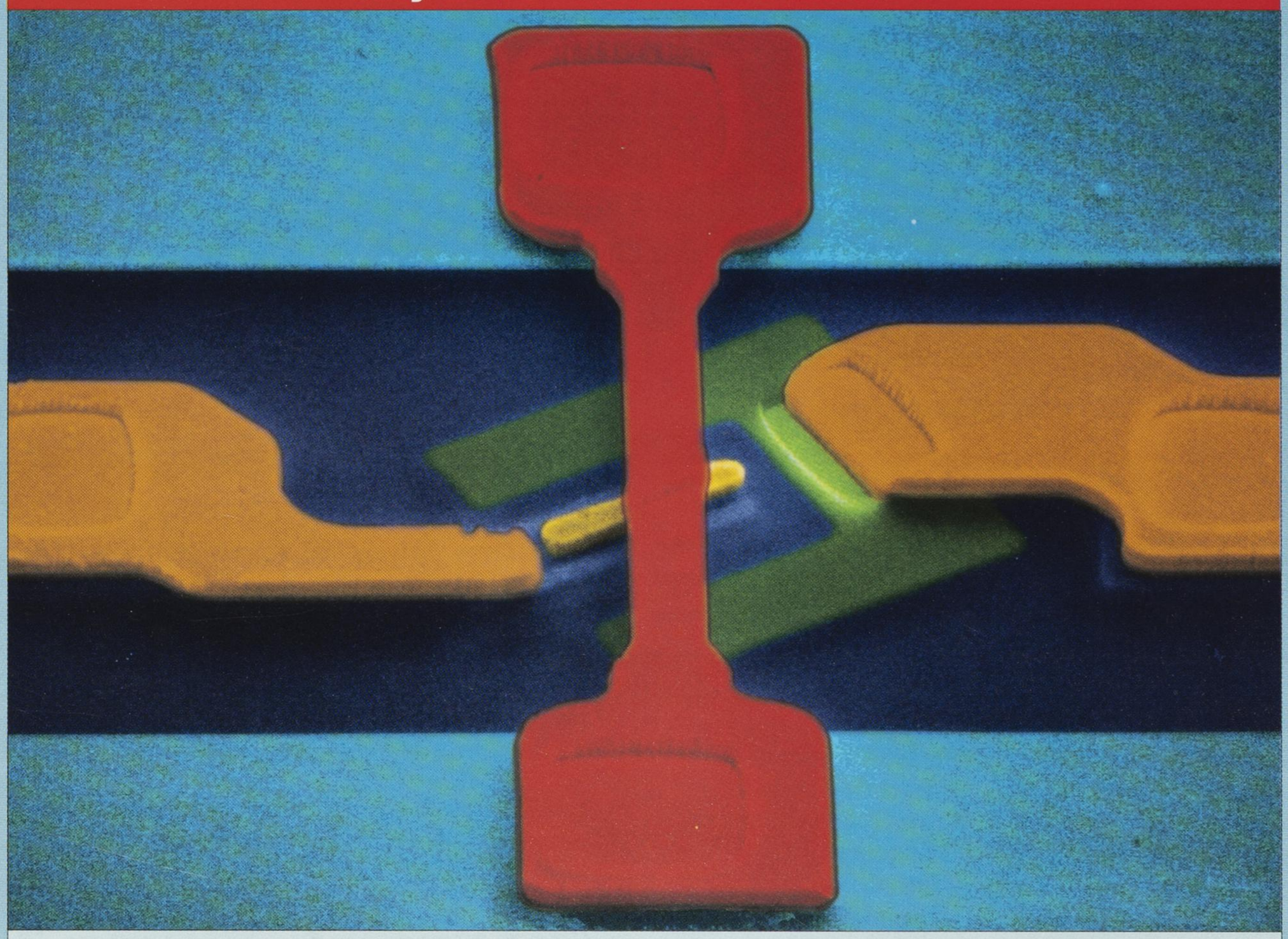
COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

July 2003 Volume 9 Number 6



INDIUM PHOSPHIDE

New compounds emerge as InP battles to beat the slump

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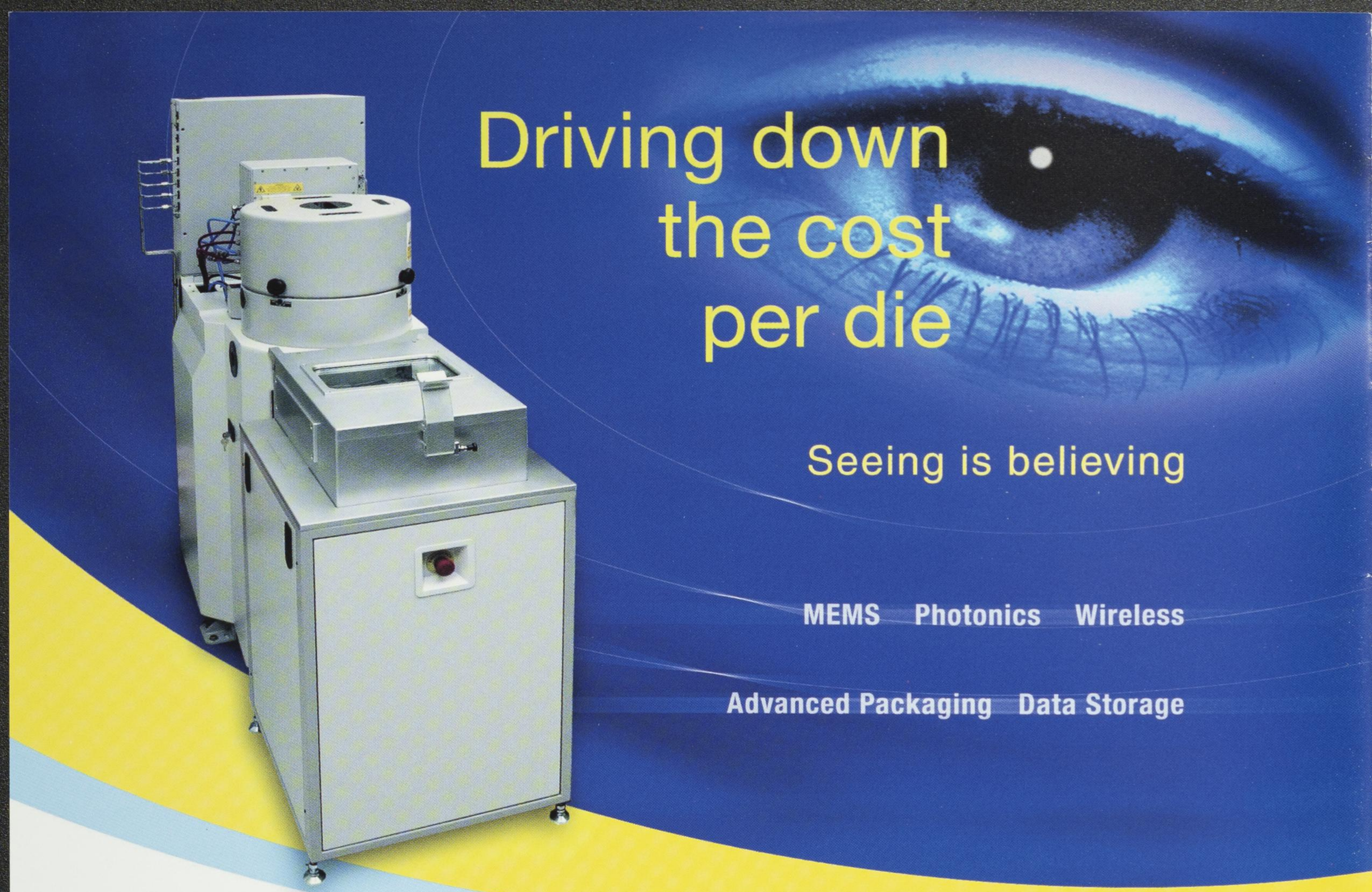
Mantech and LightFair reports	AXT plans to exit opto business	RFMD tops PA revenue league

Driving down the cost per die



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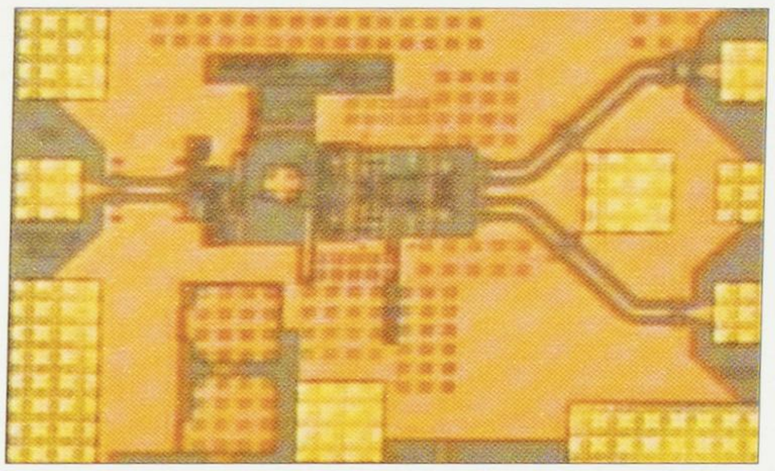
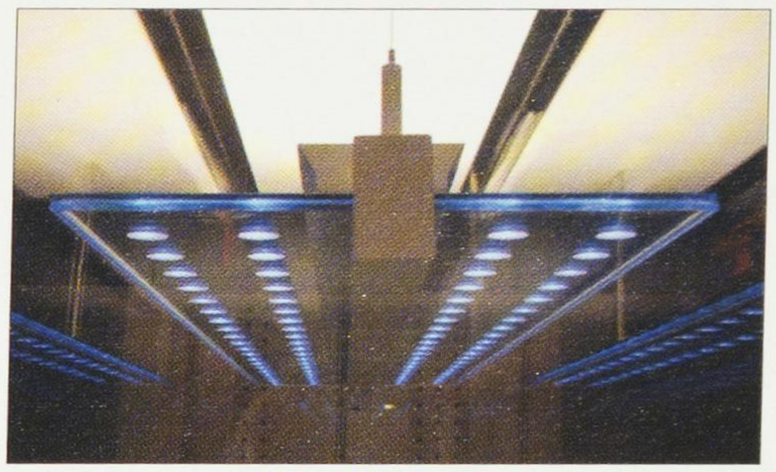


InP-based HBTs were one area discussed at this year's IPRM conference **p20**



Around 10% of exhibitors at a recent lighting trade show used LEDs in their products **p23**

Boston Laser has purchased the assets of Semiconductor Laser International **p37**

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27 **GaAs industry embraces new technology trends**

Despite temperatures of over 100 °F and several no-shows due to the effects of SARS, the attendees at this year's Mantech conference enjoyed a high-quality program covering GaAs and InP manufacturing technology, as well as wide-bandgap devices and the threat posed by silicon, writes Tim Whitaker.

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On the cover: *New processing technologies are pushing the performance of InP microelectronic devices (InP HBT image courtesy of UCSB) – see p20.*

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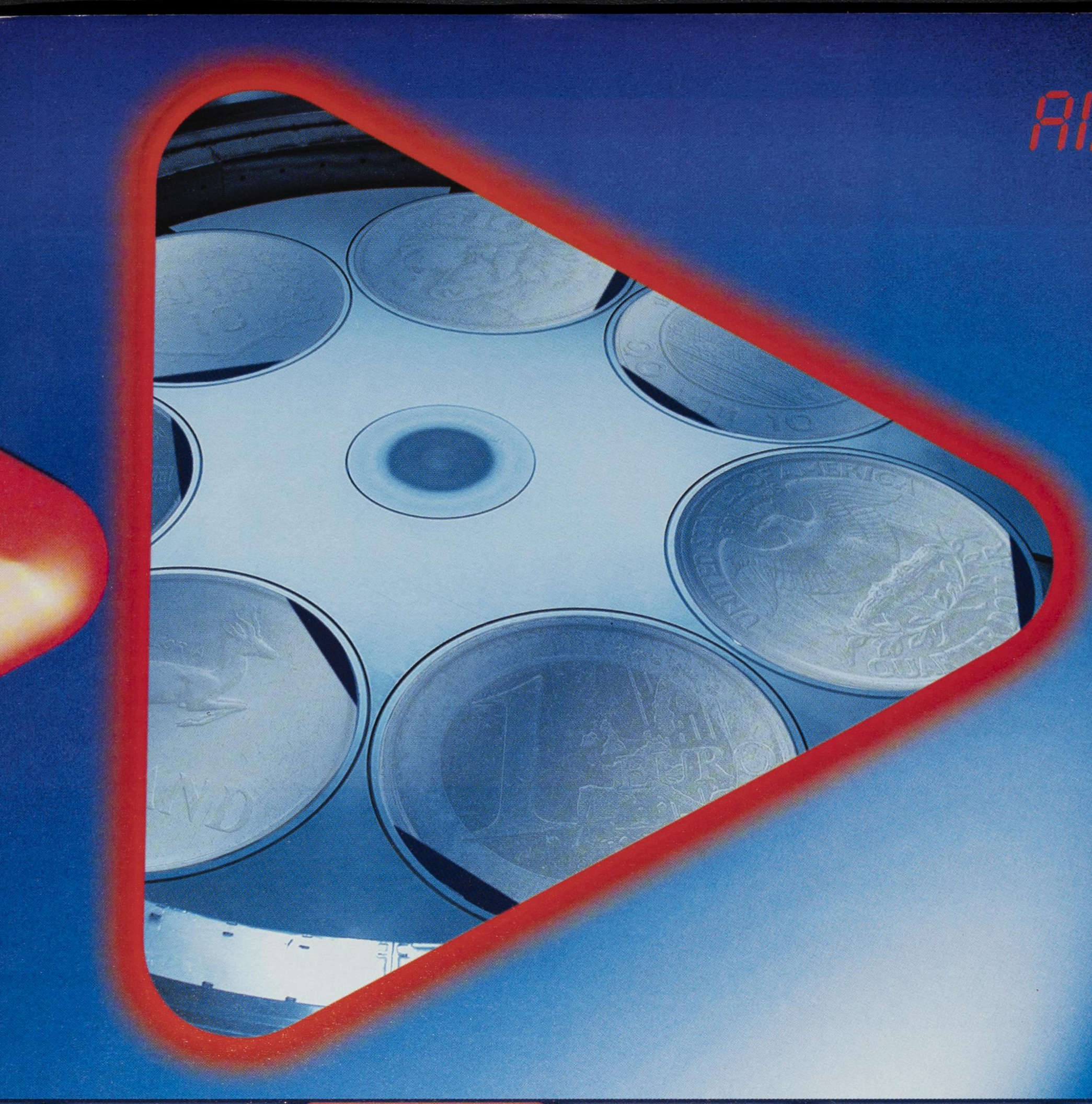

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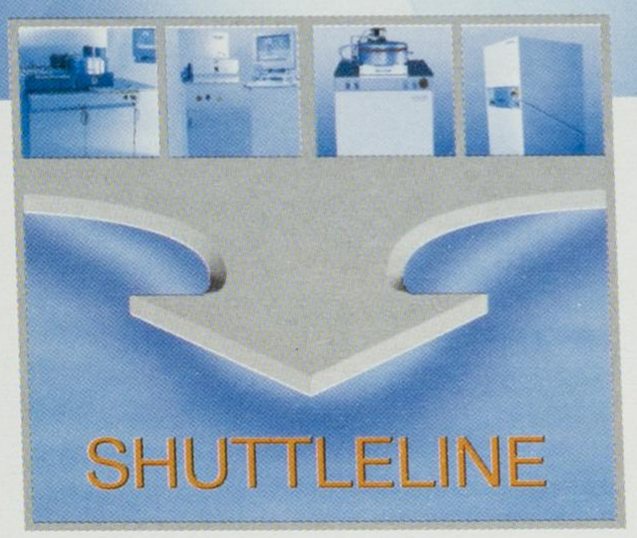

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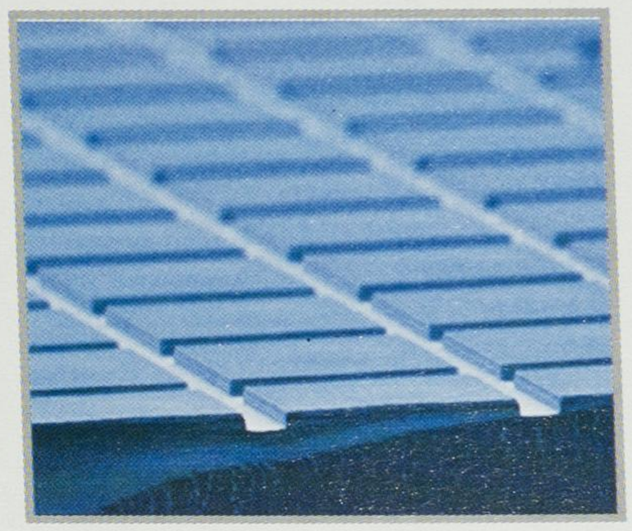

Etching of quantum well LEDs

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AXT plans to dispose of its opto unit

AXT is to discontinue the majority of its unprofitable optoelectronics production in order to concentrate on its core substrate business. The company is looking at ways to dispose of its optoelectronics unit.

AXT produces VCSELs, edge-emitting lasers and nitride-based LEDs at its facilities in California and China. On May 14, it announced a temporary shutdown of its optoelectronics production facilities in the US (*Compound Semiconductor* June 2003 p6). This followed a significant slowdown in sales of optoelectronic products at the start of May, which AXT blamed on the SARS virus.

Approximately 165 employees at the California facilities of AXT's optoelectronics division will be given notice that they will be laid off in 60 days. In the near future, the company will keep a minimum workforce to produce and ship current customer orders and to continue to sell products from its inventory. One option for the discontinuation of the optoelectronics business will be to spin off the division, possibly through a joint venture; other options could include the sale of the division or all or part of its assets, or liquidation.

However, AXT says that revenues from its core substrate business remain on track for the second quarter of 2003. "By taking this step, we will be able to focus our attention on growing our core substrate business and bringing it to profitability, while conserving the company's cash," said Morris Young, president and CEO of AXT.

For the second quarter ending June 30, 2003, revenue from AXT's substrate business is expected to be $8.2–8.4 million and net loss from continuing operations is expected to be $2.9–3.1 million or $0.13–0.14 per share.

AXT's net loss for the second quarter will also include charges related to the discontinued optoelectronics business. Its second-quarter results will be announced on July 23.

Cree files patent lawsuit against AXT

Cree Lighting Company, a wholly owned subsidiary of Cree, and Boston University have filed a lawsuit against AXT alleging infringement of a patent relating to buffer layer technology for GaN growth. The lawsuit seeks enforcement of US patent number 5,686,738, entitled "Highly Insulating Monocrystalline Gallium Nitride Thin Films", and requests damages and an injunction against infringement. The patent is owned by Boston University and licensed to Cree Lighting Company on an exclusive basis.

AXT has stated that it believes the lawsuit is without merit and that it intends to defend itself vigorously.

● **Correction:** In our last issue we wrote about a patent infringement lawsuit filed by Sumitomo Electric against AXT (*Compound Semiconductor* June 2003 p6). The article stated: "SEI's patents relate to its vertical Bridgman (VB) method for making GaAs substrates." However, only the carbon-doping patent (Japanese patent number 3,201,305) relates to SEI's VB process, while the strain patent (Japanese patent number 3,156,382) is a result of a vertical Czochralski process and does not relate to VB growth.

Cree entangled in multiple lawsuits

A lawsuit has been filed against Cree and its chairman by Eric Hunter, the company's former CEO and current part-time employee, and his wife. The couple are seeking to recover damages in excess of $3 billion for unspecified harm resulting from the alleged conduct of the defendants, Neal Hunter, current Cree chairman and Eric Hunter's brother, and Cree, Inc.

The lawsuit contains a number of allegations, including that beginning in August 1995, Cree and Neal Hunter filed false and misleading statements with the SEC relating to public stock offerings. The complaint also alleges that Neal Hunter and his brother Jeff, then chairman of an affiliated company, C3 (now Charles & Colvard, Ltd), entered into an undisclosed side agreement in connection with a requirements contract. This contract required C3 to accept unlimited shipments of SiC crystals for the manufacture of moissanite gems, thereby artificially increasing Cree's operating income and share price.

As news of the lawsuit broke on Friday June 13, Cree's shares tumbled from an opening price of $21.91 to a low of $15.65 before recovering to $18.10 at the close, down 18.5% on the previous day's closing price. Such a reaction was perhaps not surprising given the nervous state of the markets after high-profile cases of financial malpractice by companies such as Enron and Worldcom. However, comparison with such cases would be unfair given that the SEC has not announced any formal investigation into Cree's filings and that Cree has a strong trading position, recently reporting record revenues (see table) and a ramp-up of its LED manufacturing capacity to meet soaring demand.

