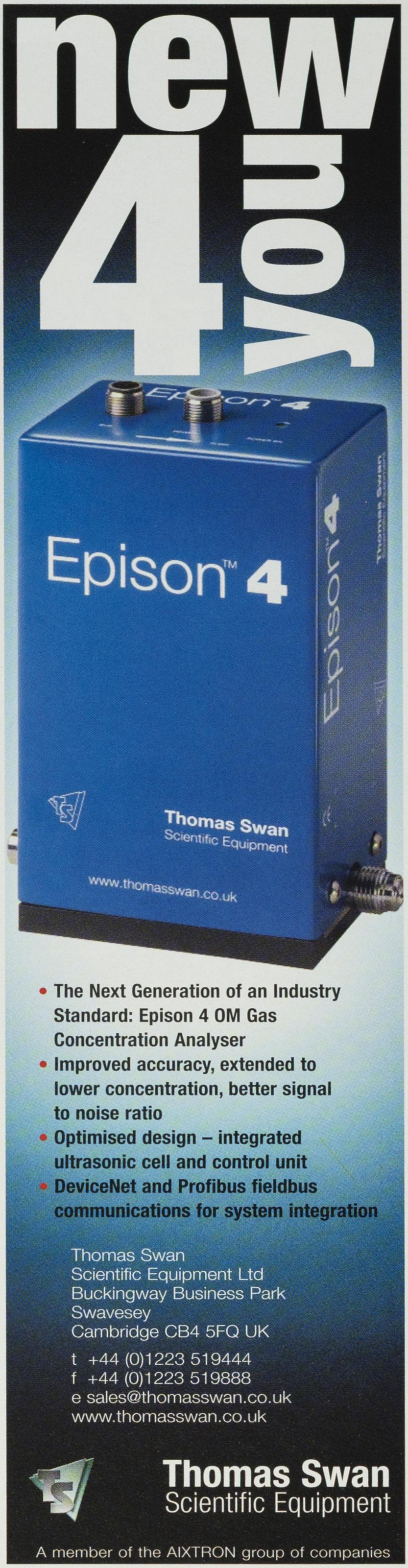
State-of-the-art optical sensors allow the monitoring of growth processes in the GaN material system in virtually any growth environment. The most important parameters detected are the emissivity-corrected true wafer temperature and the reflectance of the growing layer at one suitable wavelength.

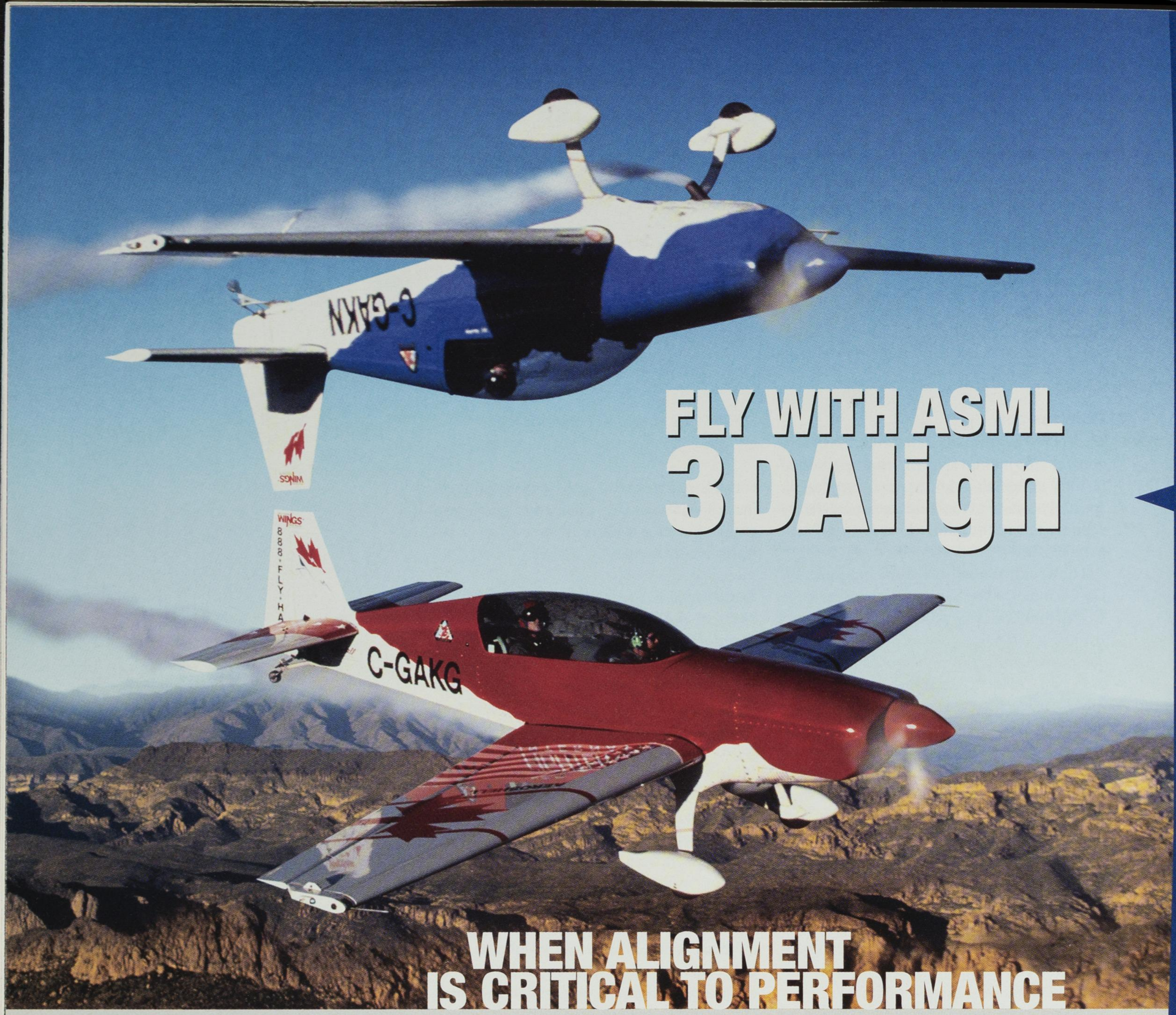
More advanced sensors offer a fully spectroscopic measurement, enhancing the performance and even allowing device growth monitoring. Even in multiwafer systems, all measurements can be performed wafer-selectively to enable not only run-to-run but also wafer-to-wafer comparisons. Through real-time and post-growth analysis, important information like growth rate, roughness, optical constants and composition can be extracted. In the near future the data measured in real time by the *in situ* sensors will be used for feedback control of growth parameters and will further increase the efficiency of MOCVD growth.

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Kolja Haberland (e-mail haberland@laytec.de) is responsible for system integration and customer support at LayTec (www.laytec.de).





