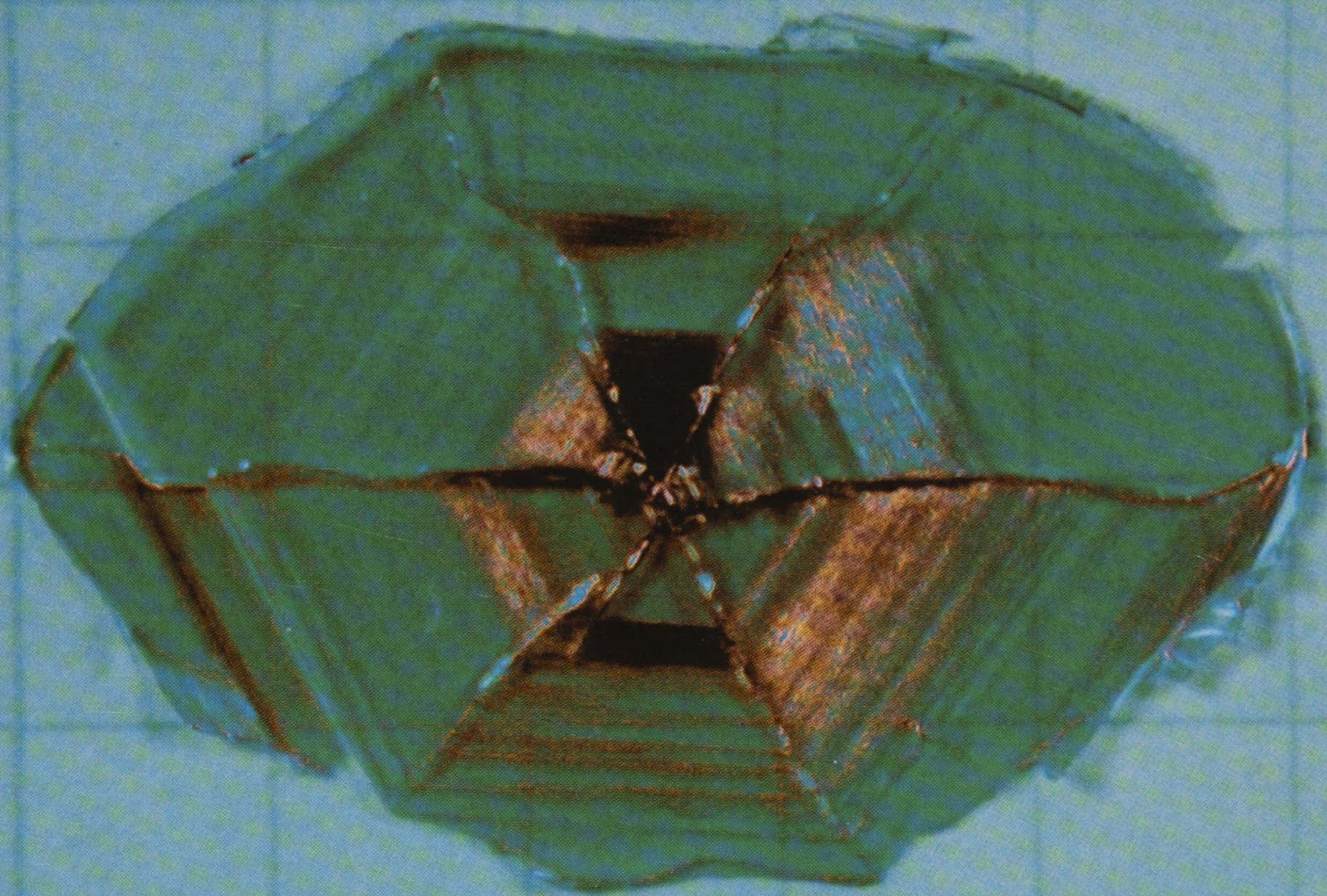
COMPOUND SEMICONDUCTOR

July 2002 Volume 8 Number 6

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WIDE-BANDGAP MATERIALS

Substrates, EU programs and Japan's LED collaboration

ALSO INSIDE

Change in the air at Agilent and Nortel	DARPA funds more research	Positive mood prevails at Mantech

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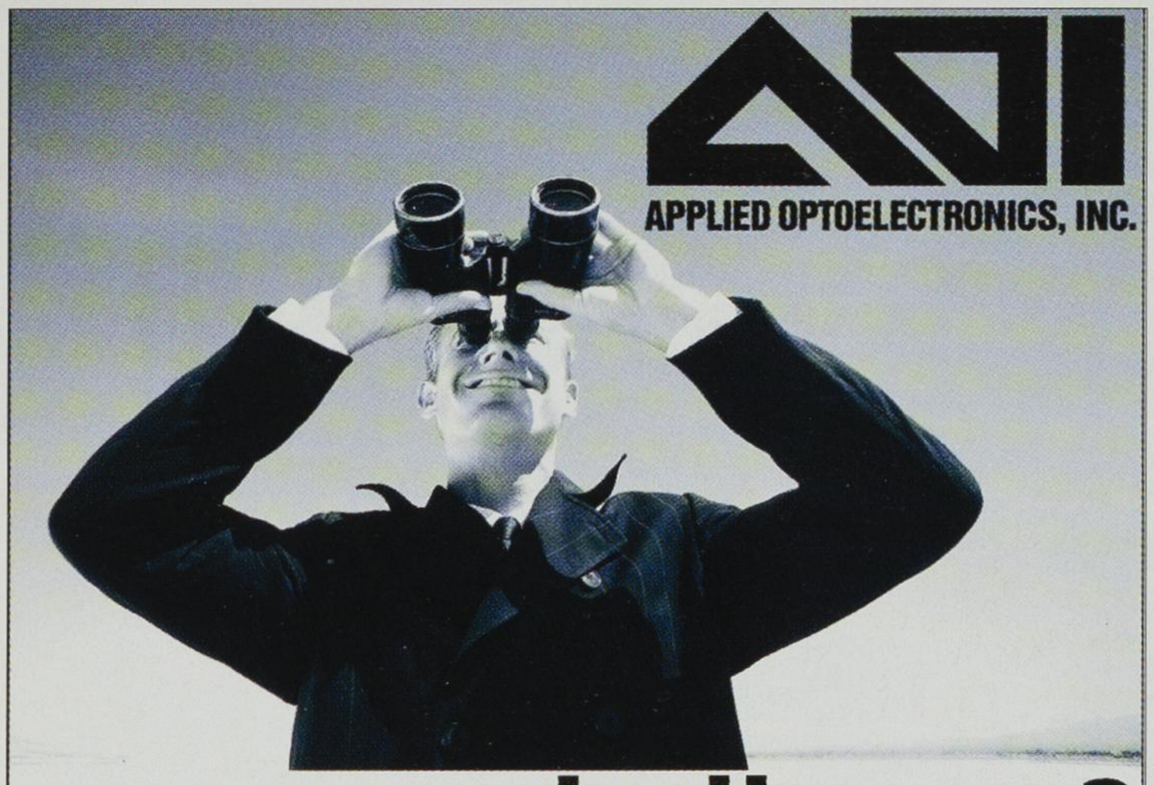
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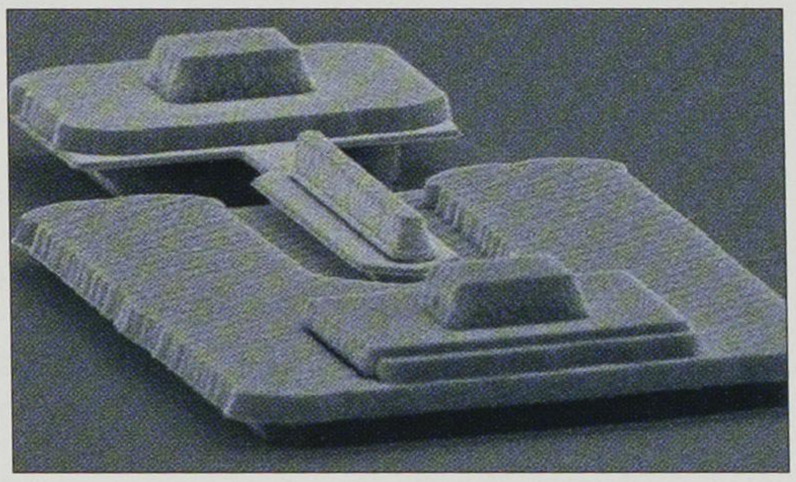
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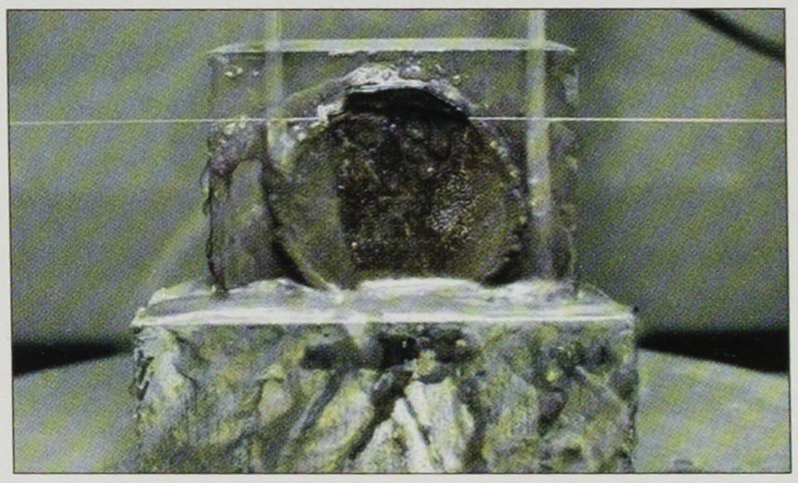
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Aixtron's Tricent tool will be used to develop AmberWave's III-V on silicon technology **p25**



GaAs and InP devices were both discussed at this year's Mantech meeting, held in May **p33**



A GaN boule is sawn into wafers using a diamond wire saw **p45**

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On the cover: *Japan Energy and Yamaguchi University have grown a 25 mm GaN single crystal with a dislocation density of less than $10^5/cm^2$ – see p41.*

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Umicore deal to buy Sterling collapses

Uniroyal Technology has revealed that its agreement to sell Sterling Semiconductor to Umicore USA has collapsed, because of disagreements about forward-looking revenue estimates. Umicore USA, a subsidiary of the Belgian materials company Umicore (formerly known as Union Miniere), announced on April 18 that it had made an agreement to buy the outstanding shares of Sterling for $13 million in cash (see *Compound Semiconductor* June 2002, p4).

Uniroyal did not provide any more information about the reason for the deal's collapse in its press statement, but stated that the company "continues to explore all options to secure necessary financing for its businesses". However, according to a report in the *Sarasota Herald Tribune*, Uniroyal's chief financial officer George Zulanas said that the decision to close the deal followed "a kind of mutual disagreement on forward-looking numbers". He added, "This is not a devastating blow – this is a bump in the road."

Zulanas's comments correspond with those of Marc van Sande, the president of advanced materials at Umicore. Van Sande explained that, owing to Uniroyal's status as a public company, the announcement was made once the sale was agreed in principle, but this occurred before Umicore entered the due-diligence process.

"At Uniroyal we are having the best quarter we have ever had since we've been in the hi-tech arena. What we need is our debtors to stand back and be a little more patient."

"We started the normal due-diligence process after the announcement in April," said van Sande. "While I cannot give details, the outcome was not satisfactory, and as a consequence we stopped the project." Van Sande added that despite the failed deal, Umicore will continue to install a SiC growth facility in Europe as part of its work with the European Space Agency, and also has plans for GaN epitaxial growth.

Focusing on optoelectronics

High-brightness LED manufacturer Uniroyal has been suffering from a financial crisis which led to the decision to try to sell Sterling. According to the *Sarasota Herald Tribune*, however, Uniroyal is still keen to pursue a plan of focusing on its optoelectronics business.

"We are going to proceed on trying to sell Sterling as well as our coated fabrics [Naugahyde] division," Zulanas told the newspaper. "We are having the best quarter we have ever had since we've been in the hi-tech arena. What we need is our debtors to stand back and be a little more patient."

Perhaps surprisingly, Uniroyal's share price rose slightly after the Umicore deal fell through. Sterling recently won a US Department of Defense contract, worth $9 million over the next two years, to develop silicon carbide chips (see p11). This contract does not affect Uniroyal's decision to sell Sterling, but investors feel it may improve Uniroyal's cash flow in the short term.

Agilent consolidates electronics production

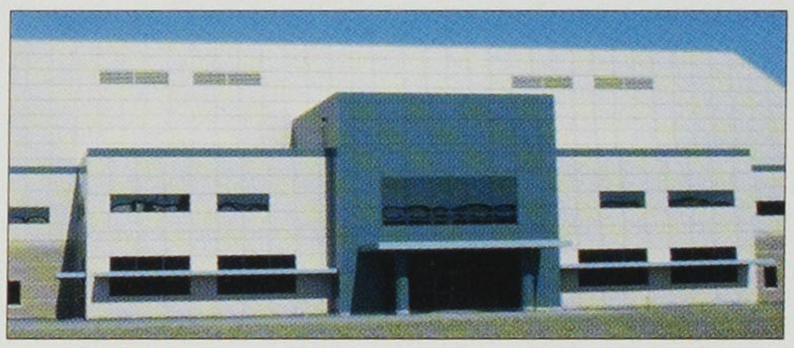
By Rebecca Pool

Agilent is to transfer its electronics manufacturing from two of its Californian fabrication plants to its Fort Collins plant in Colorado.

According to Mark Alden, worldwide press manager for the Semiconductor Products Group, Agilent will move the production of GaAs diode and transistor devices as well as film bulk acoustic resonator (FBAR) MEMS filters from its Newark fab to Fort Collins. PHEMT PA manufacturing will be transferred from Santa Clara to Fort Collins.

"After these transfers are complete, the Newark and Santa Clara fabs will be shut down, and we expect this to happen by the end of 2002," Alden told *Compound Semiconductor*. Alden added that the fab relocations will cause 200 job losses in Newark and 130 in Santa Clara. These redundancies are part of the 8000 job cuts that were announced by Agilent in 2001.

The Fort Collins facility manufactures CMOS image sensors, optical navigation ICs and high-speed bipolar devices. However, Alden points out that the plant has already installed 6 inch GaAs wafer-fabrication lines that can take on the new GaAs demand. Agilent announced plans in October 2000 to build these fabrication lines.



AGILENT

Agilent's Fort Collins, CO, facility is gearing up to manufacture GaAs diodes and transistors and PHEMT PAs. Recently installed 6 inch GaAs wafer-fabrication lines will take on this production.

Alden also says that Agilent has no current plans to shift its laser and LED fab activities to Fort Collins. Multimode VCSELs, LEDs and singlemode lasers will continue to be made at their respective plants in San Jose, CA, Singapore and the UK.

As well as consolidating its electronics business Agilent is working on an InP process. "We are developing our InP process in our Santa Rosa facility," Alden said. "Initial applications will be demanding test and measurement products, including test equipment for 40 Gbit/s communications systems."

SiGe still has its place

According to Alden, Agilent still has plans to use SiGe technologies despite its InP development activities. "SiGe technology cannot compete with advanced InP bipolar transistors. For communication applications above 40 Gbit/s, InP will be required," he said. "But for lower-speed applications SiGe remains an attractive option and we have several SiGe suppliers that satisfy our requirements."

Alden adds that Agilent's merchant wireless semiconductor division is investigating a number of technologies for wireless devices and is currently using E-mode PHEMT technology to manufacture PAs for CDMA and GSM handsets. "[E-PHEMTs] are more power-efficient than HBTs," said Alden. "But we are also working on double-heterostructure HBTs with a GaAsSb base."

Nortel considers drastic measures

By Richard Dixon

The news that Nortel is cutting a further 3500 positions from its optical long-haul business arrived with a warning that second-quarter 2002 revenues are now expected to be at best flat and at worst down 5% from the $2.91 billion reported in the March quarter. The company says it may also sell or resize its optical components group as part of its plan to return to profitability.

Although many companies are suffering, Nortel appears to have been hit particularly hard by drastically reduced carrier spending over the last 18 months. Nortel has been losing market share in the optical components business for several quarters, with some industry analysts putting its share at the end of 2001 at just 7%, compared with 27% in the third quarter of 2000.

The beleaguered Canadian telecom equipment maker has now cut its break-even sales target for the year to $3.2 billion, from the $3.5 billion it had previously anticipated for the quarter ending in December. Nortel now does not expect a "meaningful recovery" in the long-haul optical market before late 2003 or early 2004.

Nortel expects the cutbacks to reduce its workforce further – to about 42,000 compared with previous estimates of 44,000. In contrast, the company employed 94,500 at its peak at the end of 2000.

Optical components up for sale

During the boom, Nortel invested hugely in expanding and automating its High Performance Optical Components group to meet demand for source and pump lasers, detectors, and transmit and receive modules. As recently as early 2001, Nortel bought JDSU's 980 nm pump-laser business in Switzerland.

When the downturn hit, much of the investment turned up in a huge inventory sale. The company shed more than 10,000 pieces of equipment from its fabs in Ottawa,Canada, as well as those in Harlow and Paignton in the UK (see *Compound Semiconductor* December 2001, p4).

A checklist of potential buyers would include Alcatel, Corning, JDSU, Agere and Furukawa. But many have been forced to rationalize their businesses in the face of severe cutbacks in spending on telecom and wireless infrastructure. For example, Corning had to suspend plans for a second Lasertron facility, and Agere has now consolidated several operations back into a single facility in Allentown, PA. Also, Alcatel is cutting 25% of its workforce, citing the continued poor market conditions (see p17).

One company that has been spending and not cutting is Intel, which is investing heavily in optical-networking expertise. Intel has bought 17 companies since the beginning of 2000, including two that provide physical-layer components and laser/VCSEL drivers and amplifiers for 10 Gbit/s SONET and Ethernet applications. The most recent acquisition was tunable laser manufacturer New Focus (see p13). Cisco Systems, one of Nortel's big customers, has also been mentioned as a potential suitor.

Infineon agrees to buy Ericsson Microelectronics for €400 million

Ericsson is to sell its microelectronics arm, Ericsson Microelectronics, to Infineon Technologies. The €400 million ($378 million) share-based deal is expected to conclude this summer. However, an Ericsson source said that the deal does not include its optoelectronics group, which makes lasers and other fiber-optic components.

The move is in line with Ericsson's ongoing plan to focus on its core business of providing systems and services to telecom operators. The deal also makes Infineon one of Ericsson's key suppliers of components for wireless infrastructure and mobile phones.

"This strategic partnership strengthens our communications business and builds up our wireless design expertise," said Infineon's CEO, Ulrich Schumacher. "We will team up with Ericsson as a leader in the wireless world and a strategic partner."

Infineon recently sold its GaAs business to TriQuint as part of a collaboration between the two companies (see *Compound Semiconductor* June 2002, p3).

Agere completes its spin-off from Lucent

Agere Systems finally spun off from Lucent Technologies on June 1. The separation took more than a year to complete and concluded with Lucent distributing 945 million Agere shares to nearly 5 million shareholders. Lucent's chairman Henry Schacht and CFO Frank D'Amelio have also stepped down from Agere's board of directors. "As a completely independent company, we are beginning an exciting new phase," said Agere's president and CEO, John Dickson. "We plan to sharpen our focus on our target markets, improve our performance and reduce our cost structure."

GaAs giant named Skyworks Solutions

Skyworks Solutions has been chosen as the name for the wireless supplier that will be formed by the merger of Alpha Industries with Conexant's wireless business (see *Compound Semiconductor* Jan/Feb 2002, p3). The companies say the name signifies the growing nature of the wireless business and an accent on working on integrated wireless solutions.

When the merger is completed at the end of June, Skyworks shares will be traded on NASDAQ with the ticker symbol SWKS. The merger creates the largest standalone RFIC supplier for all major air-interface standards, which will have market strength in switches, power amplifiers and highly integrated power amplifier modules. Handset manufacturers will also benefit from comprehensive 2.5G GSM/GPRS solutions, say the companies.

Skyworks will have a range of process technologies, including GaAs PHEMT, InGaP and InP HBT, and an RF module assembly and test facility in Mexicali, Mexico. Skyworks says it aims to be the industry's leading wireless company focused on RF and complete semiconductor system solutions for mobile communications applications.

"Today's handset customers look for more highly integrated products from fewer suppliers," said Alpha's CEO David Aldrich, who will head up Skyworks as CEO. "Out of the gate, our top four customers will be the world's leading cellular handset manufacturers."

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Raytheon invests in WIN for wireless

Raytheon RF Components has formed a strategic alliance with Taiwanese foundry WIN Semiconductors to manufacture GaAs components for the wireless market.

Raytheon will invest $5 million in WIN, and has transferred its high-volume 3.0 μm InGaP HBT process to WIN's 6 inch GaAs foundry. Details of the transfer to the Taiwanese facility, which is being expanded to reach an annual capacity of 100,000 wafers by 2005, were revealed in an exclusive article in our last issue (see June 2002, p35).

WIN will manufacture InGaP HBTs for Raytheon, providing identical drop-in replacement MMICs for handset PA modules. WIN will also guarantee access to a portion of its capacity. Raytheon says the move will allow it to focus production at its own 4 inch facility in Andover, MA, on lower-volume commercial and military applications up to 100 GHz. The agreement is also designed to cement co-operation between the two companies on future process development.

"[The combination of] our expanding operations into Asia, continual technology development and access to WIN Semiconductors' foundry strengthens our position as a key supplier to the wireless market," said Steve Kaspar, president of Raytheon RF Components. "This alliance also allows Raytheon RF Components to focus its internal manufacturing capabilities on lower-volume commercial, aerospace and defense products."

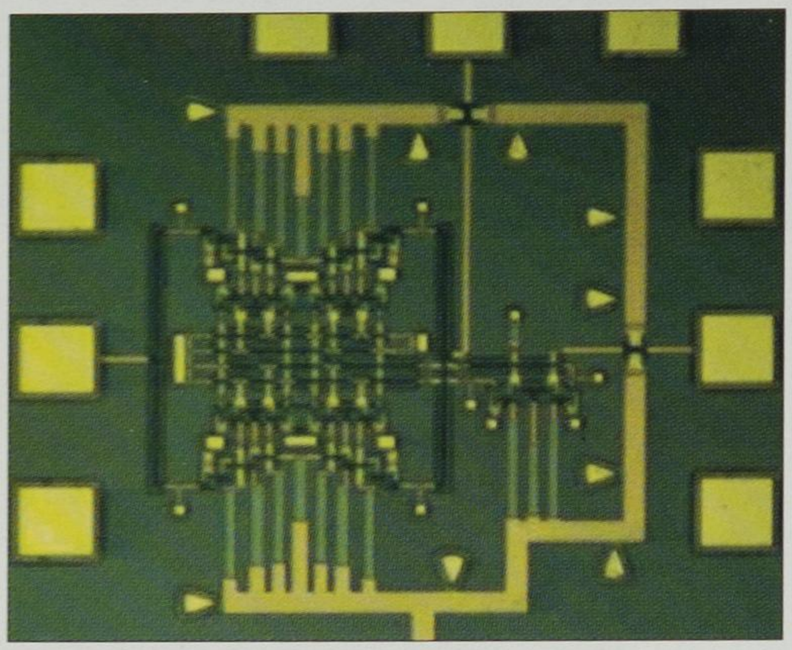
UCSB and IQE announce record-breaking 450 GHz InP DHBT

The University of California at Santa Barbara (UCSB) and IQE have announced what is believed to be the fastest HBT structure to date. The InP DHBT exhibited an f_{max} of more than 450 GHz and was reported at the recent Indium Phosphide and Related Materials (IPRM) conference in Stockholm.

The device material was grown by IQE on 3 inch semi-insulating InP wafers using MBE. The epitaxial structures included a graded C-doped base, in addition to superlattice composition grading at the base–collector junction.

The devices were fabricated at UCSB by Mark Rodwell's group using a conventional mesa HBT structure. The cut-off frequency f_t reached 282 GHz, and the device exhibited a current density of 2.3 mA/mm^2. Prior to this work, the highest f_{max} reported for a DHBT was 300 GHz, while InP single HBTs have reached 340 GHz (*Compound Semiconductor* June 2002, p10).

"The results show that InP HBTs will continue to see large improvements in speed as dimensions are scaled and epitaxial growth technology advances," said Rodwell. "IQE has been a tremendous partner in our efforts to develop fast transistors and ICs."



UCSB

UCSB has manufactured an InP DHBT featuring an f_{max} of more than 450 GHz, using MBE material grown by IQE.

Velocium, Endwave renew agreement

Endwave and Velocium, TRW's telecommunication products company, have revised and renewed their supply agreement up to the end of 2005. The new deal includes both TRW and Velocium processes and products, including GaAs HBTs and HEMTs. These devices are used in Endwave's antennas, millimeter-wave transceivers and outdoor units for point-to-point and point-to-multipoint links.

The agreement continues the arrangement that followed Endwave's formation from the merger of TRW Milliwave and Endgate more than two years ago, and gives Endwave continued and expanded access to GaAs products and processes. This includes wafer-processing services and lower-frequency products for wireless infrastructure applications. The deal also covers Velocium's InP circuits and guaranteed pricing and purchase commitments.

"Endwave's design expertise and world-class manufacturing capability coupled with Velocium's processing technologies will give leading radio OEMs and other equipment manufacturers access to TRW technology and performance, packaged as they need it," said Velocium's president, Dwight Streit.

Anadigics responds to wireless demand by expanding facility

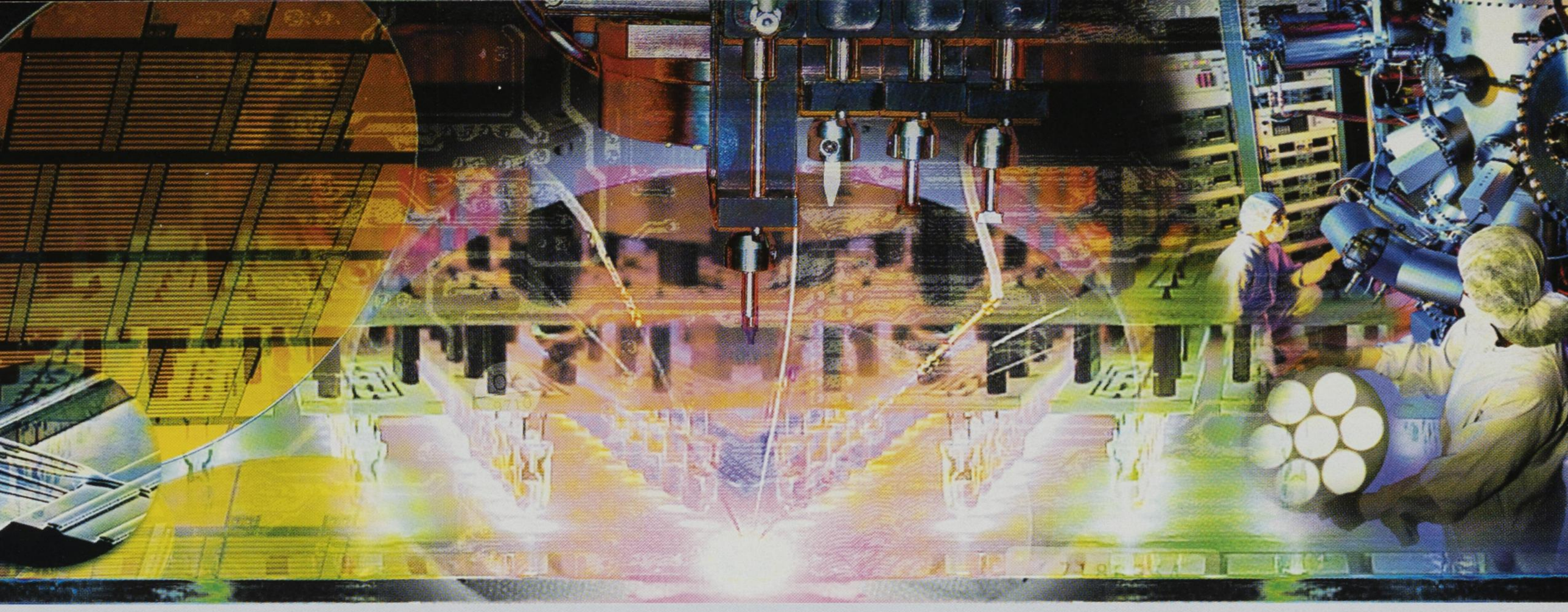
Anadigics has added 10,000 sq. ft of class-10 cleanroom space to its fabrication facility in Warren, NJ. The company invested approximately $10 million in the expansion, which doubles its capacity and gives it the infrastructure to meet anticipated increases in demand for its wireless products. The company's last expansion at its 6 inch facility took place in January 2000 (see *Compound Semiconductor* Jan/Feb 2000, p25).

The additional space will accommodate the increased production of 6 inch InGaP HBT wafers, which are used to manufacture the power amplifier circuits used in cell phones and PDAs.

Anadigics says it has seen an increase in demand for HBT PAs from handset makers such as Kyocera, LG and Sony Ericsson, and other areas of the Asian manufacturing sector. Recently, the company raised its second-quarter revenue expectations from $21 million to $23 million on the strength of the growing demand for its wireless devices.

"We are delighted to announce the opening of the expansion because it will provide the platform for the future of Anadigics," said president and CEO Bami Bastani. "We were one of the first companies to recognize the potential of 6 inch InGaP HBT technology, and we are now reaping the results in terms of increasing revenues through a growth in demand for our power amplifier products."

"We have also won market share through the outstanding quality and performance of our products, and investment in this new fabrication facility can only enhance our capabilities," he concluded.



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GCS banks on predicted increase in HBT orders

Global Communication Semiconductors (GCS) is anticipating an increase in orders for InGaP HBT wafers, driven primarily by an improvement in the wireless market and new demand for wireless LAN applications.

The company, which manufactures InGaP HBT, InP HBT and *pin* diode wafers at a 4 inch wafer foundry in Torrance, CA, has also outlined its plans to accommodate demand.

"GCS's InGaP HBT wafers have been qualified by domestic, Japanese and European customers for volume production," said founder and corporate strategy officer, Owen Wu. "Wafers from these volume programs target handsets, base stations, 10 Gbit/s telecommunications infrastructure and the burgeoning WLAN market."

According to Wu, GaAs power amplifiers offer performance advantages over silicon for WLAN applications at 5.7 and 2.4 GHz. "We believe WLAN power amplifiers will be the next killer application for GaAs technology, requiring large volumes of wafers in the second half of 2002," Wu added.

Planning for the wireless recovery

GCS says it is in the process of identifying a 6 inch foundry partner for future high-volume production, which the company expects to occur sometime in 2003.

According to Bill Vitez, director of marketing and sales, the company's long-term goal hinges on having access to a 6 inch foundry capability at a separate location.

"Our customers need to be assured that we will have a viable 6 inch source as a solution to their requests for lower prices," said Vitez. "In some of our customers' minds, 6 inch manufacturing costs less, so we need to meet the requirements of their future capacity expectations when the market recovers."

The longer-term plan includes establishing manufacturing facilities in Taiwan and mainland China. GCS is looking at various solutions, including acquisition and partnering.

"We believe that WLAN power amplifiers will be the next killer app for GaAs technology."

"Five major international customers have recently qualified their processes at GCS in anticipation of an increase in volume," said Vitez. "Our customers are telling us that, just as the market dried up quickly, we shouldn't be surprised it if returns very strongly. This means we may have to ramp from low volumes of current products to huge volumes in a year or so, and it would be easier for us to transfer a process than to try to build out that capacity rapidly in our existing facility."

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CDMA handset orders

● **LG Electronics** has placed high-volume production orders for **Anadigics'** InGaP HBT power amplifiers for its 2.5G CDMA handsets. Anadigics' power amplifier modules are housed in $6 \times 6 \times 1.6\ mm^3$ packages and have been designed to support PCS CDMA, CDMA-1X and cellular applications.

● **Alpha Industries** has received volume orders from **Samsung**, Asia's largest wireless handset manufacturer, to supply its latest SPDT switch for several high-volume phone platforms. The AS211-334 switch is made with Alpha's GaAs PHEMT process, and operates from DC to 4 GHz with an insertion loss of 0.3 dB at 0.9 GHz.

The PHEMT design also features single positive voltage operation and a low DC power consumption for longer battery life. Alpha says the new switch, which is housed in the industry's smallest lead-less package, is expected to ship in quantities of up to 10 million units this year.

● **Conexant Systems** has begun production shipments of InGaP HBT power amplifier modules for use in two new handsets manufactured by **Samsung**. The company expects orders for the modules to exceed 1 million units over the next several quarters.

Samsung will use Conexant's PAs in a new CDMA2000 handset planned for the Korean market, in addition to handsets designed for a new network from China United Communications. This network is expected to support 50 million subscribers by 2005.

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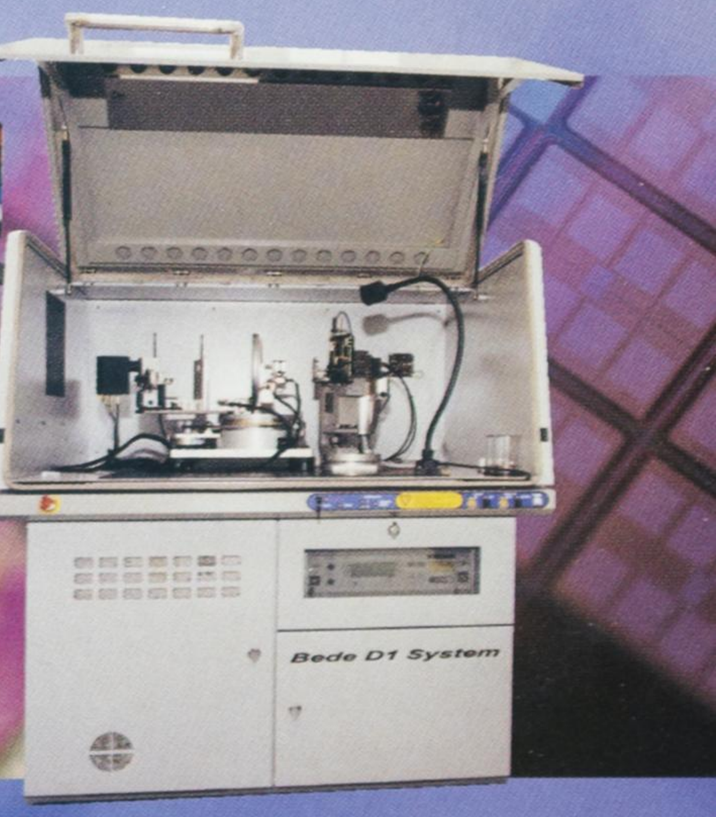
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Cree reveals progress with SiC and GaN devices

Cree Microwave (formerly UltraRF – see below) unveiled a new SiC MESFET power transistor and several SiC and GaN demonstration devices at the recent IEEE International Microwave Symposium, which took place in Seattle, WA.

The company is now sampling the CRF-22010, which is a 48 V class-A SiC MESFET operating at 10 W. The transistor features a gain of 12 dB at 2.2 GHz and has been designed for wide bandwidth radio and cellular infrastructure applications.