Cree's rising revenues

Quarter ending	*Revenue ($m)*	*Net profit ($m)*
Mar 30, 2003	60.2	10.6
Dec 29, 2002	56.7	9.0
Sep 29, 2002	48.8	3.9
Jun 30, 2002	37.8	–22.5

"Cree has no knowledge of an SEC investigation at this time," said Chuck Swoboda, Cree's CEO. "The complaint and the damages sought make no sense to us, and we intend vigorously to defend the claims against us."

Cree will be asking a committee of independent directors to investigate any allegations of wrongdoing. It believes that the allegations are without merit and that they arise in part from personal and family matters.

Class action lawsuits proliferating

The activities on June 13 resulted in a number of class action lawsuits, charging that Cree's stock price was artificially inflated by a number of false statements to the marketplace. The lawsuits also claim that Cree did not disclose that $5 million of the proceeds of a share issue were to be invested in a speculative start-up company in which Eric Hunter was a substantial shareholder.

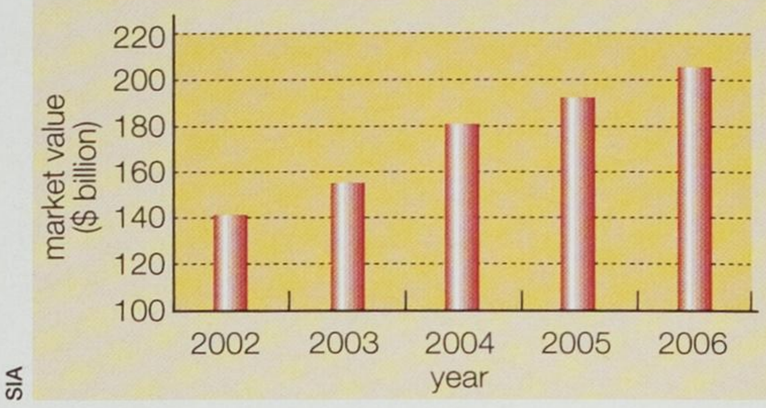
In addition, allegations have been made concerning Cree's purchase of the UltraRF division from Spectrian Corporation. The lawsuits allege that Cree falsely told the market that UltraRF would be accretive to earnings, and that it did not disclose that a two-year supply agreement only required Spectrian to purchase products from Cree at the lowest available commercial price. Although the UltraRF division continued to lose money for Cree, a charge for the division's goodwill was delayed until March 2002, when Cree announced that it would take a $60–77 million write-down for the division.

Growth returns to global semiconductor industry

After a difficult couple of years, the Semiconductor Industry Association (SIA) has released a positive growth forecast for the global semiconductor market, which includes 16.8% growth in 2004 and a compound annual growth rate of 9.8% to mid-2006.

SIA expects the market for discrete components, including power transistors and RF devices for wireless consumer products, to grow by 7.3% to $13.2 bn in 2003 and by 12.1% to $14.9 bn in 2004. Sales of optoelectronic components, including laser devices, image sensors and various communication devices, will increase 22% to $8.3 bn in 2003, and by 15% to $9.5 bn in 2004, says the SIA.

Global semiconductor market



SIA

LG replaces Sony Ericsson in top five handset manufacturers list

According to Strategy Analytics, the first quarter of 2003 saw a change to the top five handset manufacturers, with LG pushing Sony Ericsson down to sixth, and Samsung capitalizing on CDMA growth in China and India. The market research company estimated that 113 million handsets were sold to consumers during the first quarter of 2003, while 108 million units were shipped to distributors.

Nokia remained the leading handset maker with a 35.1% share of the market. By Nokia's own estimates, global shipments in the quarter were 98 million units. However, Strategy Analytics says that Nokia's figures ignore a large number of small handset vendors in China and Europe. Nokia and second-placed Motorola saw their market shares fall (to 15.4% in Motorola's case) during the quarter. During the final quarter of 2002, Nokia cornered nearly 40% of the market. Samsung's share rose to 12.8% in the first quarter of 2003, while Siemens' slipped to 7.4%. LG entered the top five with 5.2% of the market. Samsung's success is partly due to the strong growth in overall CDMA handset shipments, which grew by 49% as a result of new CDMA networks in China and India, while GSM shipments grew by 13%.

Strategy Analytics has also released its forecast for handset shipments during the remainder of 2003 and beyond. Its figures show that global handset sales will grow 5% in 2003 to 458.4 million units, and 11% in 2004 to 506.9 million units as demand continues to recover in mature markets and growth surges in developing regional markets.

3G handset sales take off

The breakdown of the figures by air interface standard shows CDMA sales growing 19% in 2003 to 89.4 million units and 17% in 2004, with a healthy CAGR of 12% through to 2008. GSM sales will grow 7% in 2003 and 17% in 2004 as emerging markets in Asia-Pacific and other regions gain critical penetration. GSM sales will grow at a CAGR of 12% through 2008 as color displays, multi-media messaging and Java-enabled devices diversify in availability and the average retail selling prices on these handsets fall to mass-market consumer price levels. 3G handset sales will account for 14% of total global sales in 2003 and 23% in 2004. By 2008, 75% of sales will be 3G handsets.

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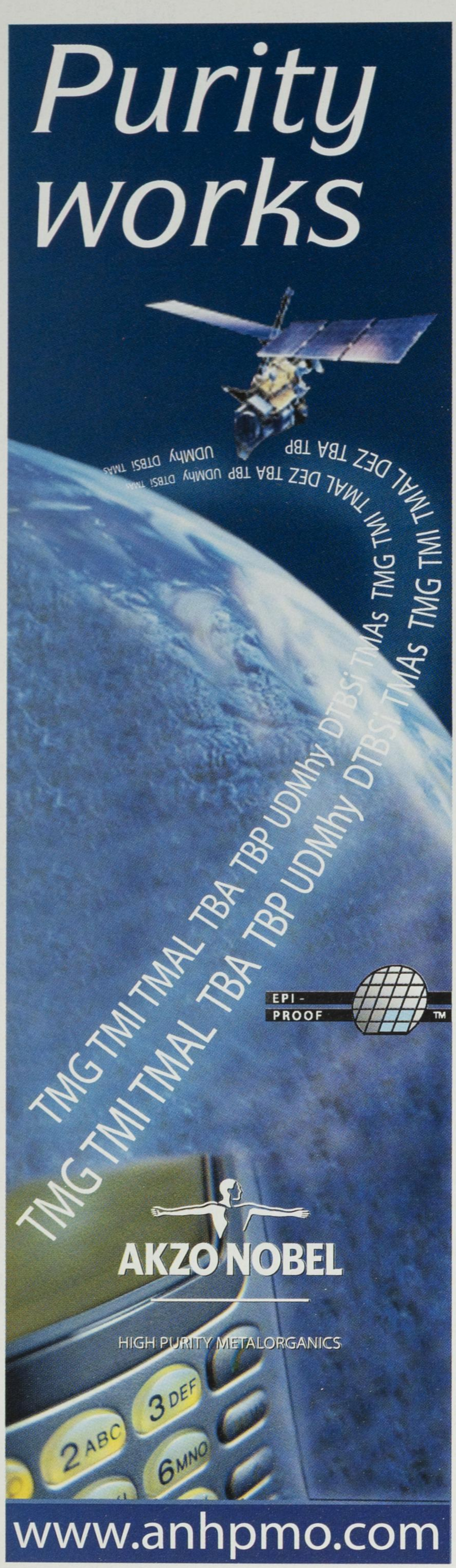

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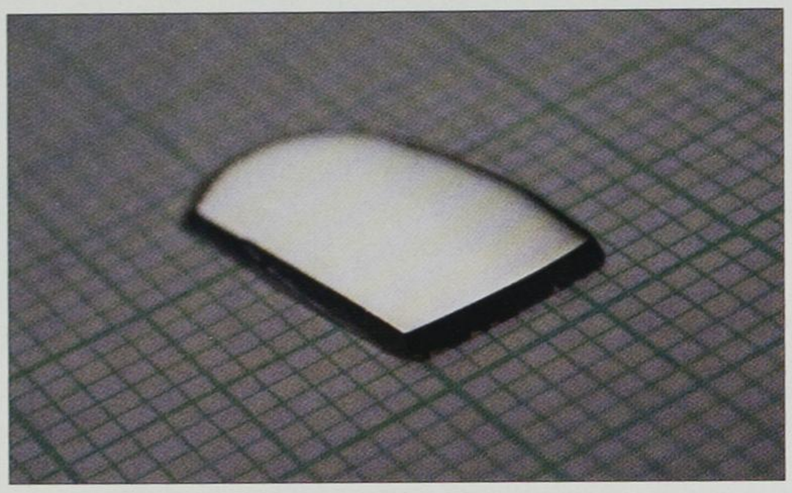
Crystal IS wins DARPA funding for R&D

Crystal IS, a supplier of single-crystal AlN substrates, has been selected to participate in DARPA's Semiconductor Ultraviolet Optical Sources (SUVOS) program. The program aims to accelerate the development of UV sources for defense applications, including biological agent detection and covert communications (*Compound Semiconductor* October 2002 p49). It has already awarded R&D funding to companies such as Cree, Crystal Photonics and Lumileds Lighting, as well as universities including Boston, Cornell, the University of South Carolina and the University of California, Santa Barbara.

Although Crystal IS would not comment on the details of its role in SUVOS, it did indicate that its boule growth technology is scalable in its ability to produce longer and larger diameter boules. The company currently offers 12 mm substrates made from boules that exceed 2 cm in length, and it plans to demonstrate 50 mm substrates by the end of the year.

Pushing AlGaN-based emitters deeper into the UV requires higher Al fractions in the active regions of the devices. AlN substrates provide a good lattice match for such materials, ensuring high crystal quality for efficient device operation. AlN's high thermal conductivity takes heat away from the active region, reducing thermally induced degradation and extending device lifetimes.



Bulk growth allows Crystal IS to produce non-polar AlN substrates such as a-plane material or this m-plane sample.

Crystal IS recently announced the availability of limited quantities of ultra-low dislocation density a-plane, m-plane and c-plane AlN substrates. "Our native AlN substrates are fabricated from our patent-pending boule growth process, and are the only commercially available AlN substrates to our knowledge that are not produced using heteroepitaxial techniques," said Keith Evans, COO and VP of business development. "As a result, we can offer virtually any customer-specified crystallographic orientation while maintaining industry-leading dislocation densities of less than 1000/cm^2."

The company's AlN substrates are also attracting interest from those developing high-power, high-frequency HEMTs (*Compound Semiconductor* April 2003 p14). The c-plane material that normally results from heteroepitaxial quasi-bulk substrate growth results in the strong polarization effects that induce charge at the AlGaN/GaN interface in HEMTs. While this is desirable in HEMTs, polarization effects have also been linked with certain HEMT performance issues, and may limit performance in other device types. There is therefore a growing interest from device researchers to investigate non-polar (for example a-plane and m-plane) substrates, which Crystal IS can slice from its boules.

GaN activity continues to thrive

There is still rapid growth in the level of commercial and R&D activity in the GaN field, according to a new report from Strategies Unlimited. Since 1999, the market for GaN devices (primarily blue, green and white high-brightness LEDs) has grown by 221% to reach $1.35 billion in 2002, and overall the market for GaN devices of all types is forecast to grow to $4.5 billion by 2007.

The report, *Gallium Nitride 2003 – Technology Status, Applications and Market Forecasts*, provides analysis of applications and market forecasts to 2007, and says that the worldwide growth and momentum for both commercial and R&D activity relating to GaN devices and materials has never been more robust.

As of the first quarter of 2003, 184 companies were involved in GaN production or development (devices, materials and equipment), and 293 universities and research centers were involved in GaN R&D, including 51 government-funded research agencies. These figures represent an increase of 74% and 24%, respectively, since the publication of Strategies Unlimited's previous GaN survey in May 2000.

Since the beginning of the first significant commercial shipments of GaN LEDs in 1995, the market has grown at an average annual rate of 64.5%. Blue-violet laser diodes based on GaN devices began shipping in 1999 and the market achieved modest levels through 2002. However, in 2003 the long-anticipated market for blue-violet (405 nm) laser diodes in optical storage has finally begun in earnest, as several companies have announced the first shipments of the next generation of high-density DVD recorders. At present the data storage market is still mainly 780 and 650 nm devices, but GaN-based short-wavelength emitters are beginning to make their presence felt as a solution to increasing storage density. The data-storage market is now the largest consumer of laser diodes, far outstripping the optical communications sector which dominated laser diode consumption until 2001 (*Compound Semiconductor* April 2002 p35).

GaN-based electronic devices are still under development, but the first significant commercial shipments are expected to begin in 2004 as companies such as RFMD and Nitronex complete prototype testing with potential customers.

Kyma Technologies wins $4 m in funding

Kyma Technologies, a supplier of GaN substrates based in Research Triangle, NC, has obtained $4 million in its Series B round of funding, led by Digital Power Capital, Siemens Venture Capital, and supported by former Kyma investors. The funding exceeded the goal of $3 million and will support commercialization, product development and staffing. The company plans to significantly increase its staff by the end of 2003.

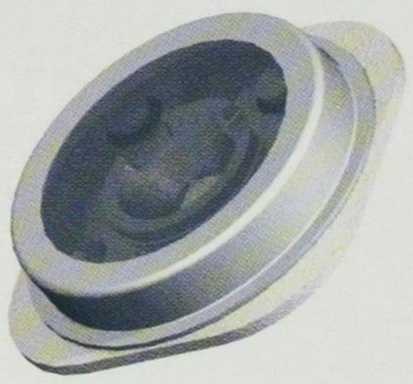
High-purity GaN substrates will eventually allow device manufacturers to grow lattice-matched GaN-based devices. This will eliminate the complicated buffer layers required to grow GaN on Si, SiC and sapphire substrates, and will also improve device quality.

"Kyma's technology is a substantial improvement over current alternatives, and we believe it will become a premier global GaN materials company," said Harald Kirchner of Siemens Venture Capital.

Kyma has continued to accelerate its development of GaN substrates to optimize quality and reduce defect densities, and says it has received positive feedback from customers.

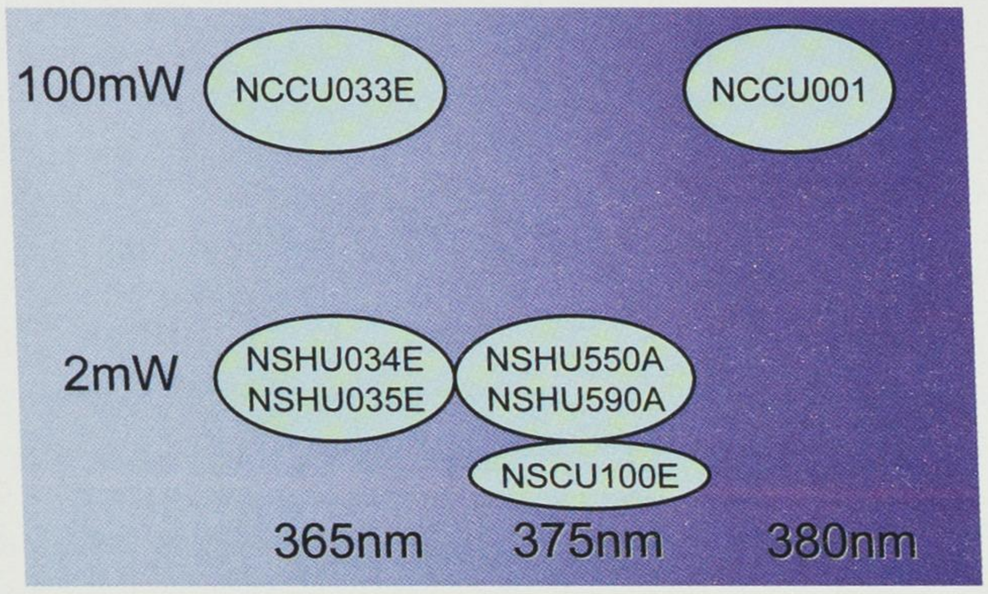
NICHIA

365nm, 100mW.
We named it
i-LED



Nichia has developed 365nm LED.
Peak Wavelength, just on i-line, 365nm.
100mW, most powerful in the market.

Again, from Nichia.



Nichia UV-LED Products

Model	Λ(p)	Power	Window	Available
NCCU033E	365nm	100mW	Flat	2004
NSHU034E	365nm	*2.0mW	Flat	2004
NSHU035E	365nm	*1.4mW	Lens	2004
NSHU550A	375nm	2.0mW	Flat	Now
NSHU590A	375nm	1.4mW	Lens	Now
NSCU100E	375nm	*1.0mW	SMD	2003/11
NCCU001E	380nm	100mW	Flat	2003/12

*Preliminary number. Subject to change without notice.

For Product Guide : www.nichia.co.jp
Contact: Email : uvled@nichia.co.jp
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Ever Researching for a Brighter World

Cree to offer foundry service in US for SiC MMICs

Cree is to become the first company to offer a foundry service for wide-bandgap MMICs to customers in the US. The service will be based on Cree's second-generation 3 inch SiC MESFET production process, the development of which has been partly funded by the US Department of Defense (DoD). The foundry service adds to Cree's standard discrete SiC Schottky diode and MESFET products.

"We have received significant interest in providing this type of foundry service, and are pleased to begin offering it to US-based companies for domestic use," said Jim Milligan, Cree's manager of wide-bandgap microwave products. SiC MMICs will find uses where high-power and wide-bandwidth amplifiers are required, for example in pulsed-power radar and cellular infrastructure.

Cree's 3 inch SiC MMIC capability has made rapid progress recently, due in part to $26 million in defense contracts awarded last July from the Office of Naval Research and Air Force Research Laboratories for SiC MMIC process development. The contracts are jointly funded by the US Navy, the Missile Defense Agency and the Title III program run by the DoD. Cree's funding forms part of Title III's producibility program, which covers substrates (3 inch semi-insulating SiC), SiC epitaxy for MESFETs and cleanroom processes for manufacturing the MMICs, including passive components, via holes and device testing.

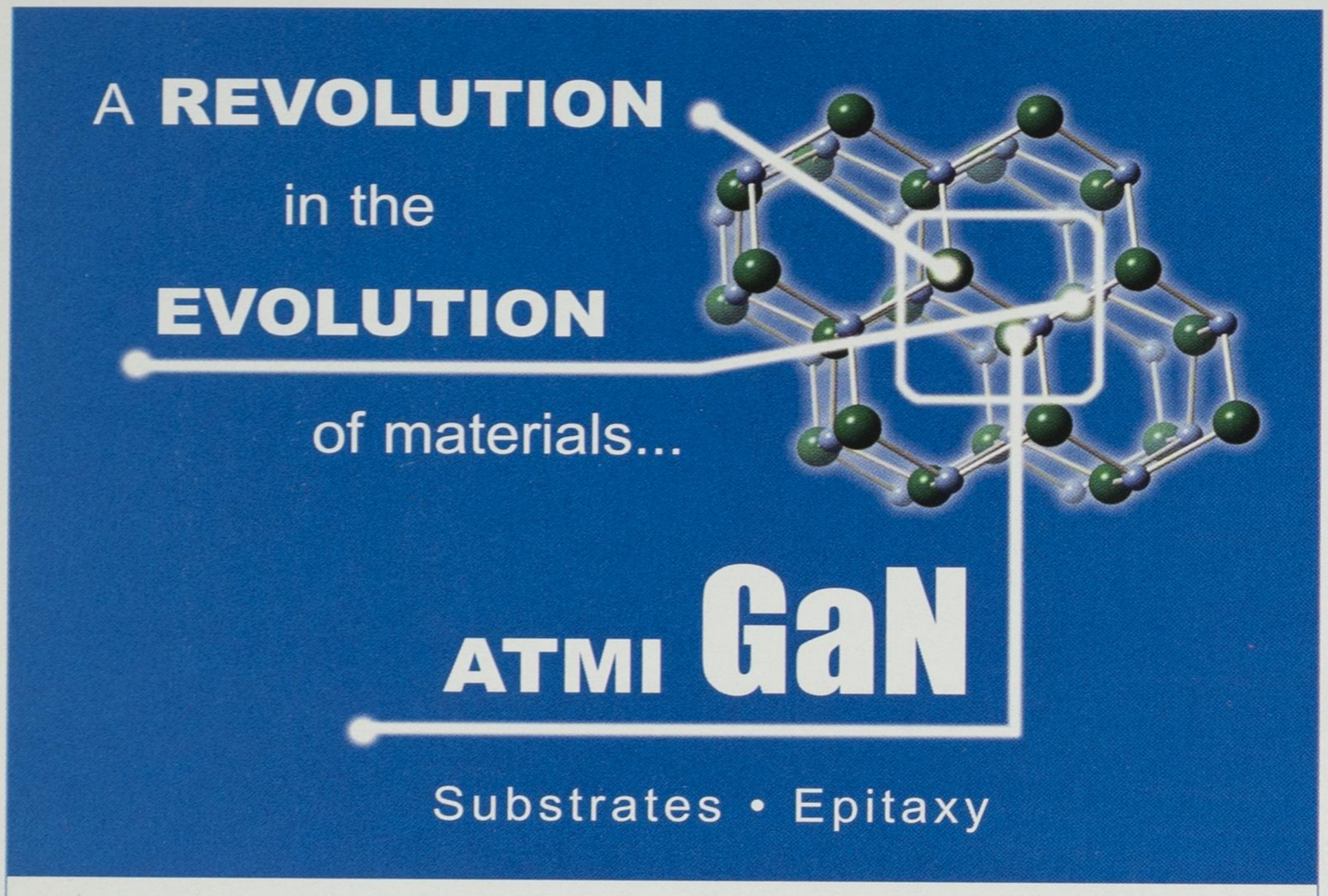
The advanced SiC MMIC process will enable similar levels of integration to those of commercially available GaAs MMIC processes, including the incorporation of resistors, MIM capacitors, inductors and through-substrate vias on a single RFIC, reducing the parts count required for high-power amplifiers.