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A building block approach to manufacturing monolithic photonic integrated circuits

MetroPhotonics has developed active and passive InP-based components manufactured using the approach of vertical monomode integration, write **Bedwyr Humphreys** and **Adrian O'Donnell**.

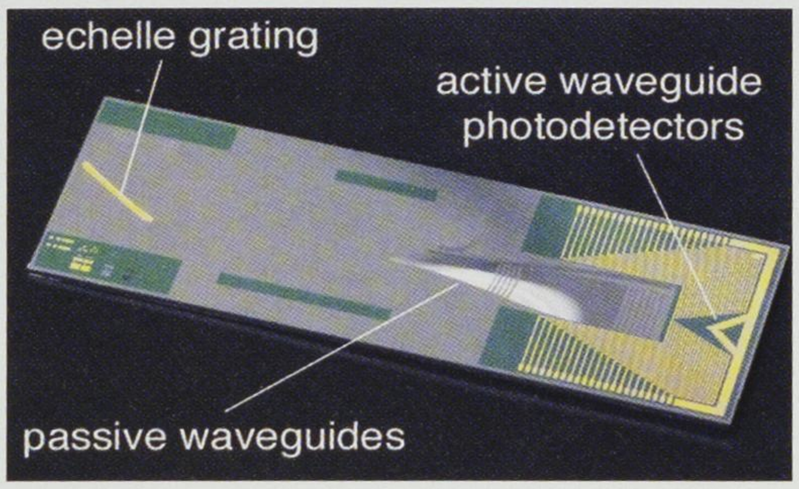


Fig. 1. A fully integrated, 40-channel optical performance monitor.

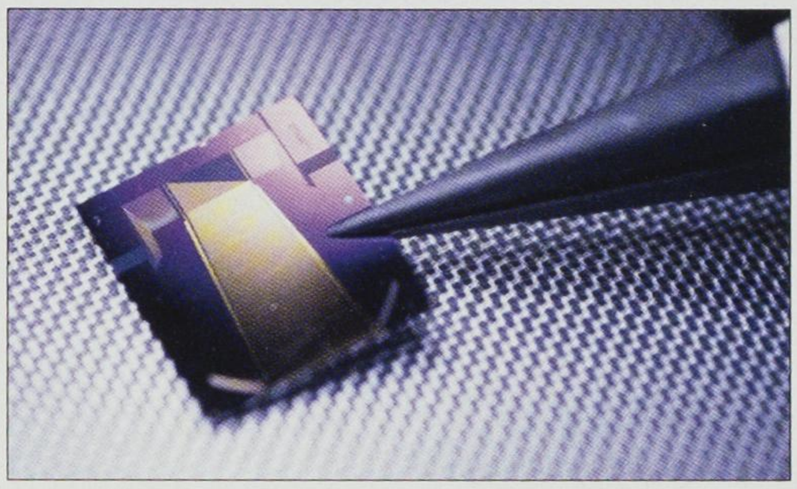


Fig. 2. A fully integrated, 40-channel dynamic channel equalizer.

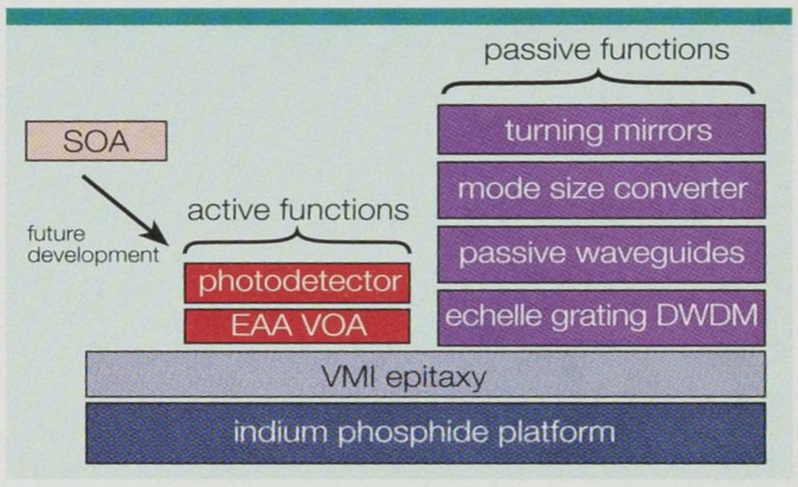


Fig. 3. MetroPhotonics' building block portfolio for PIC design and manufacture.

The demand for lower-cost solutions that provide ever-increasing performance and functionality continues to dominate the optical component landscape. Monolithic integration provides a means for combining multiple functions and devices onto a single chip, enabling orders of magnitude reduction in cost, footprint and power, while at the same time improving overall reliability and performance.

Monolithic integration for DWDM combines separate functions such as (de)multiplexing, monitoring and optical power control on a per-wavelength basis, to produce line-card functionality on a single chip. When an add–drop function is also added to the chip, monolithic integration enables cost-efficient and reliable solutions for bandwidth provisioning in optical networks. Overall, this results in a more flexible, simple and manageable network.

With limited investment in new systems, there is a need to add greater functionality to existing networks through upgrades, for example optical monitoring throughout the network, without increasing incremental costs. Monolithically integrated optical monitors (figure 1) are one example of a fundamental leap to a lower cost curve that changes the entire industry structure, permitting ubiquitous deployment of optical monitors for real-time network monitoring at all optical nodes at a fraction of today's costs.

Component vendors have attempted to meet the demands of system vendors for lower-cost and higher-performance components with hybrid solutions – stitching together multiple discrete components to produce integrated functionality. While this initial level of integration lowers cost to some extent and simplifies design for system vendors, it is a short-term solution that does not significantly address cost and fundamental technology challenges.

In many WDM system components, the incoming multiwavelength signal is demultiplexed, then processed on a per-wavelength basis and, optionally, multiplexed back into a multiwavelength output signal (for example the dynamic channel equalizer in figure 2).

The search for compact and cost-efficient solutions enabling such a functionality has led to the development of monolithically integrated planar components, in which the multiplexer/demultiplexer is a waveguide spectrograph having active devices integrated within its input/output passive waveguides for controlling the optical signals.

The material system of choice for monolithic integration is InP, which allows the design of both the active and passive waveguides for operation in the spectral ranges of interest for WDM systems, such as communication S-, C- and L-bands. Although InP-based waveguide spectrographs, for example those using arrayed waveguide gratings (AWGs) or echelle gratings, have been around for some time, practical realization of these integrated components has been limited due to the absence of a simple and efficient method for integrating the active and passive semiconductor waveguides. This article discusses the building block approach adopted by MetroPhotonics in the design and manufacture of photonic integrated circuits (PICs) that provides a simple and efficient means of integrating active and passive components onto a single chip.