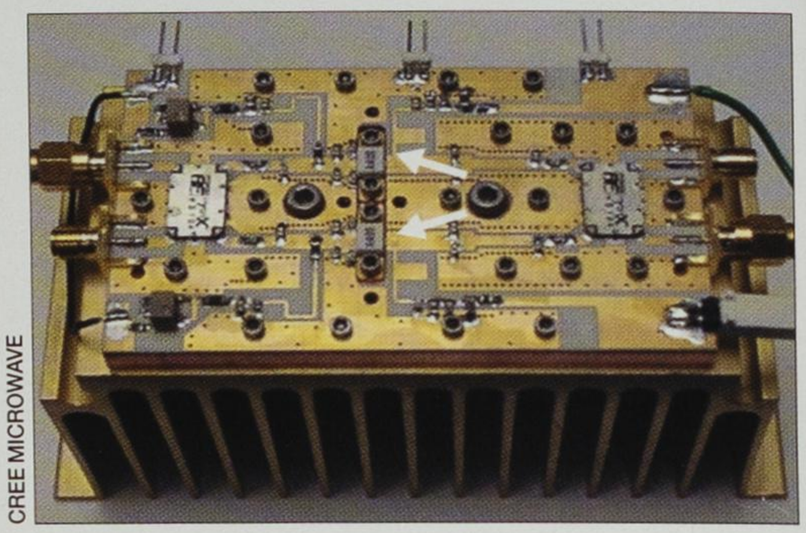
John Palmour, Cree's director of advanced devices, says that SiC and GaN devices can withstand a much higher power density than Si and GaAs devices, which enables a much smaller gate periphery for the same power. The smaller gate dimensions lead to much higher impedance in the circuit, simplifying impedance matching and enabling broadband amplifiers that cover the entire 1.8–2.2 GHz frequency range.

To demonstrate this, Cree incorporated two CRF-22010 devices into a balanced amplifier that delivered a constant 22 W across a bandwidth of 400 MHz (see picture). A 60 W version of the SiC MESFET designed for 2 GHz wireless infrastructure applications will be sampled by the end of the year.

"We believe this outstanding wide bandwidth demonstration highlights the future impact of wide-bandgap semiconductors on the cellular infrastructure market," said Palmour. "One amplifier design can serve multiple frequency bands and multiple air-interface protocols such as WCDMA, CDMA, GSM and EDGE."

The high power and high temperature performance of SiC and future GaN devices should also simplify the PA circuits used in base stations, added Palmour.

"For reasons of size and weight, typical high-power RF sources are placed at the bottom of base-station towers," he said. "These sources lose up to 500 W, or around half of their power output, when the signal is 'piped' through cables to the top of the tower. RF sources with wide-bandgap devices could be placed at the top of towers to reduce these losses, because heat sinks could be used instead of active cooling from bulky fans or expensive liquid cooling."



CREE MICROWAVE

Cree recently demonstrated a balanced amplifier using two MESFETs (arrowed) that provides 22 W in the 1.8–2.2 GHz range.

Wide-bandwidth GaN amplifiers

Cree Microwave also provided an update of its development of GaN transistors, which have previously shown CW power outputs of up to 108 W at 2 GHz. Reported at last December's IEDM meeting in Washington, these GaN HEMTs featured 24 mm peripheries. Recent efforts have focused on establishing reliability in smaller devices. Although the periphery of the smaller devices is being kept under wraps, the company's 10 W GaN amplifiers have provided a gain of 17 dB in the 1.8–2.2 GHz range.

New name for UltraRF

Cree has changed the name of its wholly owned UltraRF subsidiary, which manufactures high-power RF semiconductors, to Cree Microwave. Located in Sunnyvale, CA, Cree Microwave will continue to make silicon LDMOS and bipolar devices at its 25,000 sq. ft premises, which have 8500 sq. ft of class-100 cleanroom space as well as a 5000 sq. ft assembly area.

For the development of SiC and GaN transistors, materials and device fabrication will continue at Cree's facility in Durham, NC. All devices, including those developed by Cree Lighting in Santa Barbara, CA for solid-state lighting applications, will now go through Cree Microwave's Sunnyvale site for packaging and testing.

"Cree Microwave is really bigger than just the Sunnyvale location," explained Palmour. "The site incorporates on-going efforts on both east and west coasts, and for marketing purposes has many advantages.

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DARPA awards $14m in wide-bandgap funding to Sterling Semiconductor, Emcore and Crystal IS

The Defense Advanced Research Projects Agency (DARPA) is to fund separate projects at Sterling Semiconductor, Emcore and Crystal IS to develop wide-bandgap semiconductor technology.

Sterling, which for now remains a subsidiary of Uniroyal Technology (see p3), will develop improved 3 and 4 inch SiC substrates, advanced SiC epitaxy and SiC devices. The two-year contracts, worth $9 million, include initiatives for developing conducting substrates for high-power electronics as well as semi-insulating substrates for the high-frequency electronics used in communications and radar.

"Our contract bid to DARPA responded to their requirements for the basic materials needed to develop the military systems of the future," said Robert Soran, Uniroyal Technology's president and CEO. "At the same time, Sterling expects that its research under the contracts will lead to significant commercial applications."

Emcore has won a $4 million contract from DARPA to develop epiwafers for GaN-based high-power RF electronic devices. The company will use its MOCVD production tools to make devices on 4 inch wafers.

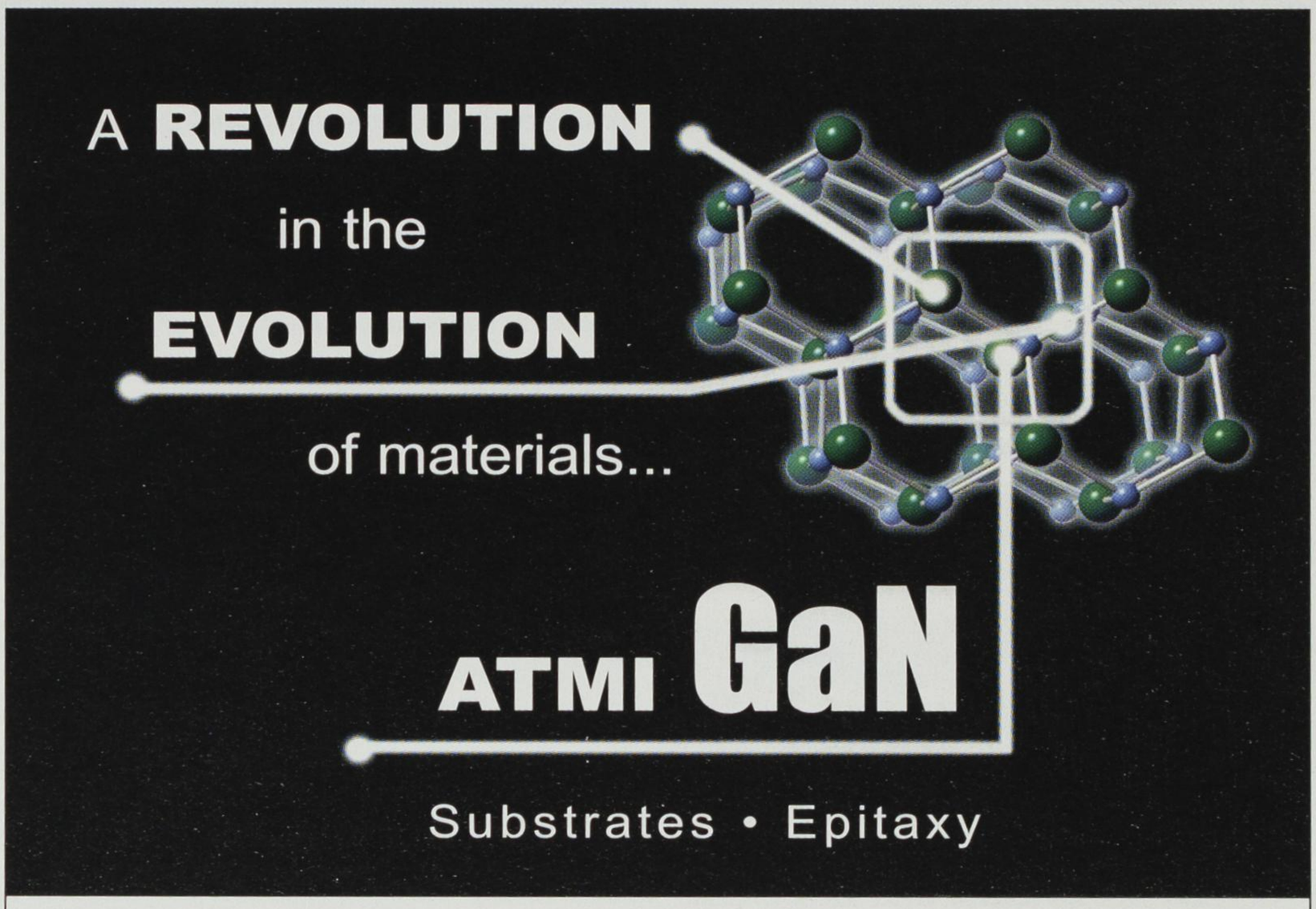
The contract forms part of DARPA's mission to develop wide-bandgap semiconductors for high-power and frequency electronics in military applications.

"Emcore has already produced FETs on 2 inch wafers that have industry-leading levels of uniformity and reproducibility," said DARPA program manager Edgar Martinez. "The scalability of their technology will enable them to make materials on 4 inch wafers. This is essential for manufacturing affordable RF and analog components."

In addition, Crystal IS of Latham, NY, has won $1.16 million from DARPA to develop further its AlN substrate technology for UV LEDs, blue laser diodes and high-power, high-frequency devices. The company will use this money together with $226,000 of its own investment to increase the size of its AlN substrates to 50 mm.

If Crystal IS can accomplish this within 18 months, the company will be granted a further $366,000 to increase the wafer diameter to 100 mm. Rensselaer Polytechnic Institute, which Crystal IS spun out from, and Virginia Commonwealth University will act as the project's subcontractors.

The US Department of Defense is funding projects at a number of US companies that are involved in wide-bandgap semiconductor research and development. Recent contract awards include those to Cermet for the development of GaN substrates and to Cree for the development of UV-LEDs and lasers for biological agent detection.



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European universities develop GaN blue lasers

Researchers at the University of Bremen, Germany, and the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, have become one of the first European university teams to achieve lasing from a GaN-based laser diode. Emitting at 401 nm, the electrically pumped, pulsed laser had a maximum power output of 130 mW and a 15 minute lifetime.

Bremen University researchers Detlef Hommel and Tim Boettcher, and Marc Ilegems of EPFL, say that their breakthrough follows two years of research into MOCVD growth. "Before this time we could only use MBE," said Boettcher. "[However,] by using MOCVD and the process technology developed at EPFL we have [managed to] fabricate a [working] laser."

Boettcher says the team used MOCVD, rather than MBE, to deposit GaN onto the sapphire surface as this technique produced smoother layers with fewer dislocations. "In MOCVD, the chemistry and high growth temperature meant we could grow islands on a low-temperature nucleation layer. These then coalesced to form a smooth layer with fewer dislocations," he explained. "This mechanism did not work in MBE."



BREMEN UNIVERSITY

A German–Swiss team has achieved pulsed emission at 401 nm with a GaN-based laser.

The laser's active region comprises three 4 nm InGaN quantum wells with GaN:Si barrier layers and an AlGaN electron blocking layer. This active region is sandwiched between GaN waveguides and AlGaN cladding layers. The researchers say they achieved high-efficiency lasing by altering the thickness of the QW and barrier layers, and adjusting the doping levels within the barriers.

The team has also introduced a wet-etching step that simplifies laser fabrication. The rotational misfit between the nitride unit cell and the sapphire substrate means that chip manufacturers typically have to thin the substrate before cleaving the wafer to form the laser facets. EPFL researchers have removed the time-consuming thinning process by reactive ion etching (RIE) of the GaN layers parallel to the substrate's cleavage plane, which forms the laser facets. Before cleavage each facet is wet-etched to remove any roughness caused during RIE and to optimize laser emission.

Boettcher says that the team now wants to fabricate a continuous-wave blue laser diode, but there are as yet no plans to commercialize the technology.

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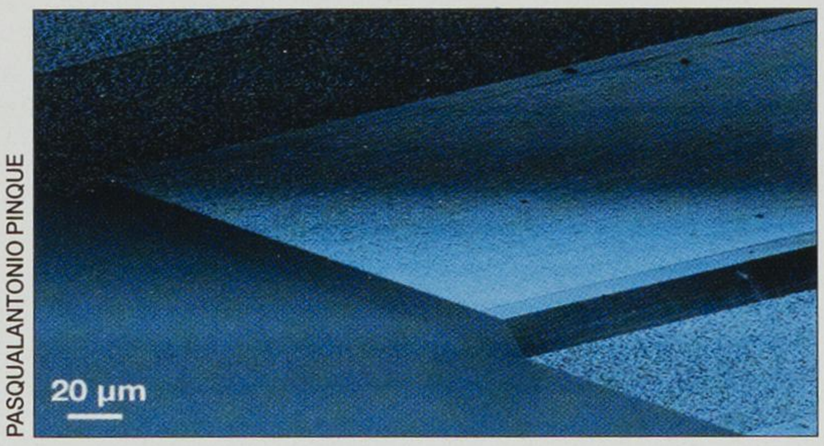
New GaAs laser emits terahertz waves

By Rebecca Pool and Oliver Graydon

A GaAs-based terahertz quantum-cascade laser (QCL) with a novel waveguide is set to advance chemical sensing, medical imaging and in-building wireless communications. Developed by Rüdeger Köhler and colleagues at the National Institute for the Physics of Matter (INFM) laboratories in Pisa, Italy, and Cambridge University, UK, the laser emits 2 mW of pulsed, singlemode radiation at 4.4 THz (67 μm).

Earlier this year Swiss scientists developed the first CW far-infrared QCL operating at room temperature (see *Compound Semiconductor* April 2002). However, attempts to make a similar laser emit in the terahertz region have been plagued with problems such as high intrinsic optical losses and short lifetimes of the excited state during laser transition. Also, until now, typical sources of terahertz radiation have either been large, cumbersome gas lasers, or germanium lasers that only operate at liquid helium temperatures and in the presence of a strong magnetic field.

Köhler and colleagues have countered the optical transmission problems by adding a novel waveguide with chirped superlattice active regions to the laser. Using MBE, the researchers deposited an 800 nm n-type GaAs layer onto an undoped GaAs substrate, followed by the active region.



PASQUALANTONIO PINQUE

SEM image of a laser ridge; the ridges were etched into the plain wafer using optical lithography and chemical wet etching.

To optimize the laser's optical gain, the researchers built an active-region stack that was 10.3 μm thick and contained 104 repeat units. Each unit contained seven GaAs QWs separated by AlGaAs barriers. Four of these QWs acted as injectors, while the other three formed the active region. A 200 nm thick n-type GaAs layer was deposited on top of the active region.

The researchers used optical contact lithography and wet chemical etching to form mesa ridge stripes. The substrate was then thinned to 200 μm to optimize heat dissipation, and the ridges were cleaved into laser bars to form a Fabry–Perot cavity.

Each ridge measured 1.5 mm in length, was 180 μm wide and 11 μm in depth. According to Köhler, light propagating along the ridge is guided by the GaAs layer beneath the active region stack and decays into the undoped substrate below this layer.

Operating their device at liquid-helium temperatures, the researchers achieved 4.4 THz singlemode pulsed lasing at 2 mW peak power and a threshold current density of 290 A/cm^2. Köhler says that the main advantage of the laser is its compactness and portability; the actual laser is just 1.5 mm long and 0.2 mm wide, and measures only a few millimeters when packaged.

The researchers are now keen to achieve CW lasing and room-temperature operation. They believe they can realize CW lasing by making the stripes narrower and optimizing their processing technique. "There are several challenges in reaching room-temperature operation," said Köhler. "First you need to design an active region that can support population inversion at higher temperatures, and heat sinking as well as power consumption need to be improved. It is difficult to tell if and when CW emission at room temperature will be achieved."

Start-up tackles quantum design

Researchers at the University of Leeds, UK, have launched a start-up called Quantum Electronic Design and Innovation (QEDI). Drawing on seven years of experience from the university's Quantum Electronics Group, the new company aims to provide design and consultancy services across the compound semiconductor industry.

"The three people involved in this consultancy have a broad range of backgrounds," QEDI founder Paul Harrison told *Compound Semiconductor*. "We want to design devices for companies across all [materials] and we're prepared to tackle any device that uses quantum principles."

The team has already worked with IV-IV, III-V and II-VI materials, including GaAs-, GaN- and AlAs-based materials, as well as SiGe and ZnS systems. Past studies cover devices that function across the entire optical spectrum from UV to far-infrared wavelengths, including QW laser diodes, QCLs and quantum-dot photodetectors.

The start-up has no plans to manufacture its own devices, but will license its patented technology to chip manufacturers. QEDI has several blue-skies projects that are centered around the applications of quantum semiconductor structures to optoelectronics and computing.

New Focus and Intel clinch tunable laser technology deal worth $50 million

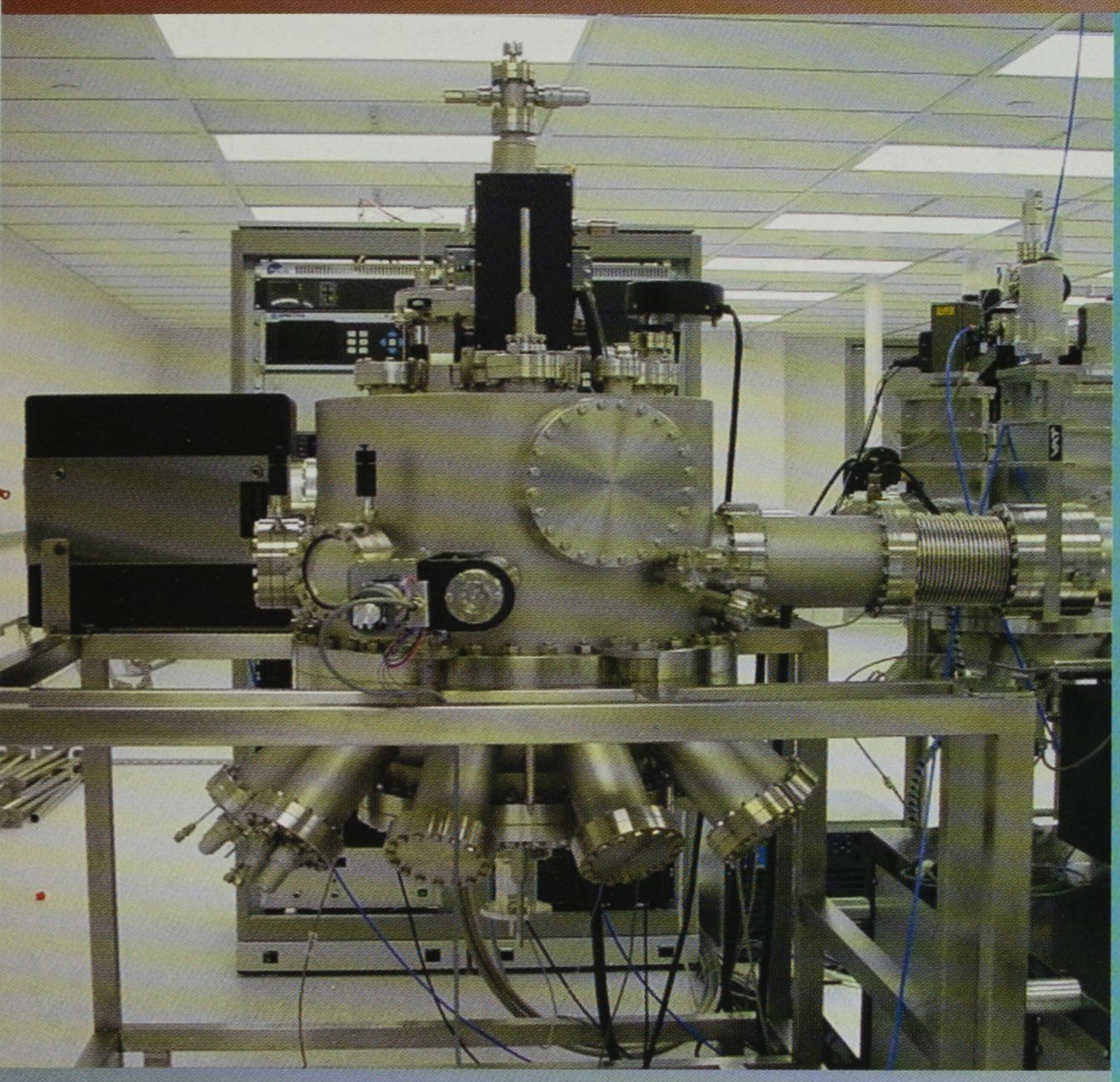
New Focus has sold its tunable laser technology to Intel for $50 million. As part of the deal Intel has taken on 40 New Focus employees at its Newark-based communications group, and has agreed to license the technology back to New Focus for test and measurement applications.

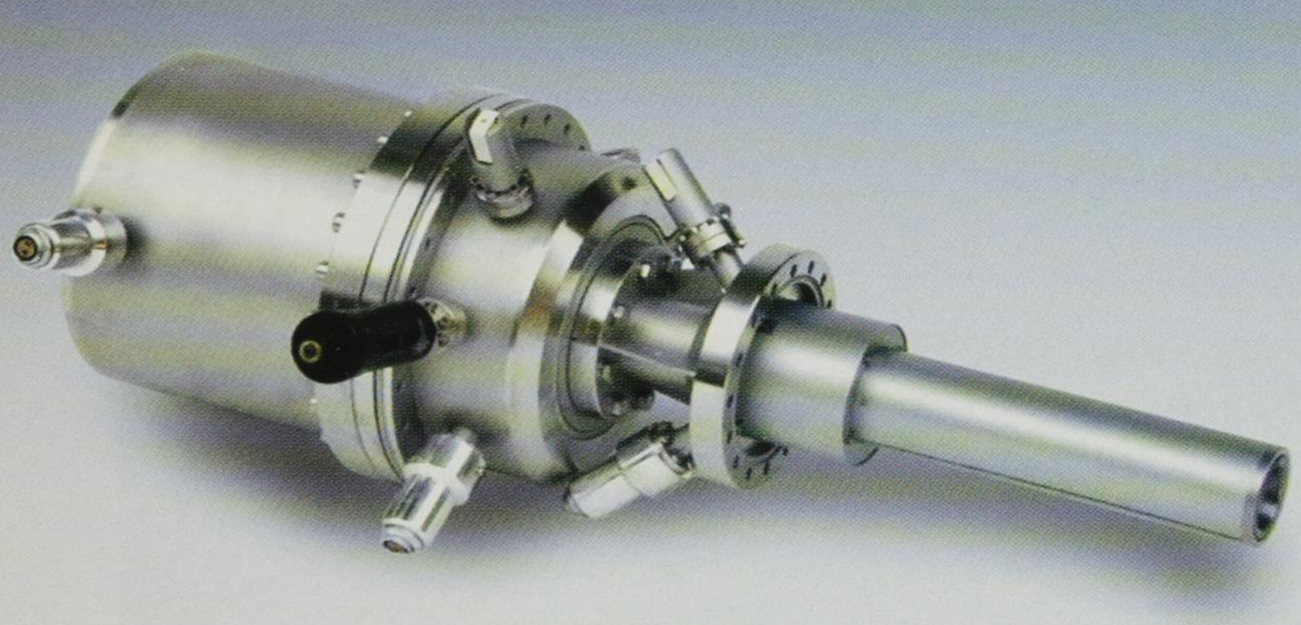
"This deal combines New Focus's tunable laser technology with the optical packaging technology that we bought from LightLogic last year," said Gordon Hunter, VP of the Intel Communications Group. "This means we can accelerate the development and adoption of small, low-cost tunable lasers for many applications." New Focus uses chips from outside sources to make its 20 mW external cavity tunable lasers that span the entire C-band.

"This transaction will also benefit New Focus by providing us with advanced tunable laser transponders from Intel," said CTO Tim Day. "We will combine this with our products to create more advanced test and measurement solutions for our customers."

In recent years, Intel's venture-capital arm has funded a range of optoelectronic start-ups, which includes VSK Photonics, Nova Crystals and T-Networks. The company has also bought low-power CMOS circuit makers Cognet Microsystems and nSeriel, as well as LightLogic, which manufactures optical transponders.

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DCA INSTRUMENTS

Funding rolls in despite the downturn

Picolight and Inphi have secured new funding despite the downturn in the fiber-optic market. Picolight, of Boulder, CO, has raised $27 million in its latest round and will use the money to ramp up production, including the manufacturing of its 850 nm and 1310 nm VCSELs and VCSEL-based transceivers.

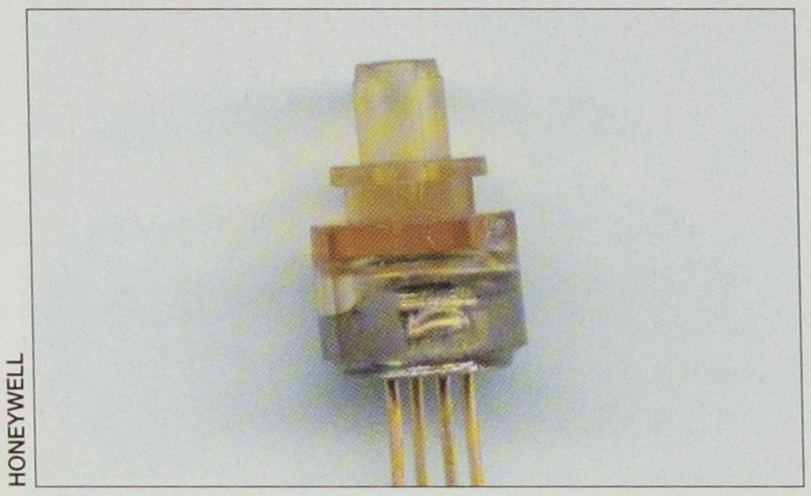
Meanwhile Inphi has received $24 million in its second round, bringing the total investment in the company to $36 million. Located in a fabless facility in Westlake Village, CA, the company is targeting 10 and 40 Gbit/s optical networks with InP mux and demux ICs, in addition to GaAs HEMT modulator drivers (see *Compound Semiconductor* March 2002, p50). Inphi will use the funding for future development and to drive the volume deployment of its products.

Honeywell adds to product line with long-wavelength detectors

Honeywell's VCSEL optical products division has developed new detectors that target 1310 and 1550 nm optical networks. Operating at speeds ranging from 100 Mbit/s to 2.5 Gbit/s over single- or multimode fiber, the HFD3X41 series features various packaging options including TO can components and fiber-sleeved components.

The new detectors are manufactured with an InGaAs *pin* photodiode as well as a high-gain TIA, and are packaged in a TO-46 header that provides differential electrical outputs in response to optical input. The detectors operate from –40 to +85 °C, and are Telcordia qualified. Honeywell manufactures the detectors at its facility in Richardson, TX, using a fully automated assembly line.

"The addition of long-wavelength detectors to Honeywell's product line is the first step to realizing a broader set of component offerings for the datacom and telecommunications industry," said Paul Chapman, VP and general manager of the company's VCSEL optical products division.



HONEYWELL

Honeywell has launched long-wavelength *pin*/TIA detectors that are packaged in TO cans, SC or (shown here) LC housings.

Agere and Yafo combine forces to develop low-dispersion receivers

Agere Systems and Yafo Networks of Hanover, MD, have joined forces to develop 40 Gbit/s receivers incorporating polarization-mode dispersion (PMD) compensation. The deal covers integrated receiver modules and will combine Yafo's compensation technology with Agere's 40 Gbit/s receiver designs and other optical component technologies.

PMD is the spreading of a pulse of light due to slight non-circularity in the optical fiber core. This dispersion, which increases signal distortion and reduces transmission distances, is magnified as the bit rate increases. At 10 Gbit/s, each bit is 100 ps long, and most systems can tolerate around 10 ps of dispersion. However, in a 40 Gbit/s network the dispersion tolerance drops to just 2.5 ps, which begins to lead to signal degradation and loss. This becomes a problem for long-haul and ultra-long-haul optical links that are more than 500 km long.

Yafo's device is engineered to compensate for PMD at the receiver and reduces pulse distortions by converting any incoming polarization state back to the intended polarization state during optical transmission. The company offers a device called the Yafo10, which uses adaptive optics and a patent-pending quality-of-bit analyzer to reduce this distortion in 10 Gbit/s networks.

Last year Yafo demonstrated that the technology will scale to 40 Gbit/s systems and is compatible with both RZ and NRZ signal formats. A new 40 Gbit/s adaptive receiver module developed by the two companies will be available at the beginning of 2003.

More firms sign up to MSA on surface-mount receivers

Agere and Nortel Networks have announced that four more companies will support a multi-source agreement for 10 Gbit/s surface-mount optical receivers. Hitachi, Multiplex, Oki Electric Industry and Velocium will independently develop and market receivers that conform to the form-factor as well as electrical and functional characteristics defined by the agreement, originally announced by Agere and Nortel Networks in March 2002.

Bandwidth9 should sample on schedule

Despite shedding 45% of its workforce, Bandwidth9, a manufacturer of tunable VCSEL-based transmitters for optical networks, is still on track to sample its G2 MetroFlex transmitter in the third quarter of this year. "The impact [of the workforce reduction] on our product strategy is zero," Jake Weise, Bandwidth9's VP of marketing, told *Compound Semiconductor*. "Customers for our V5 series are still receiving their units as planned and some of them have elected to migrate to the new G2 MetroFlex module."

The G2, launched in March at this year's Optical Fiber Communication show, uses the same VCSELs as the V5 series, but also has a wavelength locker integrated into the butterfly package. The G2 also has an optional SOA gain element that can increase output powers to 1 mA.

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CyOptics targets the metro space with new hybrid EML

CyOptics has combined the company's electroabsorption modulator with a high-power DFB laser to produce a hybrid electroabsorption modulated laser (EML). The new component features uncompensated 10 Gbit/s transmission over distances of 80–120 km, making it suitable for metro applications.

Over these distances, the device provides a dispersion penalty of less than 2 dB over standard SMF28 fiber, while amplified and dispersion-compensated links enable the transmission distance to be increased to more than 500 km. CyOptics says that the hybrid design avoids the trade-offs associated with monolithic integration, leading to a transmitter with a low chirp and high extinction ratio (see *Compound Semiconductor* March 2002, p50). The bandwidth is rated at more than 12 GHz, making it suitable for 10 Gbit/s forward-error-correction systems.

Toshiba integrates TIA/limiting amplifier into receiver module

Toshiba has integrated a TIA and limiting amplifier into a 10 Gbit/s *pin* receiver module that has been designed for intermediate-reach SONET and datacom applications. With sensitivities of –17 dBm, the company's new receivers deliver the same performance as previous products, but require less board space. Production is scheduled to start in the third quarter of the year.

Modulight signs UK sales representative

Modulight has appointed Mi-Net Technology to sell and promote its products in the UK. Located in Tampere, Finland, Modulight manufactures optoelectronic chips and epiwafers, and also sells packaged chips.

"The agreement with Mi-Net Technology opens a big market for us inside Europe," said Modulight's CEO Petteri Uusimaa. "It adds to our international visibility and allows more efficient customer service with major corporations and companies in the UK."

Alcatel Optronics sheds a quarter of its workforce

Alcatel Optronics will cut 25% of its 1800-strong workforce by the end of the year as part of a new "industrial redeployment plan". While the move affects all its manufacturing sites, optical chip fabrication in Nozay, France, remains relatively intact with a company source saying there are no plans yet to shed jobs there.

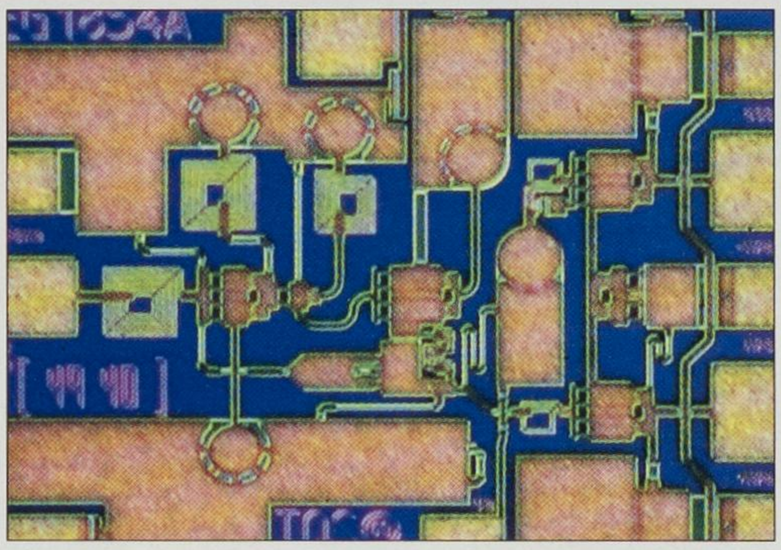
The company will move the production of fiber Bragg gratings in Gatimeau, Quebec, to its Livingston, Scotland, plant, with job losses in Quebec reaching 120. The plan also includes relocating the optical fiber amplifier/optical interface subsystem assembly in Illkirch, France, back to Nozay.

Jobs will be cut at the Plano, TX, board-assembly plant in a bid to reduce production, while a management buyout will see an end to MEMS and planar design activities. There are no lay-offs planned for pump-module manufacturing in Lannion, France.

Blaming the "persistent market downturn", chief executive Jean-Christophe Giroux said, "An action plan was initiated a year ago and we are accelerating our efforts to better adjust our cost structure to current conditions."

TriQuint's TIA suits the 10 Gbit/s market

TriQuint has introduced a new transimpedance amplifier for the 10 Gbit/s telecommunications market, including Ethernet and metro DWDM systems. Based on the company's 0.25 μm GaAs PHEMT process, the TGA4805 delivers 11 GHz of bandwidth and provides 1000 Ω of differential transimpedance. The single supply voltage is rated at 5 V, and the device dissipates 225 mW of power.



TRIQUINT

TriQuint's new GaAs TIA suits 10 Gbit/s SONET/STM, Ethernet and metro systems.

Agility opens center in Silicon Valley to develop new products

Agility Communications, a manufacturer of widely tunable lasers for the metro, switching and long-haul markets, has expanded into Silicon Valley with a new product development center in San Jose, CA.

The company has recruited around 10 additional staff with experience in RF and digital electronics, forward-error-correction techniques, receivers and lithium niobate modulators, and optical system design.

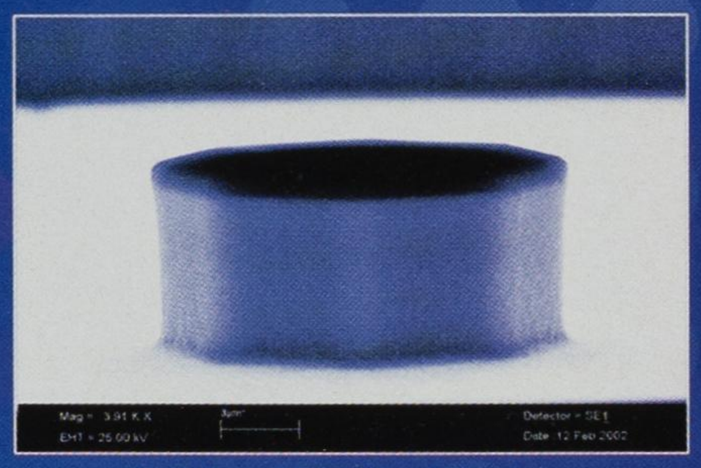
"Many of our 'tier one' customers are shedding huge numbers of people," said VP of sales and marketing, Arlon Martin. "We now find that their design teams are very small, and we can help fill that gap with our experience in tunable lasers and board-level integration."