Initially, Cree will provide foundry and engineering support services based on custom design solutions developed by Cree's internal MMIC design staff. By the end of calendar year 2003, the company intends to support external customer designs using standard device models and layout rules.

"In addition to providing unmatched RF performance, this service will allow external customers to design into our SiC MMIC process using their own proprietary circuit designs and architectures," said Milligan. "Cree is the only company to commercially offer the higher-power, wider-bandwidth capability of SiC compared to Si or GaAs in a MMIC format."

The company is still undecided as to whether to offer a multiproject wafer service. "Die sizes are large [up to 6×6 mm^2] so it's difficult to put more than one MMIC on a reticle," said John Palmour, VP of advanced devices at Cree. "If we have enough customers wanting small numbers of small die then we probably will, but right now it's still an open question."

Coming in September – a special issue on silicon carbide



Cree offers brighter LEDs

Cree has introduced enhanced versions of its XBright and MegaBright products, as well as very thin LEDs for keypad backlighting. The new MegaBright Plus (MB Plus) and XBright Plus (XB Plus) blue LEDs will both be offered in 460 nm and 470 nm versions.

The typical brightness level for the new XB Plus device is approximately 20% higher than Cree's XBright product, which is currently the highest-performing Cree device. The 470 nm XB Plus LED has a typical radiant flux of 17 mW (minimum 15 mW). The MB Plus device has a typical brightness level approximately 30% higher than Cree's current MegaBright product. The 470 nm MB Plus has a typical radiant flux of 13 mW (minimum 12 mW).

The MB Plus and XB Plus specifications make these devices particularly well-suited for white LED backlighting of color liquid-crystal displays (LCDs) in mobile appliances. Production quantities are currently available for both the MB Plus and XB Plus products.

Mike Dunn, Cree's VP of Optoelectronics, said "These brighter versions of our MegaBright and XBright products offer exciting opportunities targeted specifically at the white LED market. We believe our customers can achieve even greater performance by using these products in applications requiring white light, such as color LCD backlighting."

RazerThin LEDs

Cree also announced that it is providing initial samples of its new RazerThin LED products to select customers. These products are 60% thinner than Cree's standard products at approximately 100 μm in height, and also offer a lower forward voltage, typically 2.9 V when operated at 5 mA. Applications for next-generation keypad backlighting require subminiaturization and a thinner form factor for LEDs. The full release of this product is targeted for early July.

Lumileds LEDs used in underwater lights

LEONE

A new range of scuba-diving lights using Lumileds Luxeon LEDs has been launched by an Italian company, Leone, to provide long-lasting, high-brightness underwater lights suitable for photography and film. The lights utilize either 6 or 12 white Luxeons, which provide 25 lm/W and allow the light batteries to last up to five times longer than traditional gas-filled dive light systems. The LED-based lights are also smaller and more robust than conventional lights, and switch on instantly without a warm-up period.

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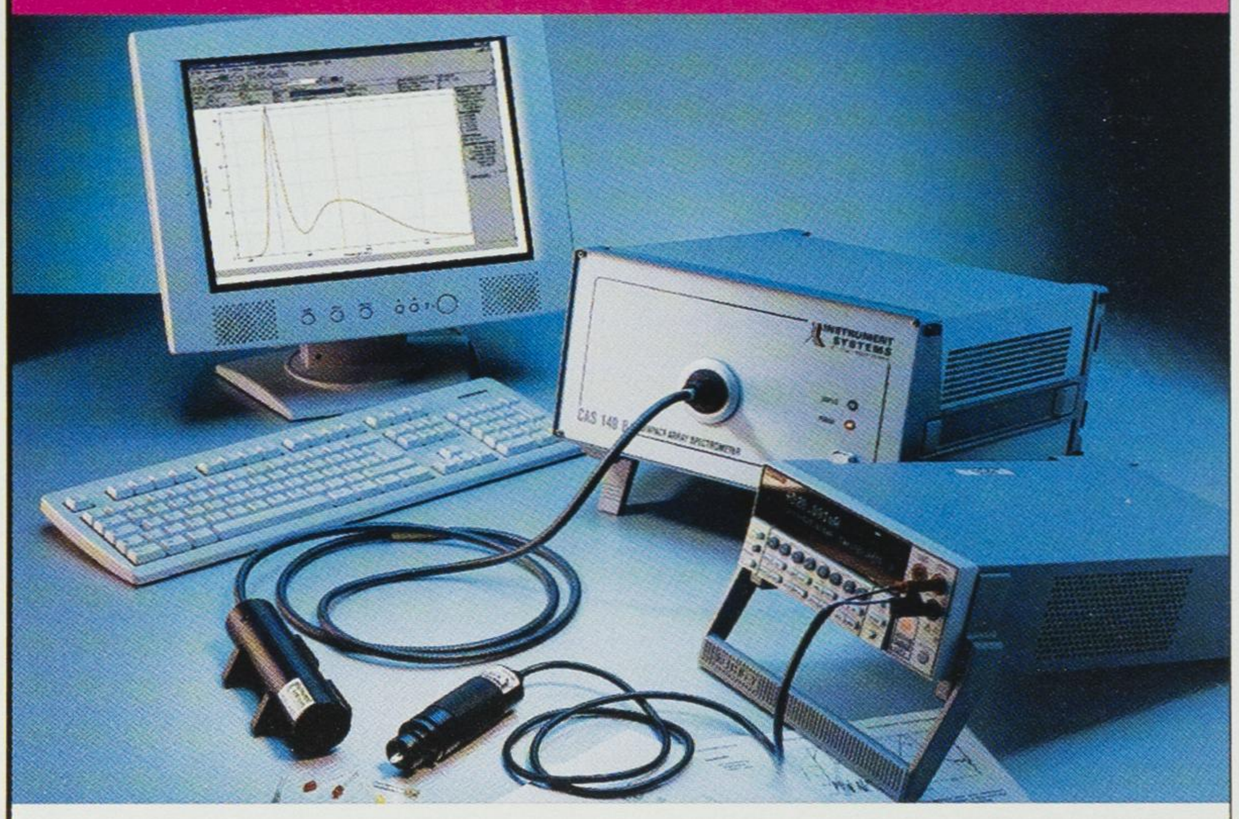

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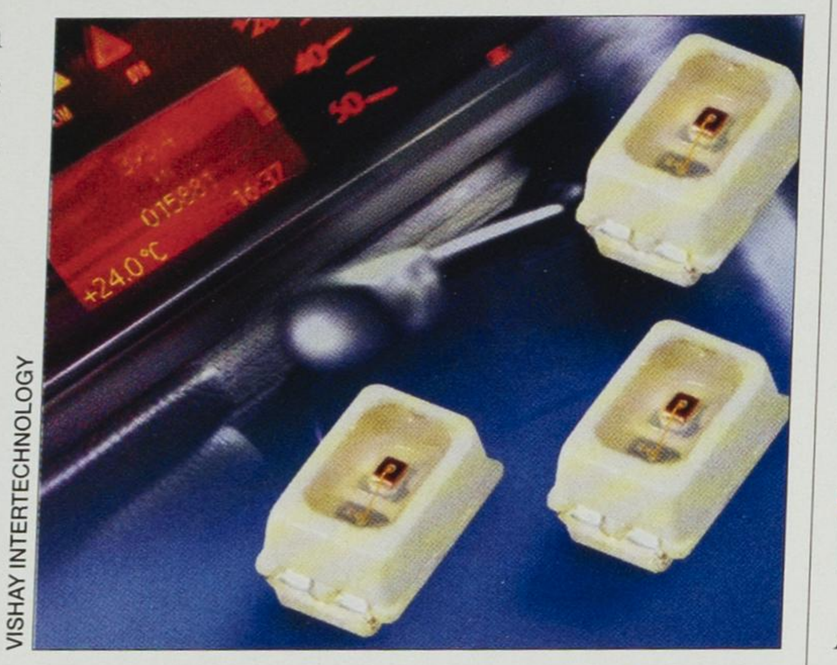
Vishay 30° LEDs give up to 4 cd luminous intensity

Four new high-intensity 30° LEDs have been introduced by Vishay Intertechnology. The TLCx52xx series are clear, non-diffused, 5 mm LEDs featuring an untinted plastic case, together with a lens and viewing angle (±15° angle of half intensity) optimized to provide the greatest light output and visibility. The TLCR5200 red (616 nm) and TLCY5200 yellow (590 nm) LEDs are AlGaInP-based devices, and offer a typical luminous intensity of 4000 mcd at a forward current of 50 mA. The TLCTG5200 true green (525 nm) and TLCB5200 blue (470 nm) nitride-based LEDs provide luminous intensities of 2000 and 700 mcd, respectively, at a forward current of 30 mA. The AlGaInP and nitride LEDs can withstand ESD voltages of 2 and 1 kV, respectively, and are rated for junction temperatures of 125 and 100 °C, respectively.



VISHAY INTERTECHNOLOGY

Vishay has introduced a series of nine miniature SMD LEDs in packages measuring just 2.3 × 1.3 × 1.4 mm. The LEDs feature a 120° angle of intensity and have a brightness of up to 120 mcd for yellow and orange AlGaInP-on-GaAs devices.

Sanyo supplies blue and white LEDs

Sanyo has a introduced a new range of blue and white LEDs. The white LEDs combine a blue InGaN chip with a phosphorus filter in the lens of the LED, producing a cool white light (high color temperature). The white devices range in intensity from 0.2 cd with a divergence angle of 150° in a 3 mm package up to 3.0 cd at 25° in a 5 mm package. The blue LEDs range in intensity from 0.35 cd with a divergence angle of 65° in a 3 mm package, up to 4.0 cd at 25° in a 5 mm package.

New gel encapsulant

A new optical gel, made by Lightspan, is a soft encapsulation material designed to protect HB-LEDs from mechanical shock, thermal shock, dust and moisture. LS-3357 is optically clear from the near UV to the near IR, has a refractive index of 1.57, and cures in 6 h at 100 °C, or under 1 h at 150 °C.

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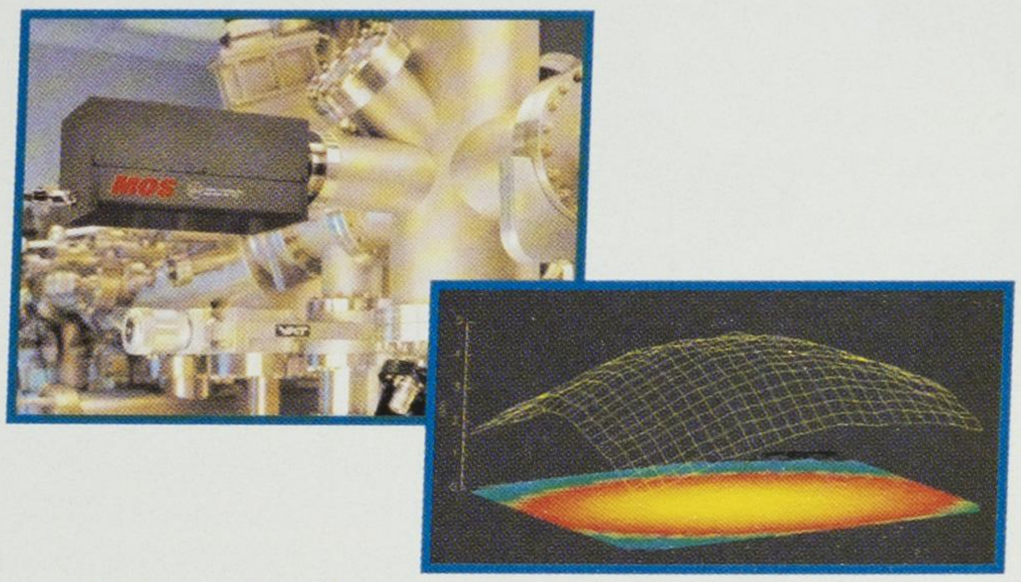

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Vitesse acquires Multilink

Vitesse Semiconductor is to acquire struggling Multilink Technology of Somerset, NJ, a fabless supplier of digital and mixed-signal ICs for optical communications, in a stock-based deal. Vitesse will exchange 4.2 million shares for Multilink's assets, valuing the deal at about $23 million. The transaction should close in the third quarter of 2003.

Multilink, which was targeting its products at long-haul and metropolitan networks, has suffered from dwindling revenues since the recession in optical communications took hold. For its March 2003 quarter, the company reported losses of $12.2 million on revenues of under $1 million.

"This acquisition brings a highly experienced team of system, mixed-signal and digital design engineers that have successfully developed products which would cost us more than the purchase price to reproduce," said Lou Tomasetta, president and CEO of Vitesse.

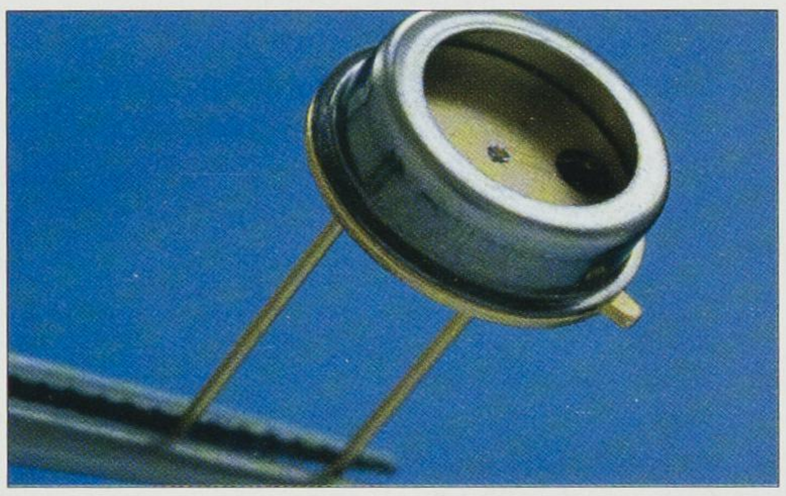
The product portfolios of Multilink and Vitesse are almost all CMOS, although both companies have some compound semiconductor activity. Vitesse is winding down its 6 inch GaAs fab in Colorado, but is still involved in InP and offers a foundry service from its fab in Camarillo, CA. Multilink has a stake in German company IPAG, a developer of InP-based optical receivers and modulators.

Vertilas introduces InP-based long-wavelength VCSELs

Vertilas, a start-up based in Munich, Germany, has announced the availability of long-wavelength InP-based VCSELs operating in the 1450–2050 nm range. The devices utilize a buried tunnel-junction (BTJ) design to enable low-resistive lateral current confinement and waveguiding. The BTJ structure also has a hybrid metallic/dielectric bottom mirror and an integrated heat sink to assist with the removal of heat from the InGaAlAs quantum well active region.

Vertilas was formed in late 2001 as a spin-off from the Walter Schottky Institute of the Technical University, Munich, and secured a first round of funding in mid-2002 (*Compound Semiconductor* August 2002 p21). The company is targeting two main markets, namely optical communications and trace-gas sensing. Vertilas has already demonstrated 10 Gbit/s operation of a 1550 nm BTJ VCSEL, and expects the device to supplant DFB lasers in applications where power levels of about 1 mW are sufficient.

With excellent single-frequency performance, long-wavelength VCSELs are ideal light sources for optical spectroscopy applications. The wavelength of the devices can be adjusted by about 3–4 nm by simple current tuning, allowing the wavelength to be scanned near absorption lines of interest. These include water vapor at around 1.8 μm, methane and ethane at 1.68 μm and carbon dioxide around 2 μm. Other advantages of VCSELs include fast tunability for time-resolved measurements of combustion processes, and low operating current for low power consumption.

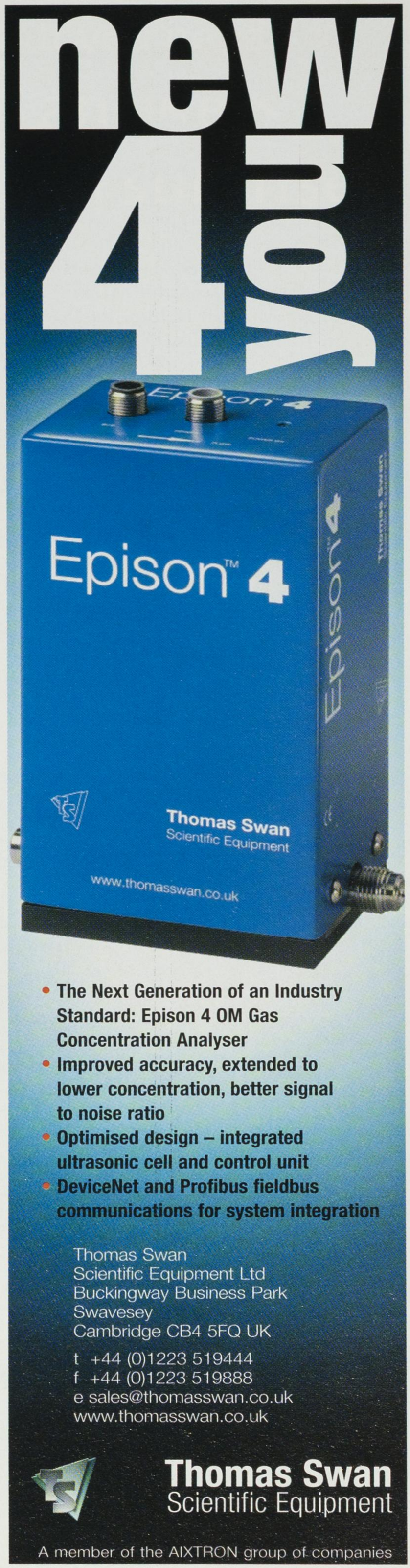


VERTILAS

Vertilas is producing VCSELs in the 1450–2050 nm range for communications and spectroscopy applications.

Essient Photonics goes under

Essient Photonics, a Scottish company developing integrated optoelectronic devices based around resonant tunneling diode structures (*Compound Semiconductor* April 2003 p22) has gone into liquidation. All the company's equipment from its facility in the Strathclyde Business Park was offered for auction at the end of June. The company was awarded a $7 million funding round in March 2002 (*Compound Semiconductor* May 2002 p29), but only received part of the money since it failed to achieve various milestones.



Irish photonic test companies merge

Tsunami Photonics Limited, which manufactures fast test system software for photonic components, has acquired the PXI business of fellow Irish test company PXIT. Both companies are based in Dublin, Ireland. The merged company, trading as PXIT, will focus on providing test solutions for manufacturers of optical and opto-electronic components, and has also received an investment in excess of $1.5 million. Venture capital company Delta Partners led the investment round, together with Enterprise Ireland and several private investors.

Consolidating its commitment to the PXI (PCI extensions for instrumentation) modular instrument standard, the company will combine PXI optical instrument modules, proprietary technology and powerful analysis software to provide high-speed, cost-effective optical test solutions (*Compound Semiconductor* November 2002 p47).

Products from Mitsubishi, EpiWorks and Multiplex

Mitsubishi introduces uncooled DFB laser

Mitsubishi has introduced the ML9xx40 series of DFB lasers, enabling 2.5 Gbit/s, 100 km transmission in a 0–85 °C temperature range. The 1.55 μm lasers do not require temperature control, reducing size, cost and power consumption. A key factor is the use of a quarter-wavelength phase-shifted grating. Samples will be available in June 2003 and mass production is scheduled to begin in August 2003 at a rate of 10,000 units per month.

EpiWorks has 1550 nm InP laser epiwafers

Epiwafer supplier EpiWorks has announced the availability of a new capability to produce high-performance 1550 nm InP laser wafers. Typical production data from customers of EpiWorks' AlGaInAs/InP 1550 nm laser epiwafers include a transparency current density of 330 A/cm^2 and threshold current density of 500 A/cm^2 (for a 500 μm cavity), with an internal quantum efficiency of 73%.