A building block approach

Figure 3 shows the building blocks developed at MetroPhotonics that are used in the design and manufacture of PICs. To date, the building block library consists of passive and active functional elements that can be fabricated on the MetroPhotonics vertical monomode integration (VMI) epitaxy platform. The passive building blocks consist of a multiplexer/demultiplexer function that comprises an echelle grating and polarization compensator, passive shallow waveguide interconnects,

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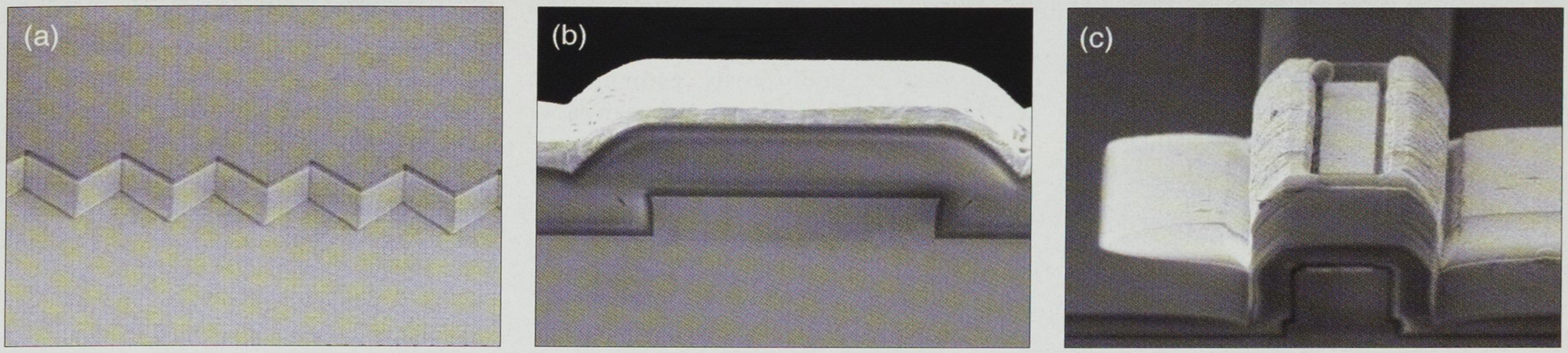


Fig. 4. Various InP-based building blocks fabricated by VMI. (a) An echelle grating for multiplexer/demultiplexer functions. (b) A passive waveguide feature shown with planarization dielectric. (c) An active waveguide feature shown with metal interconnect track.

turning mirrors and mode size converters. The active building blocks consist of a *pin* photodetector for optical monitoring and/or an electroabsorption attenuator (EAA)-based variable optical attenuator (VOA) for dynamic channel equalization. In addition to these basic active elements, it may be possible to include a semiconductor optical amplifier (SOA) as part of the building block library, thus providing optical amplification on a per-channel basis. Such a building block element forms part of a future product roadmap at MetroPhotonics, which addresses gain and optical switching elements.

Examples of the building blocks used are shown in figure 4. Adopting a building block approach provides a means to create a library of design and fabrication components that can easily be rearranged on the chip to create any number of different components. Such an approach dramatically reduces new product development cycles and time to market, as well as providing a continuous history of reliability data associated with the overall technology, thus limiting the additional reliability qualification typically required during the introduction of a new product.

Semiconductor manufacturing

Monolithic integration of components on InP-based platforms has existed in R&D laboratories for many years. However, the successful commercialization of fully integrated active and passive devices has always been frustrated by the historically low yields associated with complex InP-based fabrication.

To combat this issue, MetroPhotonics designs and fabricates all devices with a single epitaxial growth, thus eliminating the well known yield-busting regrowth step. In addition, all wafer fabrication processes have been migrated to stepper lithography to further eliminate the wafer breakages associated with contact lithography. Simply implementing these two approaches provides a significant yield enhancement and cost reduction.

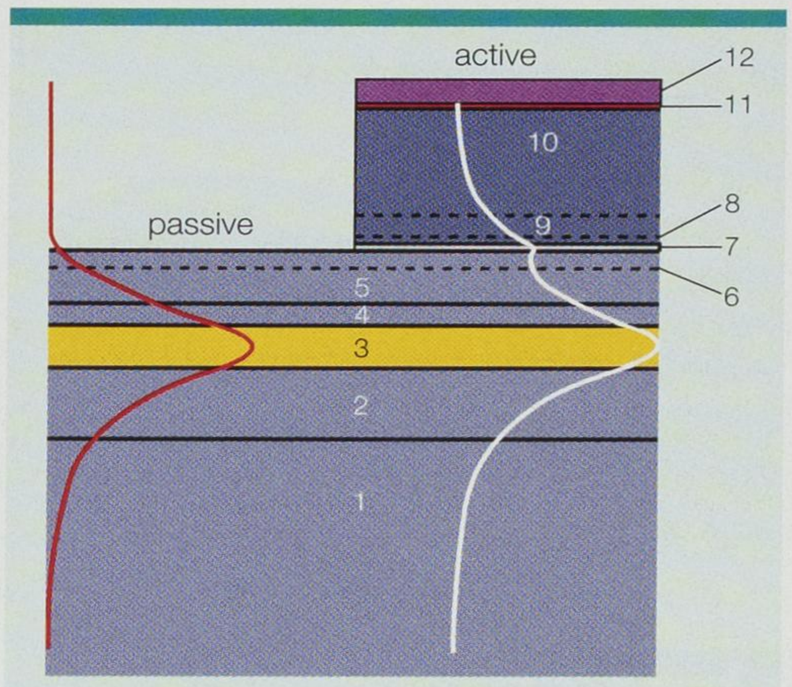


Fig. 5. Layer structure and TE_0 mode profile in the passive (left) and active (right) waveguide portions. Layers are: (1) InP substrate; (2) InP buffer; (3) GaInAsP core; (4) lower portion of InP cladding; (5) upper portion of InP cladding; (6) InP n-layer; (7) active layer; (8–10) InP p-layers; (11) GaInAs cap; and (12) p-contact metallization layer. The substrate, layers 2–5 and 7 are all undoped. Layers 6 and 8–11 are n- and p-doped, respectively, such that the level of p-doping rises from negligible in layer 8 (immediately above the active layer) to a very high level in layer 11 (just below the p-contact metallization layer 12).

The single epitaxial growth approach to monolithic integration, VMI with patents pending, is explained in figure 5, which shows the layer structures and vertical mode profiles in the passive and active waveguide portions of a monolithically integrated device. The entire structure is grown in a single epitaxial growth run. Subsequently, layers 7–11 are etched from all areas except in the active waveguide portion where they form a *pin* structure. Output/input waveguides of the planar demultiplexer/multiplexer are processed in the form of ridges physically separating the individual wavelength channels, such that the p-contact is placed on the top of each active ridge portion. The n-contacts are placed on the top surface of layer 6, at the end of the active ridge portion.

The material composition, strain and thickness of the active layer (7), positioned within the i-region of the *pin* structure, are chosen on the basis of device application, so that the bandgap is adjusted to the operational photon energy in some predetermined way. In any event, this layer has the narrowest bandgap energy as compared with the other layers.