Optillion outsources test and assembly

Optillion, a Swedish manufacturer of high-speed fiber-optic transceivers based in Stockholm, has announced a strategic outsourcing agreement with Flextronics to provide test and assembly services. Optillion makes 10 Gbit/s Ethernet XENPAK transceivers for both 10 and 40 km, and is currently developing optical chips and optical sub-modules at its new 15,000 sq. ft cleanroom facility.

Optillion says that the agreement will enable it to deliver its products at volume quantities, and with the quality control and cost-efficiencies that its customers demand. Production will take place at Flextronics' operation in Vasteras, Sweden, and will commence in the third quarter of 2002.

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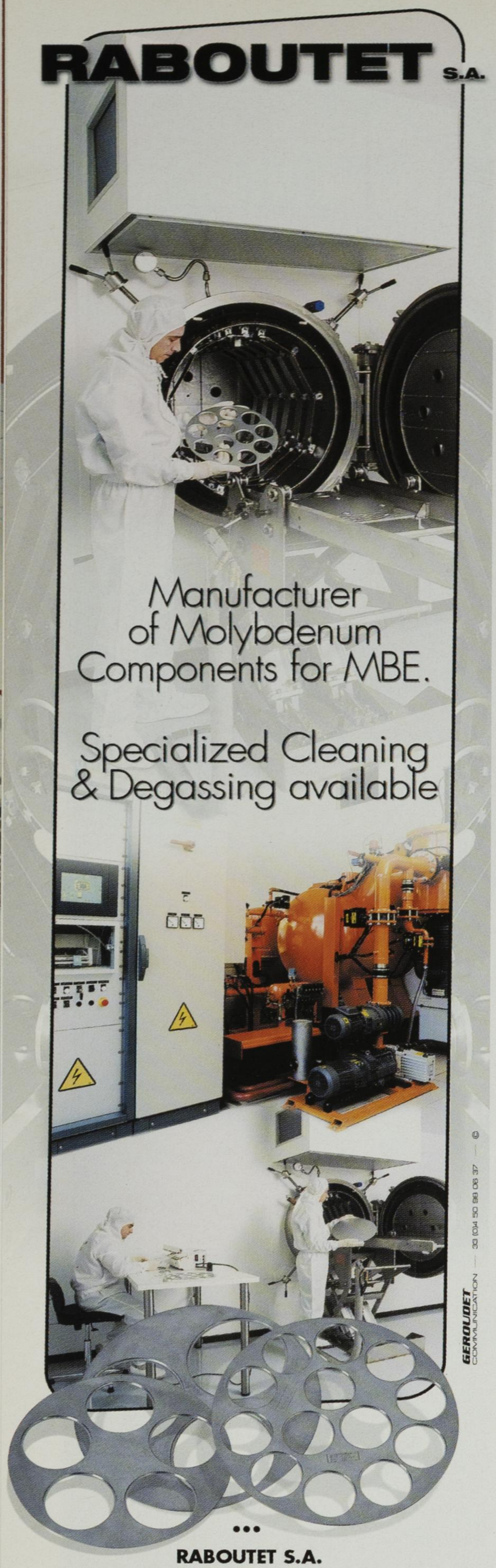
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NEWS FROM ASIA

IN ASSOCIATION WITH *OPTOTECH* MAGAZINE

Procomp invests in China

Procomp Informatics, Taiwan's largest GaAs epiwafer foundry, has signed a letter of intent to co-operate with All Ray of mainland China. Procomp will invest $6 million to acquire 40% of All Ray, which works on the R&D and production of optoelectronic devices, including LEDs, lasers for fiber-optic communications, photodiodes, SOAs and optoelectronic sensors.

As part of the collaboration, Procomp will provide epiwafers, and devices will be fabricated at Suntek Compound Semiconductor, a foundry which is owned by Procomp. All Ray will carry out downstream manufacturing, testing and packaging at its production base in Zhenjiang, Jiangsu Province. The companies also plan to set up a design center in Nanjing, focusing on fiber-optic and LED modules.

According to Yeh Su-Fei, Procomp's chairman, the company is investing in All Ray in order to get close to the market in mainland China. All Ray is a supplier to four leading communication equipment manufacturers in China. At present, optoelectronic products comprise about 20% of Procomp's epiwafer business, and these products are mainly for DVD lasers (see *Compound Semiconductor* June 2002, p20). Yeh Su-Fei expects the deal with All Ray to expand Procomp's business in the areas of fiber-optic communications and LEDs. Procomp has finished developing VCSEL and photodetector products.

Procomp had previously been considering an investment in Beijing Orient Electronics, a high-technology company that was planning to set up an epiwafer or GaAs IC foundry in China. However, these plans have been temporarily shelved because of various regulatory problems. Also, for an epiwafer or IC foundry there is little to gain from manpower savings, compared with packaging facilities that tend to be highly labor-intensive.

Good results for LED makers in Taiwan

LED makers in Taiwan recorded outstanding results in April and May. Everlight Electronics, Taiwan's largest LED packaging company, received record orders in May, including orders for blue LEDs and infrared devices. Everlight expects that its output of surface-mount device (SMD) LEDs will increase to 180 million per month in the third quarter, and will reach 200 million per month by the end of the year.

Epiwafer and chip manufacturer Epistar is working at full capacity. Blue and green LEDs now constitute more than 35% of Epistar's output, and the company estimates it will soon be producing 20 million blue LEDs per month.

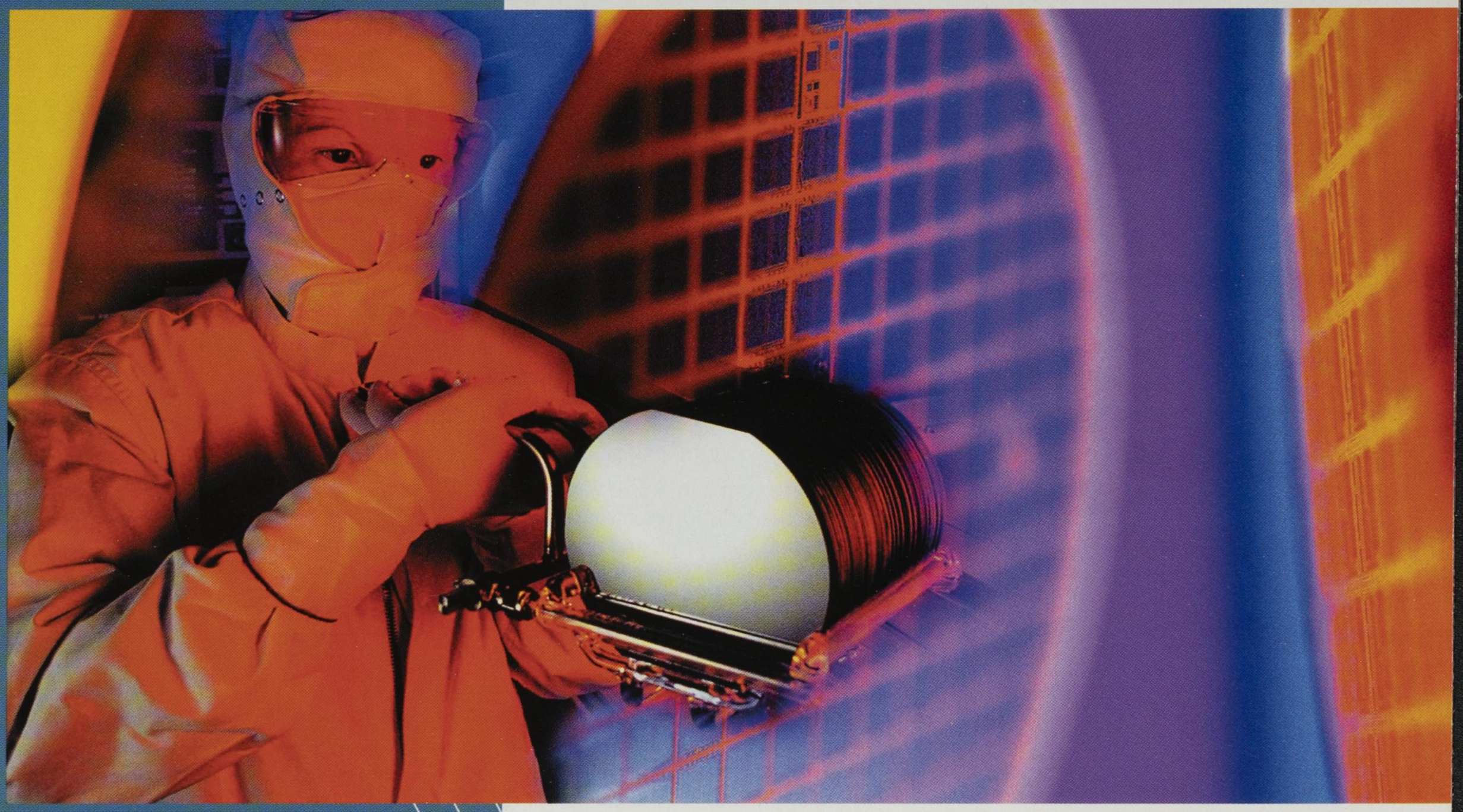
Harvatek plans to invest NTD 200 million ($5.9 million) this year to expand the productivity of its SMD LED packaging line. These devices are in strong demand from mobile-phone makers, and Harvatek plans to install 11 new packaging machines this year. The company hopes to reach a production volume of 200 million LEDs per month by the end of the year.

Lite-On Electronics is to double its productivity of SMD LEDs to 120 million units per month. The company plans to introduce white LEDs at the end of this year in order to further enhance the productivity of its optoelectronics business, which has had a book-to-bill ratio exceeding one for the past seven months. In 2000, UEC purchased Lite-On's chip manufacturing capability (see *Compound Semiconductor* September/October 2000, p28).

Para Light develops high-power LEDs

Para Light Electronics has developed a high-output-power LED with a total luminous power that is several hundred times that of traditional LEDs. According to Lin Ming-Te, assistant manager of Para Light, the company has developed mounting and packaging technology that results in improved heat dissipation and a good radiation function. The LED operates with a drive current of 2 A. Para Light plans to begin trial production in July, and will commence volume production in September. Ma Chin-Peng, Para Light's chairman, says that the company is in negotiation with a car manufacturer, and will also target lighting markets.

Para Light is also co-operating with the Opto-Electronics & Systems laboratories at ITRI, the Industrial Technology Research Institute, to develop white LED panels that have improved heat dissipation and light focusing (see *Compound Semiconductor* March 2002, p9).



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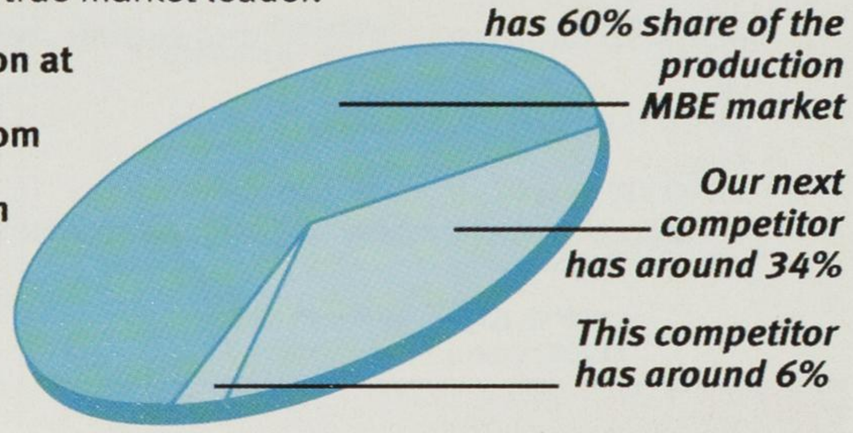
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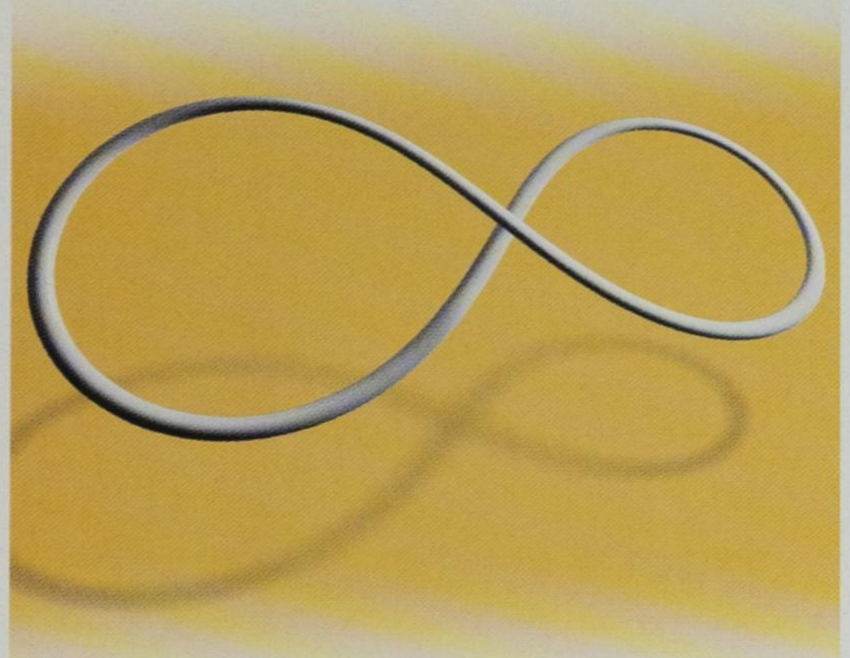
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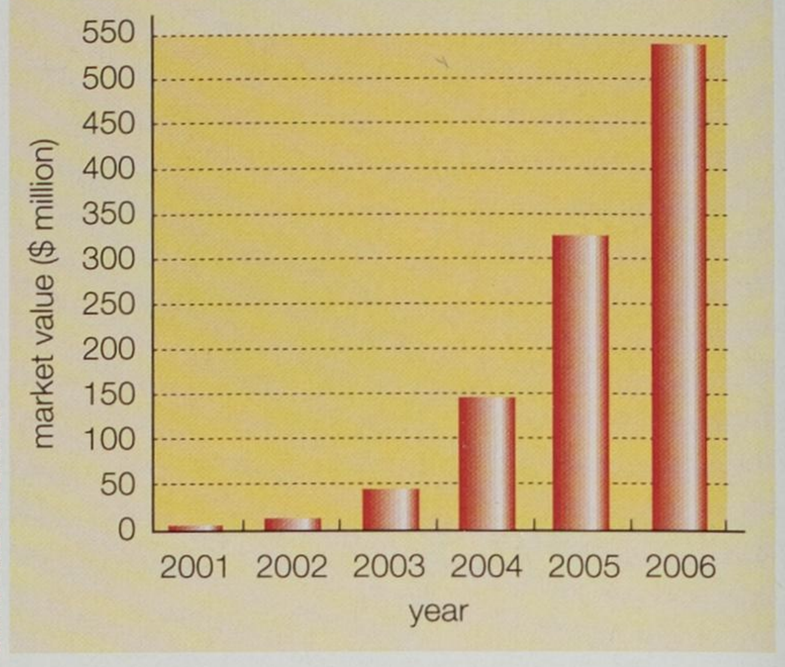
InP-based electronics ready for high growth

Although InP-based optoelectronic devices are well entrenched in optical networks and other applications, InP-based electronic devices are a relatively immature technology and are only just emerging into the marketplace. Strategies Unlimited has published a report that analyzes the growing market for InP-based electronics and reviews suppliers and major applications. The report puts the market value for InP electronic components in 2001 at $6 million, and predicts that the market will have a value exceeding $0.5 billion in 2006, a CAGR of 146%. In 2001 the market value of InP-based optoelectronic devices was $2.6 billion.

Strategies Unlimited says that there are almost 130 companies and more than 100 universities worldwide that are working on InP electronics. The report identifies the major applications as being power amplifiers for 2.5G and 3G mobile phones, and ICs for 10 and 40 Gbit/s optical networks.

Indium Phosphide Electronics 2002 – Technology Status, Applications and Market Forecasts is available from Strategies Unlimited. See www.strategies-u.com.

InP electronic components



STRATEGIES UNLIMITED

Report shows 3.8% decline in worldwide mobile-phone sales

Gartner Dataquest has published figures showing a decline in global sales of mobile phones for the first quarter of 2002. Unit sales were 93.8 million, a drop of 3.8% on sales for the same period in 2001. Although the North American market showed healthy growth, this was offset by low demand in Europe and Latin America.

The world's leading producer of handsets, Nokia, maintained its number-one position, registering a small drop in unit sales and a small increase in market share to 34.7%, compared with 34.4% in the same period last year. However, Nokia's nearest competitors experienced significant growth in their market share. Motorola's share grew to 15.5%, helped by its dominance of the large Chinese market. Third-placed Samsung added almost 50% to its share, growing to 9.6% from 6.2% in the first quarter of 2001, and its overall 2001 share reached 7.1%. Siemens grew its share to 8.8%. Samsung's impressive growth is the result of its successful strategy to manufacture a wide range of products using different technologies in different geographical markets.

A report from Strategy Analytics estimates that handset sales in North America will grow by 15% this year. Strategy Analytics expects that by 2007 CDMA handsets will account for 60% of unit sales, and 66% of the value of the North American market. The 2002–3003 period is seen as significant because replacement handset sales will begin to pass sales of handsets to new customers in North America.

Nokia updates its forecast

Nokia has further downgraded its sales growth targets for its mobile phone and wireless infrastructure businesses. The company now expects growth in its mobile-phone sales to be 0–4% in 2002, compared with the guidance of 5–10% given after its first-quarter financial results (see *Compound Semiconductor* June 2002, p23). The sales forecast for Nokia's infrastructure business has been cut from a growth of 0–5% in 2002 down to a 20–25% decline.

Gartner Dataquest's research reports are available at www.gartner.com. *North America Cellular Handset Forecasts, 2002–2007*, is available from Strategy Analytics. For further information see www.strategyanalytics.com.



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VCSELs to capitalize on transceiver sales recovery

The market for long-wavelength VCSEL-based transceivers is on the verge of recovery, predicts a report from ElectroniCast. Unit sales are expected to reach 16,000 this year, and are then predicted to rise to 111,000 in 2003. "Early production deployments [of 1310 nm VCSELs] are expected by 2003, when these new VCSELs are proved to be reliable," commented Saba Hailu, a senior analyst with ElectroniCast. "New transceiver designs are slated to take advantage of these components."

Hailu expects that, with time, 1310 nm VCSELs will become more widely used in singlemode transceivers for Gigabit Ethernet and Fibre Channel applications. "VCSELs will compete with low-cost Fabry–Perot edge-emitters and uncooled DFB edge-emitters [in transceivers]," explained Hailu. "These transceivers will not be used in new applications, [but rather] in applications where singlemode transceivers are already in use."

According to ElectroniCast, the VCSEL-based transceiver market grew from $245 million in 1999 to $388 million in 2000. The market then dropped to $290 million in 2001, following the downturn in the telecoms market.

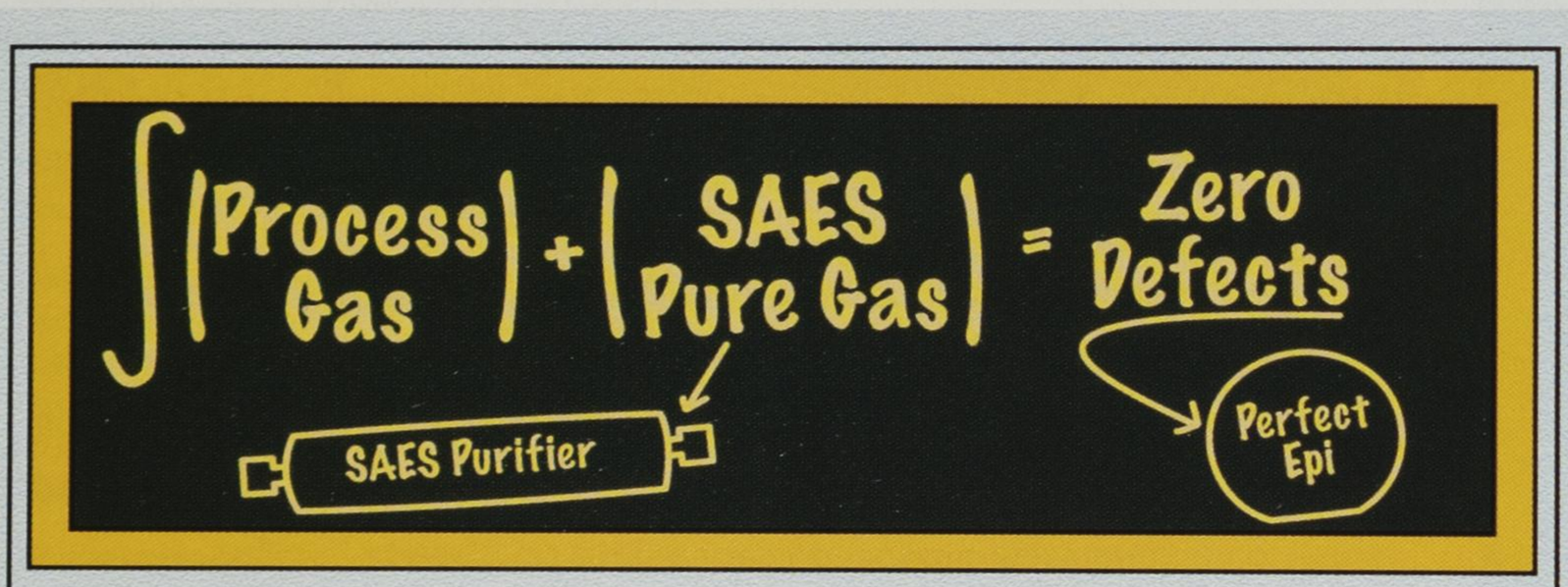
VCSELs cut costs for multifiber links

A further report from ElectroniCast says that the global consumption of multifiber transmit link components will grow rapidly from $48.7 million in 2001 to $1.25 billion in 2006. The report predicts that the growth will be most rapid in the period from 2001 to 2003. Multifiber transmit links are most commonly used in short-distance interconnects, such as from building-to-building and in intra-cabinet links.

The growth in the use of multifiber transmit links is being driven by the increasing level of data traffic that is in turn forcing the use of optical interconnects in servers, routers and other traffic management equipment. These relatively short links are an important application for VCSELs that, as yet, do not have the power output required to transmit over long distances.

"The VCSEL has emerged as the lowest cost optical solution in this application," said ElectroniCast's founder and chairman Jeff Montgomery. "The performance of VCSELs is advancing rapidly to higher data rates, higher output powers and both singlemode and multimode 850 and 1310 nm devices," added Montgomery. "It is not surprising that several multifiber transmit link competitors have a strong base in VCSEL research and fabrication."

VCSEL Transceiver Global Market & Technology Forecast and *Multifiber Transmit Link & Components Forecast* are available from ElectroniCast. For further information see www.electronicast.com.



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Global GaAs IC market set to reach $2 billion in 2002

According to a report by the market research company The Information Network, the worldwide market for GaAs ICs will grow to $2 billion in 2002, a rise of 16%, and will reach $4.2 billion in 2005. RF Micro Devices is expected to remain the market leader in 2002 after accounting for a 16.1% share of the market in 2001. The report says that GaAs will increase its share in the front-end transmitter portion of mobile handsets, overtaking silicon, thanks to performance benefits and the lowering of costs brought about by the use of HBT and PHEMT technologies, and production on 6 inch GaAs wafers.

The Information Network assigns the market growth that is expected in 2002 to an upturn in the demand for cellular handsets. However, Nokia's further lowering of its 2002 sales forecast (see page 20), and RFMD's lowering of revenue expectations for the quarter ending June 30, 2002 (see page 64), suggest that the growth in handset sales may be slower than predicted by many earlier this year.

The GaAs IC Markets is available from The Information Network. For further information see www.theinformationnet.com.

Akzo Nobel and Mochem in metalorganics merger

Akzo Nobel's High Purity Metalorganics (HPMO) unit and Mochem GmbH of Marburg in Germany have signed a letter of intent to form a new metalorganics business. Akzo Nobel will acquire all of Mochem's stock as part of the transaction, after which Mochem will become a part of Akzo Nobel. Both parties are still deciding if Mochem will retain its name and how the new entity will be organized.

Founded in 1993 as a spin-off from the Material Science Center at Philipps-University, Mochem is a leading manufacturer of liquid group V products such as tertiarybutyl arsine, tertiarybutyl phosphine and dimethyl hydrazine. Before shipping, the company's products are tested using epitaxial growth and characterization of test layers in a procedure called Epi-Proof.

Akzo Nobel complements Mochem's group V materials with a range of group III metalorganics for MOCVD and CBE, including trimethyl gallium, trimethyl indium (TMI) and trimethyl aluminum. The company expanded its Deer Park facility in Houston, TX, last year to meet the demand for TMI, increasing its production capacity by 50%.

"This deal puts together an excellent combination of group III with group V metalorganics, of manufacturing and engineering capabilities with sophisticated semiconductor know-how, and of global sales and logistics reach with proven epitaxial certification," said Barry Cottrell, global business manager for Akzo Nobel HPMO. "It is another step in our long-term plan to support the development of compound semiconductors."

"A small company like Mochem joining with a big player such as Akzo Nobel has many advantages, including access to an established worldwide network of logistical supply and sales operations," said Mochem's CEO Arnd Greiling.

Epichem relocates Haverhill facility

Five years after opening its Haverhill, MA, plant, Epichem is moving to a larger purpose-built facility in Haverhill. The new site will house Epichem's US production, analysis, R&D and customer training activities for its metalorganic (MO) products. The site has room for future expansion and the addition of new product lines. Beginning in June and scheduled for completion in July, all existing equipment will be transferred to the new facility.

● Epichem has installed an EpiFill system for TMG delivery at IQE's Cardiff, UK, facility. EpiFill is an automated system for refilling MO bubblers on MOCVD tools from bulk storage vessels. It is designed to reduce reactor downtime due to bubbler changes and qualification. Safety is also improved by minimizing the risk of staff exposure to the MO chemicals.

Equipment sales

● **Epitech Corporation**, an epiwafer manufacturer located in Tainan, Taiwan, is to buy several GaN LED production MOCVD systems from **Thomas Swan Scientific Equipment**. These include two reactors with capacities of 6 × 2 inch and 19 × 2 inch wafers. The companies have also signed an exclusive agreement for technical collaboration relating to GaN LEDs.

● Taiwanese foundry **Suntek Compound Semiconductor**, has ordered a 943NTX in-line sputtering system from **KDF**. The machine has a planetary pallet for GaAs wafer production.

● **Bede Scientific Instruments** is installing a combined high-resolution X-ray diffractometer and scanning photoluminescence system at the Semiconductor Epitaxy and Analysis Laboratory (SEAL) at **Ohio State University**. The new instrument allows compound semiconductors to be simultaneously studied using X-ray diffraction and photoluminescence.

● **Riken** of Wako, Japan, has recently acquired an **Aixtron** AIX 200/4 RF-S MOCVD reactor for the growth of GaN/AlGaN epitaxial wafers.

LayTec expands and teams with EpiServe

LayTec, a manufacturer of optical *in situ* monitoring tools for epitaxial reactors, located in Berlin, Germany, has moved from the Technical University to larger laboratory and office facilities within the city. LayTec has also formed an alliance with EpiServe of Munich (formerly Riber GmbH). EpiServe will provide sales and marketing services for LayTec's products.

Greene, Tweed opens office at SMC

Greene, Tweed, a maker of seals and plastic and ceramic parts for plasma and wet chemical semiconductor processing tools, has opened an office at the Scottish Microelectronics Centre (SMC) in Edinburgh. This will give Greene, Tweed access to a range of semiconductor process equipment in use at the SMC, allowing the company to test and develop its products.

TePla merges with vacuum company

Plasma etch and cleaning tool specialist TePla of Feldkirchen, Germany, has agreed to merge with another German company, PVA Vakuum-Anlagenbau, which makes vacuum furnaces and crystal growth systems.

Suss signs probe test systems deal

Innovative Microelectronic Production Systems (Imps) is to represent Suss MicroTec for sales and service in the UK and Ireland of Suss probe systems for electronic and optoelectronic device test and measurement.

StratEdge receives packages patent

StratEdge has received a Republic of China patent, no. NI-118360, for its family of high-frequency passband microelectronics packages. The DC-23 GHz ceramic packages provide an interconnect system that ensures electrical integrity, mechanical protection and thermal control in the harshest environments for high-frequency GaAs MMIC devices.

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RIBER

Products and Services for the Compound Semiconductor Industry

AmberWave and Aixtron develop CVD equipment for SiGe and strained silicon

AmberWave Systems and Aixtron have signed a licensing and development agreement to jointly develop and qualify CVD equipment for the production of SiGe and strained-silicon epitaxial layers.

The move follows AmberWave recently licensing its strained-silicon technology to IQE Silicon Compounds to accelerate the volume epitaxial production of high-mobility strained-silicon layers for CMOS circuits (see *Compound Semiconductor* May 2002, p15).

The three-year worldwide license lets Aixtron access AmberWave's technology to continue the development of both single and multiwafer strained-silicon epitaxy equipment. Aixtron has installed two AIX 2600G3 systems at AmberWave's R&D facility in Salem, NH, to facilitate basic research into SiGe growth on 150 and 200 mm Si substrates. However, AmberWave operates on a fabless business model that relies on royalties from design teams licensing its intellectual property to fabricate chips.

"This is another step towards bringing SiGe technology into the mainstream," said Mark Wolf, CEO of AmberWave. "Working with Aixtron to optimize their equipment will allow us to provide the industry with the lowest-cost solution for strained silicon."



AIXTRON

The Tricent CVD cluster tool will be used to develop AmberWave's III-V on silicon technology on substrates of up to 300 mm.

"Working with Aixtron will allow us to provide the industry with the lowest-cost solution for strained silicon."

AmberWave manufactures strained-silicon MOSFET circuits by growing a graded layer of SiGe several micrometers thick on a bulk Si wafer. A thin layer of silicon is grown on top of the SiGe buffer, and is strained as a result of lattice mismatch to the larger SiGe lattice. Electron mobility in the strained silicon is higher than in the standard silicon used in CMOS devices.

However, the growth of the graded SiGe layer produces dislocations as the material relaxes to accommodate lattice mismatch. This lattice relaxation leaves a roughened SiGe surface that must be smoothed to provide a planar surface for growing a high-quality strained-silicon channel layer. AmberWave has developed a proprietary chemical mechanical polishing (CMP) technique to planarize the SiGe surface. Strained-silicon FETs also enable standard CMOS processing steps to be used, says the company.

Ge surface for GaAs epitaxy

AmberWave says it can also produce high-quality Ge surfaces that provide a good lattice match to GaAs using a graded SiGe layer grown on a silicon wafer. The company has demonstrated GaAs MESFETs and solar cells on Si and was recently awarded a Phase II SBIR grant for GaAs/SiGe/Si optoelectronics development.

Meanwhile, Aixtron has said that it intends to further develop AmberWave's III-V on silicon technology on 300 mm silicon substrates using its Tricent CVD cluster tool.

SiGe Semiconductor unveils TIA designed for 10 Gbit/s networks

SiGe Semiconductor of Ottawa, Canada, has unveiled a new 10 Gbit/s transimpedance amplifier (TIA) for use in short-reach, metro-access and long-haul optical networks. The SE1050 is the first in a planned series of 10 Gbit/s physical-layer ICs to include limiting amplifiers, EA modulator drivers, DFB laser drivers and VCSEL drivers, scheduled for later this year.

Available as bare die, the SE1050 operates from a 5 V supply and delivers 9.8 GHz of bandwidth and 1200 Ω transimpedance, in addition to providing a sensitivity of –20 dBm for a 10^{-10} bit-error-rate.

RFMD and Sirenza launch SiGe devices

RF Micro Devices has launched its first GPS receiver designed for asset tracking and automotive navigation systems. The RF8000 uses a SiGe RF front-end and has a 38 × 38 mm^2 footprint. RFMD gained a fast track into the GPS business when it acquired IBM's GPS unit earlier this year (see *Compound Semiconductor* Jan/Feb 2002, p4).

Also, Sirenza Microdevices has expanded its SiGe-based active-mixer product family. The STM-2226, -2116 and -3116 mixers have been designed specifically for use in 2G, 2.5G and 3G wireless base-station IF to RF up-conversion. The devices are now sampling and should be available in production quantities in September.

Milestone shipment for IBM's SiGe chip

IBM's 100 millionth SiGe chip was dispatched from its Burlington, VT, fab in May to Tektronix. IBM was the first company to produce SiGe devices in high volume and has licensed its technology to various companies. IBM's production accounted for more than 80% of the global SiGe business in 2001.

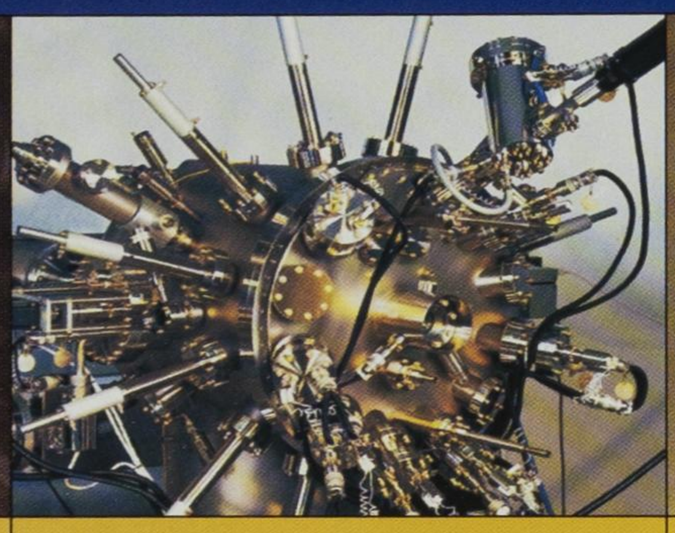
EpiFill system is used to deposit Al oxide

Epichem has installed its EpiFill automated metalorganic precursor delivery system (see p23) onto a Veeco Instruments Nexus atomic-layer deposition (ALD) tool. EpiFill delivers TMA to the tool for the deposition of aluminum oxide. This is the first time the system has been used in this application.

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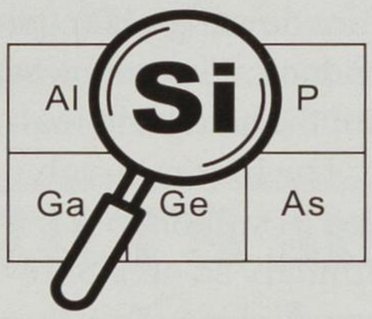
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WITH BOB METZGER

A new spin on compound semiconductor devices

Compound semiconductor materials are ideally suited for the development of spintronic devices thanks to the ability to epitaxially grow ferromagnetic metals on their surfaces.