Multiplex transponder has 40 km reach

Multiplex's new 300-pin transponder for 40 km links contains a 1310 nm electro-absorption modulated laser and an APD receiver. Typically, 40 km transponders utilize a 1550 nm source laser and a *pin* receiver. As a result, the MTP-13 has a power of –2 to +2 dBm (a 1.5–2 dB saving over 1550 nm-based transponders), an APD receiver sensitivity of better than –24 dBm at a bit-error-rate of 1E-12, and provides a system margin of at least 20 dB for 40 km, 1310 nm applications.

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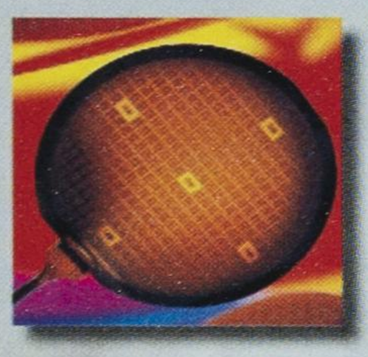

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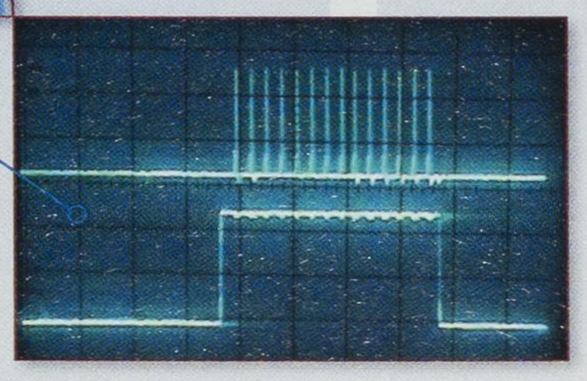

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RFMD remains at top of revenue league for PAs

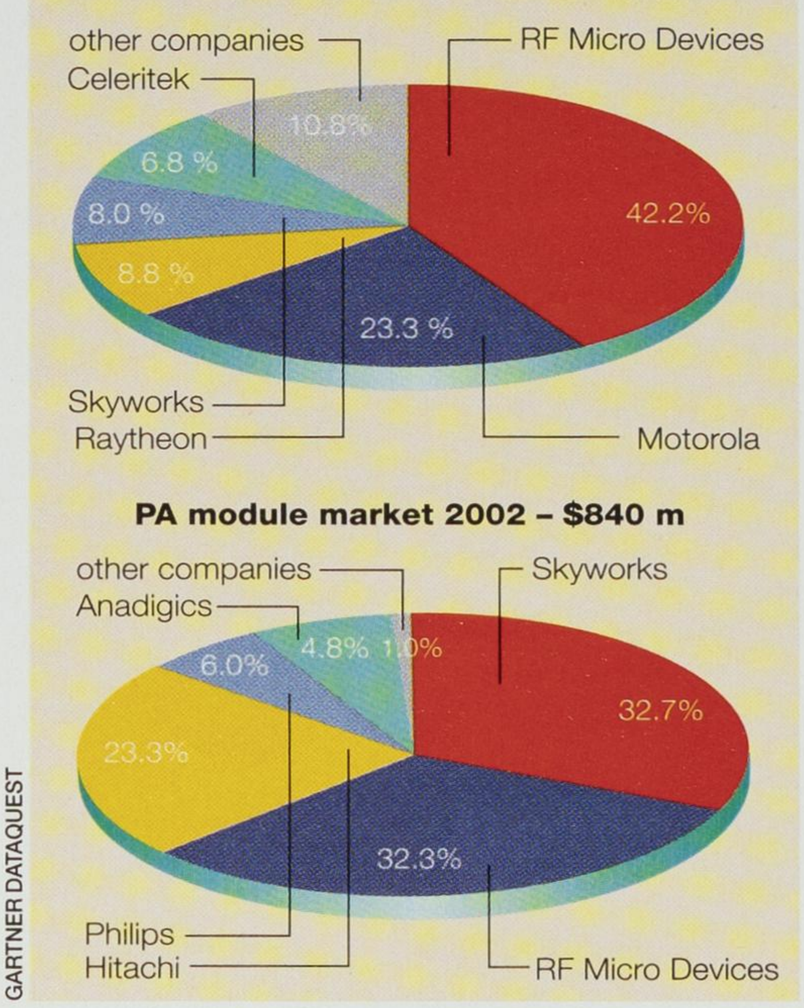
Gartner Dataquest's annual look at positions in the market for wireless handset PAs reveals that RF Micro Devices (RFMD) and Skyworks outstripped the competition in 2002. RFMD was the number one PA MMIC supplier, pushing Motorola off the top spot, and the number two module supplier with a total revenue in 2002 of $376 m. Skyworks, with a total PA revenue of $291 m, was the leading module supplier in 2002 with $275 m and 32.7% market share for modules, just ahead of RFMD with $271 m and 32.3% module market share.

The report *Wireless Communications Semiconductor Competitive Market Shares for 2002* also highlighted the significant shift from selling MMICs to ready-assembled PA modules as suppliers seek to add value and lower costs for wireless OEMs. The PA MMIC market declined from $387.2 m in 2001 to $249 m in 2002, with only RFMD registering an increase in its revenue in this sector, up 9.4% to $105 m in 2002.

By contrast, the PA module market expanded by 86% from $451 m in 2001 to $840 m in 2002, helping to push the overall PA market from $838.9 m in 2001 to $1.09 bn in 2002. Modules accounted for 34% of the PA market in 2000, 55% in 2001 and 83% in 2003. RFMD and Skyworks together accounted for 65% of the module market in 2002, growing their module revenues by 122% and 83% respectively.

The most impressive growth came from Philips and Anadigics, which occupied the number four and five module slots respectively in 2002. Philips' module revenue climbed from $11 m to $50 m, and Anadigics grew its module revenues from $10 m to $40 m. Hitachi, the world's leading LDMOS-based PA supplier, grew its module revenues by 40% to $196 m in 2002. However, its market share declined from 29% in 2001 to 23.3% in 2002, and it lost the number two module position to RFMD.

PA module and MMIC markets



GARTNER DATAQUEST

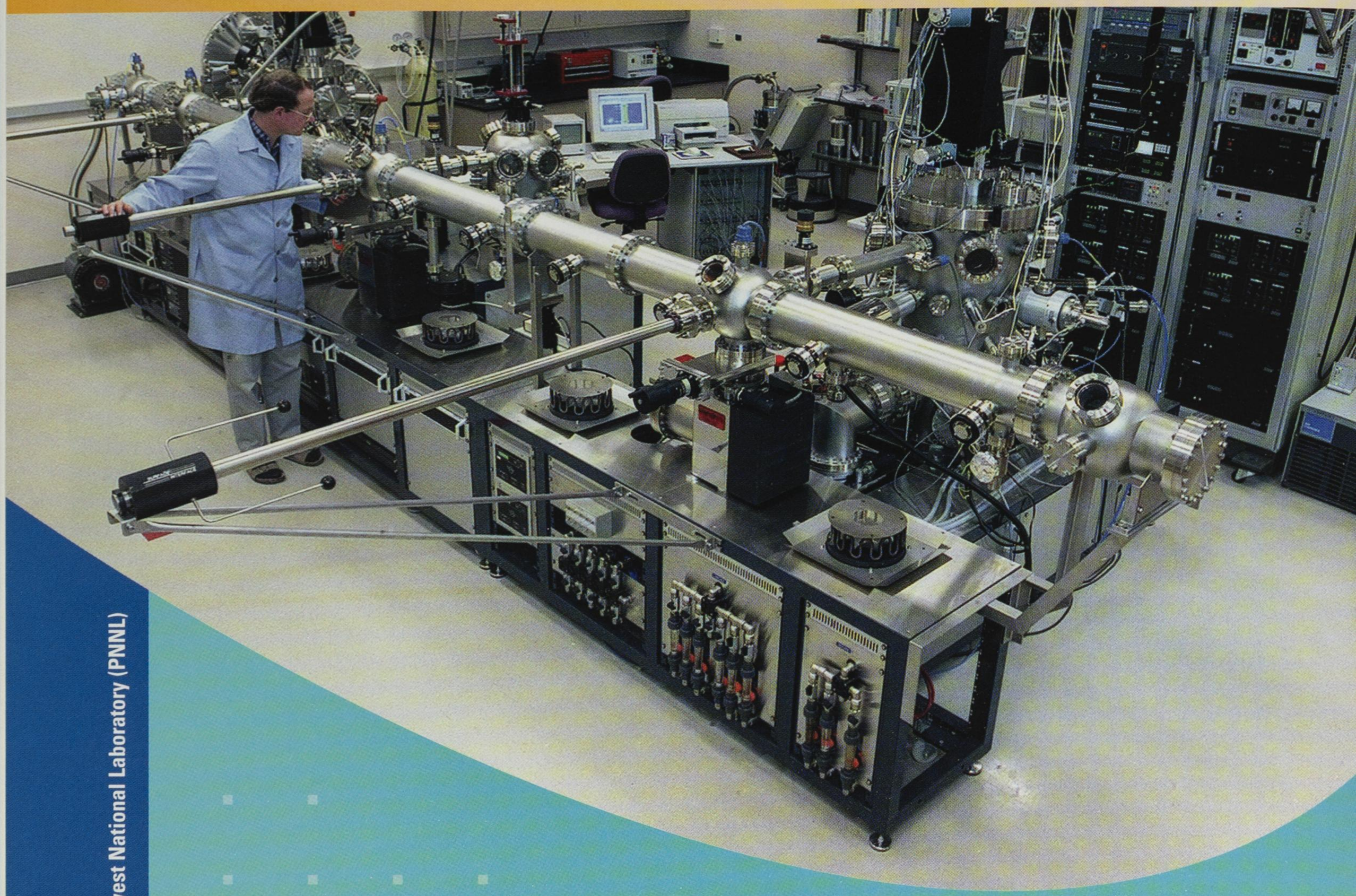
EpiWorks and partners complete InP/GaAsSb HBT epiwafer project

EpiWorks, a developer and manufacturer of epitaxial wafers, has successfully completed a collaborative research project to develop the growth of carbon-doped GaAsSb. Epichem supplied the growth precursors for the project and InP substrates were supplied by InPact.

The project's goal was to obtain carbon-doped GaAsSb layers suitable for the base region of DHBTs. This required the layers to have a majority carrier mobility greater than 40 cm^2/Vs for a doping level greater than $7 \times 10^{19}/cm^3$. Carbon doping levels above $8 \times 10^{19}/cm^3$ were also demonstrated. The process was developed in a production-style MOCVD system, with a capacity of eight 3 or 4 inch wafers. The single-layer cross-wafer non-uniformity was less than 2% as determined by contactless resistivity measurements. DHBTs with GaAsSb base layers are attracting interest because of their potential use in high-speed digital ICs and for military applications. The type II band line-up in InP/GaAsSb DHBTs allows operation at high speed and high current densities.

Spintronics Research

Proven Technology for Demanding Materials



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

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INSTRUMENTS

WIN and RF Integration form a strategic manufacturing alliance

Taiwanese GaAs IC foundry WIN Semiconductors has formed a strategic alliance with RF Integration of Lowell, MA, to design and manufacture GaAs MMICs. RF Integration designs and manufactures RF and mixed-signal products for wireless communications.

Using RF Integration's RF/mixed-signal design expertise, the companies will work together to provide complete solutions that require MMIC designs, which will be manufactured using WIN's broad portfolio of GaAs wafer fabrication processes.

Products will range from MMICs with single functions, such as PAs, attenuators or switches, to integrated solutions, such as complete transceivers. Through this collaborative supply chain, both companies can support customers from system specification to chip manufacturing.

"Our 6 inch GaAs HBT and HEMT processes are tuned for affordable mass production of MMICs in high-volume applications, such as handset PAs and switches, to high-frequency and high-performance components, such as broadband amplifiers and 77 GHz automotive radar MMICs," said Simon Yu, WIN's general manager of North American and European sales.

Anadigics receives wafer patents

Anadigics has received two new patents relating to the improvement of its semiconductor manufacturing processes. The patents are for a newly developed wafer demount gas distribution tool (US patent number 6,470,946) and for a wafer demount receptacle for separating a thinned wafer from its mounting carrier (US patent number 6,491,083).

During processing, wafers pass through a number of steps, which involve exposing them to potentially aggressive conditions such as chemical processes, physical contact, and large ranges of pressure and temperature. The wafers are mounted onto carriers, which provide support and stability during processing, at the completion of which they need to be demounted, a step that can result in delicate wafers being damaged. Anadigics' wafer gas demount distribution tool will be used during the demounting process to help aid the separation of the wafer from the carrier, reducing the risk of damage.

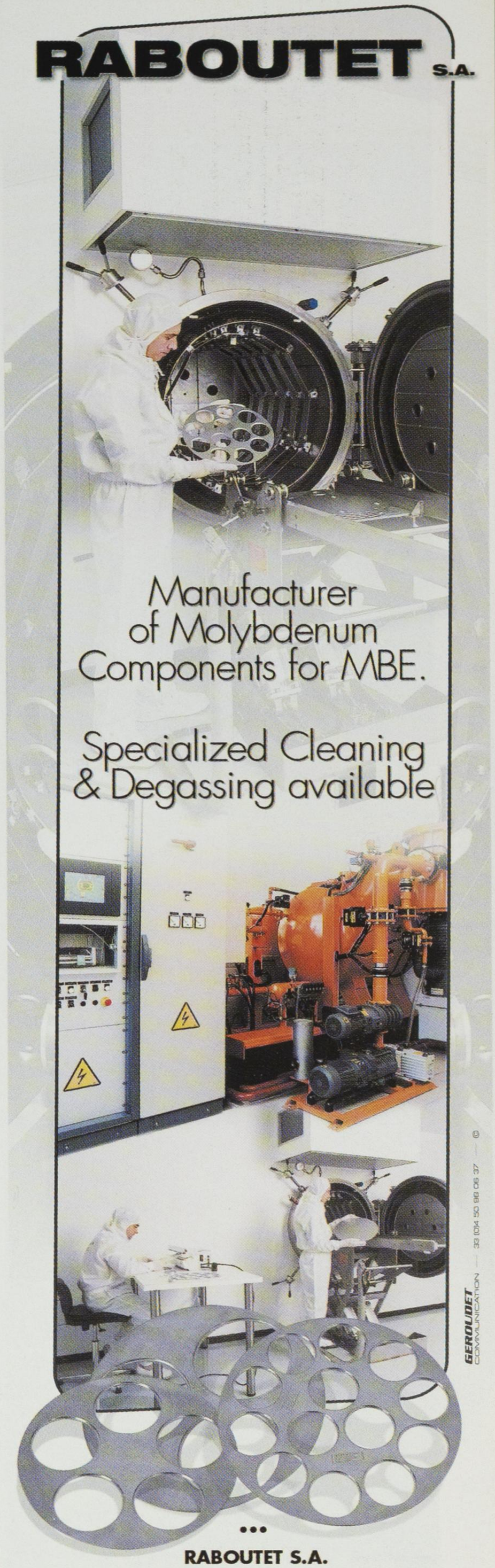
New products

● **Sirenza Microdevices** has unveiled its prototype 60 GHz InP TIA, fabricated using GCS' InP HBT process. The TIA achieves 36 dB of differential gain and 60 GHz of bandwidth while consuming only 271 mW of DC power. The achieved transimpedance-bandwidth product per DC power of 797 GHz/mW is four times greater than prior state-of-the-art results.

● **Mitsubishi Electric** has developed a new 76 GHz MMIC chipset for automotive radar. The GaAs PHEMT chipset consists of a three-channel antenna switch MMIC, five transmitter MMICs covering 19, 38 and 76 GHz, and two receiver MMICs. The 76 GHz transmitter produces 30 mW of output power. The receiver LNA exhibits less than 3.5 dB of noise, with a maximum 4.5 dB noise figure between –40 and 100 °C.

IceFyre selects TriQuint process for WLAN PA production

IceFyre Semiconductor, a fabless provider of wireless LAN products, has selected TriQuint's 0.5 μm, GaAs PHEMT process technology to fabricate IceFyre's switch-mode 802.11a/b/g PA products. The company will use TriQuint's process and production capacity to deliver the PA element of its SureFyre 802.11a and TwinFyre 802.11a/b/g system solutions. IceFyre uses its patented orthogonal frequency division multiplexing technology in the SureFyre 802.11a and TwinFyre 802.11a/b/g products. This results in up to 75% less power consumption than alternative products, and delivers twice the output power with improved receive sensitivity and transmit signal linearity, to achieve 50% greater range at all 802.11a/g data rates.



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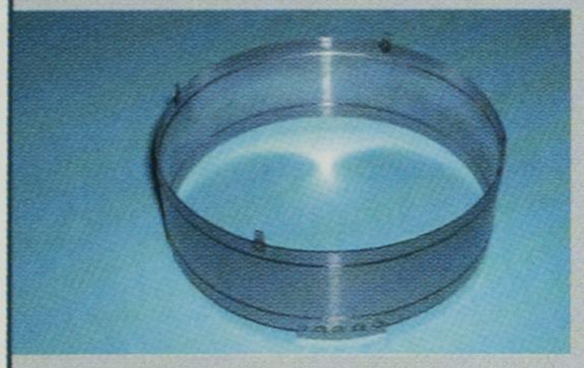

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Soitec hopes for reissue of Smart Cut patent

French research organization CEA has filed for a reissue of US patent number 5,374,564, which is licensed exclusively to French SOI wafer maker Soitec and forms the basis of Soitec's comprehensive Smart Cut technology portfolio. The patent was the subject of a legal argument between Soitec and its competitor, Silicon Genesis. In April 2002, a jury found that a number of the patent's claims were invalid (*Compound Semiconductor* June 2002 p32).

If granted, the reissued patent will include revised claims to clarify the Smart Cut process using hydrogen or helium ions in the implantation step to achieve layer transfer. These claims, which will have the same priority date as the original patent, will provide additional protection for the Smart Cut process.

SiGe samples WLAN front end

SiGe Semiconductor is sampling what it describes as the industry's highest-performance, most cost-effective RF front end for dual-mode 802.11b/g WLAN systems. The RF front end integrates a high-performance power amplifier, power detector, transmit/receive switch, diversity switch and filtering into a compact chip-scale device that is fully matched to 50 Ω. It is priced at less than $2 per unit in quantities of 1 million units. The SE2526A consumes just 160 mA in 802.11g mode operating from a single 3.0–3.6 V supply, and delivers +16 dBm of output power. In 802.11b mode, it delivers +20 dBm output power with an ACPR below –35 dBc.

SIGE SEMICONDUCTOR

The SE2526A WLAN front end replaces up to 40 components, and is supplied in a 5.5 × 7.0 × 1.4 mm laminate package.

Toshiba announces CMOS milestones

Toshiba announced two new process developments at the VLSI Symposium in Kyoto, Japan. One is a new high-k gate dielectric, HfSiON, for 65 nm CMOS, while the other is the world's first embedded DRAM technology manufactured using SOI wafers.

Using HfSiON, Toshiba developed a 50 nm gate-length CMOS transistor with a gate leakage current of only one-thousandth that of a device with a conventional SiO_2 gate dielectric. New dielectric materials such as HfSiON are required for future CMOS generations, in which the gate dielectric gets progressively thinner if SiO_2 is used, leading to larger gate leakage currents.

Toshiba has also taken steps to increase the transistor processing speed in memory ICs by developing embedded DRAM system LSIs on silicon-on-insulator wafers.

UMC describes strained Si process

At the recent VSLI Symposium, UMC described the speed enhancement provided by strained silicon technology, using wafers supplied by AmberWave, in its high-performance CMOS foundry process. UMC has demonstrated a 70 nm strained silicon transistor with a speed enhancement of over 10%.

"UMC's strained silicon process offers an alternative path to realize performance improvements without aggressive gate-length shrinkage," said S W Sun, VP of UMC's central research and development division. "We believe many of our foundry partners will benefit from this enabling technology in the future."

UMC is working with AmberWave to enhance p-channel transistor performance, improve strained layer defect density, and decrease substrate costs associated with this strained silicon technology.