The VMI method may seem similar to an evanescent-field coupling technique, but there is a fundamental difference between the two. A standard scheme of evanescent-field coupling implies that there is at least one more mode in the active waveguide portion, with the field maximum within the active layer. The scheme relies on a transfer of the only mode of the passive waveguide portion into this higher mode of the active waveguide portion. On the contrary, VMI implies that there is only one mode (in either TE or TM polarization) in the active waveguide portion, which substantially matches the only mode in the passive waveguide portion. As a result, coupling between the active and passive waveguide portions is stable and very efficient.

Wafer fabrication

In much the same way that integration in the silicon semiconductor IC industry has reduced the cost per megabyte, photonic integration will drive down the cost per bit transmitted, while at the same time increasing functionality. Automation, wafer size, yield, volume and design for manufacture have been key drivers to cost reduction in the silicon industry, and the same is true for photonics.

Lessons learnt during the pioneering years of wafer fab manufacturing are being exploited

in the photonics industry with the added benefit of being able to pick and choose the proven and established techniques such as design for manufacture, FMEA and statistical process control (*Compound Semiconductor* November 2002 p67). Additionally, the parallels between the silicon and photonics industries are such that much of the semiconductor processing equipment used in the silicon industry can be used in photonics, with the added benefit of being able to use proven technology.

The need to drive down costs makes yield the main focus for many PIC manufacturers. Yield issues in fabs can be minimized through the use of techniques such as reducing physical handling of wafers and adopting established process control techniques from the silicon industry.

The historical barriers to volume deployment of monolithic PICs are thus being eroded as a result of innovative and robust techniques that enable significant cost-per-chip reductions, while increasing on-chip functionality. Even though much of the focus on monolithic PIC manufacture has historically been on the wafer fabrication side, the majority of the cost of the finished product derives from the packaging and assembly costs, estimated at 60–80% of the final unit cost. Although packaging is an area where the potential cost savings are huge, manufacturers must first embrace standardization along with increasing levels of automation. There should be a focus on creating "IP on chip", such as mode size converters that allow the use of standardized packaging materials and fiber-attach technologies. Adopting a building block approach has allowed MetroPhotonics to follow that path of increasing "IP on chip", while still maintaining a relatively simple design and manufacturing philosophy.

An integrated future

Through using a building block approach to solve a number of monolithic integration issues, MetroPhotonics has developed a technology library that can be applied to the design and fabrication of a wide range of optical components for DWDM applications. This approach is also highly cost-effective when coupled with a single epitaxy approach (VMI) and the use of high-quality non-contact stepper lithography, providing a means to dramatically increase yields that more complex designs philosophies cannot achieve.

Through focusing the building block approach to creating "IP on chip", MetroPhotonics has developed a model for the design and manufacture of PICs that has the potential to revolutionize the optical component industry. Within this new model, strategic supply partnerships and contract manufacturing play a key role in speeding production and development, while allowing MetroPhotonics to focus on the core technology competencies of design and wafer fabrication.

In summary, monolithic photonic integration provides a path towards fundamentally revolutionizing the optical components industry with the potential for redefining the frameworks of strategic competition.

Bedwyr Humphreys is the director of fabrication and Adrian O'Donnell is the CTO at MetroPhotonics Inc, Ottawa, Canada.

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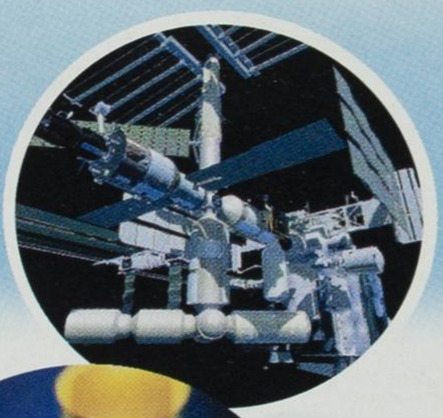
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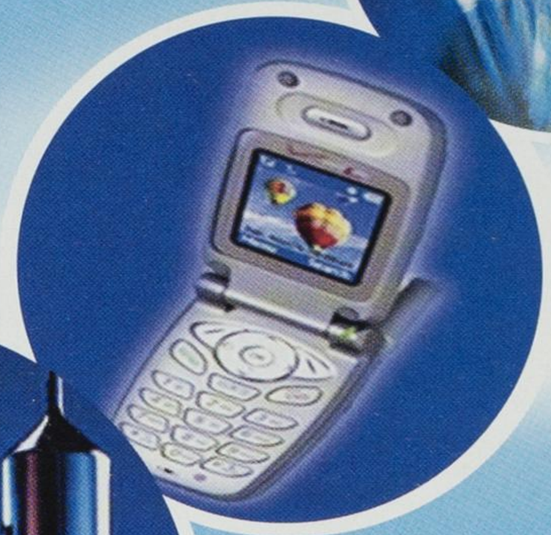
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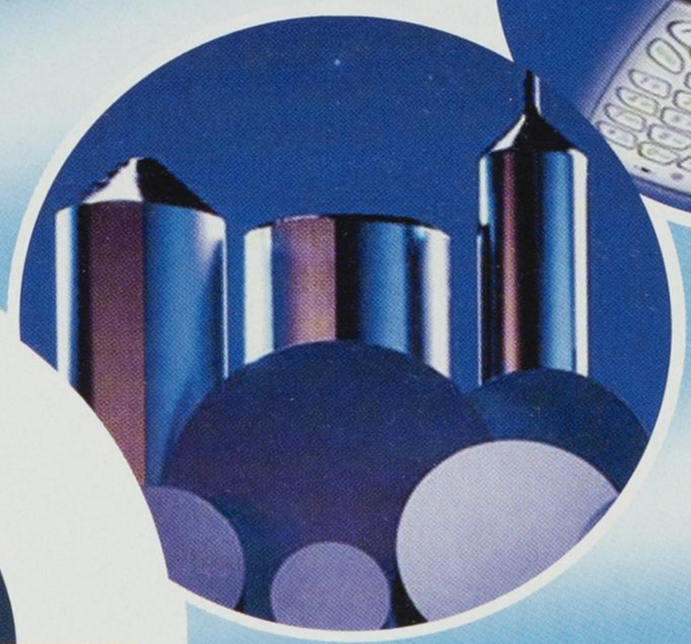
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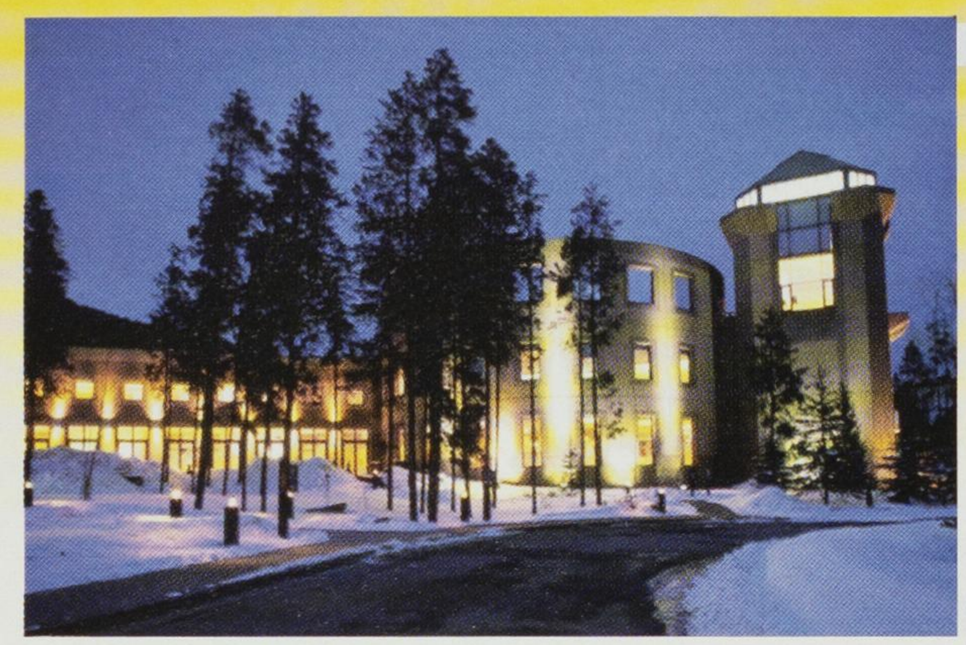
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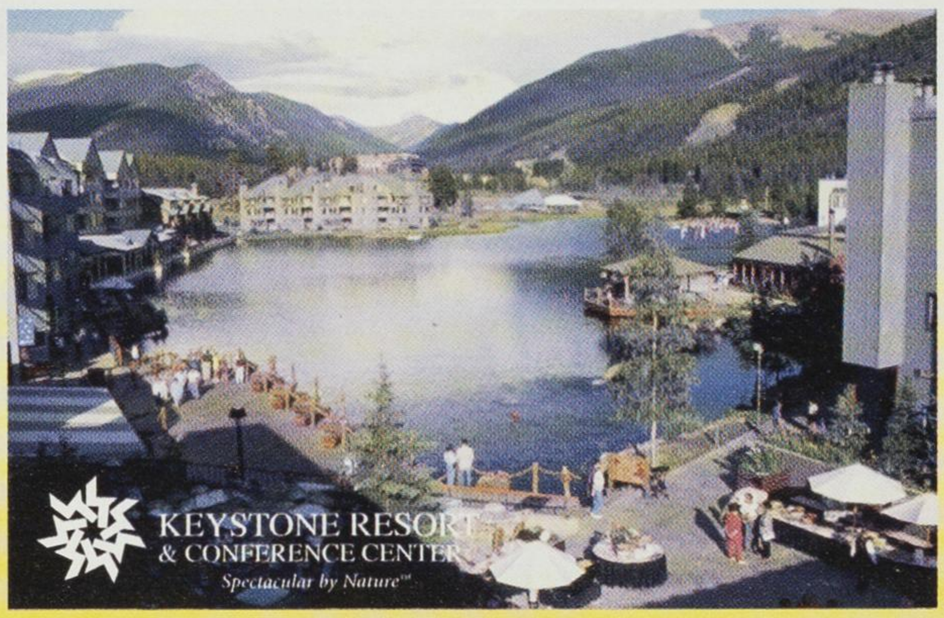
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www.boulder.nist.gov/div815/nambeweb2.html