By using modest external magnetic fields, the relative collector currents in these spin-valve transistors could be increased by 240%.

At the most fundamental level, electronic devices, whether fabricated out of silicon, III-Vs, II-VIs, or even metal and glass in the case of vacuum tubes, operate through the manipulation of a charged particle (usually an electron) by an electric field. While relying on the charge of an electron to control motion has without doubt led to the implementation of devices with an almost infinite range of capabilities and performances, there exists another characteristic of the electron that has been totally ignored. This characteristic could be used to manipulate motion just as easily as an electric field does.

Moving electrons with magnetism

An electron can be viewed as a spinning sphere of charge. For those of us who can dredge up those old memories from our undergraduate electromagnetics courses, a spinning charge generates a magnetic field. In the case of the electron, this magnetic field is referred to as its spin, with the direction of the magnetic field pointing up or down depending on the direction of the electron's rotation. Of course an electron cannot be treated as a classical sphere, but it is a quantum mechanical object in which the spin (or magnetic strength) is quantized to a value of one half its angular momentum – a fixed quantity. But still, a magnetic field can be used to manipulate the electron.

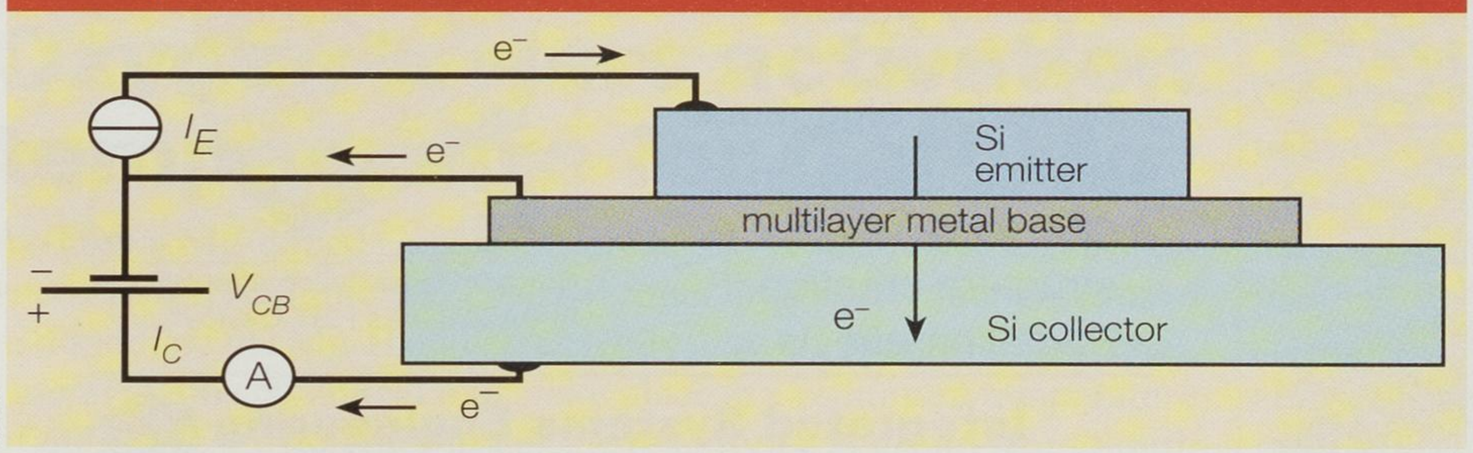
The key to controlling an electron's motion is by the use of external magnetic fields that can align the direction of the electron's spin. While this behavior has yet to be exploited in commercial electronic devices, it is the key element in state of the art read heads within magnetic hard-disk drives, through the use of the giant magnetoresistance (GMR) effect. When a layered magnetic thin-film structure consisting of alternating ferromagnetic and nonmagnetic layers is exposed to an external magnetic field, the spin directions of the electrons in the ferromagnetic layers align. This minimizes the spin-dependent scattering of carriers moving through the material and thereby reduces the thin film's resistance. When the spins in the material are anti-aligned, scattering is maximized and resistance is increased. These changes in resistance can now be obtained with very small changes in magnetic fields, hence the name GMR. The very small magnetic domains in hard disks can therefore be read, since these small domains induce large resistance changes in a GMR hard-disk drive head.

GMR-based devices

To extend the exploitation of GMR to electronic devices, an obvious approach would be to introduce the ferromagnetic layers between two semiconductor layers, in an analogous manner to a metal-base transistor, to create what is called a spin-valve transistor (Kim *et al.*).

Researchers at the University of Twente in the Netherlands have recently reported such a device in which the spin-valve transistor is formed by using an n-type Si emitter and collector, and a ferromagnetic/nonmagnetic-layered base consisting of a Pt/$Ni_{0.8}Fe_{0.2}$/Au/Co/Au stack (Monsma *et al.*). Using a Si/Pt Schottky diode at the emitter, operating under forward bias, ballistic electrons are injected into the emitter at an energy of 0.9 eV. When these high-energy electrons enter the base, they experience scattering dependent on the alignment of the electron's spin within the base material. Therefore, just as in GMR-based disk drives, transport through the base's metallic stack can be manipulated by an applied magnetic field that realigns the electron's spin. By using modest external magnetic fields ranging up to field strengths of 60 Oe, it was observed that the relative collector currents in these spin-valve transistors could be increased by 240%. While such a device as currently configured has few practical applications, it clearly demonstrates the manipulation of transport behavior through an electronic device as a result of external magnetic fields and the subsequent control of electron spin.

The spin-valve transistor



AAAS

When electrons enter the base, they experience scattering that is dependent on the alignment of the electron's spin within the base material. Electron transport through the base's metallic stack can therefore be manipulated by an applied magnetic field that realigns the electron's spin.

The ability to epitaxially grow a spin-valve transistor structure would simplify processing and could open up a wider range of device types and performance capabilities.

An obvious question when considering such a device is in the fabrication sequence used to place the metallic layer between the emitter and collector. In an approach similar to that of the wafer bonding techniques used to insert an SiO_2 layer beneath a thin Si layer and a Si substrate, the metallic spin-valve base layer is deposited on a n-type Si substrate. A second Si wafer is bonded to the metallic layer, and then etched back to form the emitter layer. Unfortunately, such bonding techniques double substrate costs, increase processing complexity, and decrease overall device yields.

Compound semiconductor spintronics

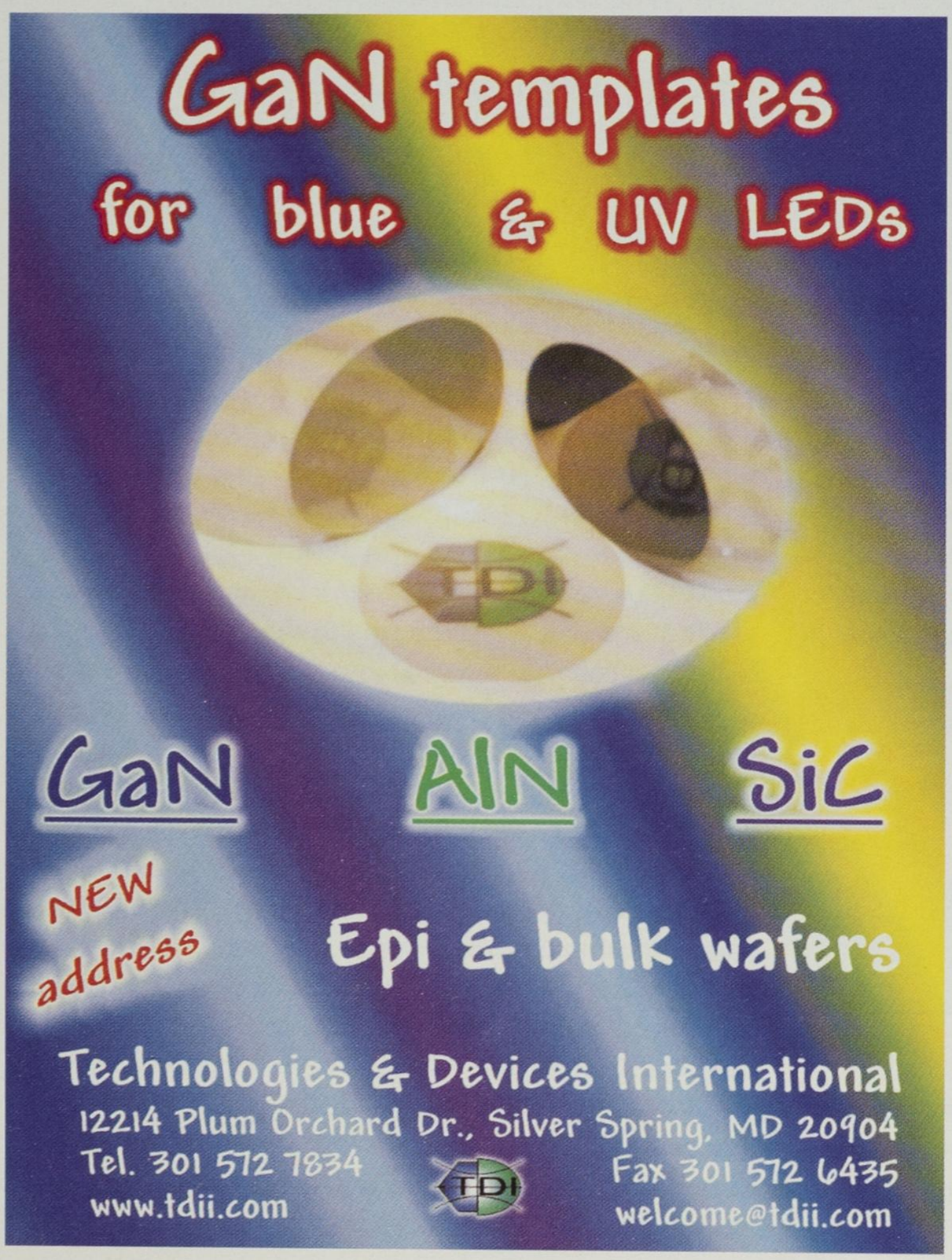
Despite the fact that these first spin-valve transistors were fabricated in the Si-material system, there was nothing inherently unique to Si that made these devices work. In fact, it was the use of Si that dictated the necessity of implementing the wafer bonding approach to fabricate the metallic base, due to the lack of suitable ferromagnetic materials that could be epitaxially grown on Si. The ability to epitaxially grow a spin-valve transistor structure, or other electronic devices that exploit the behavior of an electron's spin rather than its charge (collectively referred to as spintronic devices), would simplify processing and open up a potentially wider range of device types and performance capabilities.

While many epitaxial metals and semiconductors can be grown on compound semiconductor substrates, only those that exhibit ferromagnetic behavior at room temperature would be practical for spintronic applications. Fortunately, investigators are beginning to identify such materials, including Fe and Fe–Co alloys on GaAs, and zincblende CrSb/GaAs/CrSb layers, along with (Ga,Mn)As and (In,Mn)As alloys. In addition, it has been shown that in some Mn-doped III-V materials the normally paramagnetic Mn ions can exhibit ferromagnetic behavior in the presence of light, which offers another element of device control beyond that of simply using magnetic fields (Wolf *et al.*).

The extensive epitaxial capabilities developed for the manufacture of compound semiconductor devices now make these devices ideally suited for the study and realization of many spintronic devices. The first spin-valve transistor may have been fabricated in silicon, but the overall subject of spintronics is definitely an area of research, and hopefully eventual commercial products, that could be dominated by compound semiconductors. ●

Further reading

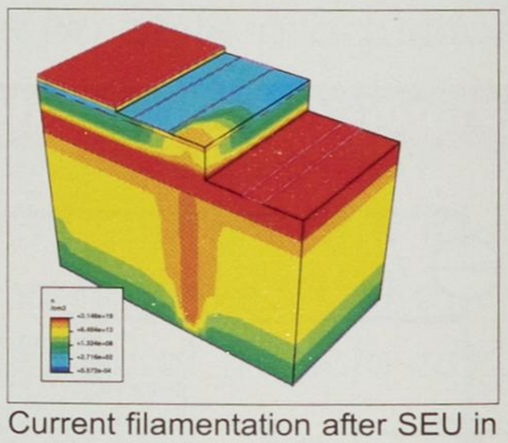
Kim *et al.* 2002 *Trans. Elec. Dev.* **49(5)** 847.
Monsma *et al.* 1988 *Science* **281** 407.
Wolf *et al.* 2001 *Science* **294** 1488.



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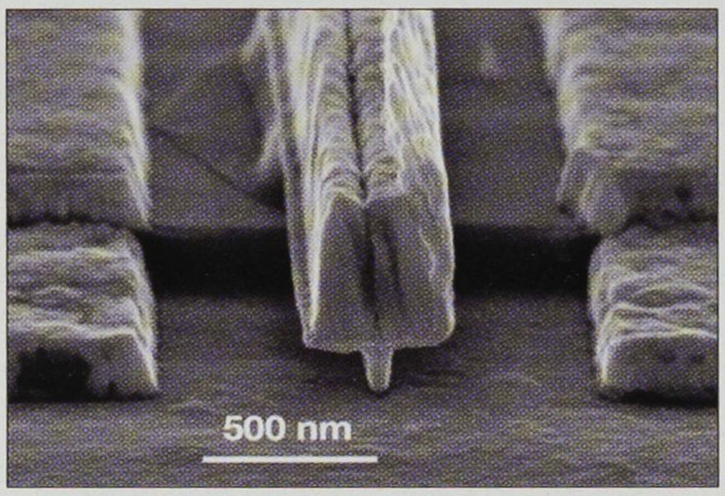
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IEMN achieves record f_{max} for MHEMT

Sylvain Bollaert and colleagues from the IEMN in France have reported what they believe to be the highest f_{max} to date for a metamorphic device grown on a GaAs substrate. The InAlAs/InGaAs MHEMT had extrapolated f_t and f_{max} values of 260 and 490 GHz, respectively (*Elec. Lett.* 2002 **38(8)** 389).

A 1.3 μm InAlAs buffer layer was grown on a GaAs substrate, with the In content graded from 1% at the substrate up to 52%. A 25 nm $In_{0.53}Ga_{0.47}As$ channel layer was then grown, followed by a 5 nm $In_{0.52}Al_{0.48}As$ spacer layer, onto which the Si delta-doping was deposited with a coverage of 6×10^{12} atoms/cm^2. A 15 nm $In_{0.52}Al_{0.48}As$ Schottky barrier layer was then grown and capped with a 10 nm Si-doped InAlAs layer. Room-temperature Hall measurements gave values for carrier density and Hall mobility of 4.18×10^{12}/cm^2 and 9180 cm^2/Vs, respectively.



IEE

An SEM image of the IEMN 60 nm gate length metamorphic HEMT that gave an extrapolated f_{max} value of 490 GHz.

T-gate HEMTs were fabricated with 60 nm gate lengths, and the devices exhibited excellent I-V characteristics, with a pinch-off voltage of –0.8 V demonstrating that short channel effects were minimal. An I_{ds} of more than 600 mA/mm was observed at a drain-source voltage of 1.6 V, with an extrinsic transconductance (g_m) of 850 mS/mm.

DLTS adds weight to virtual-gate theory

AlGaN/GaN power transistors show a characteristic drop in drain current at high voltages. This has been blamed on the presence of surface states that act as electron traps to form a second so-called virtual gate. To overcome this, Si_3N_4 films are used to passivate the surface, though the exact passivation mechanism is not yet understood. Vertiachikh *et al.* from Cornell University have reported using deep-level transient spectroscopy (DLTS) to monitor the changes that passivation makes to trap-states (*Elec. Lett.* 2002 **38(8)** 388).

DLTS spectra were measured for devices with and without a Si_3N_4 passivation layer. The spectra show similar features, with two trap states, E_1 and E_2, visible in both. The amplitude of the signal for E_2 was five times greater for the unpassivated device. The close proximity of the observed trap energies for the two types of device indicated that the same trap was being observed in both cases. These observations support the theory of the generation of a virtual gate and further highlight the need for careful surface passivation to achieve good RF performance.

Sapphire nitridation controls GaN surface polarity

The nitridation of a sapphire surface is an important step that influences the polarity of a GaN surface and its crystal quality during growth by plasma-assisted MBE. However, a clear understanding of the nitridation process and its effects has yet to be established. A team from the University of Crete has published the results of an investigation of the effects of nitridation temperature on the GaN surface polarity (*Appl. Phys. Lett.* 2000 **80(16)** 2886). Significant differences in the nitridation were seen at low (~200 °C) and high (~750 °C) nitridation temperatures, with the amount of nitridation at 750 °C being significantly higher than has generally been reported before.

TEM studies of subsequently grown GaN/Al_2O_3 heterostructures allowed the sapphire surface nitride layer to be observed directly. The nitride layer thickness was approximately 1.5 nm for 100 mins nitridation at 750 °C. The nitridation effect at 200 °C was limited to one atomic plane. The sapphire nitridation (controlled by the substrate temperature) controls the polarity of GaN epilayers when a low-temperature GaN buffer layer is used. Low-temperature nitridation resulted in N-face material while the Ga-face polarity dominated for high-temperature nitridation. The polarity was determined by RHEED and selective etching experiments with a KOH solution. A significant roughness occurred on the etched N-face that could be easily observed by AFM. Ga-face GaN could also be grown after a low-temperature nitridation step if an AlN buffer layer was used instead of a GaN buffer. The group attributed its results to the Ga-face being the energetically favorable polarity for heterostructures grown onto deposited AlN-on-sapphire after a low-temperature nitridation, or growth onto AlN formed on the sapphire by high-temperature nitridation. This is in agreement with theoretical calculations.

Oxygen lowers activation temperature for GaN:Mg

As-grown Mg-doped GaN layers are highly resistive due to the presence of Mg-H complexes. Thermal annealing in a N_2 ambient is used to dissociate the Mg-H and electrically activate the p-GaN material. However, this N_2 anneal must take place at a minimum temperature of 600 °C to sufficiently lower the resistivity. A group from South Epitaxy Corporation and the National Cheng-Kung and National Central universities in Taiwan have achieved low-resistivity Mg-doped GaN layers by annealing in an oxygen ambient at temperatures down to 400 °C (*Elec. Dev. Lett.* 2002 **23(5)** 240).

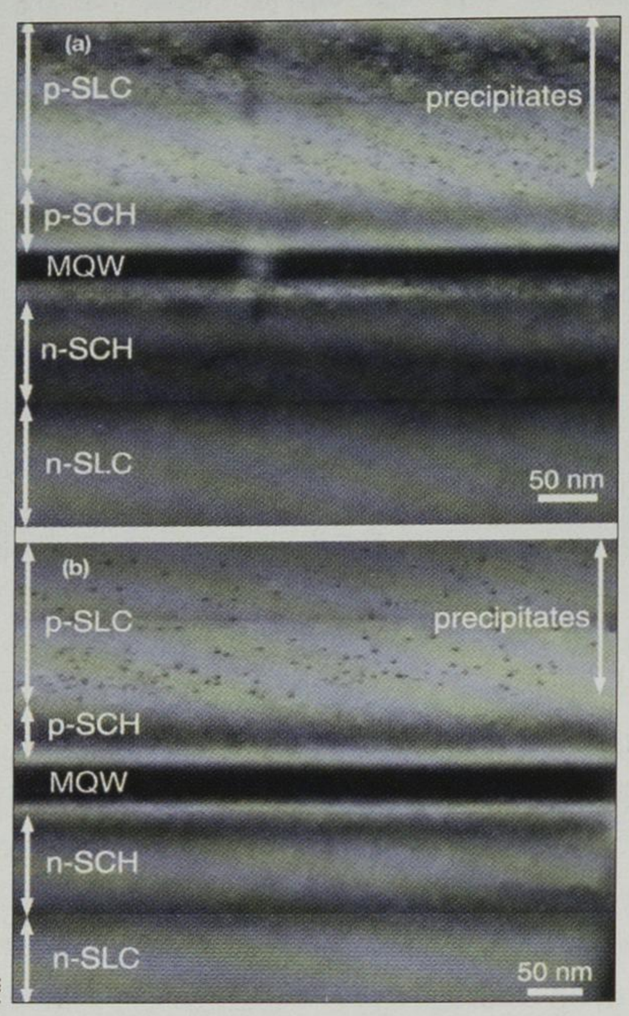
The group has interpreted its findings as the removal of H from the GaN surface by efficient reaction with O_2, lowering the H concentration in the GaN and thus improving the Mg activation during the anneal. LEDs were fabricated and annealed in O_2 and N_2 at a range of temperatures. At 500 °C the O_2 anneal gave lower resistivity material, lowering the forward voltage for the LED. Lifetime testing of the devices showed that the luminous intensity after 170 hours of operation was almost unchanged for LEDs annealed in O_2 at 500 °C, and those annealed in N_2 at 700 °C. For LEDs annealed in N_2 at 500 °C the intensity dropped by 35% over the same period. This is the result of incomplete activation of the Mg-doped GaN, leading to higher resistance material that hinders current spreading, and resulting in LEDs that require higher current for a given light output, thus increasing stress on the material.

Lower Mg doping in GaN raises carrier concentration

The high ionization energy of the Mg acceptor in GaN has created stumbling blocks to obtaining low resistivity p-type films. The high resistivity of the Mg-doped layers is responsible for a significant amount of the operating voltage in laser diodes, and is a key obstacle to obtaining CW operation.

Monica Hansen and colleagues at the University of California, Santa Barbara have used TEM to observe uniformly distributed precipitates in the Mg-doped layers of laser structures grown by MOCVD (*Appl. Phys. Lett.* 2002 **80(14)** 2469). The laser structure consists of a three-period InGaN/InGaN:Si MQW active region with an Mg-doped separate confinement heterostructure (SCH) and superlattice cladding (SLC) layers above the MQW, and Si-doped SCH and SLC layers below the MQW.

Precipitate density is in the mid-10^{15} cm^{-3} to low-10^{16} cm^{-3} range (see figure). The precipitate density decreases with decreasing flow of biscyclopentadienyl-magnesium (Cp_2Mg), which is used as the dopant gas, but the hole concentration for the reduced Cp_2Mg flow is a factor of two higher than the standard Cp_2Mg flow. The presence of the precipitates indicates that the solubility limit of Mg in GaN is exceeded, causing a decrease in hole concentration because much of the Mg is not incorporated at the desired substitutional site but in the form of Mg-rich precipitates.



Cross-section TEM of the laser structure, showing the precipitates in the p-type layers for the standard (a) and the reduced (b) Cp_2Mg flow.

The operating characteristics improved for the laser diode with a reduced Mg doping level. For a 3×400 μm^2 device, the threshold current decreased from 363 to 221 mA, and the threshold voltage decreased from 20.8 to 14.3 V when the Cp_2Mg flow was reduced. The improvement of the threshold current can be attributed to the increase in the internal quantum efficiency, which is 13.9% for a reduced Cp_2Mg flow and 7.6% for the standard Cp_2Mg flow. The higher hole concentration means that more holes are available for radiative recombination, which improves the internal quantum efficiency of the laser. The lasers with higher precipitate density also exhibited a resistance twice that of lasers with the reduced Cp_2Mg flow, which corresponds to at least a 5 V increase at threshold current levels. The threshold voltage was reduced by 30% for lasers with a lower precipitate density due to the lower resistance.

How About UV-LED?



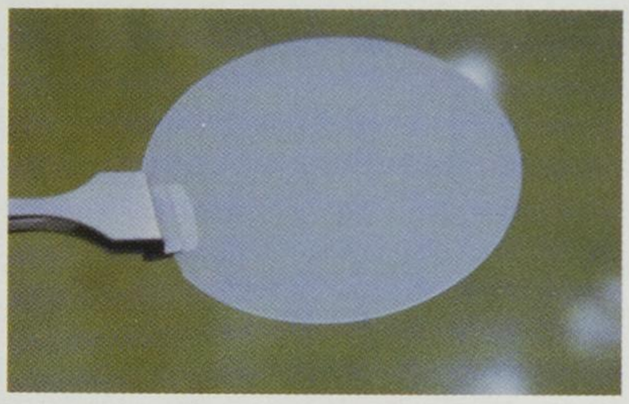
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Japanese team develops highly efficient UV-LEDs with laser diode potential

One way to generate white light from an LED is to combine a GaN-based UV-LED with phosphor material. This is one application that is driving the extensive investigations into high-efficiency UV-LEDs which are currently underway in many laboratories (see page 49). A collaborative effort between researchers at Yamaguchi University, Mitsubishi Cable and Stanley Electric in Japan has yielded UV-LEDs emitting at 383 nm and with an output power of 15.6 mW. The external quantum efficiency of 24% at room temperature is believed to be the most efficient reported to date (*Jpn. J. Appl. Phys.* 2002 **(Pt. 1, 4B)** 2484).

The InGaN UV-LEDs were grown by lateral epitaxy on patterned sapphire substrates using MOVPE. With increasing forward current, the luminescence intensity was not saturated and increased linearly with increasing injection current up to 50 mA. The emission peak was seen to shift to lower energies as forward current increased from 10–70 mA. Temperature-dependent measurements showed that the energy shift with current was negligible at 4 K, but became more pronounced as the temperature increased. This indicated that the wavelength shift was due to heat generation at higher currents.

Under pulsed current conditions at room temperature, the luminescence intensity increased linearly with increasing injection current up to 1000 mA (7 kA/cm^2), and no shift in the position of the electroluminescence peak was observed. These results indicated that the injected carriers were confined efficiently in the active layer, and also suggested the possibility of realizing UV laser diodes.

Dual metal SiC Schottky diode reduces power loss

SiC Schottky diodes with blocking voltages of up to 600 V are now commercially available and exhibit lower switching losses and higher switching speeds than high-power silicon *pin* diodes. To minimize power losses, the diodes must have a high ratio of forward to reverse current under operating bias conditions. K Vassilevski and colleagues at the University of Newcastle upon Tyne, UK, have developed a novel dual metal planar (DMP) Schottky contact that reduces reverse current and thus maximizes the on/off current ratio (*Trans. Elec. Dev.* 2002 **49(5)** 947).

Current under reverse bias is mainly the result of current flowing through the Schottky contact periphery, whereas current under forward bias results from flow through the entire contact area. To reduce current flow through the contact periphery the Newcastle group used a 1 μm strip of nickel to surround the titanium contact. The Ni surround has a higher barrier height (1.6 eV) than the Ti contact (1.27 eV), and this acts to reduce the reverse current without increasing the forward voltage drop. The on/off current ratio at 1 V/500 V was 5.6×10^8 for the Ti/Ni DMP Schottky diode. This exceeded the on/off ratios for Ti/SiC and Ni/SiC Schottkys fabricated on the same wafer, which were 4.7×10^7 and 7.4×10^3, respectively. The current ratio also exceeded figures published elsewhere for SiC Schottkys of similar breakdown voltage.

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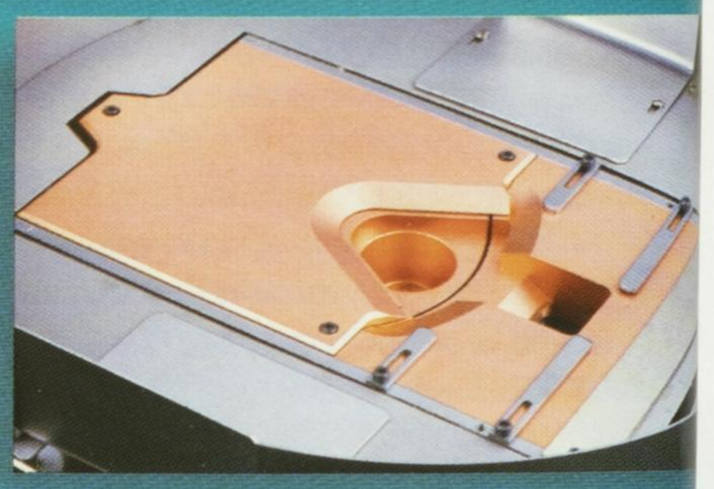
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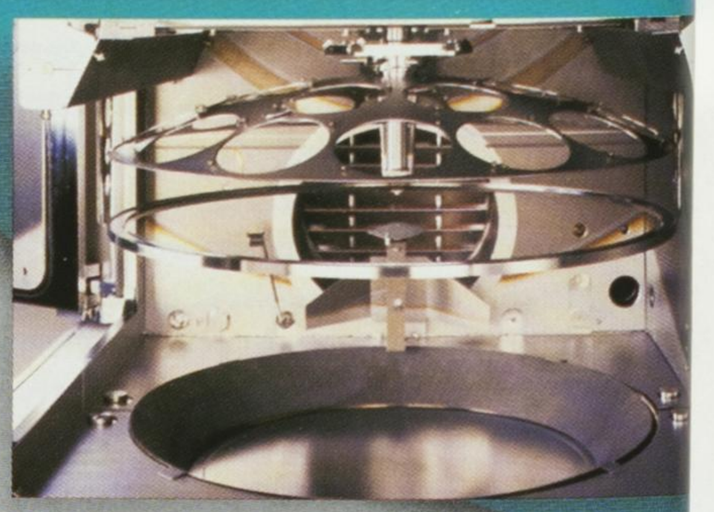


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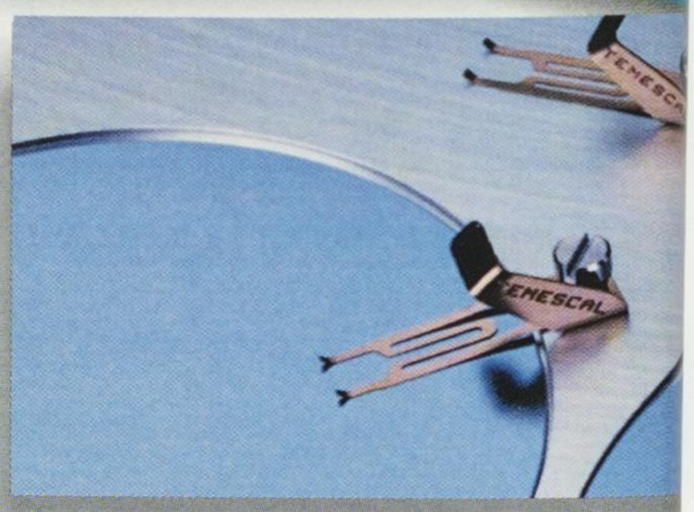


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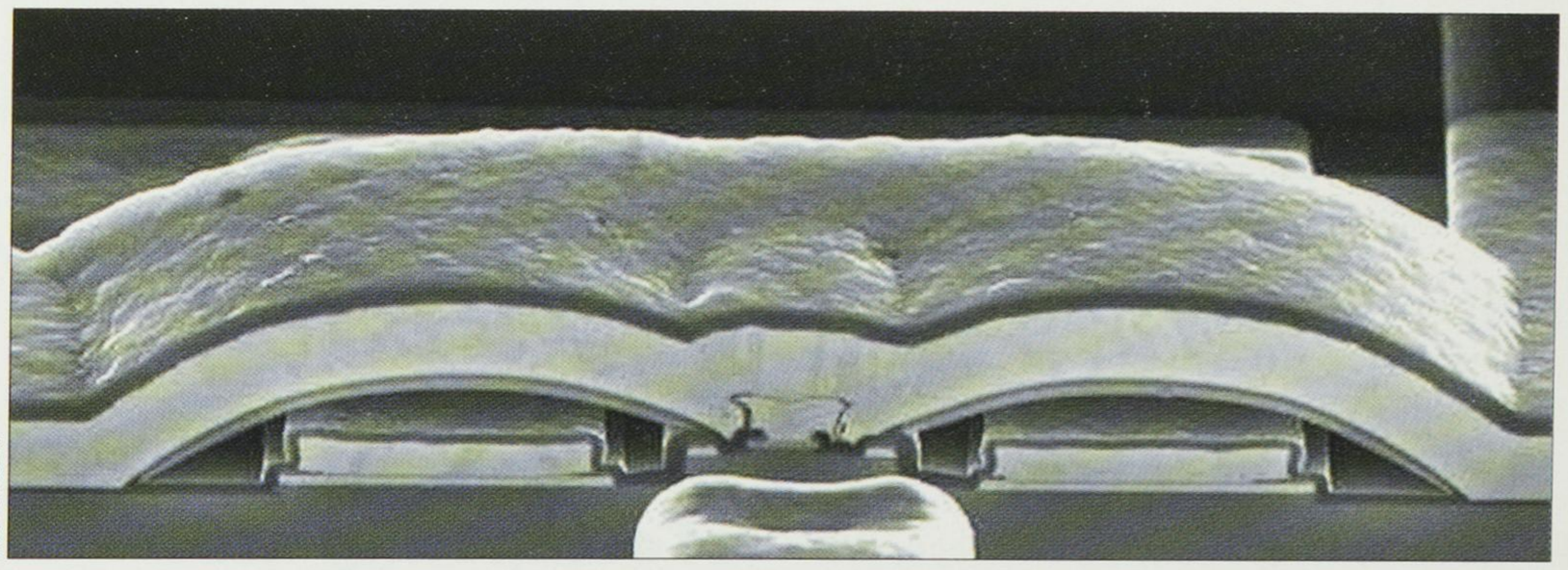


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Mantech heralds better times ahead for the GaAs industry

Business conditions might have been difficult lately, but as **Jon Newey** discovered at GaAs Mantech, the GaAs industry is busy developing new technologies and business plans to address the market as growth returns.



MOTOROLA

Fig. 1. A cross-section through Motorola's InGaP HBT, showing the metal airbridge interconnect that is designed to reduce parasitics and thermal resistance.

The past year has been a time of great upheaval for the GaAs industry. Watching the market for compound semiconductor devices and materials contract sharply and wondering when signs of growth will return makes business planning very difficult. Such an environment also makes setting conference themes a risky undertaking. Coming hot on the heels of a huge upturn in demand for compound semiconductor products, the theme of the 2001 GaAs Mantech meeting held in Las Vegas was "Meeting the Challenges of Explosive Growth". By the time the delegates met in Las Vegas in late May last year, many of them were already dealing with the effects of a downturn in their businesses.

This year's conference theme was "New Challenges, Great Opportunities", chosen no doubt to put the events of the last year in some sort of positive light. Indeed, the talk in the technical sessions, and more informally around the booths of the 90 companies in the exhibit, was of the myriad ways that businesses are adapting to the new tough operating environment they now find themselves in. These not only include the adoption of new technologies and methods of manufacture that are designed to lower costs and improve yields, but also consolidation within the industry. For example, Conexant's wireless business has recently merged with Alpha to form a separate company called Skyworks Solutions, and Infineon is getting out of GaAs manufacturing altogether by selling its GaAs business to TriQuint (see *Compound Semiconductor* June 2002, p3).

Modules are essential for success

Earl Lum of CIBC World Markets gave the opening talk of the conference with a summary of CIBC's recent global market handset forecast (see *Compound Semiconductor* April 2002, p63). CIBC has identified trends that will determine the leaders in the GaAs IC market as growth returns this year. These trends are the transitions from MMICs to multi-chip modules and from FETs to HBTs, and supply-chain consolidation. Some suppliers have been offering PA modules for a number of years, but the majority of PAs are still ICs. The move to modules should accelerate this year, with those suppliers who can manufacture most of the components that comprise the modules running out as the winners. These companies will also be able to offer a mix of substrate and IC technologies for the modules.