EMF have developed the most Advanced Closed Loop MOCVD System

TITAN

The next logical step in MOCVD Innovation

Titan's Cell

The Development team at EMF employed the latest CFD computer modelling to design a cell with ideal flow dynamics:

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- Load Lock option for increased throughput
- IR lamp heating for rapid temperature cycling
- Ergonomically designed, the multi screen console controls all aspects of the digital closed loop system
- Dynamic measurement of growth rate and layer thickness for true Closed Loop Control

Titan's Control

Growth parameters and reactor are instantly accessed via the touchscreen virtual keyboard:

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- Full Digital operation for reproducible process
- MO flow rate control for consistent process
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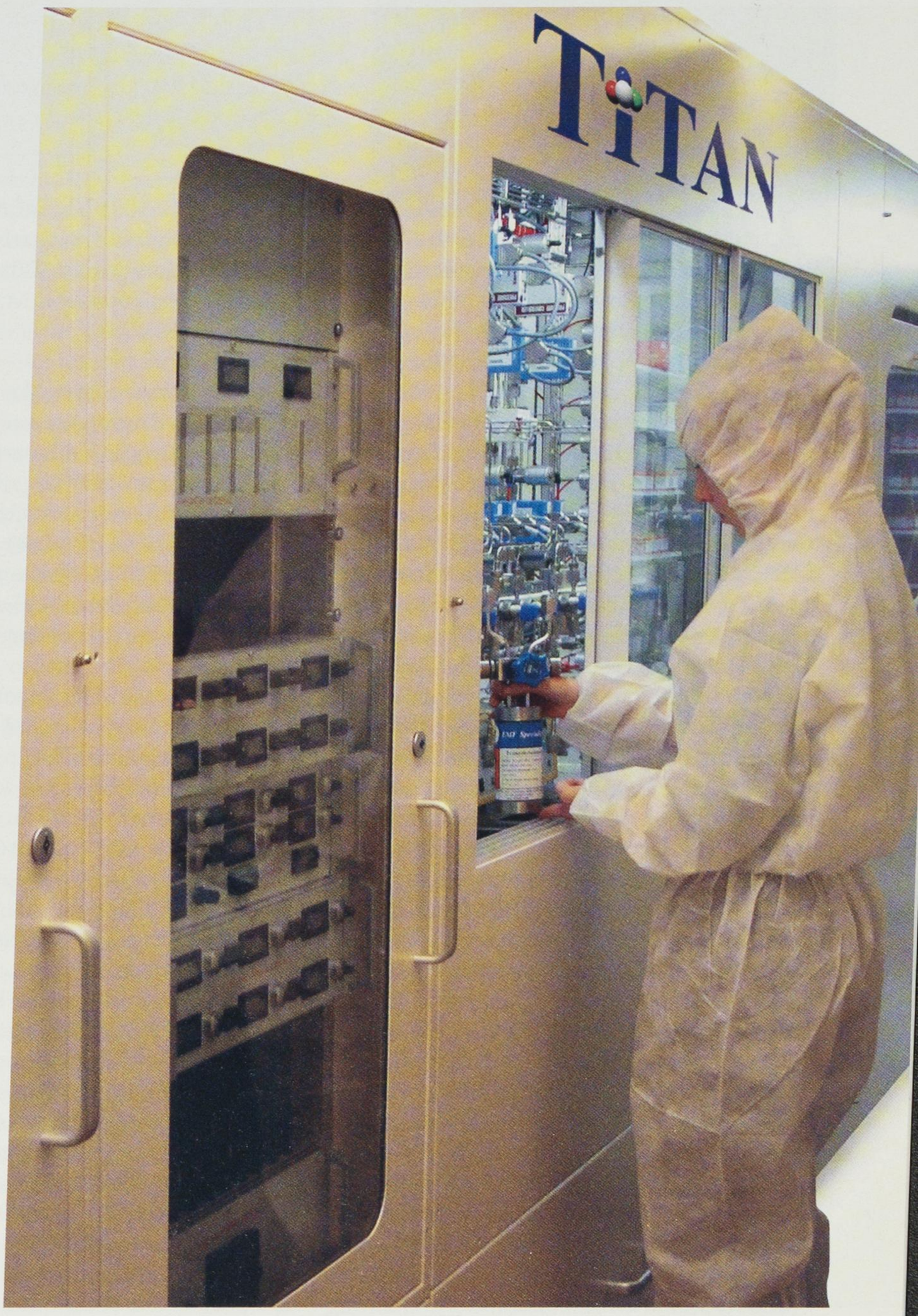

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InP battles to beat the slump

While new processing technologies ensure that InP microelectronics will keep getting faster, new compounds are displacing InP as the material of choice for some long-wavelength lasers, writes **Jon Newey**.

TFAST program goals

Metric	*Pre-program*	*Phase 1*	*Program goal*
emitter width (μm)*	1.0	0.25	0.15
f_t/f_{max} (GHz)*	200/200 (typical)	350/400	500/500
current density at fixed V_{CE} (kA/cm^2)*	<200	500	1000
flip-flop speed at fixed power (GHz)	75	150	200
super-scaled integrated transistor count	0	1000	20,000

**with BV_{CEO} >4 V*

DARPA

Table 1. The TFAST program calls for the super-scaling of InP HBTs and high integration levels to keep InP IC performance ahead of SiGe in terms of speed and power.

This year's Indium Phosphide and Related Materials (IPRM) conference took place on May 12–16 in Santa Barbara, CA. The Santa Barbara area has a distinguished history in InP and other compound semiconductors, with a number of universities and companies active in the field located nearby.

It has been a tough couple of years for those involved in InP, with the collapse of optical communications infrastructure spending meaning reduced demand for long-wavelength emitters and a limited uptake of InP microelectronics. In the current cost-conscious climate, it is often argued that InP is too expensive and that its use should be avoided unless absolutely necessary. Even InP's monolithic integration capabilities are being pushed to one side in favor of using InP with other materials in hybrid solutions. Given this situation, it was perhaps not surprising that there was considerable emphasis at the meeting on the related materials aspects, where alternatives to InP were discussed. The sessions on lasers included much on dilute nitrides and in the microelectronics area there was considerable discussion on metamorphic HEMTs. Both of these technologies rely on GaAs instead of InP substrates. However, right from the opening session it was clear that InP has some powerful backers, and that there are applications where nothing else will do the job well enough (figure 1).

The opening session of three plenary talks gave an overview of a range of subjects, including InP opto- and microelectronics for the recovering telecom industry and InP HBT mixed-signal circuit technology. Henning Riechert of Infineon discussed the status of 1300 nm VCSELs and the various approaches being taken to fabricate them. He concentrated mainly on devices with GaInAsN active regions, as this is the route Infineon has chosen and refined for its recently announced volume production of 1300 nm VCSELs (*Compound Semiconductor* May 2003 p17).

InP HBTs

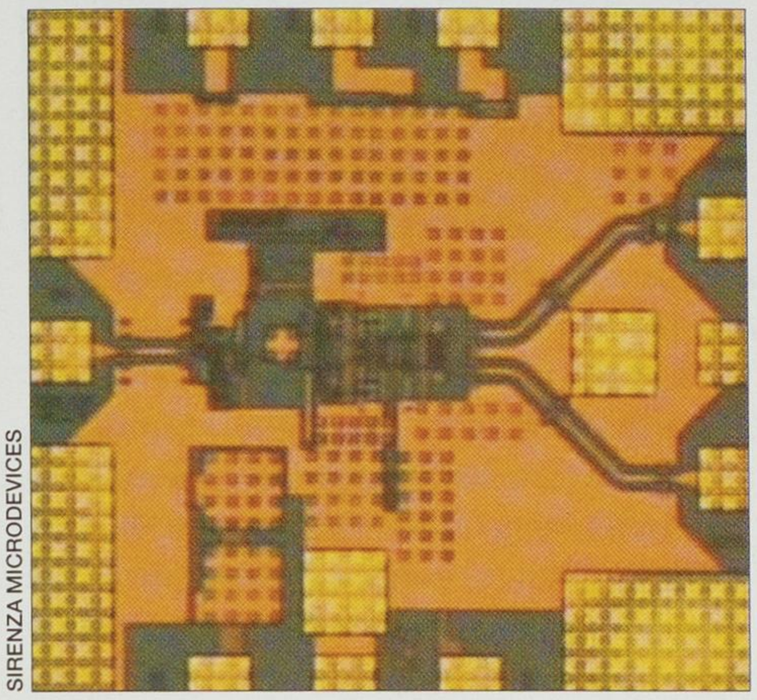
Historically it has often been a military need that has pushed compound semiconductor technology to new levels of performance, and InP HBTs are now benefiting from the attention of a DARPA program called Technology for Frequency Agile Digitally Synthesized Transmitters (TFAST). The program manager, John Zolper, described the challenging scaling and integration issues that InP HBT technology faces in its quest to stay ahead of aggressively scaled SiGe bipolar technology. InP HBT technology has relied heavily on vertical scaling and design to push its performance along, but this is no longer enough. SiGe HBTs with 0.18 μm emitters have demonstrated a peak f_t of 350 GHz with a current density of 20 mA/μm^2, although BV_{CE0} was just 1.4 V. This performance comes from processing technologies that reduce the extrinsic base-collector capacitance and extrinsic base and emitter resistance. TFAST calls for super-scaled InP HBT technology that will keep InP ahead of SiGe in speed and power by using many of the scaling approaches employed for SiGe HBTs. InP DHBTs have many attractive features that will help meet military requirements for mixed-signal circuits such as DACs and ADCs. Devices are required that can directly generate millimeter-wave frequency signals over a large range of signal levels. The desired outcomes of the TFAST program are summarized in Table 1.

Yingda Dong from the University of California, Santa Barbara (UCSB) reported on the selective area growth (SAG) of InP through narrow openings in an SiO_2 mask on InP, and also showed the DC characteristics of HBTs fabricated using the SAG material as the extrinsic base region. By fabricating SiO_2 stripe masks arranged radially on an InP substrate with various widths for the SAG openings, it was possible to establish the degree of InP lateral overgrowth onto the SiO_2 as a function of the width of the opening and its angle of deviation from the (110) direction (figure 2). Dong described a device structure where the base mesa is etched down to the subcollector, leaving a narrow base shoulder. SiO_2 is deposited to surround the collector pedestal, defining an intrinsic base-collector junction area slightly larger than the emitter-base junction, thus minimizing base-collector capacitance. The 0.6 μm base shoulder provides the opening for extrinsic base selective growth and overgrowth onto the SiO_2 (figure 3).

The DC performance of the prototype regrown devices showed a DC gain of 15 at a V_{BC} of 1.5 V, and the ideality factor for the base current was 1.93. This high factor was attributed to excess base current resulting from surface damage prior to the regrowth, and interface degradation during the regrowth. Work is now under way to improve this, and Dong hopes to be able to report RF characteristics once further efforts are made to reduce process-related damage and improve the quality of the selectively grown material.

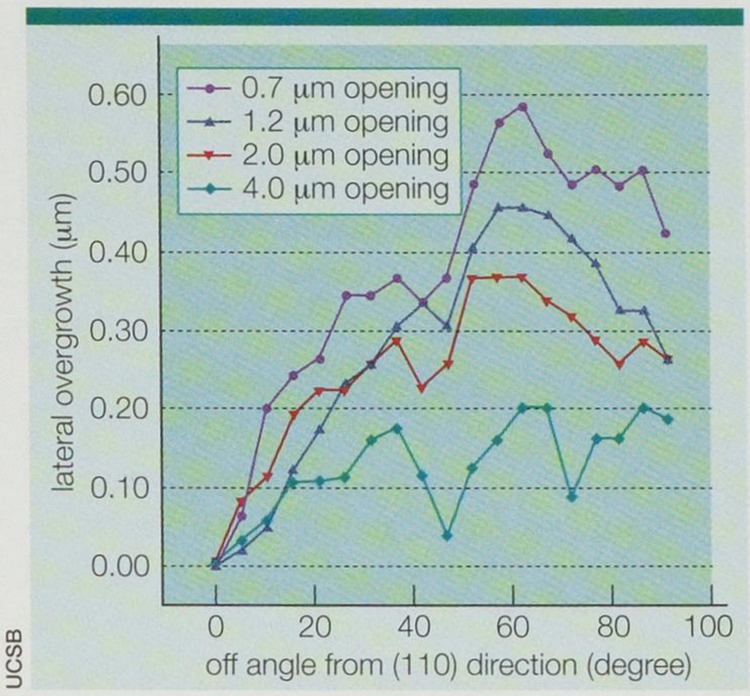
R Kopf of Bell Labs discussed the planar processing of InP DHBTs by ion implantation as a way of overcoming the heat dissipation problems that may arise in the large-scale integration of mesa HBTs. InP has a higher thermal conductivity than InGaAs, and using an ion-implanted InP subcollector reduces thermal impedance by a factor of 10 for high cur-

...p in optical communications



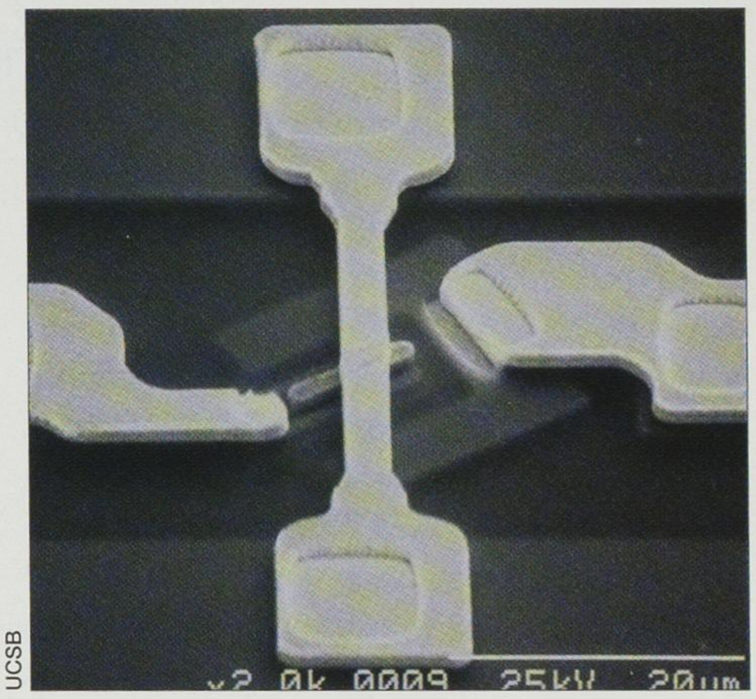
SIRENZA MICRODEVICES

Fig. 1. Sirenza's prototype 60 GHz TIA used GCS' 0.1 μm InP HBT processing technology.



UCSB

Fig. 2. The overgrowth of the extrinsic base depends on the opening and its orientation.



UCSB

Fig. 3. The completed InP HBT, which features a regrown extrinsic base region.

rent density operation. By selective implantation the extrinsic base-collector capacitance can be eliminated.

Implanted semi-insulating InP substrates were annealed at various temperatures to establish a safe upper temperature limit, which was set at 850 °C. DHBT structures were grown on the as-implanted and annealed substrates, and for comparison a device with a 400 nm InGaAs subcollector was also grown. The DC characteristics of the implanted collector devices and the InGaAs collector devices were nearly identical, demonstrating that the first steps towards a fully planar InP DHBT had been successfully taken.

The type-II band alignment provided by InP/GaAsSb HBTs provides a solution to the current blocking problem in InP/InGaAs devices. S Yi of Agilent described the MOVPE and GSMBE growth of InP/GaAsSb DHBTs with carbon as the base dopant, although at the end of his talk there was no clear decision on whether one growth technique was better than the other. The hole mobilities for a given carbon concentration were generally higher in the MOVPE grown material. This effect is thought to be a result of the difference in surface ordering due to the variation between the two techniques in the growth parameters such as temperature and the precursors used. Hole concentration also depends on the Sb mole fraction, and for MOVPE, concentrations above $10^{20}/cm^3$ were only achievable in Sb-rich growth conditions, whereas for GSMBE, lattice-matched growth conditions gave hole concentrations of above $10^{20}/cm^3$.

Typical transistors fabricated at Agilent have base and collector ideality factors of 1.04 and 1.14 respectively, indicating the good quality of the heterojunctions grown by either technique. Devices with BV_{CEO} of 7–10 V and a turn-on voltage of 0.46 V at 1 A/cm^2 have been demonstrated, and for devices with 1×9 μm^2 emitters, an f_t of more than 210 GHz has been achieved. ICs of several hundred transistors have been fabricated, and static divider circuits operating at 70 GHz demonstrated.

InP HEMTs

InP HEMTs hold the records for the fastest f_t and f_{max} values of all the different transistor families. Currently the record is with researchers from Fujitsu Labs, who in 2002 reported 25 nm gate PHEMTs with a gate-channel spacing of 4 nm operating with an f_t of 562 GHz (*Compound Semiconductor* December 2002 p10). There were no record-breaking announcements (or what Zolper called "hero results") at this year's IPRM, and much of the content dealing with HEMTs concentrated on new processes to make the difficult task of fabricating small gate-length devices faster and reproducible. This included work from Seoul National University on a highly reproducible dielectric sidewall gate process, and the fabrication of high-density (8.3×10^4 channels/cm), sub-50 nm wide channels by Fujitsu Labs. The session dedicated to HEMTs featured several talks on metamorphic HEMTs, including MHEMT-based LNAs from the Fraunhofer Institute with 70 nm gates and 80% In in the channel, and a talk from Katherine Herrick on the W-Band power MHEMTs developed at Raytheon RF Components, which also offers an MHEMT foundry service.

A joint paper from Rockwell Scientific Company and UCSB reported a significant improvement in the f_{max} values obtained from InAs/AlSb HFETs grown onto GaAs substrates. These HFETs are of interest because of the high mobility (>25,000 cm^2/Vs), saturation velocity (4×10^7 cm/s) and good carrier confinement due to the band offset between InAs and AlSb. The main disadvantage of these devices is the limited power gain and low breakdown voltage due to the narrow bandgap of the InAs channel. The presentation focused on the use of InAs/AlSb HFETs for low-voltage operation (<0.5 V_{ds}) with 0.25 μm devices showing f_t and f_{max} both of 160 GHz, well above the 120 and 100 GHz reported in the past. This was largely achieved through the vertical scaling of the previous design.

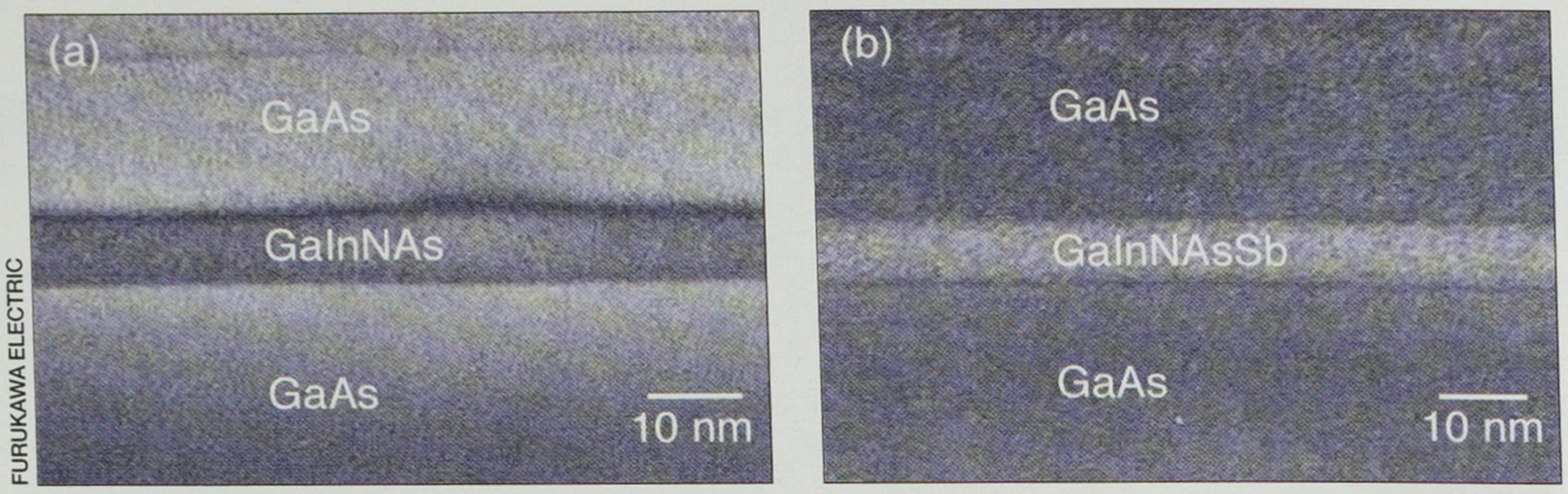
Dilute nitrides for long wavelengths

InP-based lasers could be described as a mature technology, and so it was perhaps not surprising that there was little content at the meeting directly related to these devices. There was some time devoted to the monolithic integration of different optical functions such as lasers and modulators using InP, and also to the field of quantum dot emitters. Much of the discussion about long-wavelength lasers was devoted to the dilute nitride alternatives to InP and also to the pentenary com-

pound GaInNAsSb. This complex compound has attracted researchers because of the large parameter space for bandgap and lattice strain engineering that it presents for optimizing long-wavelength laser performance.