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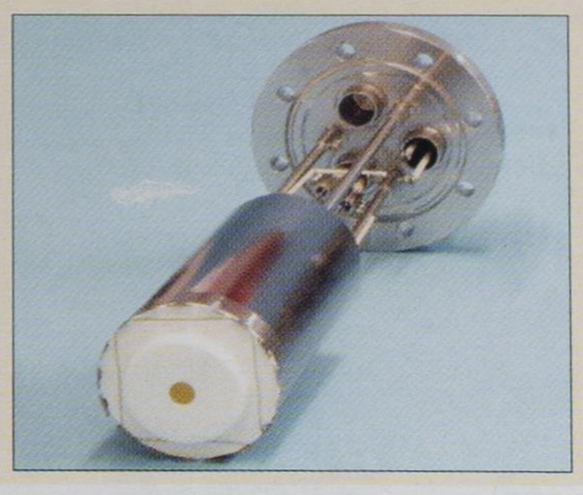


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MBE Phosphorus Source DECO

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The DECO is an ultra-high-purity source producing P_2 by thermal decomposition of GaP. Therefore it has no elemental phosphorus reservoir, and deposition of white phosphorus in the MBE chamber is significantly reduced. Due to the efficient Ga-trapping cap system, the DECO provides effusion cell-like operation and high reliability. The DECO can be used for growth of GaP or InP layers in III-V MBE or for n-doping in Si MBE. Valved DECO systems with larger capacities are also available.



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Integrated CL and EBIC system

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SmartEBIC joins MonoCL3 for an integrated solution to advanced scanning electron microscopy characterization of compound semiconductor materials and devices. With digital beam control sensing signals simultaneously and options for spectrum imaging, powerful software enables simple acquisition and interpretation of quantitative results. The modular systems are suitable for all SEMs and some STEMs, and find applications in core research as well as with devices and failure analysis techniques.

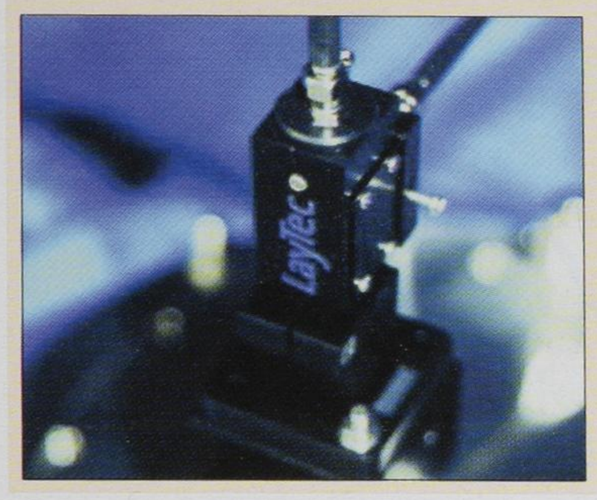


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New *in situ* sensor for GaN production

LayTec GmbH

Through collaboration with Thomas Swan Scientific Equipment, LayTec has developed EpiTT, a new *in situ* monitoring tool. EpiTT has been specifically optimized to monitor multiwafer GaN epitaxial device production. EpiTT combines both double-wavelength reflectance and true temperature measurement. In comparison with competitive systems, EpiTT's optimized reflectance measurement allows for an unbeatable accuracy of growth rate analysis, even for very thick layers. In addition, EpiTT offers an accurate surface temperature measurement (better than ±1 K) – all in real-time and wafer-selective. EpiTT comes in a complete set with an easy-to-adjust optical head, a 19" electronic rack and a control computer.