HBT technology is now firmly entrenched, and is likely to become the majority of the PA market despite the continued acceptance of enhancement-mode PHEMTs as a viable alternative. Lum predicted that further industry consolidation would be likely as GaAs IC manufacturers compete for business from a decreasing number of handset OEMs.

MESFETs still going strong

With all the talk of HBTs, PHEMTs and MHEMTs that takes place at an event like Mantech, it would be easy to dismiss the implanted GaAs MESFET as an old and inferior technology that is being phased out. To some extent this is true, and the MESFET has given way to CMOS and the GaAs HBT in many applications. But Marty Brophy of TriQuint was keen to explain that there was plenty of life yet in implanted MESFETs. Brophy discussed several areas where MESFET performance is adequate, gives a distinct performance advantage over CMOS and SiGe, and is also price competitive with these technologies. GaAs MESFETs give excellent low noise performance in the lower microwave bands, low RF losses through the semi-insulating GaAs substrate and enable the monolithic integration of high-Q capacitors and inductors.

Sub-circuits consisting of a few active devices and many passives are common in microwave receivers and transmitters. Using GaAs MESFET technology, the critical RF passives can be integrated on-chip with the active circuitry. In silicon bipolar or SiGe, the passives components require precision assembly onto a PCB, a relatively time consuming and costly process.

The MESFET's place in digital electronics has been taken by CMOS and SiGe, but significant analog niches remain in OC-48 and OC-192 circuits. Here, the low noise and high f_t x breakdown-voltage product of MESFETs can be exploited by integrating a photodetector and TIA, or laser and driver, on one chip.

Following on from Brophy was E Mitani of Fujitsu Compound Semiconductors, who presented the work that the company has been doing on high-power GaAs MESFET devices for W-CDMA base stations. Fujitsu has a

240 W (53.8 dBm) output device in mass production, with a 300 W device in development. The two critical parameters for these high-power, high-linearity devices are high transconductance (g_m) and low thermal resistance. A thin highly doped channel provides a high g_m, improving both linearity and PAE. The gate dimensions are optimized for low thermal resistance, and the GaAs substrate is thinned to 28 μm and gold plated to a thickness of 30 μm to aid heat transfer. Operating at 2.14 GHz and a saturation power of 240 W, the device's linear gain is 11.5 and PAE is 54%.

HBT development

GaAs-based HBTs are now a mainstream technology for many wireless and optical communication circuits, and HBTs with InGaP emitters are now superceding those with AlGaAs emitters. At Mantech, WIN Semiconductors and Motorola discussed the development of high-yield 6 inch InGaP HBT processes. Mariam Sadaka from Motorola's CS-1 fab in Arizona described some of the critical process steps and the challenges that the company overcame to develop its InGaP HBT process.

Sadaka described the InGaP emitter etches that were developed to overcome the problems caused by the phosphorus tail from the InGaP into the top layers. This tail gives interfaces of non-uniform thickness and composition, which are difficult to etch. Though she was giving little away, Sadaka said that a phosphoric/hydrochloric acid mixture is used to etch InGaP with different degrees of ordering and excellent selectivity to GaAs. A wet etch and single layer lift-off are used to define the base TiPtAu contact. The collector is defined by a reactive ion etch using the base metal and photoresist as an etch mask.

One of the unique features of the Motorola process is the use of airbridged interconnects designed to reduce thermal resistance and parasitic losses (figure 1). The gold airbridges are ruggedized by depositing silicon nitride over them. This means they can survive subsequent backside processing and assembly steps.

Michael Hattendorf from the University of Illinois presented the results of a collaborative project with EpiWorks, aimed at investigating the effects that lateral scaling of an InP/InGaAs SHBT's dimensions has on its performance. Theory suggests that f_t should be independent of device size, while f_{max} should be inversely proportional to the square root of the emitter width.

The HBT structures were grown by EpiWorks using low-pressure MOCVD. The double-mesa HBTs were fabricated at the University of Illinois with emitter widths ranging from 0.35 to 3 μm and emitter lengths of 4, 5, 12 and 16 μm (figure 2). Values for f_t and f_{max} were measured for devices at each emitter length, and at emitter widths down to 0.35 μm.

The GaAs industry should not be afraid of competing with silicon in niche areas.

The relationship between f_{max} and emitter area was in accordance with theoretical predictions for small-area transistors. However, f_t increased considerably with decreasing emitter width, probably as a result of reduced self-heating for smaller devices. For a device with an emitter area of $0.35 \times 12\ \mu m^2$, values for f_t and f_{max} of 180 and 340 GHz were recorded. The group believes these to be the highest yet reported for an InP-based SHBT.

The metamorphic alternative to InP

With metamorphic technology being one way to extend the range of GaAs into InP territory, the session on metamorphics drew much interest. Speakers represented most of the key protagonists in this area, including Raytheon who along with OMMIC announced the availability of a commercial MHEMT process in 2001. Indeed, 2001 was the year that metamorphic technology really came to the fore, not only with high indium content devices on GaAs, but also with the announcement of the successful development of a GaAs-on-silicon process by Motorola and IQE (see *Compound Semiconductor* October 2001, p47).

At Mantech there seemed to be much skepticism that InP would ever be cost-effective enough to seriously challenge GaAs, except where InP was the only choice, such as in the monolithic integration of electronic functions with 1310 and 1550 nm optical functions. Incremental improvements in GaAs device performance will be demanded in future from applications where GaAs currently has a foothold. The feeling at the conference seemed to be that metamorphic technology would supply the necessary performance gains and at a lower cost than InP.

Speakers from IQE and Raytheon both discussed the relative costs of using InP-based devices lattice-matched to InP substrates, and devices grown on metamorphic buffer layers on GaAs substrates. Comparison of the cost per unit area of the starting material, which includes the HEMT epilayers, shows that the metamorphic approach is considerably cheaper (figure 3). Increasing the diameter of InP wafers should narrow the price gap with the metamorphic approach. However, while 6 inch GaAs wafers are readily available in large volumes, AXT and Showa Denko have only recently announced the development of 6 inch InP wafers, and neither company is expecting volume orders in the near future.

Metamorphic HBTs

Ying Wu of IQE did a good job of clearing some of the fog surrounding the issue of metamorphic devices on GaAs substrates versus devices lattice-matched to InP, by making a straightforward device comparison. Wu's presentation compared the DC results for both metamorphic (M) and lattice-matched (LM) SHBTs and DHBTs with 50 nm C-doped InGaAs base layers and $5 \times 10\ \mu m^2$ emitters.

The LM- and M-HBTs were grown on 3 inch InP and GaAs substrates, and both used the same device structure. The MHBTs were grown on a graded InAlAs metamorphic

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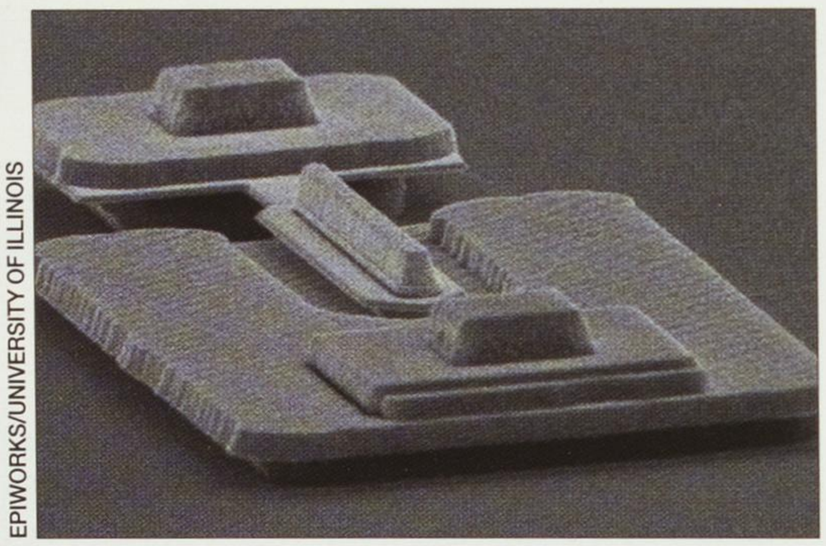


Fig. 2. An SEM of the double-mesa InP HBT design from EpiWorks and the University of Illinois, which was used for device-scaling experiments.

RAYTHEON

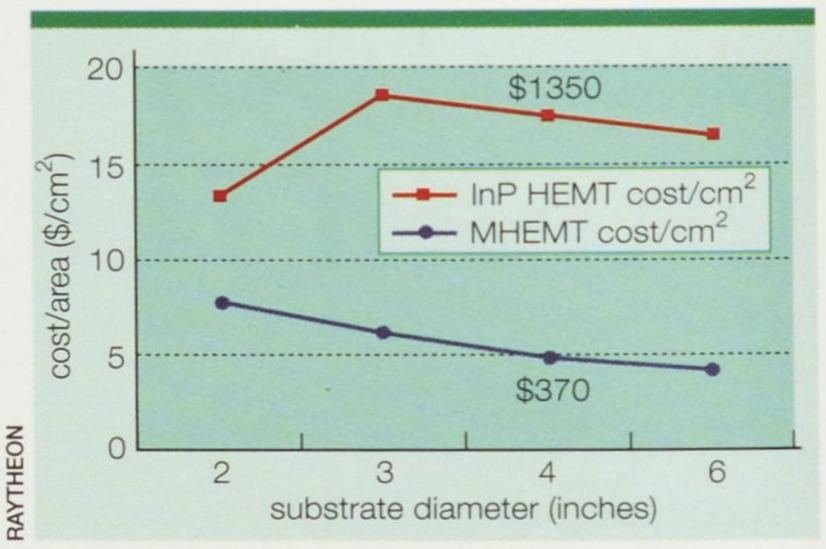


Fig. 3. The cost/cm² for MHEMT epiwafers grown on GaAs is significantly lower than for growth on InP, providing the motivation for the development of metamorphic processes.

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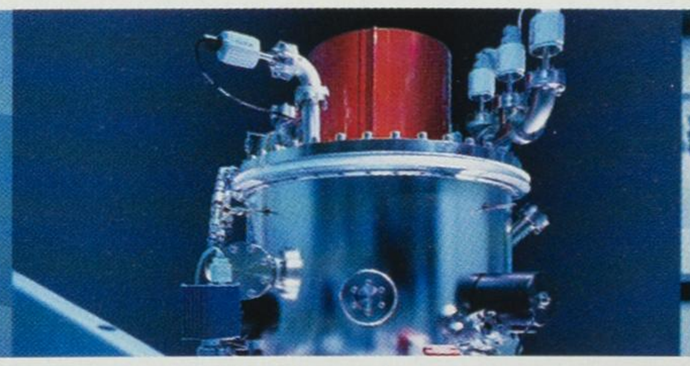
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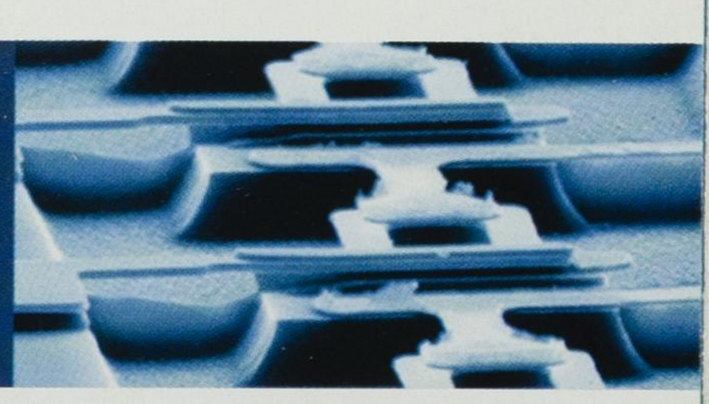
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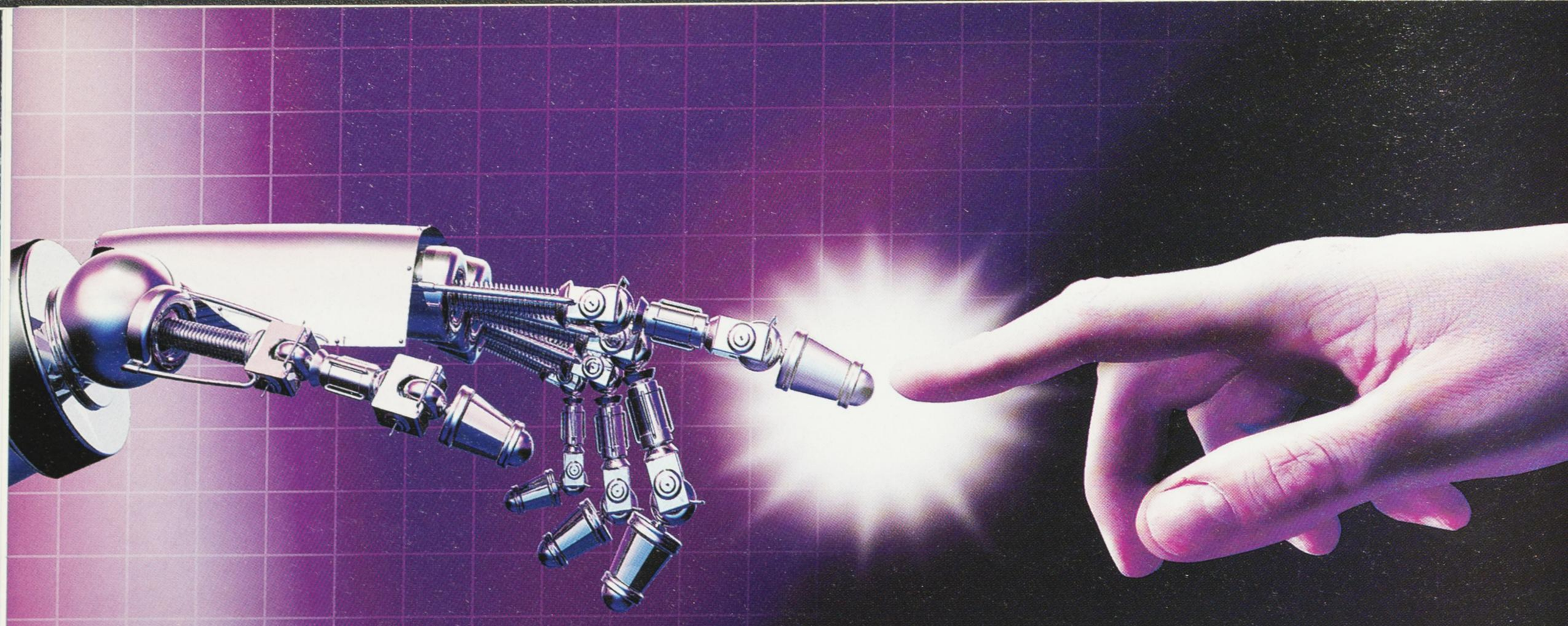
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buffer layer on a GaAs substrate. The SHBT structures had an InP emitter and a 400 nm thick InGaAs collector. The DHBTs had an InAlAs emitter and a 300 nm InP collector. The LM- and M-SHBTs showed almost identical DC characteristics, with current gains of 49 and 47, respectively, and a breakdown voltage of 4.0 V. The DC characteristics for the LM and M-DHBTs also compared well, with both showing a breakdown voltage of 8.9 V. Current gain was lower for the M-DHBT at 31, compared with 41 for the LM-DHBT.

Extrapolated f_t and f_{max} values were 75 and 43 GHz, respectively, for both M- and LM-SHBTs and DHBTs. The low figure for f_{max} is a result of the relaxed design rules leading to a non-optimum base/collector capacitance.

Wu's results indicated that apart from a lower current gain for metamorphic DHBTs, the metamorphic approach yielded devices with a broadly comparable performance to devices lattice-matched to InP, and a lower cost.

To reduce turn-on voltage and thus improve the efficiency of devices, a number of approaches are being considered, including the use of GaInAsN base layers in GaAs-based HBTs, a subject covered by Kopin during the session on epitaxy.

Yohei Otoki and colleagues at Hitachi Cable are taking another approach. They are using metamorphic growth by MOVPE on GaAs to achieve HBT devices with low indium contents. This gives low turn-on voltages and surprisingly high breakdown voltages, and makes them suitable for high-power applications. Otoki's group had chosen to keep the indium composition to a maximum of 15%, as at higher compositions the breakdown voltage is adversely affected. Devices with InGaAs collector and base layers of 5, 10 and 15% indium were grown. For the 15% indium devices the turn-on voltage was reduced by 190 mV compared with a standard InGaP HBT, though current gain was half of the standard InGaP HBT.

One unexpected result was that the breakdown voltage increased in proportion to the indium content, reaching 27.2 V for devices with 15% indium. This effect is not yet understood as heterojunction devices with low bandgap material like InGaAs usually break down at low electric fields.

Is GaAs toast?

The discussion session "Is GaAs Toast? – The Future of GaAs (or lack thereof)", chaired by Dave Wang of GCS, was always going to provoke a lively debate, not just about GaAs, but also about the other III-V materials and silicon technologies with which GaAs competes. With just about everybody in the room having a vested interest in the success of GaAs, it was perhaps predictable that the answer to the question "Is GaAs Toast?" was "No!". However, the debate was refreshingly open about the shortcomings as well as the strengths of GaAs and the industry built around it.

One thing that came across strongly was that the GaAs industry should not be afraid of competing with silicon in niche areas where silicon performs a particular function adequately. The feeling was that perhaps the GaAs industry had given way to silicon too easily in the past. "Plan for failure and you will be 100% successful," was one of the comments made. In the total addressable semiconductor market, silicon is king, but GaAs does offer a much needed performance advantage in many niches. GaAs can be cost competitive with silicon in applications that require a relatively small number of chips. Small volumes might not give silicon companies a return on their capital investment, even in applications where silicon could perform adequately.

Some time was given to discussion of the next possible "killer application" for GaAs, namely 77 GHz radar for automotive cruise control and collision avoidance. This has been available in top-range vehicles for some time and is starting to creep down into mid-range models. So far, the uptake of this technology has been hampered by cost and the unwillingness of motor manufacturers to install systems. This reluctance is because of the unsure legal position manufacturers might be in should an accident be attributed to failure of the radar system.

The recent industry downturn and competition from other technologies will mean some changes will have to be made to keep the GaAs industry in good shape. The consensus was that the industry may need to exist on lower profit margins than it has been accustomed to, and that further industry consolidation is inevitable, which would result in the closure of some fabs to lower overall capacity. A key to survival was also seen as the need to continue the trend towards grabbing a larger share of the available space in applications such as mobile phones, by putting more functions into single modules.

The rate of growth in the overall GaAs industry in the next few years remains uncertain, but there seems to be plenty that can be done to prevent GaAs from becoming toast.

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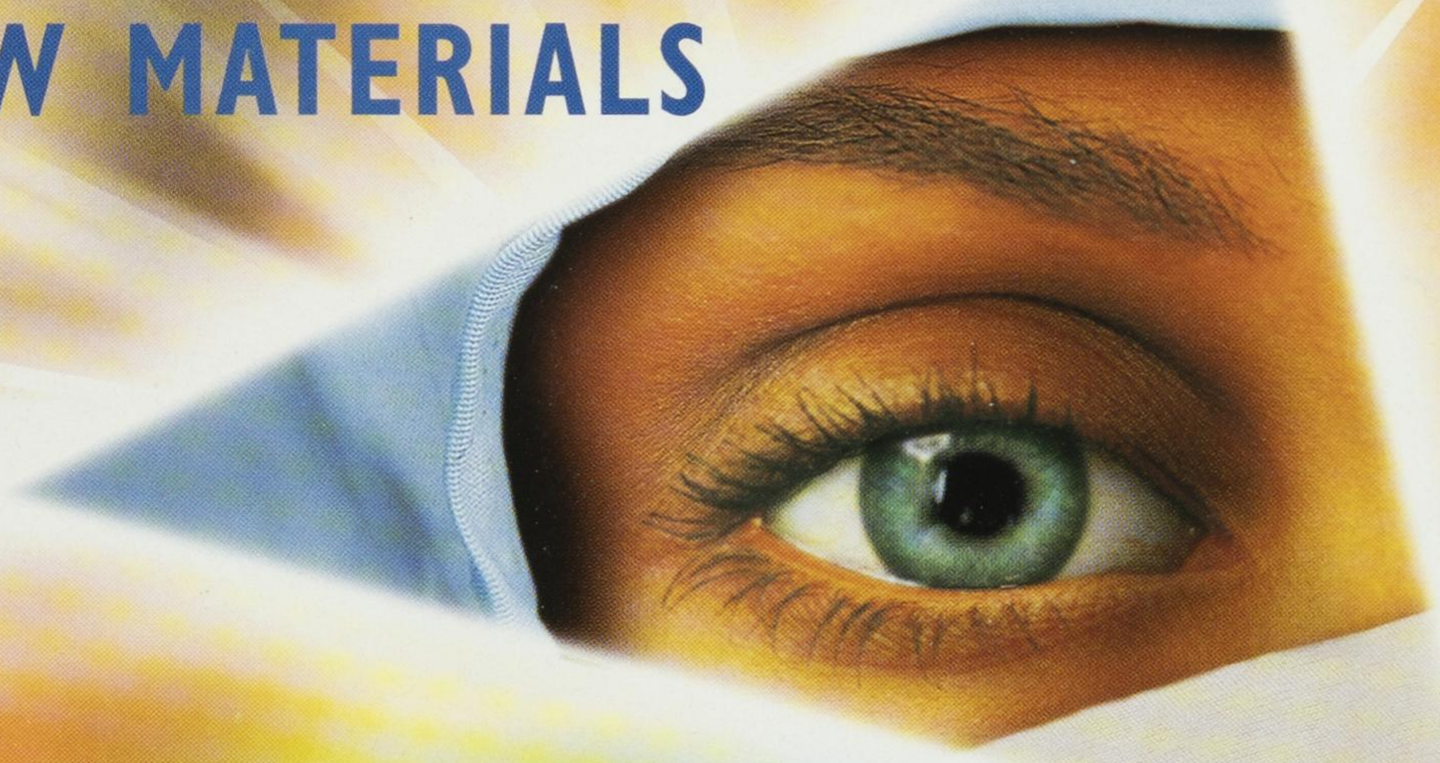
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European Union tackles wide-bandgap material challenges

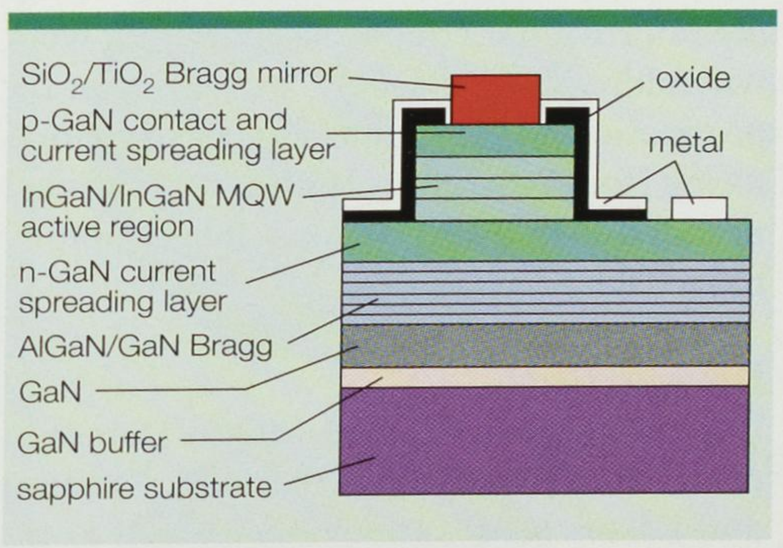
The European Union has allocated a multimillion-dollar budget to help researchers develop wide-bandgap semiconductors that can meet the needs of tomorrow's electronic and optoelectronic devices. **Rebecca Pool** talks to some of the researchers that are tackling these issues.

In 1998 the European Union (EU) set aside $13 billion (€13.7 billion) to fund its Fifth Framework Programme, a research initiative that promised to tackle Europe's major technological, industrial and social problems. From this massive budget, $3.4 billion was used to back an Information Society Technologies (IST) program, which comprised nearly 2000 projects and focused on information processing, communications and media technologies.

A key part of the IST program is research into wide-bandgap materials. One such project called DENIS was set up in April of this year, and aims to develop low dislocation density gallium nitride substrates. Headed by Acreo of Sweden, the research team also comprises Osram Opto Semiconductors of Germany, Okmetic Oy of Finland and the Polish Academy of Sciences' High Pressure Research Center, as well as the University of Bremen in Germany and Linköping University in Sweden.

Focusing on GaN

By using hydride chemical-vapor deposition (HCVD), the DENIS team aims to fabricate 2 inch GaN wafers with initial dislocation densities that are less than $1 \times 10^7/cm^2$. Their final goal is to reduce these defect densities to less than $1 \times 10^6/cm^2$. "We have been growing GaN with HCVD for a few years and at present we can grow thick layers of GaN on 2 inch sapphire or SiC substrates," said Bo Monemar of Linköping University. "Our first step is to produce free-standing 2 inch GaN of decent quality, and we are using different techniques, including laser lift-off, to remove the substrate."



NMRC

The AGETHA team is fabricating green and amber GaN resonant cavity LEDs, such as the one shown here, for POF data buses. The researchers hope that these structures will have better quantum efficiencies, coupling efficiencies and thermal stabilities than current LEDs.

"We aim to demonstrate a dramatically improved device performance that will motivate a rapid uptake of nitride technology in Europe."

The team will also attempt to grow 2 inch GaN boules later on in the project, something Monemar says is the biggest challenge he and his colleagues will face. They will also carry out device trials to evaluate material quality throughout the project. "We aim to demonstrate a dramatically improved [device] performance that will motivate a rapid uptake of nitride technology in Europe," Monemar added.

Another project called EURONIM (European sources of nitride materials) is also planning to do just this. Researchers from Thales of France, UK-based IQE, Osram Opto Semiconductors and various other European research institutes have teamed up to create a European industrial source of nitride epitaxial wafers for the electronics and optoelectronics industry.

The group intends to develop epi-ready SiC wafers, SiC wafers for the regrowth of active structures, GaN-on-sapphire and high-quality GaN wafers. Devices such as HEMTs and laser diodes will also be fabricated to test the material quality.

Preparations for an increased uptake of GaN-based materials will be good news for a research consortium working on a project called ISCE-MOCVD. Researchers from Aixtron of Germany, Thales, IQE and Philips Analytical of the Netherlands, as well as scientists from several European universities, have joined forces to develop advanced *in situ* monitoring and control of MOCVD production. As well as looking at GaN-based materials, the research team is also focusing on ternary and quaternary (Al, Ga, In)/(As, P, Sb) semiconductors.

"MOCVD [already] offers excellent control [for materials growth], especially compared with MBE," said Rainer Beccard, head of sales and marketing at Aixtron. "But the target of this project is to develop more advanced monitoring tools that offer information which has not been available before."

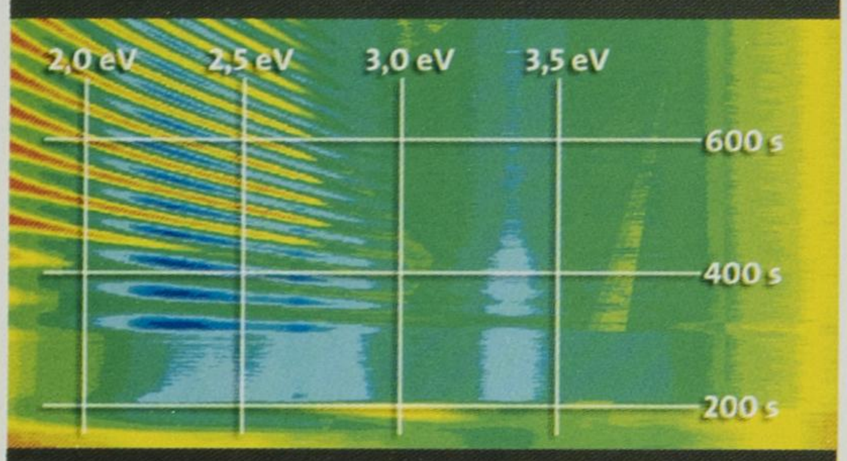
The team is designing a new reactor and plans to combine real-time monitoring techniques, including ellipsometry, reflectance anisotropy spectroscopy and X-ray diffraction, with closed-loop feedback control of epitaxial growth. Beccard says that the team

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expects their work to drive down development costs and increase process yields.

"The classical research and development process uses iteration loops, for example MOCVD growth followed by *ex situ* characterization and then a change of parameters, which is very time consuming," Beccard explained. "*In situ* control means that small process deviations will be detected during growth and easily compensated for. The impact of different substrate qualities [on epitaxial growth] will also be drastically reduced."

Adding that the team's work will be applicable across all material systems, Beccard expects that *in situ* technologies in MOCVD will become widely used across the III-V industry. "Today, MOCVD development focuses on highly sophisticated structures, novel and complex material systems, and the improvement of productivity; our work will address these issues," he said. "For the production of GaN materials, *in situ* monitoring [for MOCVD or HVPE] will increase production yield and quality, and hopefully reduce the price."

"For the production of GaN materials, *in situ* monitoring will increase production yield and quality, and hopefully reduce the price."

Beyond GaN

In a similar vein to ISCE-MOCVD, researchers from the Institute of Electronic Structure and Lasers (IESL) in Crete, as well as the Commissariat a L'Energie Atomique (CEA) in France, have just finished working on a project called QN-Laser that aimed to develop a quaternary nitride low-threshold laser diode. But rather than focusing on MOCVD, the researchers used MBE to grow high-quality InAlGaN thin films and heterostructures.

"A major reason for the poor performance of III-nitride laser diodes is giant polarization-induced electric fields in the active region," explained Nikos Pelekanos, project leader at IESL. "However, we have demonstrated InAlGaN/GaN QWs that are virtually free of such polarization fields."

Pelekanos says that the polarization field in these QWs is almost one order of magnitude smaller than an AlGaN/GaN heterostructure with the same bandgap. The researchers have also achieved room-temperature lasing from the quaternary laser structure at a lower threshold than an AlGaN/GaN "reference" laser.

The team is still assessing the lasing characteristics of the quaternary structure and intends to grow higher In-content quaternaries in a bid to achieve strictly zero-field nitride QWs. They also hope to make an electrically-pumped quaternary laser diode, but first plan to tackle technological issues such as contacts, as well as mirrors and doping.

AGETHA (amber green emitters targeting high temperature applications) involves a team of researchers from the University College Cork's National Microelectronics Research Centre in Ireland, Infineon Technologies, Thales, UK-based BAE Systems and various other research institutes across Europe. The researchers are developing high-speed green and amber transceiver components based on novel resonant cavity LEDs and complementary resonant cavity detectors (see figure). These structures are to be made from an AlGaN/GaN/GaInN material system and are crucial for the next-generation of plastic optical fiber (POF) multimedia data buses that will operate at transmission rates of at least 100 Mbit/s in automotive and aviation applications.

According to Brian Corbett, project coordinator at NMRC, the POF light sources and detectors will have to operate at the attenuation minima of POF, support 500 Mbit/s data rates and also function at temperatures up to 120 °C. The AGETHA team believes, however, that because nitrides have good thermal properties and emit at the short wavelengths of POF's maximum transparency (510 and 570 nm), these semiconductors are suited to POF networks.

The researchers will first design and then fabricate novel resonant cavity LED device structures with the aim of improving the quantum efficiency, coupling efficiency and the thermal lasing stability, compared with conventional LED structures. Packaged fabricated devices will be assessed over test-bed POF networks that simulate aeroplane and car applications. The team is aiming for a short time to market to maintain and increase Europe's market share against stiff competition from the US and Japan.

SiC takes on high powers

One project that is looking at SiC rather than GaN-based materials is ESCAPEE (establish silicon carbide applications in power electronics in Europe). Project leader Roger Bassett of the Alstom Research and Tech-

nology Centre (ARTC) in the UK explained why the research team selected SiC. "The technology is at the most advanced stage of development to be able to manufacture high-power semiconductor devices," he said.

The team comprises researchers from Linköping University, Ion Beam Services in France and Swansea University in the UK, as well as Alstom Transport in France and ARTC. According to Bassett the ultimate goal of the project is to "radically" transform the field of power electronics and replace silicon-based devices in most power electronics applications.

The research team plans to develop 3.5 kV MOSFETs and Schottky diodes with 10 times the voltage rating of silicon, and will start by developing some new manufacturing processes to improve the quality of SiC substrates. "Major defects such as micropipes need to be virtually eliminated, and other defects such as dislocations also need to be reduced to improve carrier lifetime," said Bassett. "MOS channel mobility has to be improved to enable the manufacture of practical devices."

The researchers will also develop high-quality, rapid epitaxial growth and an ion implantation process that reduces damage to the crystal structure during ion bombardment. Bassett says that other key milestones are to grow high-quality SiO_2 layers, to improve carrier mobility in a MOS structure, to achieve reliable 3.5 kV edge termination, to make reliable contacts and to develop a robust package for devices operating at high temperatures.

"SiC has the potential to significantly exceed the current-carrying density, temperature and voltage-blocking capabilities of existing silicon power semiconductor devices. For example, SiC IGBTs with a 10 kV/2000 A rating and switching speeds that match 1.2 kV silicon IGBTs could be available in five years," concluded Bassett. "Other wide-bandgap semiconductors are either less developed or do not have the correct combination of properties, but may be suitable for microwave applications."

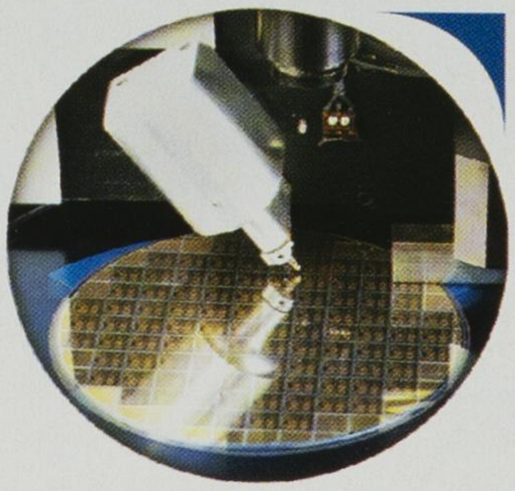
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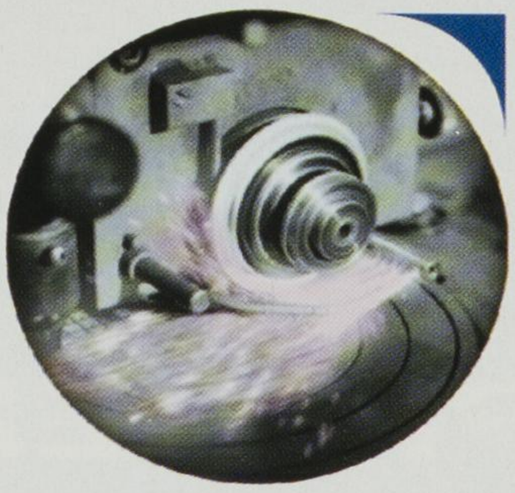
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WIDE-BANDGAP MATERIALS AND DEVICES

Perfect substrate within reach for wide-bandgap materials

The lack of a native substrate has led to a variety of choices for those developing GaN-based devices. **Jon Newey** looks at what is currently in use and what the future developments might be in this fast-moving area.