In one of two invited talks on the subject of GaInNAsSb-based long wavelength lasers, James Harris of Stanford University,CA, described in detail the growth and physical and optical properties of GaInNAsSb. In the second talk, H Shimizu of Furukawa Electric expanded on this theme by discussing the growth of GaInNAsSb and its practical application to 1300 nm edge-emitting lasers and VCSELs. The major challenge in using GaInNAs for lasers is the drop in photoluminescence (PL) intensity and optical power as the amount of nitrogen is increased to increase the emitted wavelength. The addition of Sb (<2%) during the growth of GaInAsN quantum wells (QWs) improves the crystalline quality of the wells by suppressing 3D growth. Shimizu described the systematic study carried out by his group into the effect on the QW quality and PL intensity and wavelength of varying the Sb flux during growth by GSMBE (figure 4). To increase the wavelength required an increase in the nitrogen content of the well, which in turn reduced the PL intensity. This was due to increased strain between the QW and GaAs barriers, which required the addition of N to the GaAs to relieve the strain.

Increasing the number of QWs increases the gain and reduces the threshold current (J_{th}) of the laser. Because of the strain in GaInNAs/GaAs QWs, the maximum number of wells reported to date has been four. Shimizu's group has successfully fabricated lasers with five wells using GaNAs barriers and Sb in the wells to promote better crystal quality. The group also holds the record for the lowest J_{th} per well of 150 A/cm^2 for its 3 QW device, and 160 A/cm^2 for a 5 QW device. Shimizu went on to describe the fabrication of VCSELs from the material, achieving the best to-date simultaneous low threshold voltage of 1.2 V and low differential resistance of 60 Ω for a 1.3 μm VCSEL.



FURUKAWA ELECTRIC

Fig. 4. TEM cross-sections of dilute nitride SQW lasers. The GaInNAs QW in (a) shows 3D growth. The GaInNAsSb QW in (b) was grown with 10^{-6} Torr Sb flux and shows 2D growth.

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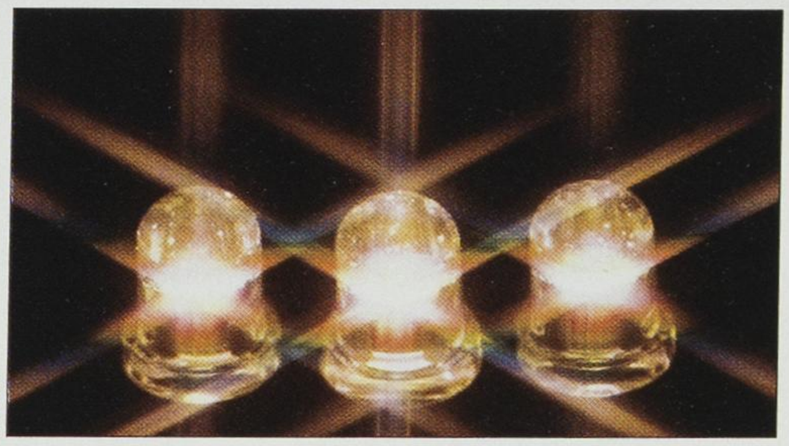
epichem group

LEDs scoop lighting awards

LED-based lighting systems received numerous awards at the recent LightFair International trade show, demonstrating the importance of LEDs to lighting designers, writes **Kate Conway**.

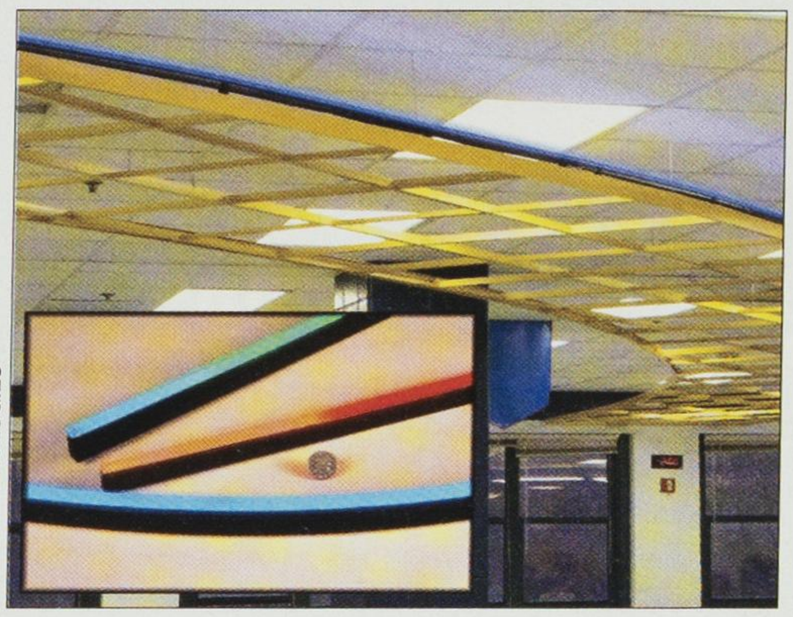
Capturing numerous awards, LEDs attracted crowds of admirers at the LightFair International 2003 trade show, held in May in New York City and attended by more than 19,000 people. At least 10% of the 600 exhibitors featured LED lighting products. As a measure of how pervasive LEDs were, Lumileds' Luxeon products could be seen in nearly 50 innovative products shown by more than 25 companies.

TIR Systems' Destiny Colorwash, a color-changing luminaire that provides a wash effect for accentuating and modeling architectural structures, won the Best New Product award as well as the Flood and Façade Lighting category award. Also honored was Nichia, which won the Technical Innovation and Specialty Lamps awards for its model NSPL510S warm white LED. By combining a new red phosphor with a YAG phosphor, Nichia has brought the lamp's correlated color temperature into the 2500–3500 K range (figure 1).



NICHIA

Fig. 1. Warm white LEDs from Nichia provide light with a similar appearance to that from incandescent bulbs.



ILIGHT TECHNOLOGIES

Fig. 2. The flexible Plexineon system (inset) can provide blue accent lighting (main picture), as well as replacing neon tubes in other applications.

Modular line-up

At LightFair, designers saw a full array of building blocks with which to create colorful coves, edges and other slim-profile architectural features. Osram Opto Semiconductors introduced Color Mix LED dimmable systems coupled with Optotronic power supplies and OTDIM dimming modules, with optional snap-on Linearlight optic lenses.

Luminous wall-mounted fixtures add visual accents to long hallways, meeting rooms and atria. Traxon's Mood Light enables designers to group square modules, each containing four translucent units with controllable LED color, into any desired configuration. The units are activated by an infrared remote control, have pre-programmed sequences, and can be synchronized with music. The Mood Light received a Roeder Award, in memory of a lighting designer well known for his colorful, dynamic installations.

Grouping or sequencing units is also possible with Io Lighting's tiles and planes. Purchasers can specify these anodized aluminum squares and rectangles with LED backlighting, luminous cube or luminous pyramid inserts, or linear step lighting inserts. Louis Poulsen Lighting expanded its LED product lines with in-ground and accent lights in a wide variety of styles suitable for architectural and landscape projects.

Neon tubes have become ubiquitous for a variety of lighting and signage applications, particularly where shapes and curves are required. However, a number of manufactures are using LED systems to replace neon. One is iLight Technologies, which presented its Plexineon product (figure 2). This is a programmable, modular linear system that can be shaped on-site into gentle waves or arcs, or factory-shaped to form letters and tighter curves. Plexineon contains LEDs housed in a durable plastic composite. It operates at low voltages with minimal power draw, is cool to the touch, and has a lifetime of up to 180,000 h.

Bruck Lighting Systems showcased Orion Belt, with LEDs embedded in a flexible, transparent and UV-resistant PVC carrier. Bruck also produces pin-base, screwbase and recessed-mount LED lamps. Meanwhile, Modular International displayed sleek, brushed aluminum luminaires with a choice of 12, 24 and 120 V LED systems.

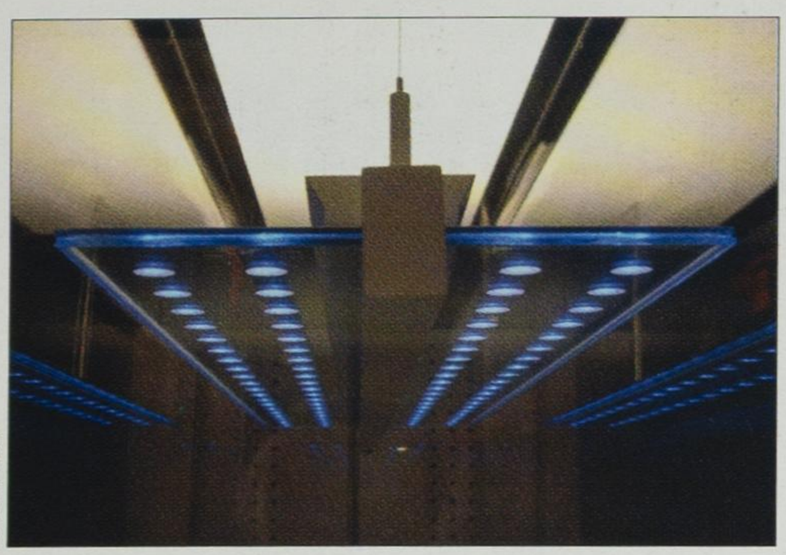
Dramatic DMX luminaires

Colors enhance the drama in any space. The DMX control protocol enables designers to use software to assign specific colors, dimming, and sequences of effects to particular luminaires. Conjuring up exactly the right color becomes easier with new theatrical-style LED luminaires, such as the Droplet from the Dutch company, Xilver BV, winner of the Theatrical and Entertainment Lighting award. The egg-shaped design and silently operating pan-and-tilt head swivel attention towards any object it illuminates.

Another Roeder Award went to Pixeon for its ColorStream tubes. With RGB pixels encapsulated in 1 m sections, uniform solid color effects or patterns can move at varying speeds, and when linked together, ripple on to the next tube. Times Square Lighting presented positionable parabolic aluminized reflector (PAR) lamps using 180 high-brightness LEDs.

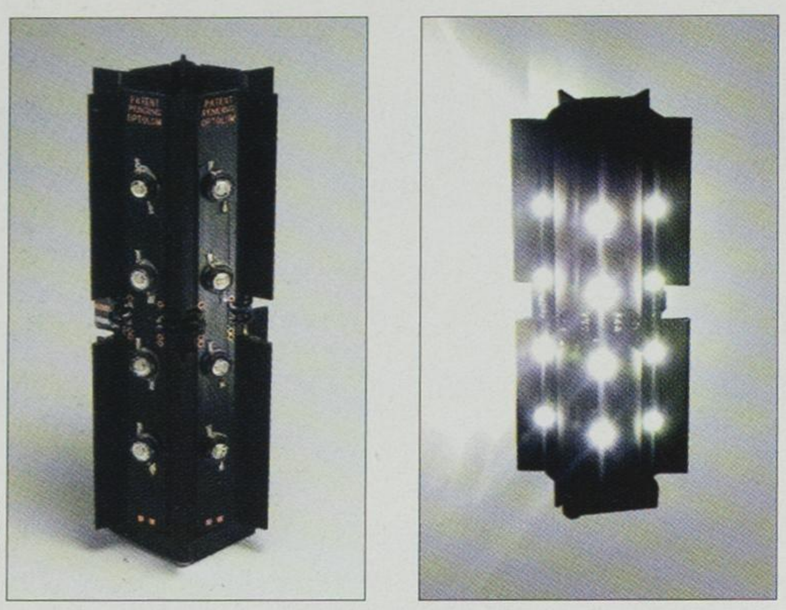
To conserve space and increase installation flexibility, James Thomas Engineering provides its PixelPAR and PixelLine products with remote power supplies. The light source fits into a housing that would typically hold an incandescent PAR lamp; the control interface is at the back of the housing where a cable connects to the power supply. Both all-white and multicolor LED options are available.

Space Cannon Illumination introduced Metamorphosis, a fixture featuring LED spotlights with dimming and strobing capabilities. The company is best known for dramatic lighting of buildings, and designed the stunning tribute in light at the site of the World Trade Center towers in New York.



ORGATECH

Fig. 3. The Lightstar LED luminaire contains two dimmable fluorescent lamps for primary lighting, together with 80 blue or white LEDs mounted in twin laminated glass panels and driven by an invisible low-voltage power supply.



OPTOLUM

Fig. 4. The BrightLife-800 utilizes 24 white LEDs to deliver 800 lm in a 360° distribution.

Suspended light

Chandeliers have long been admired for their elegance and sparkle, but their typical incandescent lamps get hot and burn out quickly. Mule Lighting liberated the chandelier from these burdens with FlameTip screw-base LED lamps. Pendants are a versatile type of luminaire that can add stylish features to any high-ceilinged space. Bruck Lighting introduced Artu, a cylindrical, glass-accented pendant with a choice of five colors of LEDs.

Seemingly floating on air, Orgatech Omegalux's LightStar LED pendant combines hidden fluorescent lamps for uplighting with LEDs decoratively embedded in glass wings (figure 3). The LEDs are connected via transparent circuitry sandwiched between two layers of glass, permitting the added effect of edge lighting.

Inching ahead of incandescent

Festoon lighting adds a decorative edge to display features in retail environments, theatre aisles, and throughout entertainment venues. Ardee Lighting introduced white Clikstrip LED elements with festoon lamp contacts, making the replacement of miniature incandescents easy. LEDtronics further enlarged its catalog of LED lamps intended to displace conventional incandescent sources with TrackLEDs in a standard MR16 bi-pin base.

Optolum, a developer of white LED-based lighting products, debuted its first product, BrightLife-800, which uses 24 Luxeon LEDs from Lumileds rated at 1.2 W each. The BrightLife bulb produces 800 lm in a 360° distribution (figure 4). Optolum utilized Lumileds' new warm white LEDs, which have a color temperature of 3200 K and a color rendering index of 85. Lumileds plans to release these products in August.

Shortly after the LightFair show, Optolum announced the award of its first US patent, which relates to heat removal from densely packaged LEDs. US patent number 6,573,536 describes LEDs mounted on an elongated support that is thermally conductive, for example a hollow tube through which air can be passed to assist with thermal cooling.

The Belfer Lighting Group's Radiant Lighting Solutions LED lines ranged from pavement and step markers to pool and spa lights, with additional products for security/off-hours low-illuminance lighting for museums and other public buildings. Delaney Industries' Envirolux Picture Light requires only a few watts of input power to illuminate a desk or other surface. With an AC to DC transformer, either wall-plug or battery operation is possible.

At LightFair 2000, LEDs were still a relatively novel light source to most lighting designers, and were used primarily in exit signs, traffic signals and other single-color products. Even so, LEDs garnered several awards at that show, and have steadily won over more lighting specifiers. Next year's exhibitors and attendees will no doubt find that LEDs are their best bet in lighting.

Kate Conway is principal of LED Consulting (www.ledconsulting.com), Nassau, NY. She is the author of LEDs for Lighting and Display Applications Directory and Source Guide, *published by Intertech Corporation. LightFair International 2004 (www.lightfair.com) will be held in Las Vegas, NV, from March 28 through April 2, 2004.*

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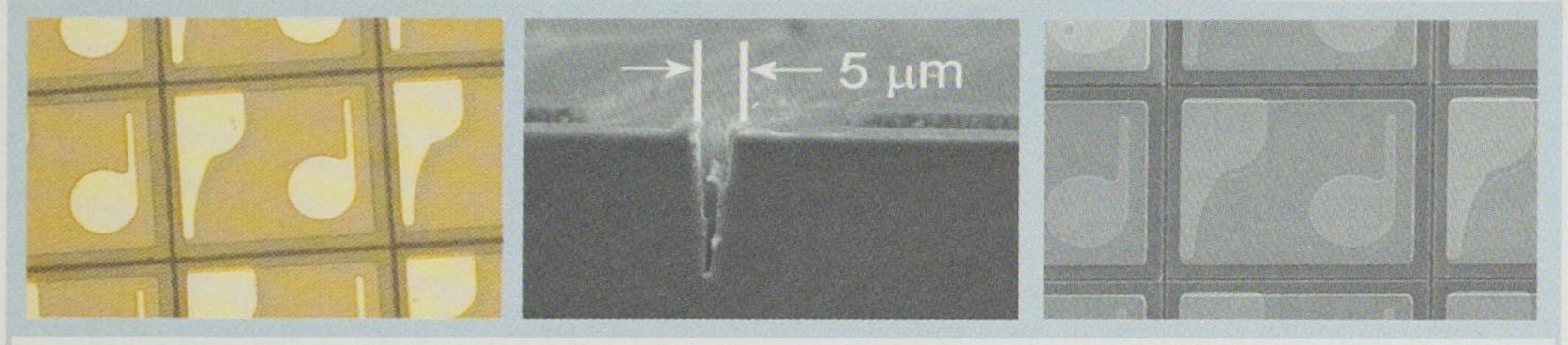

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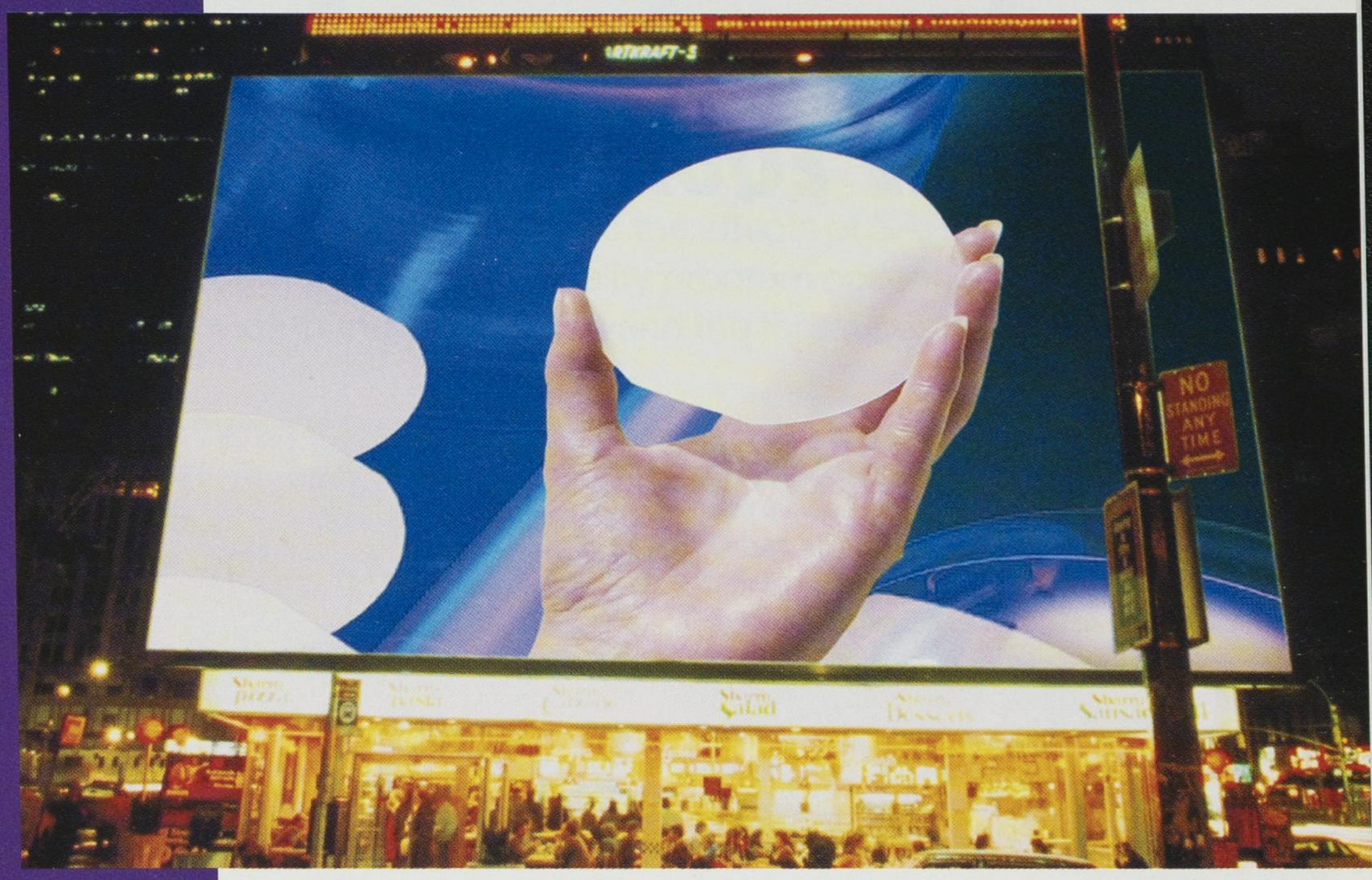

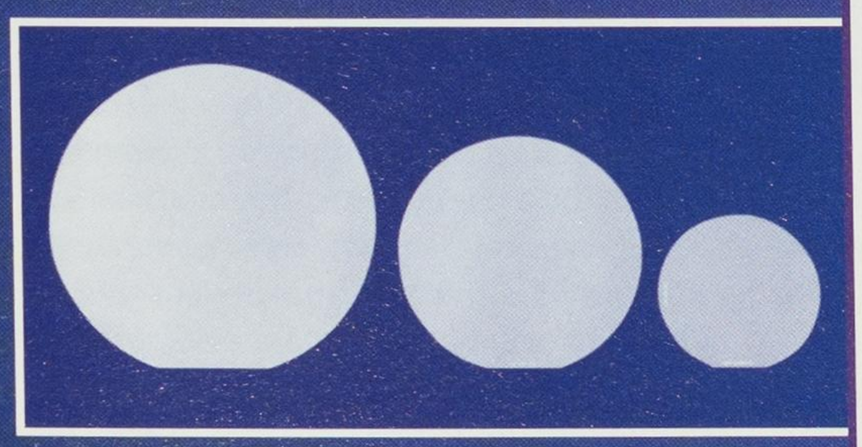

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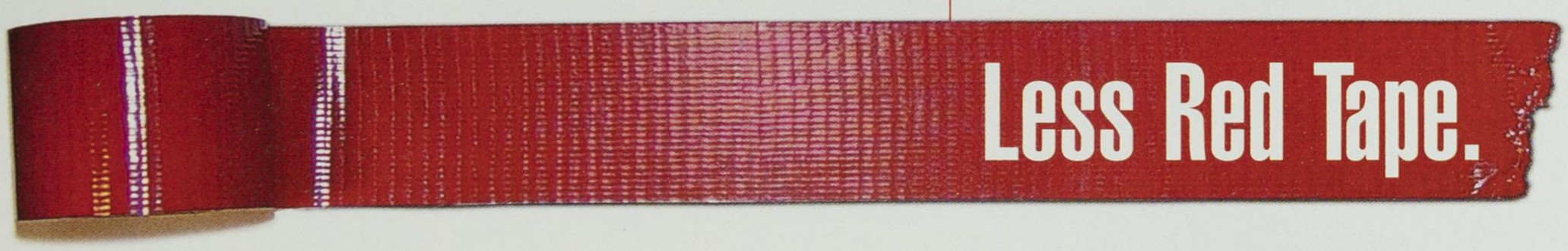

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GaAs industry embraces new technology trends

Despite temperatures of over 100 °F and several no-shows due to the effects of SARS, the attendees at this year's Mantech conference enjoyed a high-quality program covering GaAs and InP manufacturing technology, as well as wide-bandgap devices and the threat posed by silicon.