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In situ Temperature Measurement for GaN Growth

EMCORE Corporation

The RealTemp® 200 provides users with accurate, real-time temperature data that can be used to significantly improve material quality and throughput levels for GaN applications. Temperature and reflectance readings can be plotted for individual wafers as well as averaged over entire runs. Thermal stabilization times after reactor maintenance are minimized. Advanced analysis features include the ability to evaluate growth rates, obtain process fingerprints, and monitor surface morphology. The system is compatible with both sapphire and silicon carbide substrates.

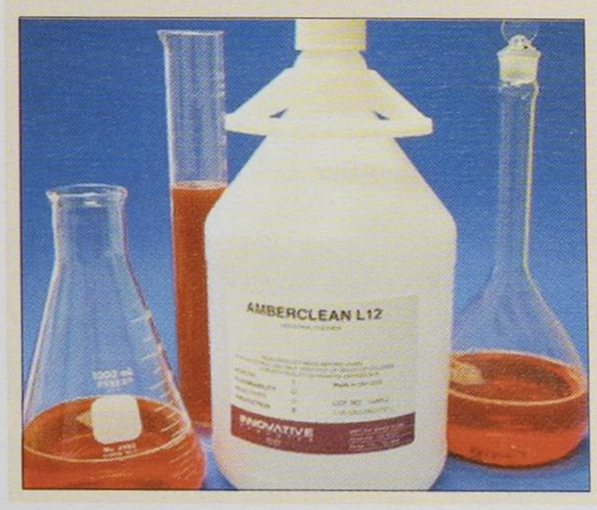


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Innovative Organics' foldout catalog describes water-based coolants, lubricants, abrasive slurries and cleaners for precision materials processing. Products include wire saw vehicles and slurries, grinding and slicing coolants, lapping and polishing slurries and an extensive range of cleaners. Products are designed to be environmentally friendly.



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OMIprobe Epiwafer Characterization

Optical Metrology Innovations Ltd

For HBT, HEMT, VCSEL, LED/RCLED, QWIP and SiGe epiwafer characterization, OMI offers the OMIprobe variable angle photoreflectance spectrometer with 2" to 200 mm wafer mapping. Device-specific parameter extraction is performed by the OMIprobe proprietary lineshape software, including bandgap to a precision of 2 meV, surface and interfacial electric fields, and strain effects on epilayer band structure. OMIprobe is configurable for spectral ranges covering GaAs, InP, SiGe, and GaN based epiwafers.

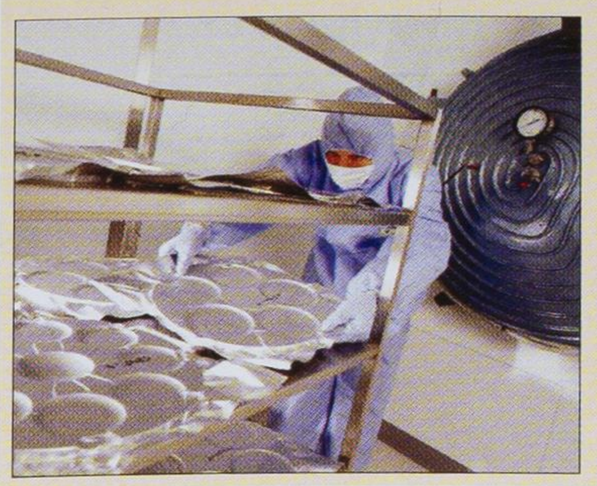


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GaN MOCVD cleaning

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AFTech announce an innovative development from their world-renowned III-V cleaning process. GaN, AlGaN and similar compounds are completely removed from silicon carbide-coated susceptors, quartz and molybdenum. Already, customers around Europe and the UK rely on our fast, strictly confidential and unique service. All parts are additionally degassed, vacuum wrapped and then double packed in a dry nitrogen-filled bag.

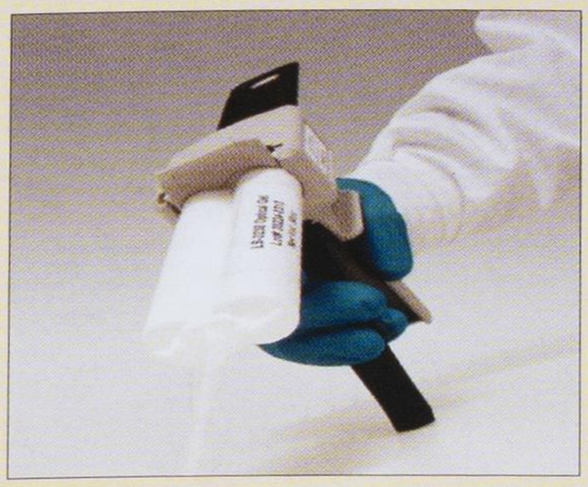


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Clear encapsulants for HB-LEDS

Lightspan, LLC

Lightspan introduces a family of optically clear encapsulation gels and thermosets for protection of display backlights and high-brightness LEDs from thermal stress, vibration, dust and moisture. These advanced materials are crystal-clear and available with refractive index ranging up to 1.57 for improved light extraction from LED dies. Service temperatures range up to +200 °C (+260 °C for 1–2 minutes for soldering operations). Visit our website for detailed product data sheets, application notes, and sample requests.



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Grazing incidence interferometer

Logitech Ltd

Logitech Ltd (ECOC, C5.799 and Photonex, C42) announces the release of the GI30 grazing incidence interferometer for high-precision flatness measurement of ground, lapped and semi-polished surfaces up to 150 mm (6")Ø. Ideal for measuring non-reflective surfaces prior to final polishing, the GI30 uses specially designed interferogram analysis software in conjunction with phase measurement techniques to display precise 3D contour maps of the sample surface.



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Veeco and UCSB enter into MBE collaboration

The University of California Santa Barbara (UCSB) and Veeco Instruments have signed a collaborative agreement whereby UCSB will transfer MBE growth processes for wireless and optical telecommunications devices to Veeco's epitaxial Process Integration Center (PIC). UCSB will demonstrate the growth processes, and will provide Veeco PIC scientists with the recipes required to grow non-proprietary versions of a number of device structures. The devices include carbon-doped InP HBTs, metamorphic HBTs (InAlGaAs), 980 nm edge-emitting lasers, 850 nm VCSELs and InP/InAlGaAsP 1500 nm edge-emitting lasers and VCSELs.

The processes were developed at UCSB on Veeco's single-wafer GEN II R&D systems. The agreement will see PIC scientists transfer the processes to multiwafer GEN200 production systems. Customers for Veeco's production systems will be able to acquire prequalified processes for their new tools.