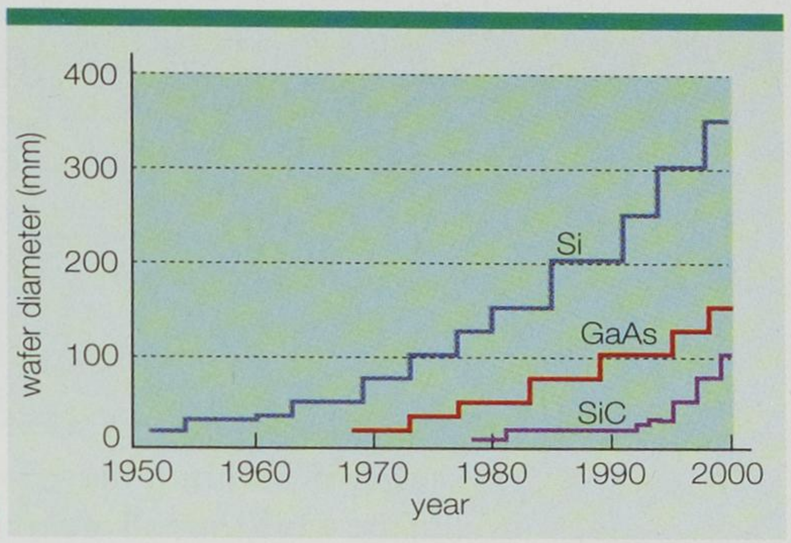


Fig. 1. The increase in wafer diameter as a function of time, demonstrated for R&D GaAs, Si and SiC wafers. SiC wafers have gone from 25 to 100 mm in about half the time it took GaAs or Si to make the same increase.

Any attempts to advance semiconductor technology rely heavily on the availability of a material that can be used as the platform upon which the end product is manufactured. The success of the silicon and GaAs industries is largely due to the availability of high-quality native substrates that can be successfully scaled to larger wafer diameters, providing economies of scale.

Wide-bandgap semiconductors, especially GaN, have been the subject of intensive research for several decades now. The lack of a suitable GaN substrate was a factor in delaying the development of blue and UV LEDs and lasers, and high-power, high-frequency electronic devices. It has also forced those wishing to exploit the benefits of GaN to look elsewhere for a substrate.

Currently, sapphire and SiC are the most popular substrate choices, with work on the use of Si progressing well. However, while each of these materials has its advantages, it has taken much effort to grow GaN layers of the quality necessary for commercially viable devices. There have been some notable commercial successes, such as GaN-based blue LEDs grown on sapphire and SiC, but such successes have not stopped the search for bulk GaN substrates. These are now becoming available, albeit at rather small sizes, in low volumes and at high costs.

SiC substrates

After sapphire, SiC is the most commonly used and well developed substrate for GaN epitaxy and of course SiC homoepitaxy. It forms the basis for high-power, high-frequency electronic devices and high-brightness blue and green LEDs. Single-crystal bulk SiC is generally produced using physical vapor transport (PVT) techniques, where the starting materials sublime and crystallize on a seed. Each manufacturer using PVT has its own proprietary variation on the technique. However, there are exceptions, for example Okmetic in Finland uses a high-temperature CVD method to grow bulk SiC directly from gas-phase precursors.

The 6H and 4H polytypes of SiC are available in 50 and 75 mm diameter wafers in production volumes. The need to lower costs by increasing wafer diameters is as pressing for the wide-bandgap semiconductor industry as it is for the Si and III-V areas. The diameter of SiC wafers is increasing at a higher rate than that of Si and GaAs wafers (figure 1). In fact, SiC has moved from 25 to 100 mm wafers in half the time that it took Si or GaAs to make the same leap.

A roadmap for SiC wafer development was discussed at the 2001 ICSCRM meeting (see *Compound Semiconductor* January/February 2002, p59). Here, the development of 150 and even 200 mm wafers was discussed, with the expectation that they would be available in 10 years' time. However, such a roadmap has a number of boundary conditions. First, does the capability to make larger wafers exist? Second, can the larger wafers actually be used? And finally, is there a market for them? Although MOCVD reactors can take large wafers for GaN deposition, manufacturers of tools for SiC epitaxy will need to develop reactors that can accommodate larger wafers and successfully grow on them. As Rob Glass, general manager and VP of Cree's SiC materials area points out, "Fewer people will buy larger wafers if they can't put a SiC epilayer on it. Three inch material is out there now being tested and prototyped with 100 mm a year, perhaps two, behind."

What the market needs it will get

Nippon Steel announced in 2001 that it had developed 100 mm SiC wafers and was expecting to have these in volume production by 2005 (see *Compound Semiconductor* November 2001, p11). It seems to be the case that companies involved in SiC wafer manufacture are being patient, and waiting for a true market to develop for larger diameter products rather than pushing a technology onto a market that is not ready.

However, supply helps to create demand. "If somebody comes out with a cost-effective, high-quality 100 mm substrate today, I think that would help push the market ahead. Nobody needs to wait until 2005," said Glass. "Cree demonstrated 100 mm wafers at the 1999 ICSCRM meeting, and market growth will help to justify volume production of these wafers. As always, those willing to do the early work with devices on large-area substrates will be in a better position when the market develops."

Micropipes: the killer defect

Possibly the most actively researched area of SiC development has been the reduction of micropipe defect density. Micropipes are voids that lie at the core of screw dislocations, reaching the surface and appearing as holes. Any device fabricated on an area in which a micropipe breaks the surface will be unlikely to work. It is this effect on yield that is driving the work to reduce micropipe density. The specifications in commercially available material are in the 10–100 micropipes per cm^2 range, depending on wafer size, grade and

how much the customer is willing to pay.

While efforts continue to eradicate micropipe formation during bulk growth, techniques have also been developed to fill the pipes. Subsequent SiC epilayers demonstrate greatly reduced or zero micropipe density, significantly enhancing device yields. However, such additional steps add costs to the production, and so the quest to eliminate micropipes during bulk growth will continue.

The user has to establish an acceptable balance between yield and cost per unit area of the wafer for their particular needs. If the yield reduction from the micropipes is minimal, then getting to the zero level may be unnecessary. However, in future some very-high-power devices will be of such a large area that a single device will occupy an entire wafer. Here, a single micropipe may prove fatal.

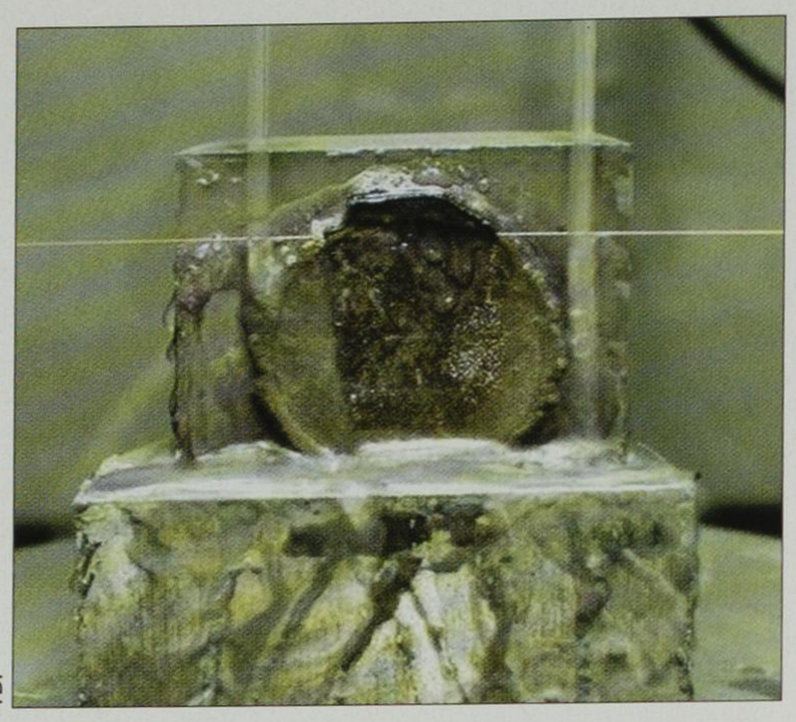
High-power, high-frequency devices

Essential to the operation of RF devices is the use of semi-insulating substrates. This adds another level of complexity to substrate manufacture as the material is usually made semi-insulating by doping with vanadium, which has limited solubility in SiC. Semi-insulating SiC is generally only available as 50 mm substrates. Although 75 and 100 mm semi-insulating material has been demonstrated, there is little market pull for this at present.

In the absence of III-N substrates, SiC is practically the only choice as a substrate for GaN-based power devices. It is no coincidence that the best-performing GaN power devices are those grown on SiC (see *Compound Semiconductor* November 2001, p69). SiC provides a smaller lattice mismatch with GaN than sapphire (3.3% for GaN versus 14.8% for sapphire) and has a higher thermal conductivity than sapphire and even GaN itself. However, this performance gain comes at a high price compared with sapphire substrates, and has led to some novel attempts to retain sapphire as the substrate, including thinning of the sapphire and bonding to a high thermal conductivity heat sink (see *Compound Semiconductor* December 2001, p43).

Gallium nitride

In an ideal world, those growing GaN epilayers would have a high-quality GaN substrate to grow on. No complicated buffer layers would be needed to account for the lattice mismatch between the GaN epilayer and a foreign substrate, and no differences in the mechanical and thermal properties of the substrate and epilayers would need to be taken into account for device processing purposes or the end application. With this in mind, there is much activity around the world aimed at providing the GaN community with GaN wafers.



TDI

Fig. 2. A GaN boule being sliced into wafers using a horizontal diamond wire saw.

Bulk GaN material can be divided into two categories. The first is GaN produced by depositing a thick layer of GaN onto a foreign substrate such as sapphire or GaAs. The substrate is then removed, leaving behind a free-standing GaN wafer. The second category of GaN is produced by the growth of GaN boules (figure 2). To some degree, the two go hand in hand. To grow a boule, a seed crystal is required and wafers produced by substrate removal can provide this seed.

"We see free-standing GaN substrates as a step in the boule growth process, but we also sell the free-standing GaN substrates for GaN epitaxy," explained George Brandes, director of GaN operations at ATMI in Danbury, CT. Although a number of companies are sampling GaN wafers produced through boule growth, the production technology is relatively immature, making yields and production volumes low. As a result, such wafers are expensive and diameters are small compared with the free-standing wafers or sapphire and SiC.

Despite the ability to produce free-standing GaN wafers, Brandes and his counterparts in other companies recognize that in the longer term it will be more cost effective to go to a boule growth process that will also yield better quality material. TDI of Silver Spring, MD, is also developing GaN boule growth techniques. "We think that for scalability and the lowest defect density, our approach [boule growth] has a much better future than the free-standing approach," said Vladimir Dmitriev, TDI's president and CEO.

GaN wafers certainly have a way to go if they are to become accepted in the commercial world. Commercially successful GaN-based devices such as blue LEDs are being manufactured in large numbers on relatively cheap sapphire substrates, and GaN-on-Si LEDs have also been demonstrated. While low- to medium-brightness LEDs are remarkably tolerant of crystal defects, blue and UV lasers are less so.

To provide epitaxial GaN of the quality necessary for lasers, researchers have adopted techniques such as epitaxial layer overgrowth (ELO) on sapphire substrates. ELO typically involves growing through openings in a silicon nitride mask. Growth takes place vertically through the openings and then laterally across the masked area. The laterally grown material has a greatly reduced level of defects. However, this adds to the complexity of laser manufacture, and laser grade material is only present in the overgrown regions of the wafer. If large-area GaN substrates were available, achieving high-quality material for laser manufacture would be much simpler.

"We believe that single-crystal, low-defect-density GaN will be the substrate of choice for laser diodes, and maybe UV and white LEDs, once the price approaches that of SiC," said Dmitriev.

Pushing the use of GaN substrates into applications other than lasers, such as LEDs and RF power devices, will require further reductions in price and an increase in wafer size. Those working on bulk GaN seem confident that this is achievable, though getting anybody to put numbers and times to their goals is understandably difficult. "There is nothing in the intrinsic costs that prevent us getting to SiC-like price levels in a reasonable time," said ATMI's Brandes. "It's a matter of getting the process streamlined enough and yields high enough. I find it hard to believe that we won't be there in four years and maybe in as little as two years."

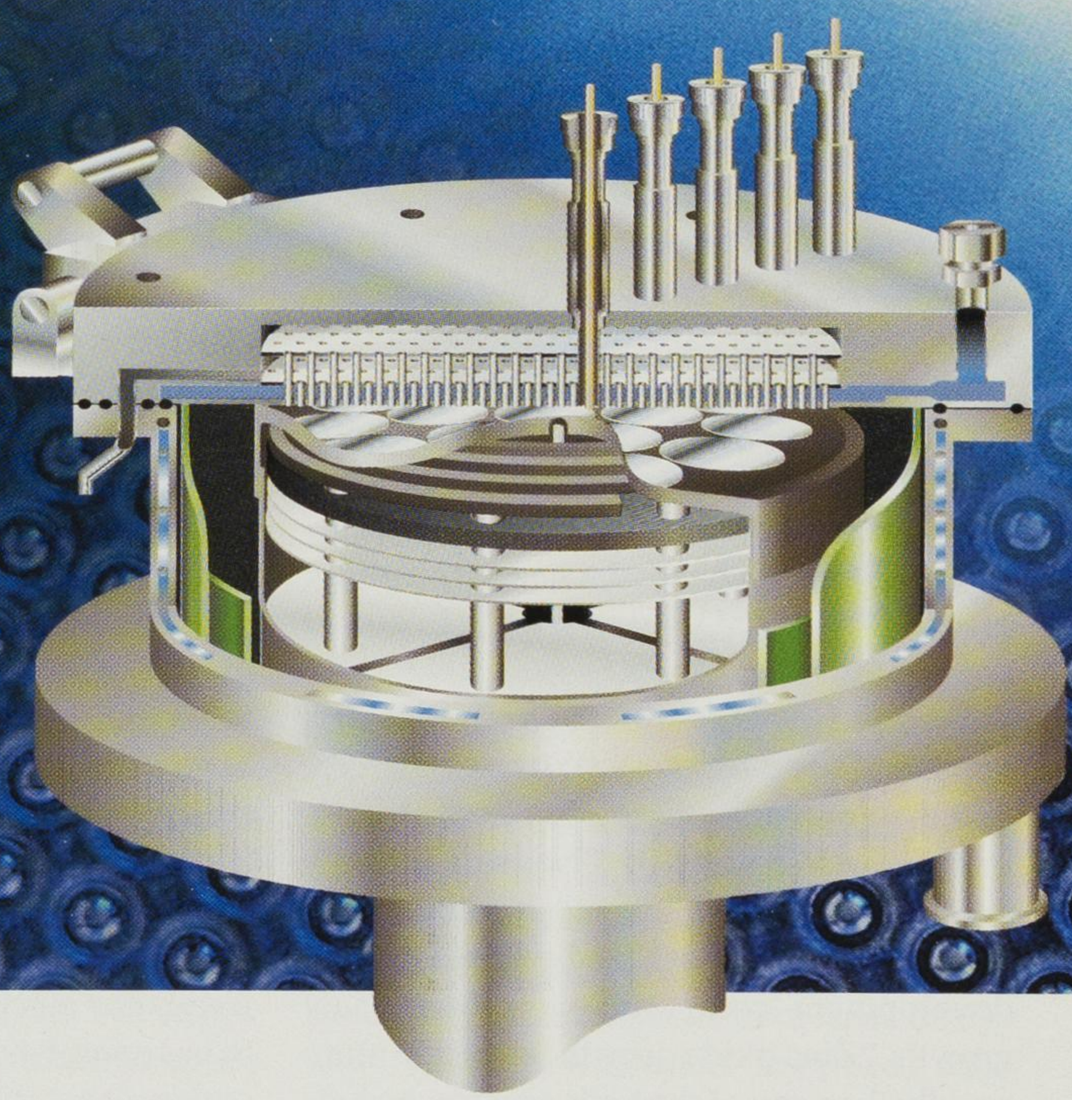
Aluminum nitride

Many of the companies working on GaN boule growth also have programs for AlN bulk growth. AlN is highly resistive, has a higher thermal conductivity than GaN (but less than SiC) and provides a lattice match to high Al content AlGaN. These properties make it an ideal substrate for high-power, high-frequency devices, and UV emitters and detectors. However, bulk growth of AlN is at a similar stage to GaN in its development. Because of the possible military applications of devices grown on AlN and GaN substrates, the US Department of Defense has provided

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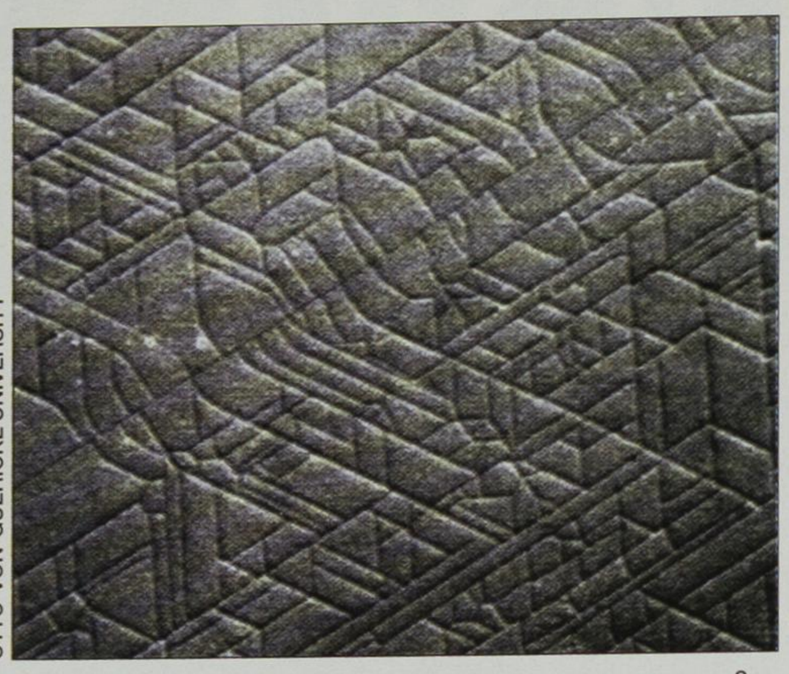
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Fig. 3. ZnO boules and wafers. ZnO is being developed as a material suitable for GaN epitaxy. The ability to also grow p-type ZnO layers has brought ZnO blue and UV optoelectronic devices a step nearer.



OTTO-VON-GUERICKE UNIVERSITY

Fig. 4. An optical micrograph of a 1 x 1 mm^2 area of a GaN layer grown onto a Si wafer. The cracks are the result of stress induced by the difference in thermal expansion coefficients between GaN and Si.

funding to companies such as Kyma (Raleigh, NC), Cermet (Atlanta, GA) and Crystal IS (Latham, NY) to accelerate the development of larger substrates.

Zinc oxide for blue LEDs?

Unlike GaN, conducting ZnO 50 mm wafers are available and provide a good lattice match to GaN with a mismatch of about 2% (figure 3). However, it is not just its compatibility with GaN that has stimulated interest in ZnO, but also the possibility of using ZnO itself as a material for blue and UV emitters. The long-running patent disputes in the GaN-based LED world have provided a strong motivating force for those pursuing ZnO as a possible alternative to GaN for short-wavelength emitters. ZnO is naturally n-type, and growing epitaxial p-type layers to form pn junctions has proved to be a stumbling block. However, with the announcement earlier this year by Eagle-Picher that it had successfully grown p-type ZnO layers by MBE, actual devices are a step nearer.

Cermet has development activities in a number of wide-bandgap substrate materials, and the company is growing ZnO using a melt growth process. Jeff Nause, Cermet's president, sees this growth method as the main reason for ZnO's advanced state of development compared with bulk GaN growth. "Zinc oxide growth will scale more rapidly than any of the bulk nitrides, including our own GaN growth," said Nause. "GaN uses a different growth technique that is inherently slower than the ZnO growth process. GaN growth will scale, but it will take longer to do so."

Despite its apparent suitability for GaN epitaxy, there appears to be some inertia to using ZnO as a substrate. Nause suspects that much of this reluctance comes from articles in the literature that suggest good-quality GaN can't be grown or is difficult to grow on ZnO. This results in the desire to wait for larger GaN substrates.

Silicon muscles in

In common with other compound semiconductor material systems, GaN is also being grown onto Si. The development of GaN growth on Si is not just confined to university research departments. A number of companies are pursuing this, including Nitronex of Raleigh, NC, which has demonstrated GaN-based electronic and optoelectronic devices grown on Si wafers (see *Compound Semiconductor* November 2001, p63).

Silicon wafers are cheap (as little as 10% of the cost of sapphire), widely available in a range of diameters, compatible with standard semiconductor processing tools, and the use of Si raises the possibility of monolithic integration with Si microelectronics. Si also has some specific advantages when the types of devices to which GaN can be applied are considered. Si wafers are available in conducting and high-resistivity forms, making them suitable for LEDs and high-frequency electronic devices, respectively. Si has a similar thermal conductivity to GaN, making heat dissipation less of a problem than with sapphire substrates.

Unfortunately, the properties of Si mean it is harder to grow GaN on Si than on sapphire or SiC. The lattice mismatch to GaN is 17% and the difference in the coefficients of thermal expansion is 100%. This results in the cracking of GaN layers that are thicker than about 1 μm (figure 4). Si and Ga also react at high temperatures. The literature is full of exotic buffer-layer materials deposited using a range of methods and temperatures. These are designed to engineer out the strain that causes cracking, and work with varying degrees of success. Also, AlN seed layers, AlN interlayers, patterned substrates and Si nitride mask layers to promote ELO are being investigated for the growth of thick, high-quality GaN layers. However, recent reports indicate that such efforts are starting to meet with some success and device results are being published, though some of these methods, such as Nitronex's Sigantic growth technology, remain proprietary.

The big question is, does the extra effort required to successfully grow on Si make the process cost-effective despite the low-cost starting material? The answer will depend on the application and if market demand is sufficient to warrant the use of large-area substrates. Any performance trade-off in going to Si must also be considered. Si will not remove heat from a power device as well as SiC, but it will perform sufficiently for medium-power devices, and also lends itself to substrate thinning processes. Si absorbs blue, green and UV wavelengths, a point of concern to those wanting to manufacture GaN-based LEDs at these wavelengths. Si process technology has been refined and perfected by the microelectronics industry, meaning that the material can, with relative ease, be subjected to additional process steps to improve light extraction.

Room for all

The substrate world is evolving quickly. While the absence of a native substrate for GaN may have hampered progress, it has certainly resulted in the development of a variety of substrate options. With GaN substrates starting to appear, the landscape will continue to change. Different types of GaN devices will suit the use of different substrates. The eventual widespread availability of a bulk GaN substrate will not necessarily mean that all GaN-based devices will be grown on GaN substrates. "GaN, sapphire and SiC will always share the market for GaN-based devices," said TDI's Dmitriev. "For low- to mid-brightness LEDs, sapphire is good enough. SiC is a good thermal conductor, so it may continue to occupy a niche in high-power devices even when high-quality GaN and AlN substrates are widely available."

Japanese collaboration seeks efficient white LED lighting

A consortium of companies and universities in Japan is developing efficient white LEDs and fixtures for solid-state lighting applications. **Richard Dixon** reports on the Light for the 21st Century project, a national program, with the overall aim of reducing energy consumption and contributing to Japan's 1997 commitment to lower greenhouse gas emissions.

Japan's Light for the 21st Century program was initiated four years ago with the goal of developing UV LEDs for solid-state white lighting. The project, which ends in 2004, brings together 13 companies and four universities. Research is proceeding in five main areas, namely substrates, epitaxy, devices, lamps and fixtures.

Other investigations include general illumination considerations such as how objects appear under lighting (known as the color rendering index or CRI), and the optimum arrangement of devices and their effects on perception. A CRI value of more than 90 (100 represents a perfect illuminator) is being sought for an LED fixture with a luminous efficacy of 80 lm/W. This is comparable to the output of a fluorescent bulb.

A team effort

The project is being jointly administered by the New Energy and Industrial Technology Development Organization (NEDO), a semi-governmental organization affiliated with Japan's Ministry of Economy, Trade and Industry, and the Japan Research and Development Center for Metals (JRCM).

JRCM hosts the collaboration, which includes Sumitomo Electric, Japan Energy and Furukawa Electric. These companies are developing suitable substrates for GaN. Sumitomo Chemical, Mitsubishi Cable Industries and Showa Denko are looking at epitaxial issues. LED fabrication is being investigated by Stanley Electric, while Kasei Optronix is developing fluorescent coatings to convert short-wavelength LED radiation to white light. Mitsubishi Electric Lighting, Omron and Agilent are addressing lamp fabrication.

Other players include lighting concern Yamada Shomei Lighting and Namiki Precision Jewel, a company that is concentrating on improving the surface preparation of sapphire substrates. The participating universities are Yamaguchi, Mie, Tokushima and Tokyo, and these institutions are joined by Japan Light Tubes, an association whose role is standardizing future LED lamps for general lighting use.

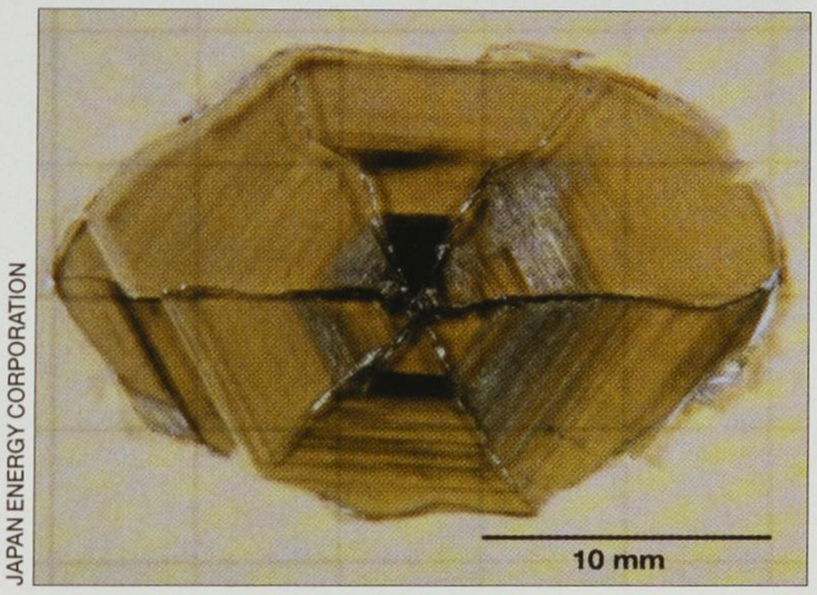


Fig. 1. GaN single crystals grown using a high-pressure solution growth have attained a diameter of 25 mm and exhibit dislocation densities of less than $10^5/cm^2$.

High-efficiency UV LEDs

According to Masayoshi Kubota, a NEDO project coordinator, one of the primary technical goals is to develop a UV LED lighting device with an external quantum efficiency of 40%.

"One of our main results so far has been the demonstration of an external quantum efficiency of 31% from a UV LED operating at 400 nm. This was achieved using a novel technology called lateral epitaxy on patterned substrates, or LEPS," said Kubota. The InGaN chip was designed by Mitsubishi Electric, Stanley and Yamaguchi University. "While our target for the external quantum efficiency is 40%," continued Kubota, "the development of a more efficient red phosphor as part of the tri-color phosphor scheme is presently our most important priority." Kubota adds that after the project ends in March 2004, there are currently no plans for a follow up. "Some of the companies may cooperate on various technologies after this program," he said.

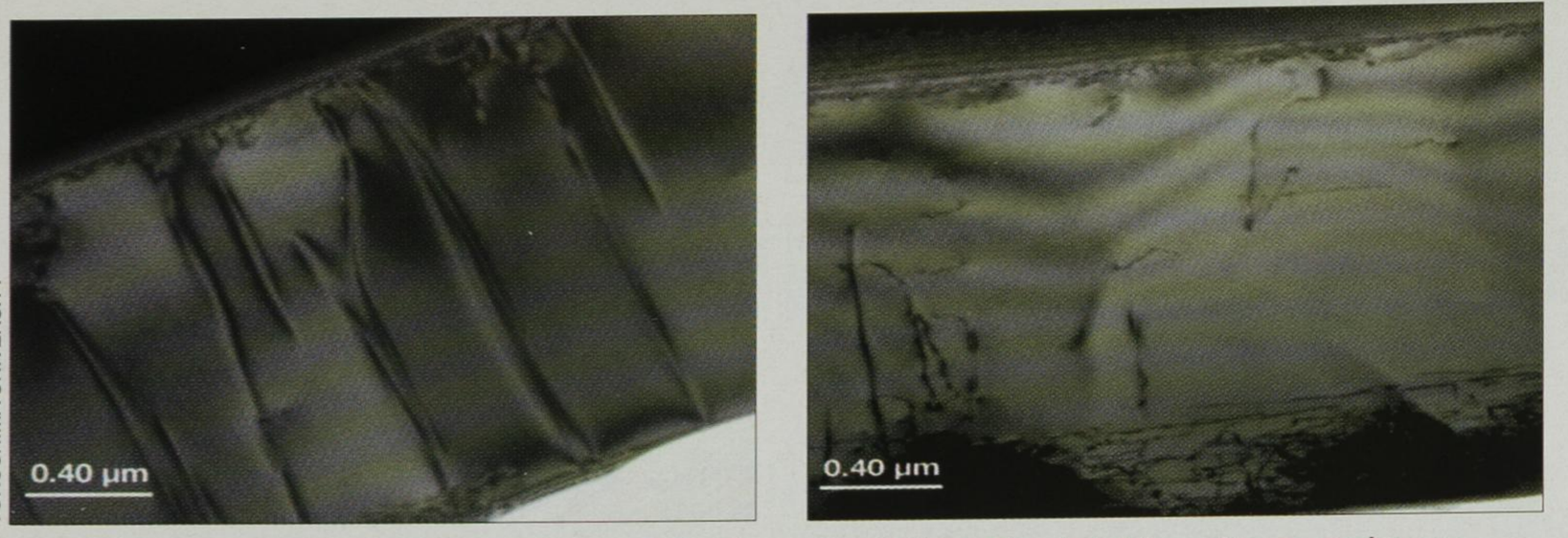
Mid-term results

An overview of the project's mid-term achievements was presented in Tokyo this March. In his overview of the project, T Taguchi of Yamaguchi University suggested that by 2003 lamps with a luminous efficiency of 80 lm/W could become a reality. The program is making some progress to achieving this end, not least with the 400 nm device mentioned above.

Taguchi says that to turn this into efficient phosphor conversion and to make white LEDs, the optimum route is a single UV chip driving tri-color phosphor combinations that provide stable color co-ordinates and a CRI value of more than 90. This approach is preferred to the combination of 470 nm blue devices with yellow YAG phosphors, which use complementary mixing of blue and yellow emission to produce white output, but have less stable color co-ordinates and a color rendering index of around 75.

UV LEDs and ZnS-based II-VI phosphors similar to those used in fluorescent lamps have been developed, so far demonstrating 20 to 30 lm/W and color rendering index values of 93. This luminous efficiency is comparable to the industry's best commercial devices, which currently offer around 30 lm/W.

To provide suitable lattice-matched substrates for subsequent growth of GaN device structures, A Yokohata *et al.* from Japan Energy and Yamaguchi University described a solution growth method. Using a hydrogen pressure of 1 GPa and a temperature of 1475 °C, single-crystal GaN substrates up to 25 mm in diameter have been grown (see figure 1). Characterization of these substrates revealed excellent crystallinity and a dislocation density of less than $10^5/cm^2$. According to Yoko-



TOKUSHIMA UNIVERSITY

Fig. 2. Cross-sectional TEM images of GaN-on-sapphire. The right-hand image shows the effect on dislocation density when a SiN buffer layer is introduced before the GaN.

hata, these crystals are reproducibly obtained primarily near the surface of the Ga melt.

S Sakai from Tokushima University described the use of SiN buffer layers as a way to reduce the number of dislocations in AlGaN-based UV LEDs grown on SiC or sapphire substrates. Due to thermal and lattice mismatch, GaN structures grown on sapphire and SiC substrates typically contain dislocation densities up to $10^{10}/cm^2$.

Such defects act as non-radiative recombination centers, but contrary to expectation the dislocations in InGaN/GaN devices do not quench the light. Instead, light emission takes place by recombination of carriers in small regions of indium-rich material formed by phase segregation in the InGaN wells, which has led to blue and green LEDs. However, Sakai notes that for near-UV devices with lower indium content, the localized carrier effect is weaker, and dislocation interactions have a more significant effect on emission.

To reduce the number of dislocations in UV devices operating below 370 nm, Sakai described a new SiN defect reduction layer. This layer is deposited on sapphire at 500 °C prior to two GaN buffer layers grown at 500 °C and 1050 °C. The SiN buffer provides a pattern of nano-scale "holes" that localize the dislocations and produce areas of defect-free material in a manner similar to epitaxial overgrowth on patterned substrates (see figure 2). The advantage is that photolithography is no longer required to mask epitaxial overgrowth regions.

Devices with AlGaN wells are also attractive because they allow devices operating in the spectrum below 370 nm, but unfortunately they suffer from poor emission.

To address this Sakai also reported a method of increasing the compositional non-uniformity in AlGaN using a Ga droplet layer prior to AlGaN deposition. This produces an effect similar to indium segregation in InGaN wells. The Ga droplet layer disturbs the growth of

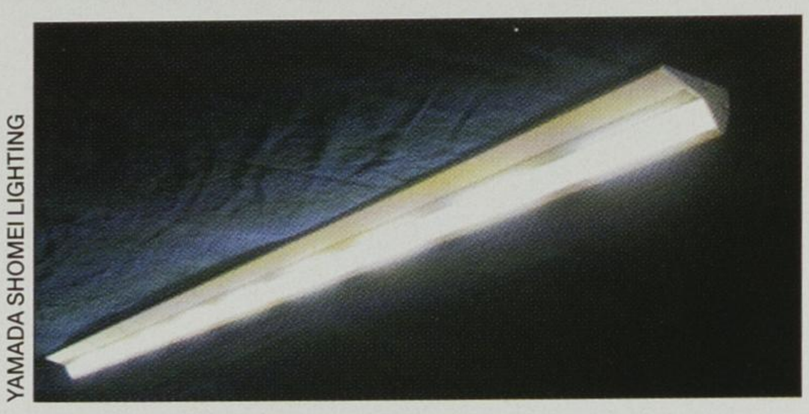

YAMADA SHOMEI LIGHTING

Fig. 3. Yamada Shomei Lighting's prototype wall-mounted light fixture is 1 m long and employs 18 white LEDs.

the AlGaN interfaces, which localizes the carrier recombination regions. This has been found to improve the efficiency at low values of current injection.

T Meada summarized work that Sumitomo Chemical and Mie University have done on a 15 × 2 inch multi-wafer system. Uniformity measurements showed that cross-wafer and wafer-to-wafer uniformity was less than ±1%. Subsequent epitaxial overgrowth of GaN layers on sapphire substrates using triangular (11-22) and square (11-20) etched facets produced smooth surfaces. In addition, the dislocation density in these structures could be reduced to around $10^5/cm^2$ in a 10 mm^2 region.