This year's Mantech conference, held on May 19–22 in Scottsdale, AZ, was opened by Dave Aldrich, CEO of Skyworks Solutions, who described current trends in the wireless market. A key trend is integration towards modules and subsystems, which is driven by shorter product lifecycles and a growing abundance of outsourced handset makers. These companies lack RF design expertise and want to use the lowest possible number of components.

As wireless companies fight for survival, the smaller ones can't afford to pay for R&D in order to integrate their products, and can only compete by lowering prices. This will lead to further consolidation, said Aldrich, who identified five key areas for survival: broad design skills; process and packaging flexibility (figure 1); product breadth and depth; system-level expertise; and manufacturing excellence.

Certain areas of manufacturing need to be internal, since the merchant market can't provide the level of value required. For Skyworks, these include InGaP HBT and GaAs PHEMT processes, and module manufacturing. In other areas, such as low-temperature co-fired ceramic (LTCC) and SiGe, Skyworks maintains strategic alliances with other companies, and also has more straightforward foundry agreements for areas such as CMOS.

Electronic component and system requirements are far more stringent for military applications than in the commercial field. These requirements include the need to operate in harsh environments, to process high-rate sensor data in real time and to operate outside commercial bands, and many others. John Zolper of DARPA described how the US Department of Defense is funding a number of programs to develop highly advanced electronic components. These include the wide-

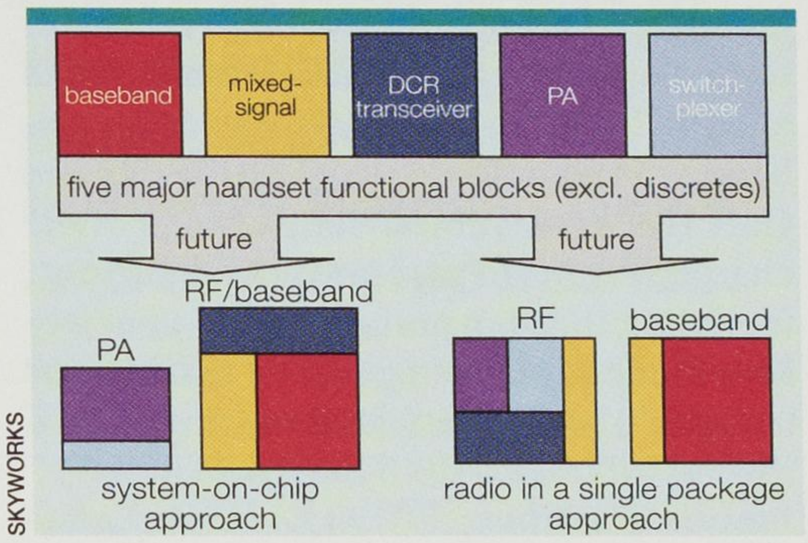

Fig. 1. Skyworks is leading the development of single-package radios with separate RF and baseband chips. Compared with system-on-a-chip approaches, single-package allows more rapid design times, optimized component performance, and unlimited flexibility for integration.

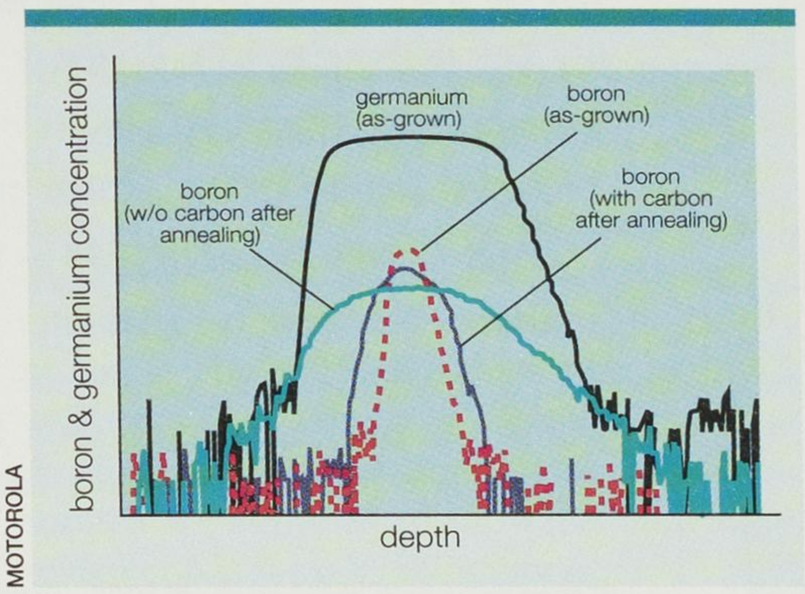

Fig. 2. SIMS trace showing the effect of C incorporation on B diffusion in a SiGe layer after a moderate anneal of 1000 °C for 20 s.

bandgap semiconductor initiative (*Compound Semiconductor* November 2002 p43), the TFAST program to develop high-speed InP DHBTs (see p20), and the antimonide-based compound semiconductors (ABCS) program. This class of materials is expected to enable extremely low-noise millimeter-wave receivers and sub-one V mixed-signal logic, as a result of their extremely high mobility and saturated electron velocity.

Zolper also discussed the technology for efficient agile mixed-signal microsystems (TEAM) program, which aims to exploit the integration and processing capabilities of aggressively scaled SiGe HBTs. The target is to develop complex mixed-signal circuits such as direct digital synthesizers and analog-to-digital converters, using SiGe HBTs that have already demonstrated f_t values of 350 GHz.

Silicon germanium

Also in the plenary session, Mark Wilson of Motorola compared the cost of using GaAs HBT and SiGe:C BiCMOS technologies in a manufacturing environment (see also *Compound Semiconductor* June 2003 p22). SiGe can be produced more cheaply than GaAs for three main reasons: substrate cost; the lower cost of running processes in very high-volume production centers; and the use of 200 and 300 mm wafers. However, GaAs is very well established in the power amplifier (PA) portion of wireless handsets, and SiGe:C is actually under threat from 90 nm CMOS, which could drive SiGe out of handsets with the possible exception of the PA driver.

Another paper from Motorola described the emergence of SiGe:C HBT technology. The SiGe base layer is B-doped, and carbon is also incorporated into this layer to prevent the out-diffusion of boron during subsequent thermal cycles (figure 2). The paper reviewed Motorola's 0.35 μm and 0.18 μm SiGe:C BiCMOS platforms, which enabled first-generation ICs in the 2 GHz range, and second-generation devices with f_f and f_{max} values of 123 GHz for the 0.18 μm version. A high-breakdown device was also developed, having a DC breakdown voltage (BV_{ceo}) of 5.5 V.

Comparison of discrete power devices

	Size (mm)	Freq (GHz)	Vdd (V)	PAE (%)	Pout (dBm)	Power density (W/mm)	Reliability	Cost ($/W)
GaAs MESFET	0.63	14.0	10	60	27.0	0.8	high	0.07
HV GaAs MESFET	0.48	3.0	25	54	29.4	1.8	medium	0.03
GaAs PHEMT	0.80	10.0	9	55	28.0	0.8	high	0.13
HV GaAs PHEMT	0.30	1.9	12	74	27.8	2.0	medium	0.05
Si LDMOS	3.00	2.0	26	46	32.8	0.6	high	0.02
SiC MESFET	0.25	3.5	50	63	31.1	5.2	low	0.05
GaN HEMT	0.50	3.5	90	34	36.7	9.4	low	0.03

M/A-COM

Table 1. This comparison for unpackaged die includes a number of assumptions, particularly relating to the processing cost of wide-bandgap devices. These offer very high-power densities but no significant advantage in terms of dollars per watt.

High-voltage PAs

While low-voltage operation is a key requirement in wireless handsets, higher voltages are readily available in wireless base stations, satellite ground stations and radar systems. There are many potential benefits of using higher voltages for PAs in such systems – for example, power density is usually increased at a higher voltage, so the device size and hence the cost can be reduced.

D Miller of M/A-COM in Roanoke, VA, compared various high-voltage transistor technologies, ranging from GaAs MESFETs and PHEMTs to silicon LDMOS and wide-bandgap technologies (SiC MESFETs and GaN HEMTs). Table 1 shows some of the characteristics of discrete power devices, including those manufactured with newly developed high-voltage (HV) GaAs technologies. The SiC and GaN technologies have the highest power densities, while Si LDMOS, the most mature technology, has the lowest. However, the much higher cost of SiC and GaN results in a higher cost per watt than LDMOS. Even so, the price of GaN might be competitive with LDMOS if factors such as higher-temperature operation result in a lower overall system cost.

It should be noted that the cost figures in table 1 include some favorable predictions for cost-related improvements in manufacturing for the wide-bandgap technologies in the coming years. Also, the improvements in power density achieved with the HV GaAs processes could allow them to compete with low-cost LDMOS technology.

Compound semiconductors in Asia

The audience enjoyed several talks about the compound semiconductor industry in various Asian countries, including China, Taiwan and Korea. Unable to travel, Yung Liu of ITRI in Taiwan made his presentation by telephone (at 4.00 a.m. Taiwanese time) while the session chair changed slides. The growth of the indus-

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try in Taiwan has been well documented, and the company is one of the top three compound semiconductor producers after the US and Japan, according to Liu. In addition to commercial interests, there are a number of ongoing collaborative programs, for example the Next Generation Lighting R&D Consortium. A number of partners, including Epistar, Forepi, Tyntek and OptoTech, are working towards a target of 50 lm/W for commercial white LEDs and 100 lm/W for R&D devices.

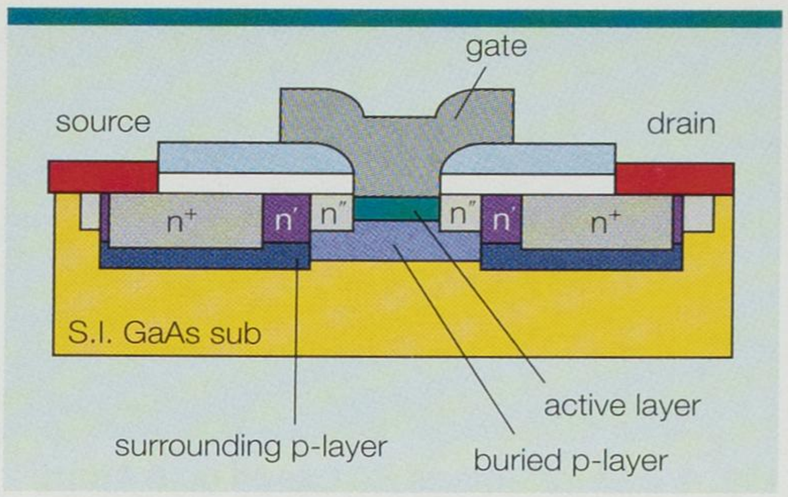
This year, ITRI's Optoelectronic Systems (OES) laboratory launched a nanophotonics program as part of a $700 million national initiative on nanotechnology. The project will feature work on quantum dots and photonic crystals manufactured in III-V materials, and includes a QD laser collaboration with the Ioffe Institute, Russia, that has already yielded 1.3 μm InAs QD lasers with a single-mode output of 400 mW. Also in Taiwan, the $260 million, three-year national Si-Soft initiative is developing system-on-chip technology for wireless, processor and optoelectronic applications.

A joint paper from Tokyo Institute of Technology and NTT Photonics Labs described InP-related activities in Japan, which have been hit by the downturn in the communications industry. Almost all commercial activity is in optical devices, although Japan leads the world in InP microelectronics, having recorded for example the highest f_t values for both HEMTs (Fujitsu, 562 GHz) and HBTs (NTT, 341 GHz).

Japan has some of the major suppliers of InP substrates, including Japan Energy, Sumitomo Electric and Showa Denko. While both Sumitomo and NTT-AT supply InP-based epiwafers, many laser manufacturers have internal epitaxy capabilities because growth is an integral part of the fabrication process for DFB lasers. Sometimes the Japanese business approach can hinder commercialization of new technologies; long-wavelength VCSELs were developed by several companies but not released as products because they are potentially competitive with edge-emitting lasers.

HBTs and MESFETs

Long-term reliability is a concern for any commercial device technology. A team from Lucent's Bell Labs reported an InP/InGaAs DHBT technology with a time-to-failure exceeding 45 years, and β-degradation of less than 20% at a junction temperature of 110 °C and a current density of 110 kA/cm^2. The technology had f_t and f_{max} values of 150 and 200 GHz, respectively, and BV_{ceo} >12 V.



SUMITOMO ELECTRIC

Fig. 3. Schematic of an ion-implanted MESFET fabricated using a single resist layer dummy gate process.

Mantech continues to address new areas of the compound semiconductor industry beyond GaAs and microelectronics.

Virginia Tech and Kopin described InGaP/GaInAsN/GaAs DHBTs with a DC current gain that is almost entirely independent of temperature over the range from –48 to +202 °C. This behavior appears as a higher collector current threshold for the onset of negative differential resistance in the common-emitter transistor output characteristic as compared with conventional GaInP/GaAs HBTs.

Although many people assume that MESFETs have been replaced by HEMTs and HBTs, certain companies such as Sumitomo Electric continue to report important MESFET developments. The company has developed an ion-implanted, 0.18 μm gate-length MESFET (figure 3), manufactured using its single resist layer with dummy gate (SRD) process. The MESFETs had a breakdown voltage of 7 V, an f_t of 100 GHz and a transconductance of 540 mS/mm. This level of performance is sufficient to allow the fabrication of driver ICs for EA modulators.

Packaging

In a section on advanced packaging techniques, a group from Georgia Tech discussed system-in-package architectures. These offer the capability to integrate MMICs with components that would otherwise be required in discrete form, leading to miniaturization, reduced assembly time and lower cost. A 2.4 GHz SiGe HBT PA module with a harmonic suppression filter and a via-fed stacked cavity-backed patch antenna was implemented on an LTCC substrate. The PA exhibited an output power of 27 dBm at 0 dBm input with a PAE of 45% at 2.4 GHz. The group also described multilayer organic packaging and demonstrated a C-band up-converter MMIC integrated with a square patch resonator band pass filter.

Substrates and epiwafers

Substrate quality, a critical factor for device performance and yield, was investigated for both GaAs-based PHEMTs and GaN-based HEMTs on SiC by Northrop Grumman (formerly TRW) and UCLA. X-ray diffraction, X-ray topography and transmission electron microscopy were all used. For GaAs-based PHEMTs, threading dislocations in the substrates act as nucleation sites for misfit dislocations in the strained-channel layer. Substrates with lower threading dislocation densities allow thicker or higher-indium-content channels.

For SiC substrates, scratches, micropipes and crystal structures all impact the quality of GaN-based epitaxial layers, Scratches can be removed from the epilayer by CMP. Micropipes tend to cluster together, so their impact is limited to the clustered region. X-ray topography clearly showed that substrate features are reproduced in GaN epilayers grown by MBE and MOCVD.

According to a paper from IQE, around 35–45% of the cost of producing an epiwafer is due to the cost of substrates (not only the actual epiwafer substrate, but also the test substrates used to calibrate the MBE reactor). Reclaiming rejected epiwafers for use in calibration is preferred to the use of mechanical substrates. For PHEMT epilayer structures, which do not have an etch-stop layer, the epilayers can be removed successfully with a chemical etch. In structures containing an etch-stop layer, CMP is used instead of etching. Since implementing its reclaim program, IQE estimates it has realized a 30% saving in prime substrate usage.

Production epiwafer control

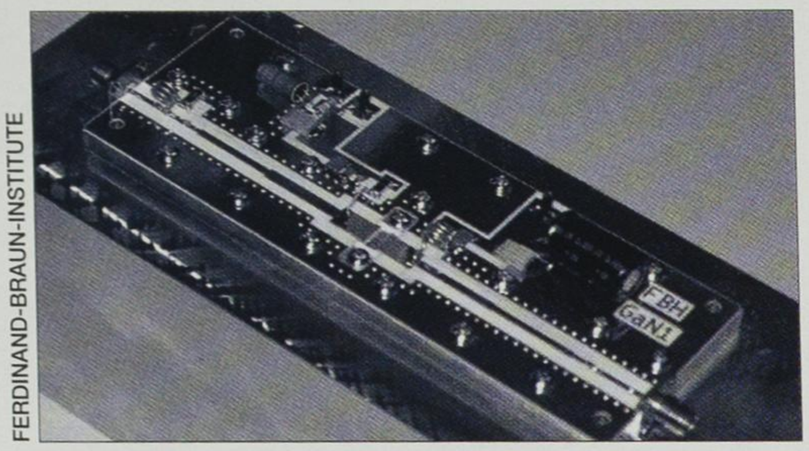
A paper from Motorola described how the company successfully ramped its internal epiwafer production capacity for enhancement-mode HIGFETs. The company has installed two Emcore 5 × 6 inch MOCVD reactors with a combined output of 900–1000 wafers per week. In order to reduce the incidence of scrap wafers, Motorola developed a basic set of non-destructive characterization tools to establish

a "known good epi" flow, which provides a go/no-go decision to move onto the next step. A sheet resistance measurement indicates the charge level in the epi structure, while PL provides information about the amount of charge in the channel region. Once the wafers have passed the initial testing, they are put back into the process line, and initial electrical measurements are obtained in four days. Motorola says that the process helps to keep its wafer costs significantly lower than the alternative of using external epiwafer suppliers.

Wide-bandgap devices

Mantech continues to address new areas of the compound semiconductor industry beyond GaAs and microelectronics. The technical conference concluded with a description by Sandia's Jeff Tsao of the US solid-state lighting roadmap to develop high-performance, low-cost white LEDs.

In another invited presentation from Cree, progress in developing high-purity semi-insulating (HPSI) 4H-SiC substrates and SiC epilayers was discussed. Cree has demonstrated micropipe densities as low as 4.7/cm^2 for 3 inch substrates, and prototype wafers are now commercially available for advanced development. SiC epitaxy showed intra-wafer sheet resistance variations of 1.4%. SiC MESFETs fabricated on 2 inch wafers had a power density of 4 W/mm and very tight gate threshold voltage distributions. High-temperature operating life testing showed a 2.5% reduction in drain current over the first 1000 h of operation at a junction temperature of 175 °C. Cree intends to transition its process to 3 inch wafers during 2003.



FERDINAND-BRAUN-INSTITUTE

Fig. 4. A single-stage PA based on a 4 mm gate width GaN-on-SiC power HEMT.

Hitachi Cable and Fujitsu investigated the growth of AlGaN/GaN HEMTs on 100 mm sapphire wafers, which showed considerable bowing to the extent of around 40–60 μm. Despite this, excellent uniformity of sheet carrier concentration was obtained, and 0.8 μm gate-length HEMTs were fabricated with sufficiently high uniformity for mass production.