Veeco sponsors award

In related news, Veeco, in conjunction with the North American Molecular Beam Epitaxy (NAMBE) organization and the International MBE organization, is to sponsor an award for individuals who have influenced the development of MBE technology. NAMBE and International MBE officials will select the winners, who will be presented with a $3000 prize at the annual meetings of both organizations.

NAMBE is now soliciting nominations for the first MBE Innovator Award, to be presented at the NAMBE Conference, which runs from September 29 to October 2, 2003 in Colorado, USA. The deadline for nominations is August 25 and details of the nomination process can be found at the NAMBE website, (www.boulder.nist.gov/div815/nambeweb2).

Industry group initiates health and safety survey

The Compound Semiconductor Forum (CS Forum), which is part of the Semiconductor Environmental, Safety and Health Association (SESHA), has launched an environmental, safety and health (ESH) survey for the compound semiconductor industry. The purpose of the survey is to identify ESH problems that will then be addressed by the CS Forum. The aim is to organize the compound semiconductor community to find better solutions to ESH issues, with the information gathered being disseminated using the forum website and at industry conferences. Interested parties are being encouraged to participate in the survey by visiting www.seshaonline.org/cs-forum/survey.

The CS Forum website offers a means to query members on related health and safety issues, and to post notices. The website has a library of relevant ESH articles, and authors are asked to submit material of general interest.

Suppliers top VLSI satisfaction survey

Several compound semiconductor equipment suppliers have been named in the annual "10 BEST" customer satisfaction survey conducted by VLSI Research. Tegal came top in the Small Suppliers of Wafer Processing Equipment category and also in the Focused Suppliers of Chip Making Equipment category. In the Small Suppliers category, Suss MicroTec was second, Aixtron was fourth, Unaxis Semiconductors was sixth and EV Group was eighth. ASML was third in Large Suppliers of Wafer Processing Equipment, while Accent Optical Technologies was fifth in the Process Diagnostics Equipment category.

In determining the 2003 "10 BEST" winners, VLSI Research distributed more than 40,000 questionnaires in six languages to semiconductor companies worldwide. The double-blind survey reaches about two-thirds of the decision-making managers and engineers within the semiconductor industry.

Respondents were asked to rate suppliers in 13 categories, which included seven measures of equipment performance and six measures of customer service. The equipment performance measures were: cost of ownership, uptime, software, build quality, usable throughput, quality of results, and product performance.

Equipment sales

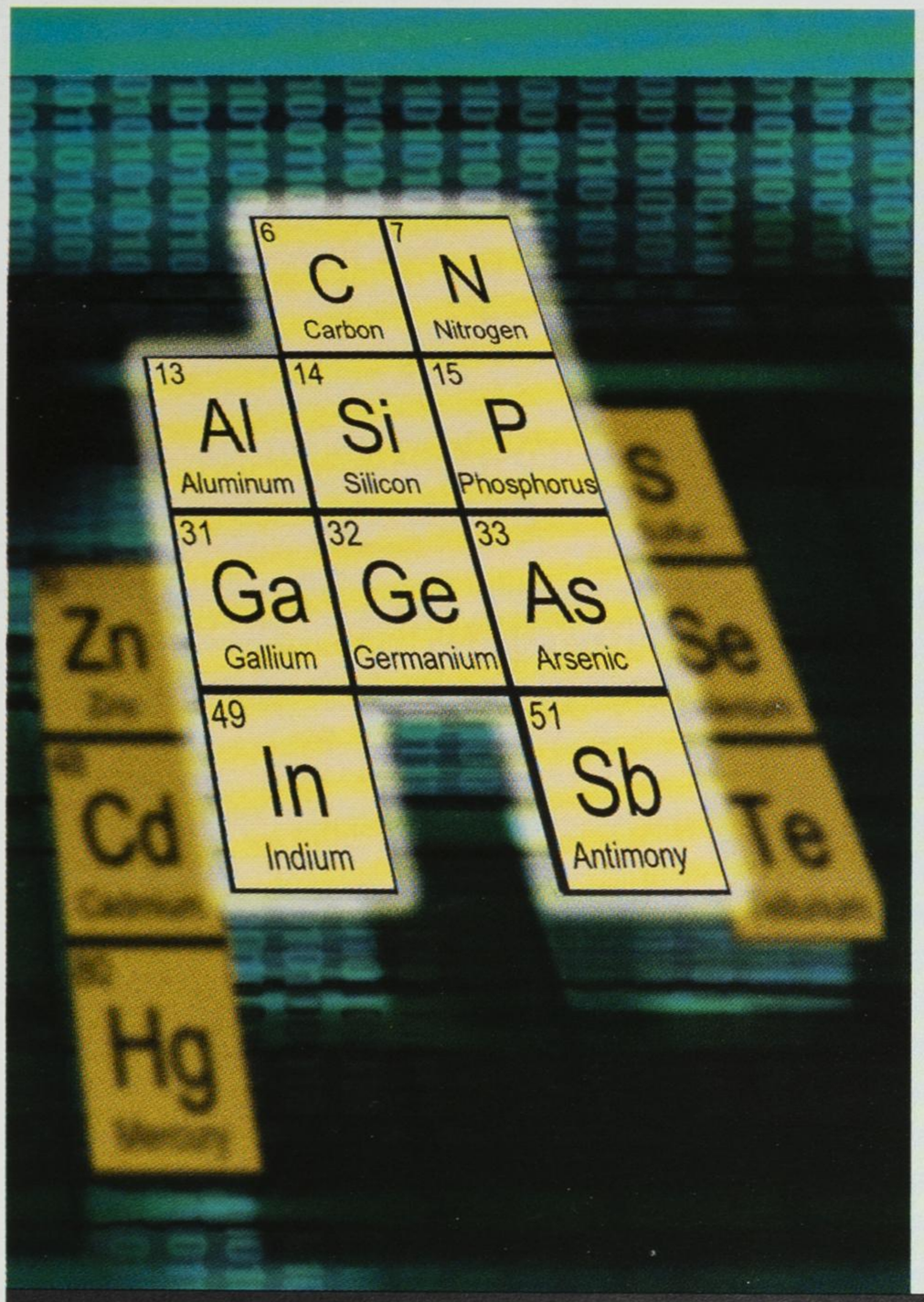
● **Aixtron** has received an order for an AIX 200/4-RF MOCVD system with EpiTune II *in situ* monitoring from the Nano Device Center of the **Korea Institute of Science and Technology** (KIST). The new system will be used for research on materials such as GaInAsN for long-wavelength lasers.

● **The Ioffe Physico-Technical Institute** in St Petersburg, Russia, has purchased Compact 21 T system from **Riber**. The machine will be used for the growth of GaN-based nanostructures for next-generation optical communication and electronic devices.

StratEdge in buyout agreement

StratEdge, a designer and producer of packages for high-speed semiconductors, has reached an agreement for a management buyout of the corporation. The company was previously funded through a venture capital firm and is now privately held through the management buyout group. All key operations staff will be retained at StratEdge's corporate headquarters in San Diego, CA, and at its manufacturing plant in Taunton, MA.