Device results

A promising approach to efficient high-power UV and violet LEDs was described by K Tadamoto on behalf of Mitsubishi Electric, Stanley and Yamaguchi University. Patterned substrates are produced using standard photolithography and RIE etching, followed by lateral epitaxy. The so-called LEPS process results in a dislocation density of $1.5 \times 10^8/cm^2$ for GaN layers grown on the patterned substrate, compared with around $4 \times 10^8/cm^2$ for GaN on non-etched sapphire substrates.

UV LEDs processed using this approach provided an output of 15.6 mW at 382 nm and 19.2 mW at 400 nm, which equals the output of commercially available UV devices. The results were obtained from flip-chip mounted InGaN/GaN chips on Si submounts. Devices were operated at 20 mA and 3.4 V, which produced an external quantum efficiency of 24% at 382 nm and 31% at 400 nm.

T Nishida and N Kobayashi of NTT Basic Research Laboratories described LEDs where InGaN was replaced by AlGaN in the wells. This gives access to the 200–360 nm spectrum.

To combat the poor emission of the AlGaN/GaN system, the authors proposed a new device. The LED features a single 2 nm thick $Al_{0.06}Ga_{0.94}N$ QW separated by $Al_{0.2}Ga_{0.8}N$ barriers, and a short-period superlattice alloy of $Al_{0.06}Ga_{0.94}N$ to improve the transparency and conductivity of the p-type layers. The device layers were grown on a low dislocation density HVPE GaN template.

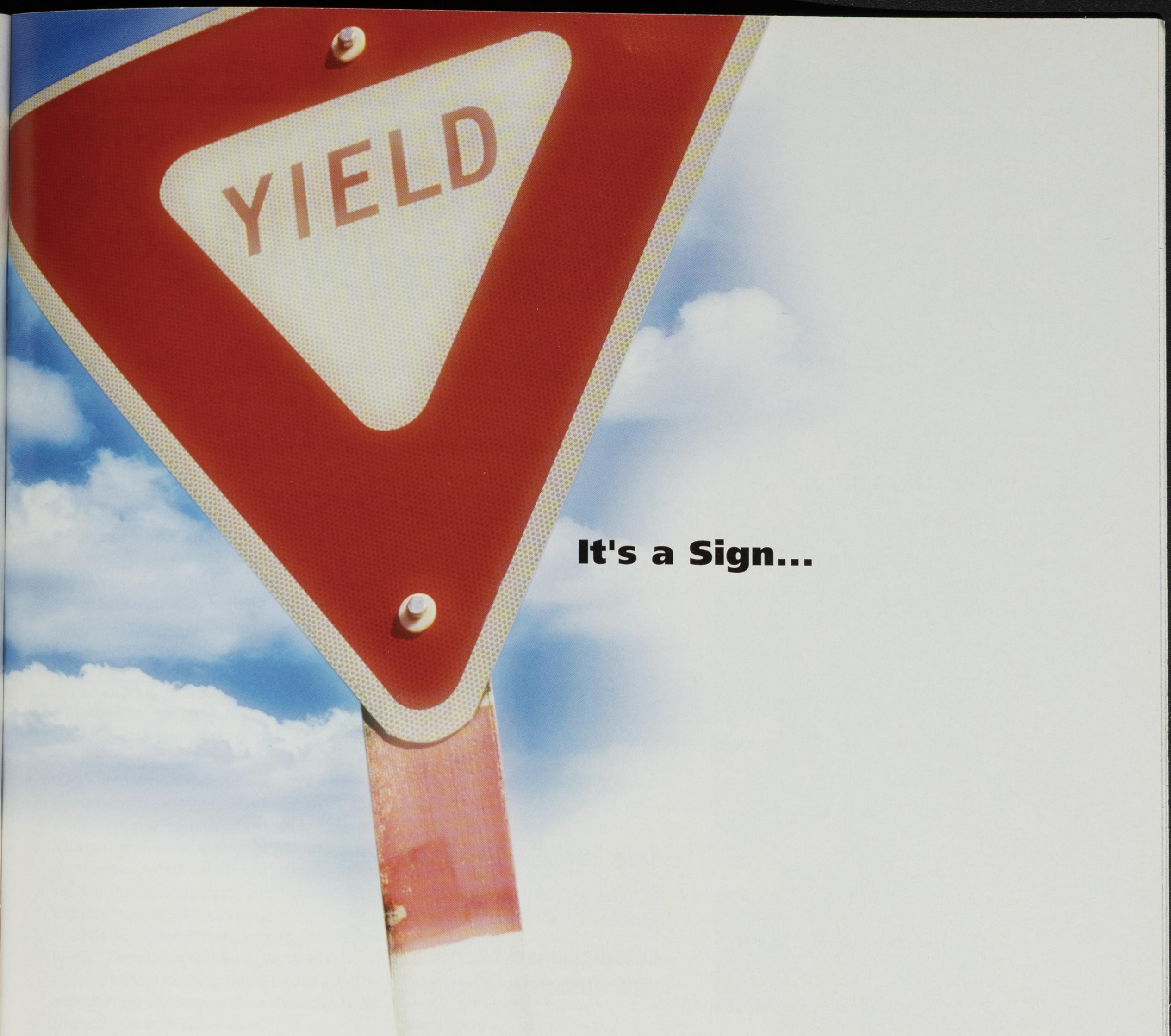
The LED was centered on a wavelength of 352 nm, and provided 3 mW at 100 mA of radiant power. Correlated to 20 mA operation, this corresponded to an internal efficiency of 80% and an external quantum efficiency of only 1%.

The short-period superlattice used for the cladding layers was also instrumental in lowering the series differential resistivity of the device to 4 ohms. This enabled the high injection current of 100 mA for a bias of only 4 V. The results were encouraging for future efficient operation of AlGaN/GaN LEDs below 360 nm, said the authors.

Phosphors and lighting fixtures

A group headed by M Yoshino from Kasei Optronix investigated phosphors for use in producing white light when excited by 382 nm UV radiation. Yoshino described ongoing efforts to find a replacement for the red phosphor Y_2O_2S:Eu. This material is typically used in televisions and is not sufficient for high-brightness applications. The company is currently investigating ZnS:Mn, which is a much brighter phosphor using 382 nm excitation. At present, this material contains too much orange, but the company is seeking to increase the red ratio of this combination.

Yamada Shomei Lighting has designed the first fixtures (see figure 3). The ceiling-mounted unit consists of 18 surface-mount LEDs arranged in two rows on an aluminum circuit board, with a diffuser to reduce glare. According to M Kanamori, the trial fixture produced around 250 lm at a distance of 0.5 m from the wall. This is sufficient as a directional light to wash sections of the wall surface. The lamp current was just 290 mA for a DC drive voltage of 24 V, which demonstrated the potential for low-power lighting sources in future.



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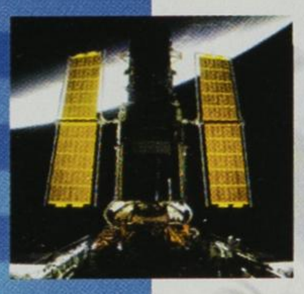
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WIDE-BANDGAP MATERIALS & DEVICES

ONR roadmap lights the way for semiconductor researchers

The National Compound Semiconductor Roadmap is an online resource from the Office of Naval Research that aims to accelerate compound semiconductor research, reports **Richard Dixon**.

The National Compound Semiconductor Roadmap (NCSR) is a Web-based document that invites parties from the compound semiconductor community to contribute to a roadmap for the industry. Conceived by the Office of Naval Research (ONR), the site gives researchers a forum to discuss problems and technological hurdles facing a range of materials such as GaAs, InP, group-III antimonides and II-VIs such as CdTe and ZnO.

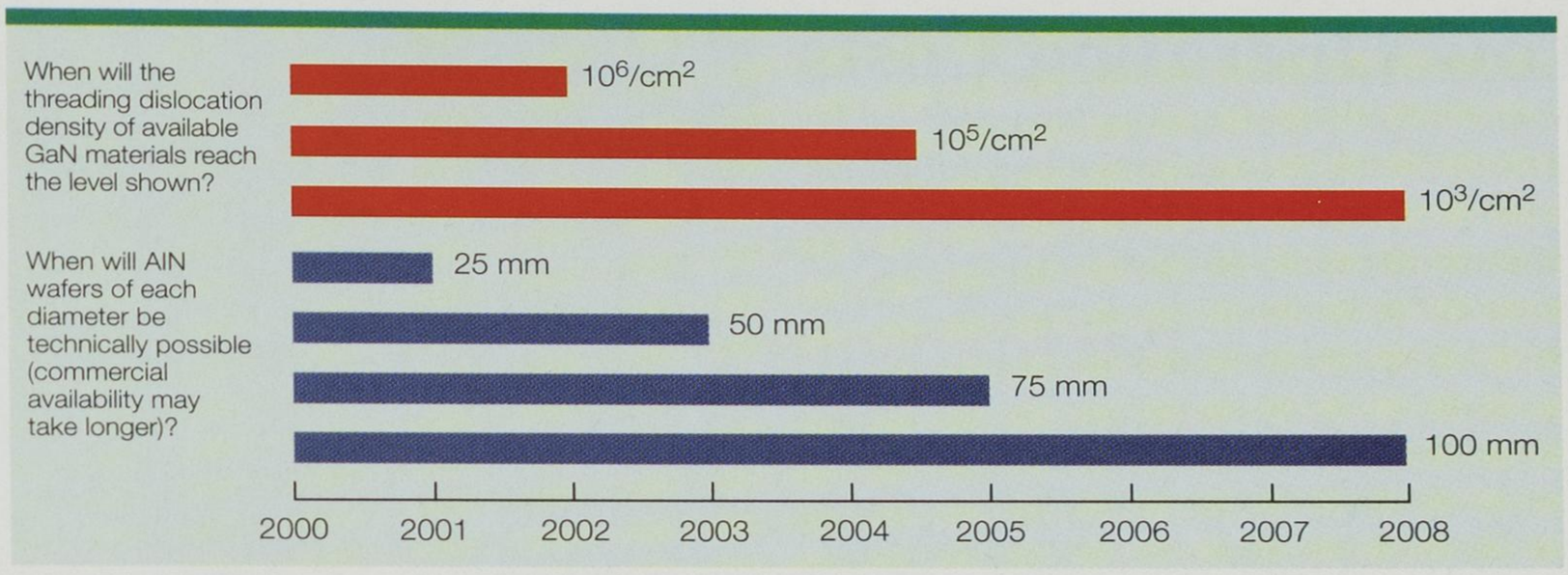
The site gives considerable coverage to wide-bandgap materials such as AlN, GaN and SiC. ONR is active in promoting this technology through Department of Defense (DoD) initiatives for defense applications (see *Compound Semiconductor* February 2001, p39). Examples include advanced sensors and high-power transistors that operate at high frequencies in potentially harsh environments, such as the radar systems used in advanced military warning installations.

ONR describes the site's standpoint as follows: "The idea is that you [the researchers] know where you are going for your specific area and may have some ideas about how your research fits with other areas."

These aims have been translated into three main targets: to create a reference on compound semiconductors for use by research and educational communities; to provide a collaborative environment for individuals to share ideas and challenges in an informal environment; and to create a roadmap of various material and device technologies, and predict their transition and implementation.

A look into the future

An interactive roadmap is the most recent addition to the website's pages. This feature has a timeline for issues relating to technological challenges in the industry. Examples include the amount of time it will take to develop conducting SiC wafers of various diameters up to 8 inches, and how quickly the dislocation density can be reduced in virtual GaN substrates used to grow GaN devices.



Examples of questions posed on the roadmap section of the NCSR website, together with average responses received from users. The site has many other resources for researchers.

While the roadmap is a new addition to the site, the original portal has been around for more than a year, and includes a database of physical data and background information on the properties of materials and devices such as LEDs, lasers, *pin* diodes, PHEMTs and HBTs. The site has more than 500 registered users, and ONR maintains its integrity by using a network of "monitors", selected from users who express an interest in refereeing the validity of submitted material.

Mike Tinston is a systems engineer for Computer Systems Center Inc (CSCI), the company that manages the daily running of the portal for ONR. "Most governmental funding agencies are requiring [research] programs to have roadmaps," said Tinston. "Roadmapping for R&D is difficult, but the method we use encourages researchers at universities and in industry to tender their opinions. This should make future programs more accurate and reflect what can realistically be achieved and over what timescale."

Tinston engages research centers and government funding agencies to support the creation of the reference data and technology challenges, and to develop realistic milestones predicting the maturity of material and device technologies. "We are looking for participants to log on to the website, register as users and browse the information," he explained. "We hope they will then participate by entering a technology challenge related to their field, or start a dialogue with the author who has posted a challenge or area that needs to be addressed to speed development in the industry."

Responding to the challenge

Around 40 compound semiconductor challenges have been posted to date, many of which relate to wide-bandgap materials. A broad range of problems is being addressed in this category, where topics include substrates, p-type doping issues in GaN, device physics and fundamental defect studies.

Examples of the submitted studies include alternatives to SiC and sapphire substrates such as lithium gallate, and free-standing GaN quasi-substrates produced by pulsed-laser lift-off processing to allow the integration of GaN devices with dissimilar substrates. Other challenges have cited the need for GaN-based electronic devices to be available with 3–4 inch growth technology. This is driven by a desire to process GaN on pre-existing InP or GaAs fabrication lines, and is limited by the availability of appropriately sized SiC wafers.

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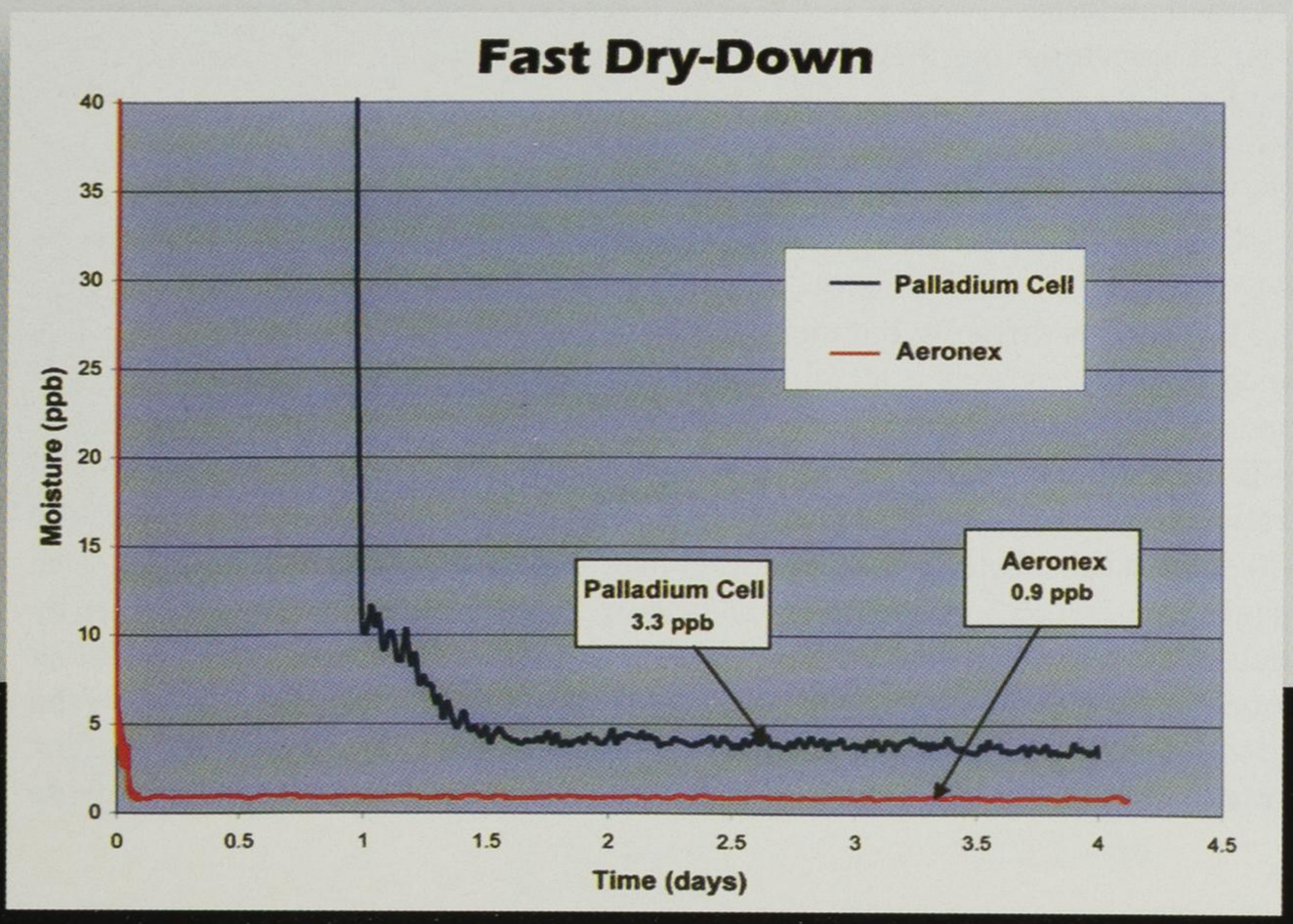


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HEMTs and SiC MESFETs is seen as vital for progress, as is solving the problem of degradation in SiC bipolar devices. In the processing arena, work is needed to improve the activation of p-type implanted dopants in GaN and to achieve large free-hole concentrations.

Several challenges have been posted that contain the first interactive timelines. One issue holding up the commercial development of SiC and GaN devices is the availability of low defect-density substrates large enough to allow increased economies of scale. GaN-based LEDs have flourished despite the presence of defect densities of up to $10^{10}/cm^2$ that occur in GaN-based devices grown on sapphire and SiC. However, reducing dislocation density should improve the performance and reliability of LEDs, lasers and transistors.

According to the timeline, the threading dislocation density in bulk or quasi-bulk GaN (e.g. a thick HVPE-grown GaN buffer removed from a SiC or sapphire substrate) is now typically around $10^6/cm^2$. Improvements aim to reduce this to $10^5/cm^2$ by 2005 and $10^3/cm^2$ by 2008. Fewer than 10 defects per cm^2 are expected by 2016. However, a comment posted on this timeline notes that it is unlikely that GaN will exist with dislocation densities below $10^5/cm^2$ at affordable prices.

A second challenge concerns conducting SiC wafers, which are already available with variable quality in several sizes up to 3 inches in diameter. These wafers require improvements to maintain the commercialization of SiC devices for military and high-power applications. Estimates of the timescale to realize different SiC wafer sizes with commercially acceptable quality include 4 inch by 2005 and 8 inch by 2013.

Other wide bandgap links

Links on the NCSR home page direct the user to a large body of resources, events and meetings, and funding opportunities for compound semiconductor research. ONR funds several nitride programs under its Multidisciplinary University Research Initiative (MURI) program. This multi-agency DoD program supports research teams whose efforts encompass more than one traditional science and engineering discipline. The parties involved usually include industrial organizations, DoD laboratories, and other organizations that perform R&D for defense, with the potential for subsequent commercial applications.

North Carolina State University (NCSU) is one location being supported under a MURI project entitled III-Nitride Crystal Growth and Wafering. The program is administered by ONR program officer Colin Wood and directed by Zlatko Sitar at NCSU's Department of Materials Science and Engineering.



RAYTHEON

Wide-bandgap research is the subject of considerable defense-related spending, largely because of the potential for high performance in extreme environments.

The interdisciplinary project brings together investigators from a number of universities and the US Navy and Air Force research laboratories. The goal is to produce high-quality single crystals of AlN and GaN in sizes that will yield wafers measuring at least 1 inch in diameter.

Several commercially viable approaches are being investigated such as physical vapor transport and growth from an alloy melt, which is based on research from NCSU, and the universities of Clemson and Cornell. Recent results include the demonstration of the seeded growth of AlN and GaN. The MURI project enables all the required disciplines in crystal growth, modeling, characterization and wafering to collaborate on a synergistic study of the problems.

Full details of this and other projects are posted on this rapidly growing resource for the compound semiconductor industry. ●

The National Compound Semiconductor Roadmap is at http://ncsr.csci-va.com. Mike Tinston can be contacted at +1 703 866 4000, email mtinston@csci-va.com.





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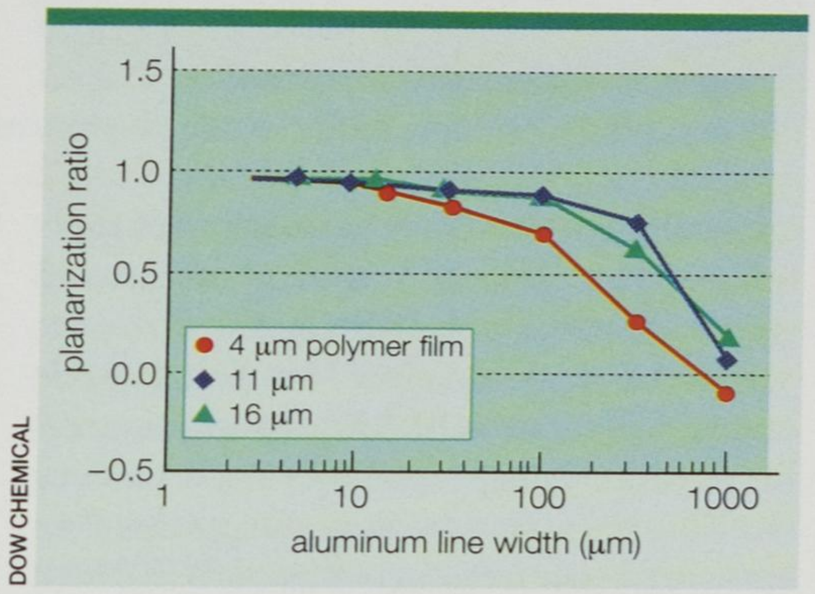
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GaAs IC makers lead the way in metals and low-k dielectrics

Low-resistance metal interconnects and spin-on low-k dielectric materials such as BCB have been widely used in GaAs IC manufacturing, writes **Philip Garrou** of Dow Chemical.

Anyone keeping an eye on the silicon industry over the last several years knows that a major trend has been the move to copper and low-k dielectrics for interconnect fabrication (Lee). The Al/SiO_2 interconnects used since the inception of the silicon IC no longer offer acceptable resistance-capacitance (RC) delays for today's faster chips. Moving into the sub-micron arena, the RC issues become so severe that chip performance is determined by the RC delay instead of the intrinsic gate delay. Changing from aluminum to copper reduces the metal resistance by approximately 40%, and changing from SiO_2 to a low-k dielectric can reduce the capacitance by as much as 50%. In spite of this, both copper and low-k were seen as radical process changes which entailed increased cost and risk, and they were only accepted slowly and one at a time. The first IBM Cu/SiO_2 process came to market in 1998 at the 0.25 μm node. Low-k dielectrics (whether spin-on organics or vapor-phase deposited inorganics) have been even slower to market, and are only now beginning to be seen in commercial products at the 0.13 μm node.



DOW CHEMICAL

Fig. 1. BCB achieves a high degree of planarization so CMP is not usually required.

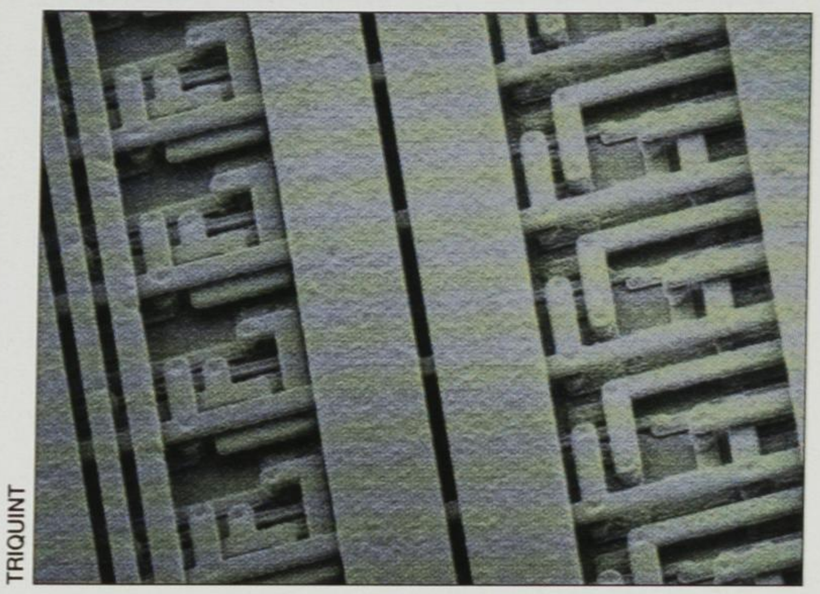

TRIQUINT

Fig. 2. SEM photomicrograph of circuitry fabricated using TriQuint's QLSI-2 process.

Electrical and mechanical properties of BCB

dielectric constant (1 kHz–20 GHz)	2.65–2.5
dissipation factor (1 kHz–20 GHz)	0.0008–0.002
breakdown voltage	7 MV/cm
coefficient of thermal expansion at room temperature	42 ppm/°C
glass transition temperature	>350 °C
stress	28 MPa

Dielectrics in GaAs fabrication

Many GaAs device manufacturers have actually led the way in the use of both lower resistance metals and spin-on low-k dielectric processing. The vast majority of GaAs devices have traditionally been fabricated using lower resistance gold interconnects. Typical interconnect metal resistivities are 2.7 μΩ.cm for aluminum, 1.7 μΩ.cm for copper and 2.3 μΩ.cm for gold.

Dielectrics can be used in several unique ways during the fabrication of GaAs devices. The dielectric can serve as an inner-, or interlayer dielectric material, insulating interconnect lines and providing a planar surface for the fabrication of the next layer of interconnect. It can be used to encapsulate air bridges, making them better able to withstand the rigors of plastic packaging. It can also be used in MMIC devices to fabricate multilayer matching circuits and passives on GaAs devices, or on silicon substrates to which active GaAs- or InP-based devices can be attached. It is also being used in optoelectronic device fabrication as a passivation and isolation layer in the manufacture of mesa diodes.

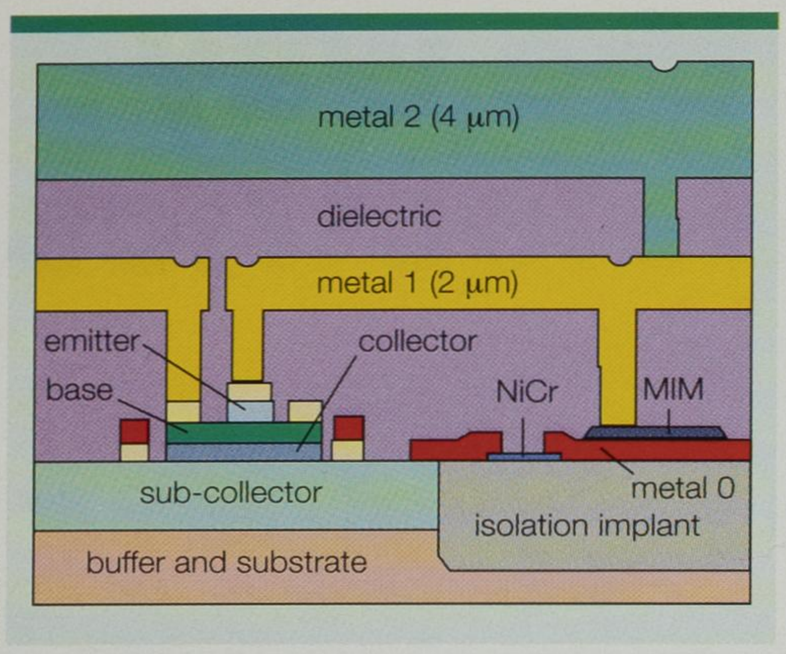
One such dielectric in commercial use is benzocyclobutene, or BCB, which was commercialized by Dow Chemical under the trade name Cyclotene in 1992–1994 as a dry-etchable (3000 series) and photosensitive (4000 series) spin-on dielectric. BCB is thermally polymerized at above 180 °C, and there are no catalysts or byproducts evolved when it is cured. Curing can be done rapidly, e.g. around 2 hours at 205 °C or less than 30 minutes at 260 °C. The glass transition temperature of BCB films is greater than 350 °C, the water absorption at 85% humidity is below 0.14%, and the material shrinks by less than 5% when cured. Some of the electrical and mechanical properties of BCB are listed in the table.

While silicon technologies with multilevel interconnects require chemical-mechanical polishing (CMP) to achieve planarized surfaces upon which to conduct sub-micron lithography, BCB is inherently planarizing (see figure 1). Structures fabricated with BCB do not require the use of CMP. For instance, isolated 20 μm wide × 4 μm thick aluminum lines have greater than 90% planarization when covered with 4 μm of BCB.

BCB as an interlayer dielectric

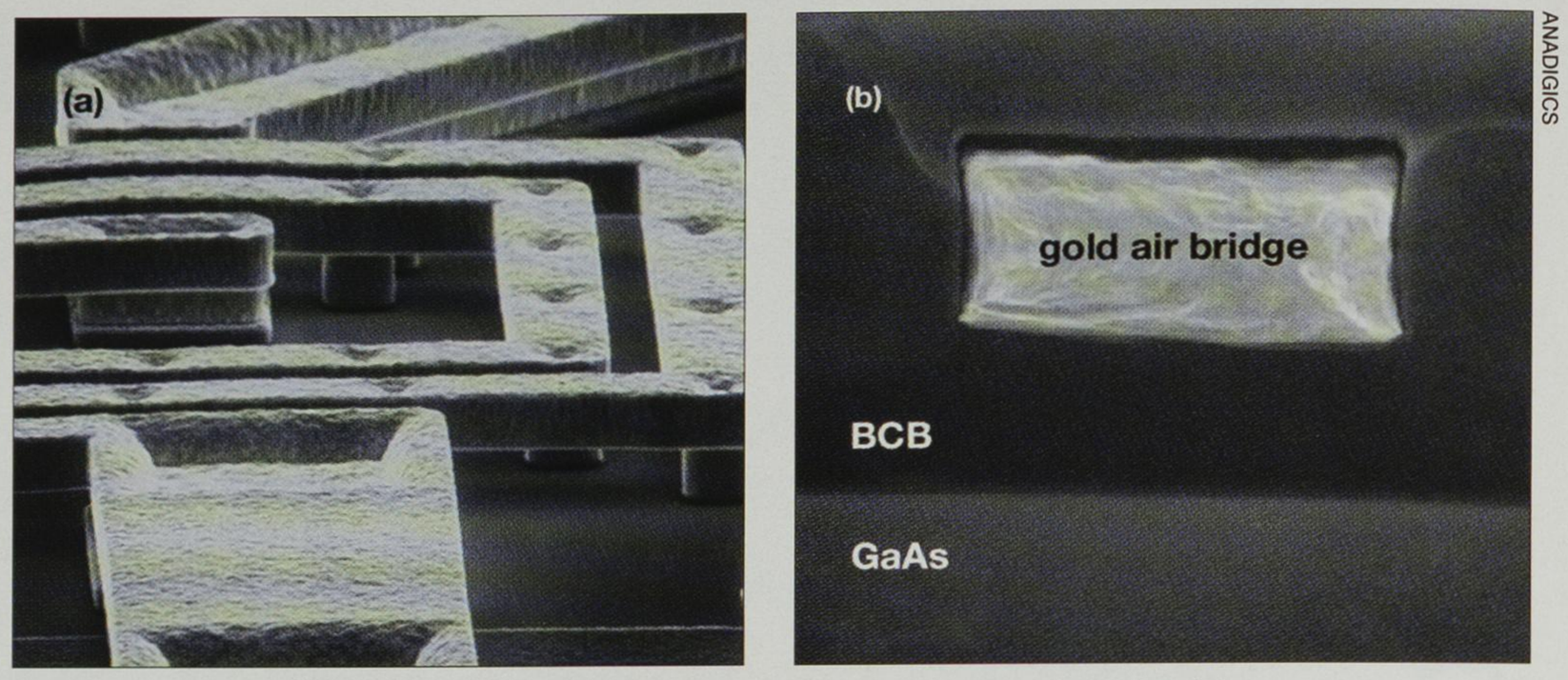
The first documented use of BCB in compound semiconductor fabrication occurred in 1993 at what was then Bell Northern Research (now Nortel). AlGaAs HBTs with cut-off frequencies of 60 GHz were fabricated, and the process was later modified to allow the fabrication of GaInP HBTs (Surridge and Lester). Products incorporating HBT-based circuits, including OC-192 (10 Gbit/s) fiber-optic components, have accumulated many thousands of years in the field (corresponding to billions of transistor hours) without any failures.

TriQuint first detailed the use of BCB in 1994 as an interlayer dielectric for GaAs in its QLSI-2 process (Finchem *et al.*). Figure 2 shows an SEM photomicrograph of circuitry



TRIQUINT

Fig. 3. Cross-section of an HBT device fabricated using TriQuint's TQHBT process.



ANADIGICS

Fig. 4. A gold air bridge (a) and a similar structure encapsulated in BCB (b).

fabricated with this production process. All four levels of interconnect are visible (the dielectric has been removed to facilitate imaging of the underlying circuitry). TriQuint reports that nearly 100% planarization of the underlying topography is achieved, and also notes that the low shrinkage of BCB is important to technologies such as GaAs that are sensitive to process-induced stress. Several successive generations of this technology have been in production since 1994.

More recently TriQuint has developed multiple process technologies using a multilayer gold/BCB technology. The InGaP HBT process, shown in cross-section in figure 3, has three levels of interconnect metal. TriQuint has also developed a 0.5 μm TQPHT technology (a PHEMT process), and a TQRCL technology, a pure passives process using thin-film NiCr resistors, MIM capacitors and high-Q inductors. In all of these processes, the interconnect layers are encapsulated in BCB.

Air bridges

Most analog devices contain air bridges. GaAs device manufacturers have traditionally built their air-bridge interconnects in photoresist and then removed the photoresist to leave structures like those shown in figure 4a. Such air bridges tend to be very fragile and are therefore placed in expensive hermetic packages. When encapsulated with a low-stress protective polymer layer, chips fabricated with air bridges can be packaged in plastic, thus significantly lowering the cost of the final packaged product. The polymer should not be cured above approximately 250 °C for fear of electrical degradation of the devices, and must flow under and completely encapsulate the air-bridge structures. BCB has been used by a number of companies for this application due to its low cure temperature, outstanding flow and encapsulation properties, and low dielectric constant (compared with other polymeric materials).

Kaleta and co-workers at M/A-COM developed a low-cost BCB/SiC coating process for on-wafer encapsulation of GaAs devices (Kaleta *et al.*). The two-step process involves applying a 10 μm thick coating of BCB (thick enough to cover the air bridges) covered with a 0.5 μm coating of PECVD SiC. The SiC layer is added to further increase the resistance of the BCB films to moisture penetration, without altering the microwave performance of the MMICs. Reliability testing of such coated devices did not show any failures after 150 hours in an autoclave (120 °C, 100% humidity).

An air-bridge protection process was also implemented at Anadigics (Garrou *et al.*). Figure 4 shows typical air-bridge structures and an encapsulated gold air bridge in cross section. Anadigics' GaAs devices measuring 1.5×2.0 mm^2 were passivated with photo BCB, packaged in 16-lead wide-body SOIC packages, and put through various reliability tests. No failures were observed, whereas numerous failures were observed in unpassivated parts. Alcatel and United Monolithic Semiconductor have also described an InGaP/GaAs HBT which uses BCB-reinforced air-bridge technology (Vendier *et al.*).