Tim Going, former VP of sales and marketing, becomes the new president of StratEdge, while executive VP John Robichaud will head the international sales effort and operations at Taunton.



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EQUIPMENT

Global Phosphorus Solutions

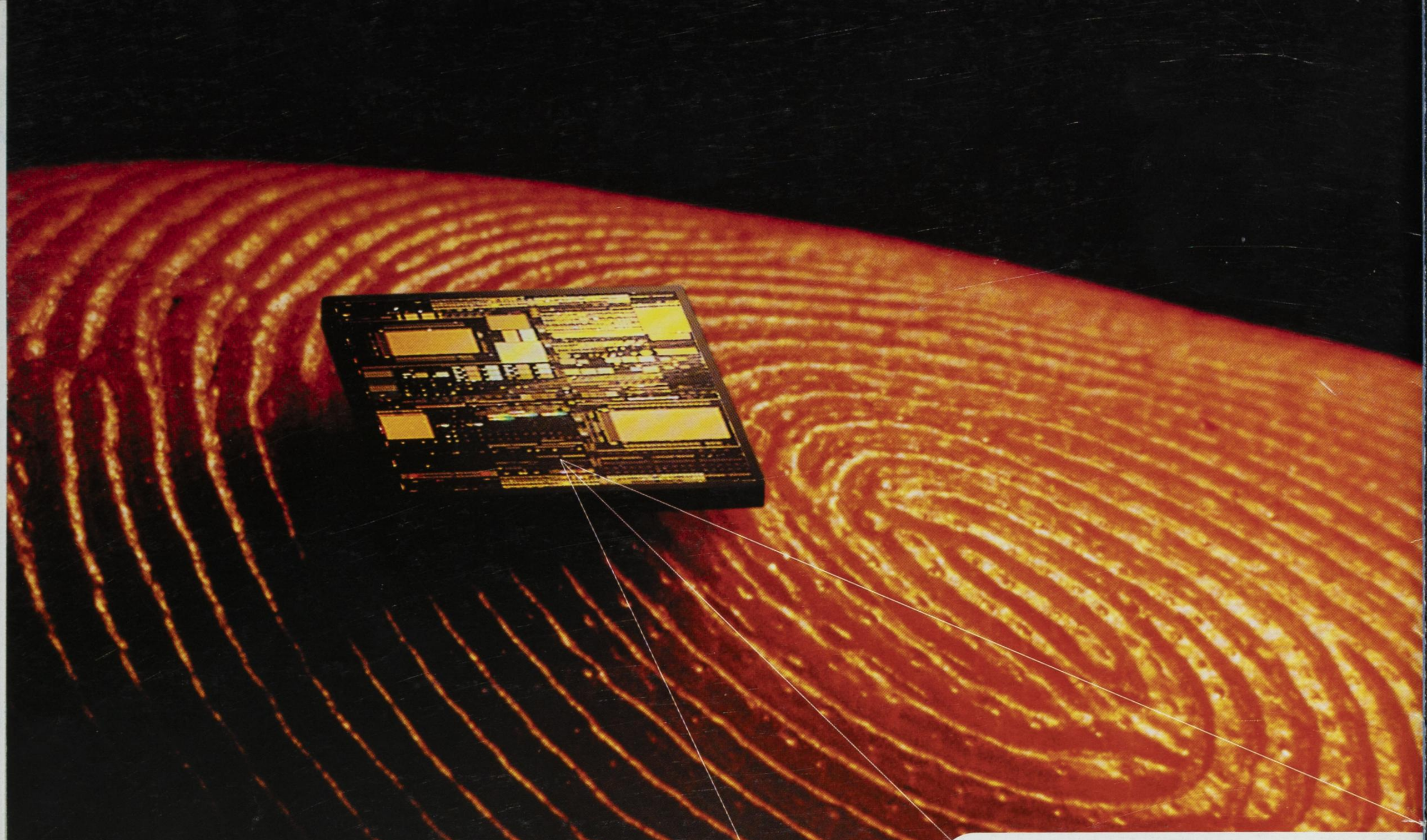
- ***Innovative Reactors***
  In 1982, Riber develops the industry's first phosphorus-dedicated MBE research system.
- ***Patented Phosphorus Sources***
  In 1992, Riber introduces the zero-burst valved phosphorus cracker cell design that is now used by all major component manufacturers.
- ***Full-Service Application Lab***
  In 2002, Riber inaugurates the industry's first indium phosphide application lab to accompany you from start up through full production of phosphorus-containing compound semiconductor materials.

If you want to visit our application laboratory and find out more about our global phosphorus solutions for growth, characterization and maintenance, please contact us today at:

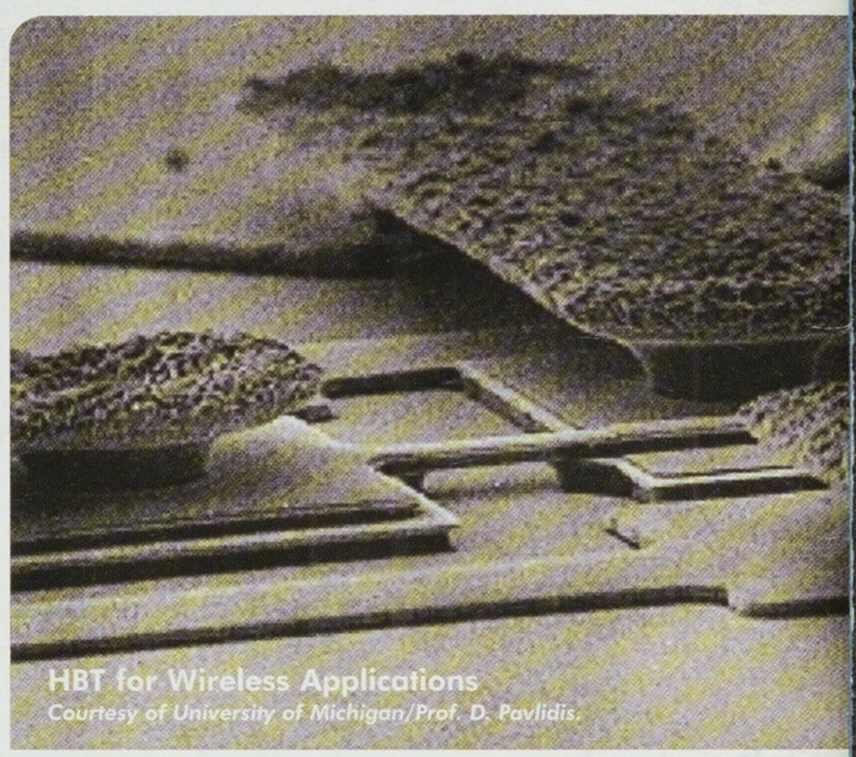
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