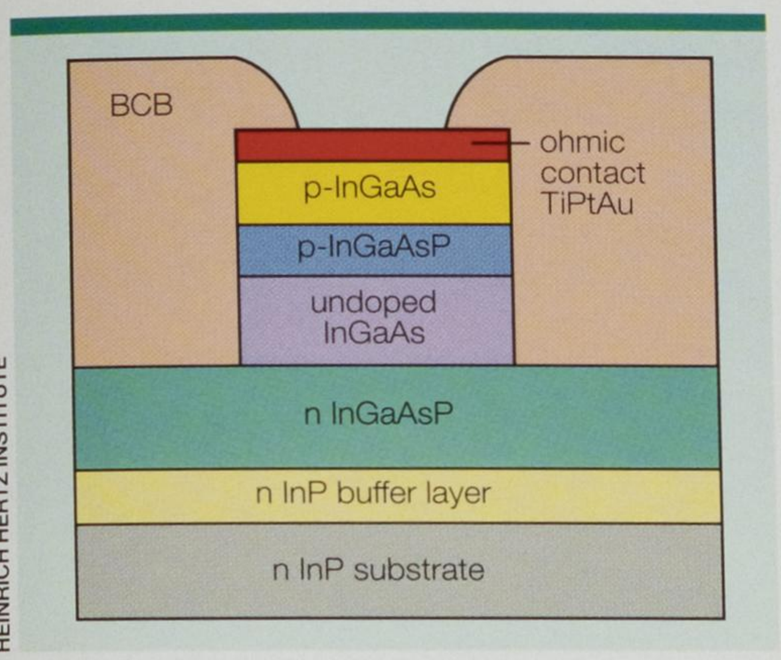
MMIC device fabrication

The recent interest in highly integrated MMICs for millimeter-wave wireless applications has been driven by the expansion of the market for wireless communications and sensors. Toshiba has described the fabrication of 60 GHz MMIC amplifiers, VCOs and mixer devices utilizing thin-film BCB PHEMT technology, while NTT, Matsushita and others have proposed the commercialization of 3D MMICs (Ogura *et al.*). The active GaAs circuits are flip-chip mounted onto a GaAs or lower cost silicon carrier substrate, carrying multiple layers of BCB into which the microstrip and coplanar waveguide interconnect, passive elements and matching circuits are built. GaAs active devices are assembled on the top surface, usually using flip-chip technology. Using such technology reduces the size of the devices by about two-thirds, and significantly improves electrical performance while reducing cost. NTT notes that such structures achieve more than three times the integration level and less than half the fabrication cost compared with planar MMICs.

InP-based devices

It is generally agreed that InP-based HEMTs offer the best solution for low noise operation. They are also the best choice for applications that require compatibility with InP-based optical devices. NTT researchers have described the fabrication of 80 GHz InAlAs/InGaAs/InP HEMT high-speed time division multiplexers. They adopted a gold/BCB interconnect scheme for high-speed transmission because the presence of BCB reduces the effective dielectric constant from 6.7 to 2.6. NTT has also studied InAlAs/InGaAs/InP HEMT technology for 64 Gbit/s mux ICs and 49 Gbit/s static frequency dividers. To decrease the interconnection delay as much as possible, signal lines are run on top of the BCB layer. The propagation delay is cut by more than 50% compared with structures that use high-dielectric-constant inorganic inner-layer dielectrics.

Lucent researchers studied various materials, including BCB, as encapsulation for InGaAs/InP DHBTs (Kopf *et al.*). They noted that device encapsulation is important for device stability since III-V semiconductor surfaces are quite sensitive to damage from plasma or thermal treatments. Spin-on glass



HEINRICH HERTZ INSTITUTE

Fig. 5. Cross-section of an InP-based photodiode passivated by BCB.

and BCB had good adhesion and were excellent gap fillers, whereas PI and CVD nitride were poor at gap filling. Cross-sections of PI structures showed the occurrence of bubbles under the emitter mesa. PI showed large shrinkage during cure, which resulted in gaps along the sidewall of the base mesa. The BCB-encapsulated devices showed no degradation in electrical properties.

Optoelectronic devices

The Heinrich Hertz Institute has recently reported on the effect of BCB coatings on InGaAs photodiodes (see figure 5). BCB passivation was found to reduce surface damage of the diode mesa sidewalls caused by plasma processing. Whereas unpassivated diodes showed an increase in dark current (especially in the high voltage region), BCB passivated diodes do not show any change in dark current after two months.

Conclusions

The use of low-k BCB dielectrics for a variety of functions during the fabrication of GaAs- and InP-based devices had its origins almost a decade ago. The commercial use of BCB has allowed the fabrication of multilevel interconnects with electrical performance levels that are comparable to those of air-bridge technology; the encapsulation of air bridges for lower cost plastic pack-aging applications; 3D MMIC fabrication with higher integration and lower cost; and photodiode mesa passivation. Such technologies can ensure further low-cost, high-reliability breakthroughs in future compound semiconductors. ●

Further reading

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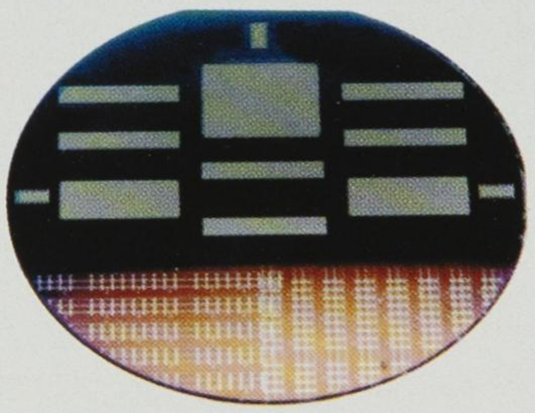
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Hybridization brings optical components together

As the market continues to demand lower cost optical communications, component makers are turning to integration. Streamlined bonding and alignment will bridge the gap between discrete and integrated components write **Robert Green** and **Stuart Morgan** of Bookham Technology.

Current market conditions demand low-cost network solutions for today's optical communication systems. The consumer wants competitive pricing from the service provider, which then pushes network operators, infrastructure designers and optical component vendors to reduce costs.

To meet these costs targets, the integration of active and passive optical components onto a single chip is key. Integrated components are inherently easier to mass-produce and therefore cheaper than discrete components that have to be installed and then calibrated separately by the infrastructure provider.

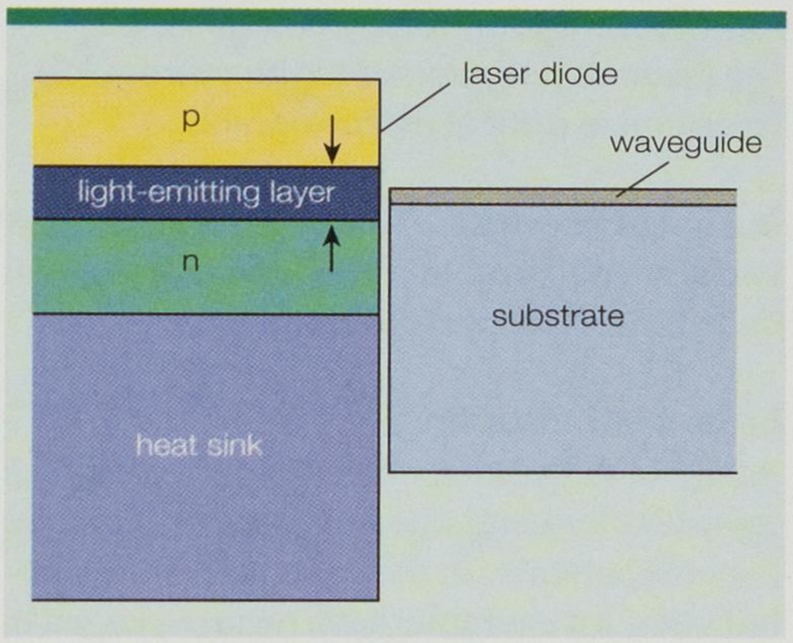
Functionality is also important. Network designers need multifunctional solutions from component vendors and favor components that can perform more functions at a lower cost. An integrated package of components means that the network designer not only gets interoperability, but also gets more functionality from fewer vendors. This also leads the way to long-standing and large order–volume customer–vendor relationships.

Network operators have to respond quickly and cheaply to today's expanding networks and changing consumer needs. This means that as well as being cheap and interoperable, the network infrastructure has to be reconfigurable and more flexible to the end-user's needs.

The never-ending demand for increased bandwidth, as well as the cost and space savings that can be made through miniaturization, are the final factors that firmly place integrated components at the top of a network designer's wish list. So what exactly is integration and how do component makers achieve truly integrated optical components?

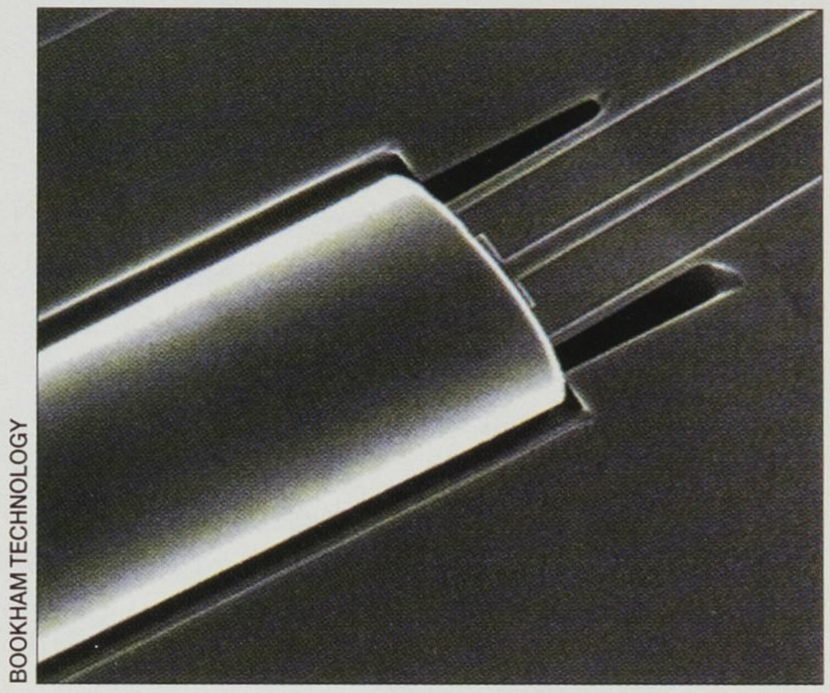
Actives and passives

Integration involves two categories of optical components: active and passive. Each part of an optical network employs different types of active and passive components to create and condition light, and channel this optical data to its destination.



BOOKHAM TECHNOLOGY

Fig. 1. End-butt coupling is a simple way to couple a laser diode to a planar waveguide. The laser's light-emitting layer is aligned with the waveguide to optimize emission.



BOOKHAM TECHNOLOGY

Fig. 2. Using V-groove technology to couple a waveguide and a fiber reduces production times and cuts costs.

Active optical components such as laser diodes and fiber amplifiers generate and amplify light. Many of these devices are based on compound semiconductor technologies such as InP and GaAs.

Passive devices, on the other hand, do not generate light. They generally route signals based on wavelength, intensity or polarization. Arrayed-waveguide gratings and power splitters are examples of components with passive functions.

Monolithic vs hybrid

There are two approaches to integrating actives and passives onto a single chip, which will give either a monolithic or hybrid device. Monolithic devices are fabricated from one material and contain all the essential functions within the substrate and the epilayers. In contrast, a hybrid device contains different materials and technologies that have been combined without the need for optical fiber interconnects.

A truly monolithic device can lead to huge cost savings during manufacturing and assembly, but in practice the properties and strengths of different materials generally dictate a hybrid approach. Using hybridization opens up the use of different materials and technologies optimized for different applications, which is why Bookham Technology has chosen this integration route.

Choosing a platform

To integrate high-performance components via hybridization, a device maker needs a platform to accommodate the actives and passives that are typically based on different materials and manufactured via different processes. While in the past many companies have favored silica, today's material of choice for the platform is silicon.

The immediate benefit of adopting silicon as an optical integration platform for hybridization is the wealth of knowledge accumulated by the semiconductor industry over the last 40 years. Techniques such as flip-chip bonding can easily be modified to suit optical component manufacturing.

Mature fabrication techniques also mean that silicon has a relatively low customization cost compared with other substrates, and gives a high integration yield. Optical integrated device makers can exploit these benefits to help make

devices at volume production levels. Silicon also has a relatively high thermal conductivity, which means that heat from active components such as laser diodes is easily dissipated.

Like competing InP and GaAs substrates, silicon offers an intrinsic way of implementing passive optical functions. For example, device makers can easily etch waveguides into the substrate using established photolithography techniques. Cladding layers can be deposited and interconnections added to the silicon substrate using standard epitaxy and lithography techniques. Silicon waveguides can also act as other passive components such as multiplexers.

As well as providing a building block for passive devices, silicon also provides an optical substrate that is easily formed into a hybrid component receptacle for active devices fabricated from materials such as GaAs and InP. Bookham has all three technology capabilities: silicon, GaAs and InP.

Bonding helps volume production

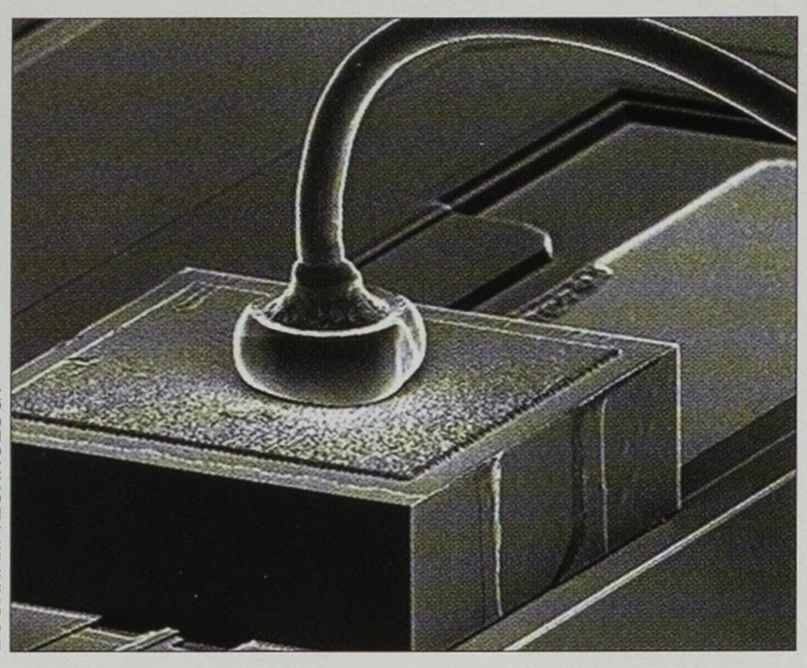
A crucial step to hybridization is to electrically connect active devices to the substrate as well as the associated cooling and monitoring elements. But because today's high-speed active optical devices currently run at up to 40 GHz, traditional wire-bond interconnects tend to act as antennas and induce noise.

However, bonding the components onto the substrate face-side down via the flip-chip method counters this effect as it eliminates wire bonding and allows shorter interconnections between the substrate and the components. Flip-chip bonding also fits into volume production needs as it is a wafer-scale operation that is widely used across the IC industry.

To prevent optical degradation during bonding, the flip-chip process has to be fluxless. This rules out conventional solder materials such as tin/lead solder balls, but materials such as gold/tin make fluxless bonding possible.

To optimize volume production during chip fabrication, gold/tin preforms are used, rather than solder balls. These preforms are wafer-sized, rigid frameworks of prefabricated bonds. To bond an edge-emitting laser diode to the substrate, the gold/tin solder preform is placed onto the silicon wafer and bumps are formed. The wafer is then diced, and diodes are positioned onto the preform.

To bond the diode, the temperature of the silicon substrate is ramped up to above the 280 °C melting temperature of the solder preform, and a fluxing agent such as a nitrogen/hydrogen cover gas is applied. The fluxing agent prevents oxidation during reflow and also cools and solidifies the molten metal once the reflow cycle is complete.



BOOKHAM TECHNOLOGY

Fig. 3. ASOC technology ensures that the laser chip is aligned to the waveguide to optimize optical performance.

Low-cost coupling

After bonding the components to the substrate or other elements, the next step is to couple the components. In the past, lasers and photodiodes, for example, have been packaged in metal cavities, with leads coming out of the sides ready for electrical connections. This arrangement, known as butterfly packaging, is costly and time consuming as each package has to be individually machined from a metal block and also requires glass-to-metal seals.

One route, however, to achieving wafer-scale production with lower costs is on-chip coupling. Rather than fiber-coupling discretely packaged components, device makers directly attach the component to the material of the signal-conditioning component, for example coupling a laser diode to a waveguide. By doing this, the light that is emitted by the laser diode can pass directly into a waveguide that has been etched onto the surface of the signal-conditioning device.

A simple way to couple a laser diode to a planar waveguide is via the end-butt coupling technique, in which the light-emitting end layer of the laser diode is positioned flush to the silicon waveguide (see figure 1). Other forms of coupling such as direct focusing, in which a lens focuses the output into the waveguide, suffer from difficulties in maintaining the position of numerous associated parts.

Once a laser diode is coupled to a waveguide, the waveguide is then coupled to a fiber with a technology called V-groove. This technology tapers the waveguide to the width of the fiber, which removes the need for a fiber interconnect (see figure 2).

ASOC tackles alignment

For integration to be successful it is crucial to accurately align active devices on the silicon substrate. Making these alignments inside the package is less time consuming and cheaper than making external alterations.

Laser diodes highlight the need for accurate alignment to optimize optical performance and package footprints. If the laser is aligned too far back on the submount, the light beam becomes partially blocked and inefficient. But if the laser is placed too far forward and overhangs the edge of the submount, a hot spot can develop that causes the laser to burn out. Also, if the laser is placed with its emitting stripe face down, the emitting edge must be placed within a few microns of the submount edge or the light will be blocked.

To ensure that such problems are minimized, Bookham has developed a technology called ASOC. Two plinths are first etched into the surface of the silicon substrate with precision accuracy, to ensure Z-axis alignment. An automated flip-chip die bonder then attaches the laser diode to the substrate and reflows the solder joint (see figure 3).

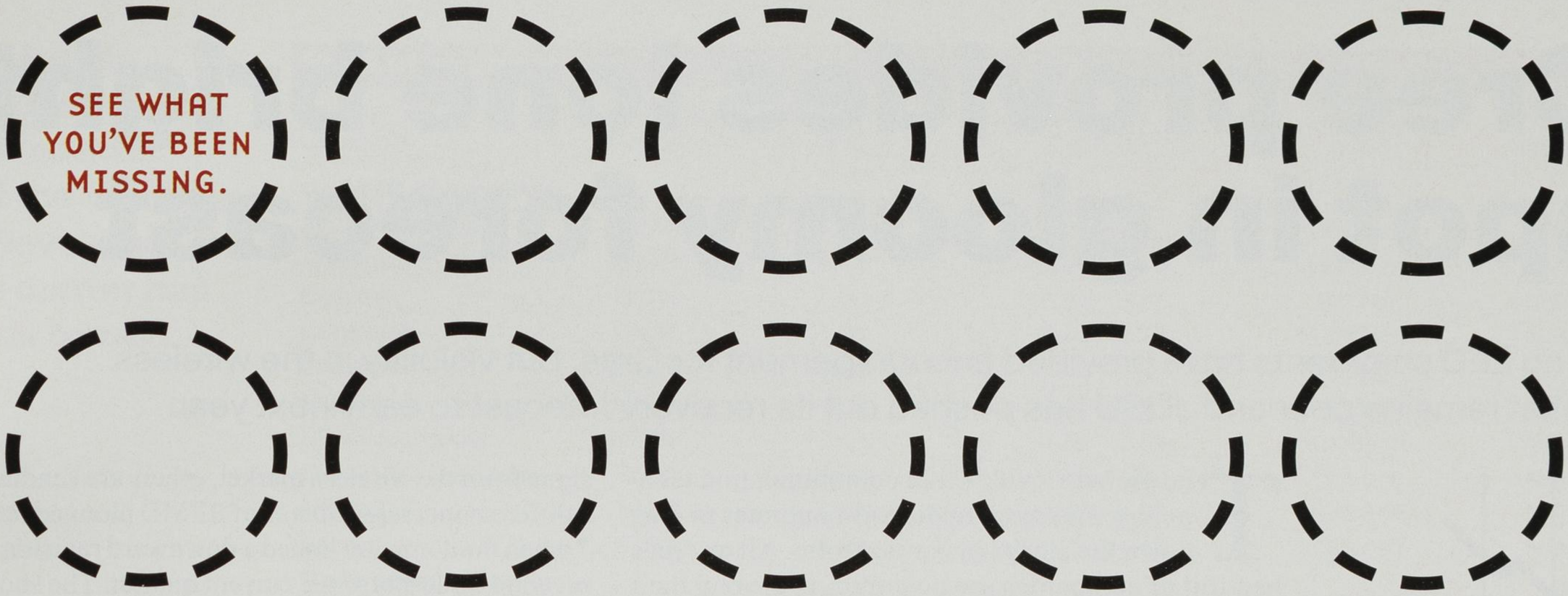
To align the diode to the substrate, the die bonder uses a fully automated pick and place robot/bond head and vision system. The vision system registers the laser diode and substrate simultaneously and corrects any offsets prior to bonding. The end result is a laser diode soldered to the silicon substrate with ±1 μm at 3σ placement accuracy. In contrast, manual systems give ±4 μm at 3σ placement accuracy at lower production throughput rates.

Looking to the future

As hybridization techniques make single-chip integration a reality, component manufacturers are providing multifunctional products at wafer-scale cost and volume. Advanced hybridization techniques are already driving down costs and leading the way to wafer-scale production.

However, this is not to say that the market for monolithic integration will decrease, as the future of integrated optics is expected to be both hybrid and monolithic. Every optical function will be performed in an optimized material system, and each optical component will be capable of integration with dissimilar technologies, on a single platform.

Robert Green is VP of business development and Stuart Morgan is team leader of automation and process development at Bookham Technology.



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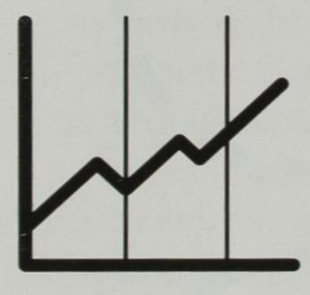
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WITH MARIE MEYER

Cree provides lone bright spot in gloomy forecast

Rising LED shipments have provided encouragement for Cree, but visibility in the wireless market remains poor and JDSU has pushed out its recovery forecast to early next year.

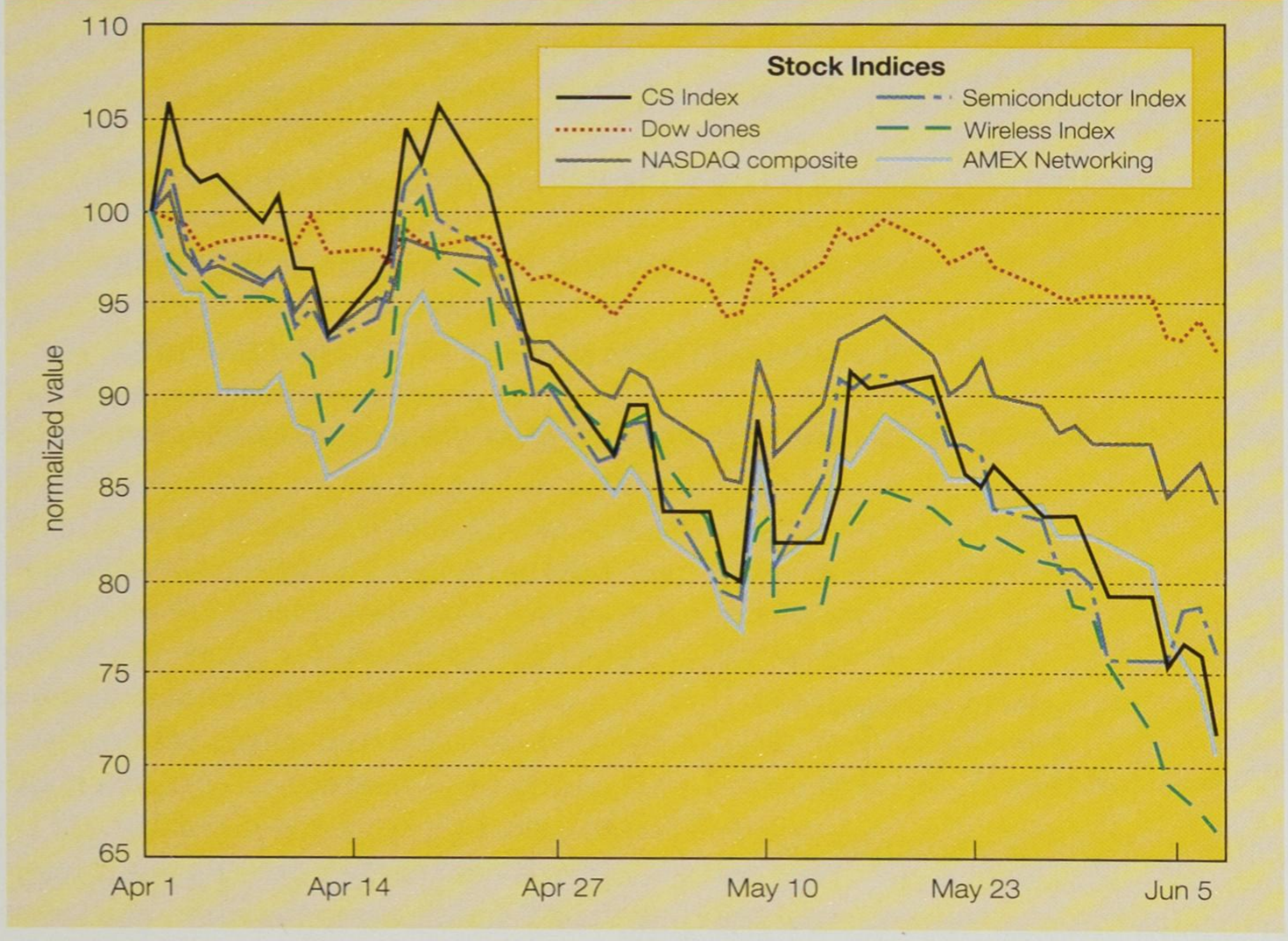


The global slowdown in communication technology and semiconductors continues to drag down the stocks in our portfolio. All except a handful of companies are now trading around their 52-week lows. The exceptions include the more diversified device manufacturers – Agilent and Coherent – as well as some of the equipment and materials suppliers. Shares in these companies were hammered earlier in the year, but have begun to inch back on the basis of cautious predictions for recovery in the chip equipment market in the coming months.

IQE kept that train of thought running in late May when it announced that its losses had widened in the first quarter, but it nevertheless believes that the corner has been turned. Company management said that it expected the first half of this year to represent the bottom of the downturn as orders picked up, especially in the wireless sector. IQE's operating loss, before goodwill and one-time charges, was £4.98 million ($7.3 million) in the March quarter, compared with a loss of £3.8 million in the previous quarter.

But while IQE and others are seeing some positive signs from the wireless market, others are sending out a different message. Shares of RFMD plunged on June 7 when the company issued a downward revision of its revenue forecast for the current quarter. The shortfall was attributed to "push-outs" from unnamed customers due to delays in introducing new handset models.

Industry indices



Wobbly wireless?

The news sent shares of RF Micro down nearly $6 to a new 52-week low of $9.76. It also pushed Nokia's shares to a new three-year low, as investors interpreted the news as a sign of trouble at RFMD's biggest customer. But Nokia executives say they are still on track for the introduction of GPRS phones, suggesting that some other cause was to blame for RFMD's problems.

"Nokia's product introductions are on time," said Olli-Pekka Kallasvuo, Nokia's CFO, during a conference call with analysts. "There are no technical issues." However, he also warned that Nokia's second-quarter sales wouldn't meet its forecasts, although the company still expects to meet its earnings target for the period. Unit sales of handsets are expected to be approximately the same as the year-ago period, while sales of network equipment are likely to be 20–25% lower. Merrill Lynch recently reduced its forecast for global handset shipments for 2002 to 385 million from 410 million. For 2003, volume was reduced to 410 million from 460 million. In April, Nokia forecast global handset sales for 2002 between 400 million and 420 million, reducing an earlier projection of 420 million to 440 million.

However, not all the news in wireless is entirely bad. RFMD believes that the orders which were delayed in the current quarter will appear on their books in the September quarter. And Kopin responded to RFMD's warning by reaffirming that it expects to see at least 10% growth in revenue from its HBT epiwafer product line in the June quarter. "Based on orders to date, our III-V and CyberDisplay businesses remain on track to achieve double-digit top-line growth," said John Fan, Kopin's president and CEO.

Most interestingly, Cree issued a rare upward revision of its sales target for the June quarter, citing rising demand for LEDs in mobile handsets. The revenue estimate has been raised to around $36.5 million, or an 8–11% increase over the March 2002 quarter.

IQE losses widened in the first quarter but the company believes that the corner has been turned.

Market overview

Company	Symbol	Closing price on June 10	52-week low–high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha Industries	AHAA	5.90	5.90–41.45	260.9 m	N/A
Anadigics	ANAD	9.42	8.25–23.00	288.0 m	N/A
Celeritek	CLTK	7.50	7.34–16.91	91.3 m	N/A
Conexant	CNXT	5.00	4.74–18.11	1.292 bn	N/A
Endwave	ENWV	0.71	0.60–1.90	25.2 m	N/A
Multilink	MLTC	0.65	0.65–18.40	48.5 m	N/A
RF Micro Devices	RFMD	10.43	9.76–32.53	1.746 bn	N/A
Sirenza Microdevices	SMDI	3.81	2.98–17.00	113.6 m	N/A
TriQuint	TQNT	7.08	6.42–25.90	930.3 m	N/A
Vitesse	VTSS	3.93	3.91–24.11	789.4 m	N/A
Opto companies					
Agilent	A	24.73	18.00–38.00	11.481 bn	N/A
Agere	AGRa	2.90	2.50–7.76	4.743 bn	N/A
Alcatel Optronics	ALAO	2.04	1.97–17.50	33.7 m	N/A
Coherent	COHR	28.45	25.05–39.50	821.6 m	71.07
Cree	CREE	12.67	10.35–33.32	922.3 m	N/A
JDS Uniphase	JDSU	2.82	2.76–16.27	4.273 bn	N/A
Stratos Lightwave	STLW	1.66	1.42–13.84	111.7 m	N/A
Uniroyal Technology	UTCI	0.37	0.27–9.25	10.3 m	N/A
Semiconductor materials and equipment companies					
ATMI	ATMI	25.50	14.50–37.10	779.0 m	N/A
AXT	AXTI	7.61	7.11–27.00	170.7 m	N/A
Emcore	EMKR	5.69	5.40–32.40	208.7 m	N/A
Kopin	KOPN	7.00	6.41–19.05	485.3 m	N/A
Tegal	TGAL	0.87	0.80–3.45	12.5 m	N/A
Trikon	TRKN	9.76	6.96–15.90	136.5 m	N/A
Veeco	VECO	26.35	19.90–49.14	765.3 m	N/A
European companies (currency data in €)					
Aixtron	AIXG.F	14.67	13.60–30.00	949.0 m	N/A
Bede	BED.L	2.29	2.29–3.32	66.3 m	N/A
Bookham	BHM.L	1.23	1.17–2.87	174.4 m	N/A
Filtronic	FTC.L	2.68	2.42–7.00	197.54 m	N/A
IQE	IQE.L	1.02	1.00–3.05	167.25 m	N/A
Picogiga	PGIG.LN	2.32	2.20–5.95	15.0 m	N/A
Riber	RIBE.LN	2.25	2.02–5.40	42.1 m	12.88
STS	SRTS.L	1.85	1.70–2.68	57.9 m	10.72

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

Previously, the company had predicted revenue growth of 5% sequentially. Cree's LED chips are used in a variety of handset designs as indicators and backlights.

Fiber: wait until 2003

One of the most interesting pieces of news to emerge from the annual CIBC Telecommunications Food Chain conference, held in New York City in the second week of June, is that JDS Uniphase expects to reach the break-even point in the first quarter of 2003. The company has been aggressively downsizing in reaction to the massive slowdown in carrier spending on fiber-optic networks.

"We are sizing to break even at $300 million in quarterly sales, with operating cash flow break even at $250 million," CFO Anthony Muller told conference attendees. "And we anticipate getting to that level by March of next year."

JDSU is cutting its staffing to 8000 from a high point of 29,000 last year, and has also reduced the number of its manufacturing plants from 41 to 24.

On June 5 fellow component manufacturer Alcatel Optronics announced that it would reduce head count by 25% and close some of its manufacturing sites. In France, a recently expanded fiber assembly plant in Illkirch will be closed and the work that was done there transferred back to the company's main facility in Nozay. And the company will also dispose of its MEMs operation in the Netherlands, through a management buy-out. Alcatel hopes to reduce its costs by €60 million ($56 million) by the end of this year. ●

14–17 July
Optical Amplifiers and Their Applications
Vancouver, Canada
Web: www.osa.org/oaa

15–16 July
PhoPack 2002
Stanford University, Palo Alto, CA, USA
Web: www.cpmt.org/scv

17–24 July
Semicon West
San Jose, CA, USA
Web: www.semi.org/web/wexpositions.nsf

22–25 July
Int'l Workshop on Nitride Semiconductors (IWNS)
Aachen, Germany
Web: www.fz-juelich.de/iwn2002

29 July – 2 August
26th Int'l Conference on the Physics of Semiconductors
Edinburgh, UK
Web: www.icps2002.org

4–8 August
14th American Conference on Crystal Growth & Epitaxy (ACCGE)
Seattle, WA, USA
Web: www.crystalgrowth.org/conferences/accge14

6–8 August
IEEE Lester Eastman Conference on High Performance Devices
Newark, DE, USA
Web: http://nina.ecse.rpi.edu/shur/EastmanConference/

18–21 August
3rd Int'l Conference on Microwave and Millimeter Wave Technology
Beijing, China
Web: www.cie-china.org/icmmt2002/

1–5 September
European Conference on Silicon Carbide and Related Materials (ECSCRM-2002)
Linköping, Sweden
Web: www.ifm.liu.se/ecscrm2002

8–11 September
Int'l Conf. on Mid-IR Optoelectronic Materials and Devices (MIOMD-V)
Annapolis, MD, USA
Web: www.avs.org/conferences/miomd2001/miomd.html

8–12 September
European Conference on Optical Communications (ECOC)
Copenhagen, Denmark
Web: www.ecoc.dk

8–12 September
Physics and Technology of Dilute Nitrides for Optical Communications
Istanbul, Turkey
Web: www.essex.ac.uk/ese/research/conference/main.htm

15–19 September
NFOEC
Dallas, TX, USA
Web: www.nfoec.com

11–13 November
Compound Semiconductor Manufacturing Expo (CS-MAX)
San Jose, CA, USA
Web: www.cs-max.com

For links to event websites, visit the Calendar section of our website at www.compoundsemiconductor.*net*.

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