A paper from the Ferdinand-Braun-Institute in Berlin and the Fraunhofer Institute in Freiburg, Germany, described large AlGaN/GaN HEMTs grown on SiC and fabricated using i-line stepper lithography. Special processing sequences were developed to overcome the problem of the transparency of SiC wafers with AlGaN/GaN epitaxy. A power density of 5.2 W/mm was obtained at 2 GHz for devices with a gate width of up to 2 mm, while the maximum on-wafer power level was 13.8 W at 2 GHz for 4 mm wide devices. A hybrid amplifier using packaged 4 mm devices delivered 15.1 W (figure 4). ●

The 2004 Mantech conference will be held in Miami, FL, on May 3–6.

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Component selection is vital for APD receiver performance

There is far more to an optical receiver than just the APD or *pin* diode – consideration of the surrounding components is crucial to good receiver performance, writes **Joe Boisvert**.

Fiber-optic receivers for telecommunication applications often employ avalanche photodiodes (APDs) as the photodetector to improve receiver sensitivity and increase link reach. A longer link reach translates into fewer transponders and reduced system deployment costs. The cost savings can be particularly significant in metropolitan-area networks, where many thousands of transponders will be deployed. Even a 1 dB improvement in receiver sensitivity can have a large impact on the overall system cost, which makes sensitive APD receivers market-driven products that are currently the focus of intense interest. While APD-based receivers offer the potential for higher sensitivity than their *pin*-based cousins, there are several careful choices that an APD receiver designer must consider before setting out to bring a new product to market.

Figure 1 is a block diagram of a typical receiver portion of a fiber-optic transponder. The receiver is denoted by the enclosed box, and typically contains at least a photodetector and a transimpedance amplifier (TIA). The TIA converts the output current from the photodetector into a voltage signal for the subsequent amplification and signal processing required to convert the analog signal to a digital data stream. Additional functionality such as power-supply conditioning (filter capacitor and resistor) may also be included in the receiver, depending on subsystem requirements. How much additional functionality to include in the receiver plays a key role in determining the designer's cost versus value-added trade space, and can have a significant impact on package assembly complexity.

APD versus *pin* receivers

With a *pin* diode as the photodetector, the input optical power from the fiber is converted to a current with a response efficiency of approximately 0.8 A/W at 1550 nm. An APD provides first-stage amplification through an internal gain mechanism known as avalanche multiplication. An APD will have a typical response of about 8 A/W at its optimal operating point near a gain of 10 (the responsivity simply scales with the internal gain). The photodetector output current establishes the signal level. The noise level is set by the combination of noise from the photodetector, TIA and photodetector bias supply.

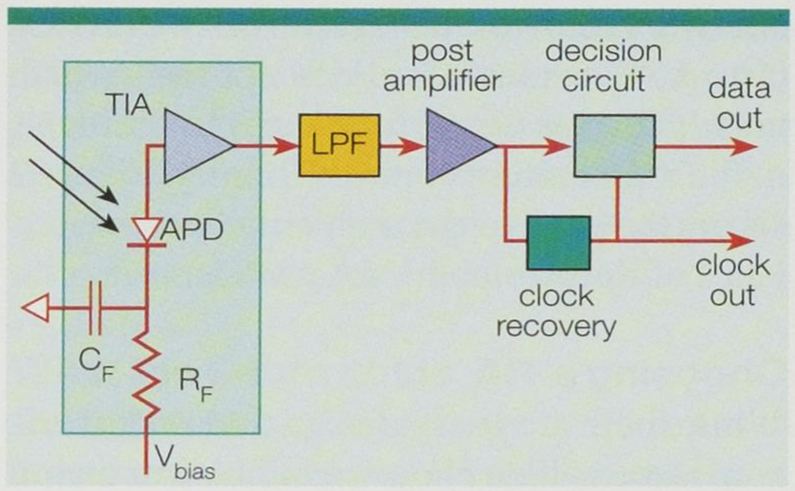


Fig. 1. The receiver portion of a transponder. The components typically found in the analog receiver front end are shown in the shaded box.

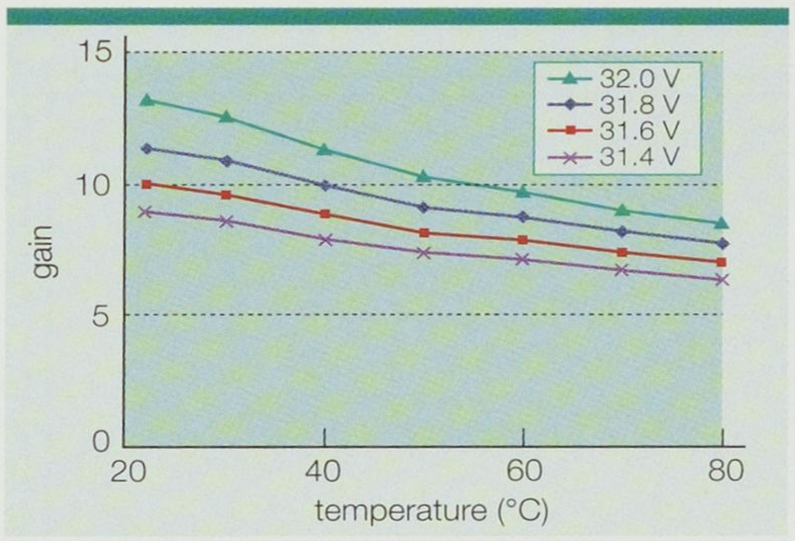


Fig. 2. The typical dark current and optical gain versus bias characteristics of a Spectrolab InAlAs APD.

Typically, the TIA noise dominates at telecommunication frequencies greater than about 1 GHz, so increased optical response from an APD leads to a larger signal-to-noise (S/N) ratio and improved sensitivity of about 6–8 dB over a *pin* receiver. The improved signal response does not come without problems, however, because avalanche gain amplification introduces additional noise known as excess noise (F), which increases with the internal APD gain. Increasing the APD gain increases S/N until at some gain the S/N ratio reaches a maximum, and any further increase in APD gain has a deleterious effect. At that point receiver sensitivity is optimized. Because the noise floor at telecommunication bandwidths is strongly dependent on the TIA noise, the specific improvements in sensitivity will hinge not only on the designer's choice of an APD, but also on the selection of the TIA and on passive bias supply filtering components.

Choosing an APD

Most telecommunication APDs use separate absorption and multiplication regions with InGaAs as the light absorbing layer, and another wider bandgap layer, such as InP or InAlAs, as the material in which avalanche multiplication takes place. The use of two different semiconductors for absorption and multiplication functions is essential in this technology, because the electric fields that would be required to achieve reasonable gains in InGaAs alone result in very large tunneling dark currents that degrade receiver sensitivity. The wider bandgap InP or InAlAs layer is able to sustain much higher electric fields without producing significant dark currents.

The choice of an InP versus InAlAs APD is influenced by several factors. InP APDs have been available for several years, and have been fielded in many networking transponders. However, because of the way that multiplication is achieved, the excess noise factor is not as low as can be achieved in InAlAs APDs ($F \sim 5$–6 in InP; $F \sim 4$ in InAlAs at an internal gain (M) of 10). InAlAs APDs have only recently started to be used in telecom APD receivers, but have already set world record sensitivities and appear to be poised to supplant InP APDs in very-high-sensitivity applications. Table 1 lists some of the important figures of merit for these two APD material technologies.

Another parameter that the receiver designer must consider is the bias required for the APD to operate. Because InGaAs-based APDs operate close to the avalanche breakdown electric field, they typically require 30–60 V of bias that must be supplied though an external, filtered bias supply. As discussed in the following section, the bias supply noise as well as passive component size, performance and cost are all functions of the APD operating bias – lower is better. A good rule of thumb is to keep the APD bias to less than 50 V, because this is a break point in the maximum DC voltage ratings and sizes of filter capacitors and resistors. Spectrolab InAlAs APDs are designed to operate at 30–40 V. At a gain of 10 these APDs have about 65% quantum efficiency, resulting in a responsivity of 8 A/W.

Because APDs work with high internal fields, they can be sensitive to changes in operating temperature. When holding the APD bias constant, an increase in temperature will decrease the avalanche gain. A temperature compensation circuit on the APD bias supply is typically used if the required operating temperature range is large enough to significantly impact on receiver performance. The change in breakdown voltage with temperature is about a factor of 10 less in InAlAs APDs (10 mV/°C versus 100 mV/°C for InP), which greatly relaxes the performance requirements of the temperature control circuitry. Figure 2 shows the gain versus temperature characteristics of Spectrolab InAlAs APDs.

APD figures of merit for different gain region materials

	InAlAs	*InP*
operating bias (V)	35	60
responsivity at 1550 nm (A/W)	8	8
excess noise (F) at M = 10	4	4–6
change in breakdown voltage with temperature (mV/°C)	10	100

Table 1. APDs with InAlAs gain regions can be operated at a lower bias, have a lower excess noise and are more resistant to temperature variations.

Choosing a TIA

While there are many design trade-offs to be considered when choosing a TIA (for example cost, operating bias and transimpedance gain), here we will focus on the impact of the TIA on sensitivity. Figure 3 displays the predicted effects of TIA input referred noise on sensitivity for a typical Spectrolab InAlAs APD. As the TIA noise increases, the optimum APD operating gain also increases until the avalanche noise reaches the noise floor established by the TIA. For reference, the sensitivity of a typical InGaAs *pin* diode is also shown in the figure. The choice of TIA is critical to receiver sensitivity. In the example shown in figure 3, there is a 4 dBm difference in sensitivity at an APD gain of 10 between receivers built from the best and worst performing TIAs. As a point of reference, state-of-the-art 2.5 Gbit/s TIAs have about 6 pA/√Hz of spectral input-referred noise current density, while the best 10 Gbit/s TIAs have about 10 pA/√Hz of noise.

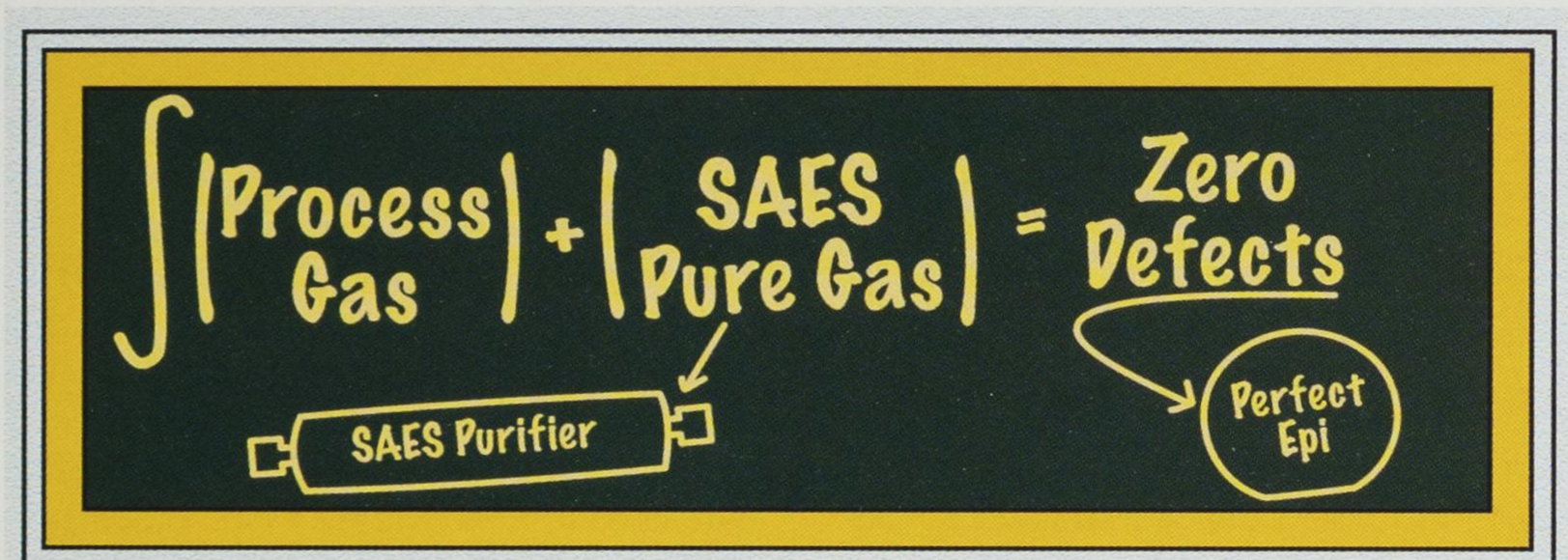
Figure 4 shows predicted and measured sensitivity of a 2.5 Gbit/s APD receiver. As predicted, there is an optimum operating APD gain, above which receiver sensitivity degrades. The disagreement between the prediction and measured data at large gains is due to bandwidth compression effects that begin to have an impact on the bit error rate (BER).

Filtering components and packaging

While sensitivity is a very important performance parameter for telecommunication receivers, there are other design requirements that must be addressed. The range of temperatures and optical input powers are also important to the subsystem customer. Sometimes simply cramming many components into very small form factor packages dominates assembly costs and the design space.

An APD bias power supply will have ripple noise at the output that will couple onto the TIA input through the APD capacitance. Minimizing both the APD bias voltage and capacitance can reduce this effect, but these measures alone will not suffice for high-sensitivity receivers. The power supply must be filtered either in the receiver itself or by external components.

The reduction of bias supply noise at the TIA input through the use of filtering is shown in figure 1, where a filter capacitor (C_F) and resistor (R_F) are included on the bias supply



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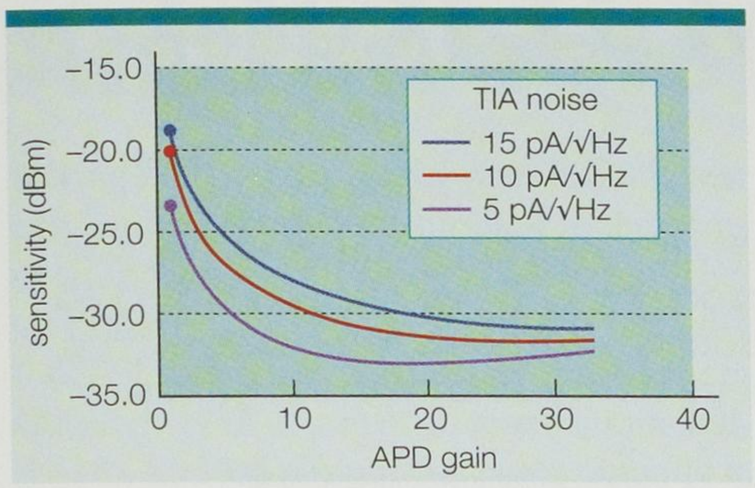

Fig. 3. The influence of TIA noise on the sensitivity of a 2.5 Gbit/s APD. The receiver sensitivity versus gain characteristics show a minimum that is a function of the TIA noise. The circles represent the typical sensitivity of InGaAs *pin* photodiodes.

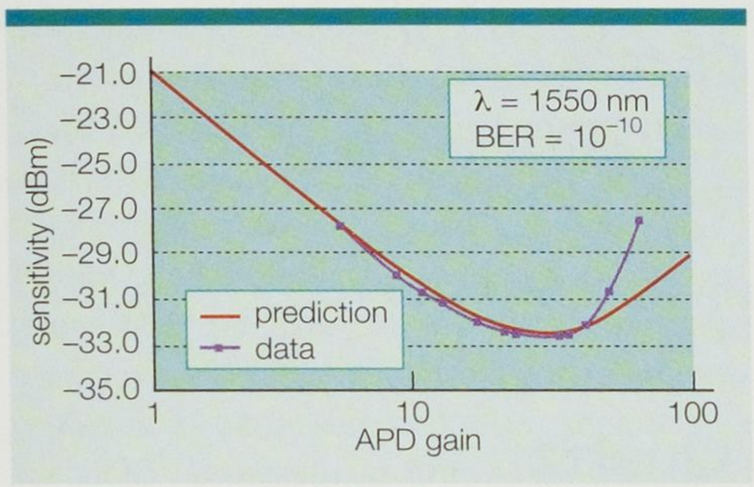

Fig. 4. The measured and predicted performance characteristics of a 2.5 Gbit/s APD receiver made with a 10 pA/√Hz TIA.

line. High-quality, low-noise APD bias supply IC networks will condition the output voltage so that the peak-to-peak ripple is about 100 mV, which in the absence of filtering would result in about 6 pA/√Hz of spectral input noise current density at the TIA with a 2 GHz bandwidth, assuming a 500 fF APD capacitance. This noise source gets added in quadrature to the TIA input referred noise, and will degrade sensitivity if it is not filtered out. Using a 6 pA/√Hz TIA without bias supply filtering results in a 1.5 dBm penalty in sensitivity – clearly unacceptable when the other components have been carefully selected to maximize performance.

Adding a filter capacitor and resistor into the receiver may appear to be straightforward, but in fact requires careful attention if package size is a constraint. With the general trend in telecommunication receivers of smaller form factor packages, the package design engineer is forced to fit several components into a small area. There is a trade-off between the size of the filter components and the filter performance. While a 1 μF filter capacitor rated to 100 V DC may seem like a good idea to reduce bias supply noise, in reality that component will be much too large to fit into a TO-46 package. Even a 1 nF capacitor sized to fit into the common TO-46 header can compromise performance over a wide range of operating temperatures, because high-k dielectric capacitors tend to have a large dC/dT, which will impact the filter performance as temperature changes.

The choice of filter resistor is also complicated, because at high-input optical power levels, the voltage drop across this resistor will tend to de-bias the APD, reducing its gain and leading to the onset of bandwidth compression. A good general rule is to keep the voltage drop at maximum input optical power (typically –4 dBm) to less than 1 V. This requirement quickly leads to a maximum filter resistance of a few hundred ohms.

What the future holds

Recent work at the University of Texas at Austin has led to new "I^2E APDs" that have very thin "impact-ionization-engineered" epitaxial layer designs and have resulted in InGaAs/InAlAsP APDs with extremely low excess noise levels (Wang *et al.* 2002). These APDs have been demonstrated with F = 3 at M = 10, and hold the promise of improving telecom receiver sensitivities by about 1.5 dBm. While these devices are at a proof-of-concept stage, production units could be available within a few years.

Another very promising APD technology involves fusing a III-V semiconductor absorbing layer to a Si multiplication layer to create an APD that incorporates the spectral response of the III-V material with the very low avalanche multiplication noise properties of silicon to result in F = 2 at M = 10 (Kang *et al.* 2002). This technology has been under development for several years, and has shown steady performance progress that could very well result in commercially available devices in the near future.

Acknowledgments

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Further reading

Kang *et al.* 2002 *Photon. Tech. Lett.* **14(11)** 1593.
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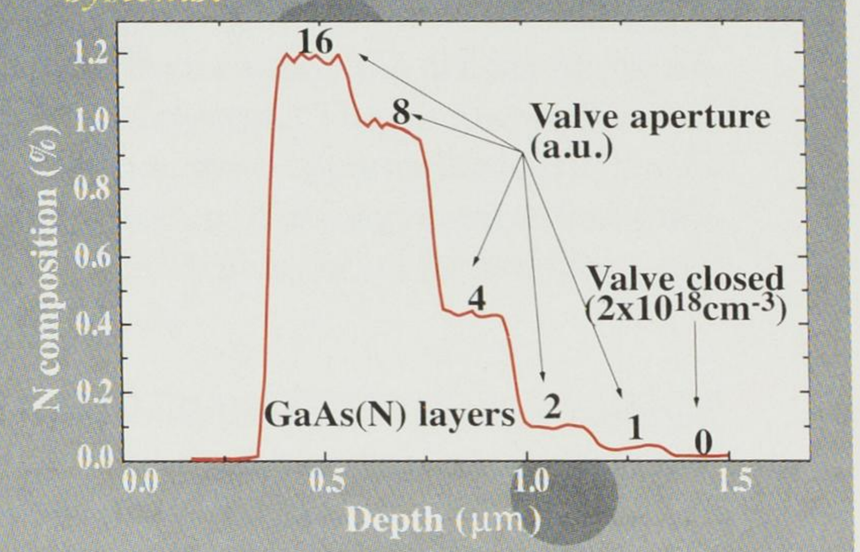

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imagination at work

Aixtron celebrates its 20th anniversary

During 2003, Aixtron celebrates its 20th year as a leading equipment supplier to the compound semiconductor industry. The company was founded in 1983 as a spin-off from the RWTH technical university in Aachen, Germany, with a team of 10 scientists, including Holger Jürgensen (who was eventually to become the chairman of Aixtron). The company quickly developed advanced technology for MOCVD, and sold the first AIX 200 system in the summer of 1984. This system has since changed ownership, but is still in service at Prague University. In 1987, Aixtron opened its first subsidiary in the US, and today is located in Chicago and Los Angeles.

From 1987 to 1991, Aixtron was proactive in the development of the first commercially available multiwafer production system. Working in parallel, the R&D division at Philips had successfully developed and patent-protected the Planetary Reactor concept which, when combined with Aixtron's developments, became a key enabling technology for MOCVD growth. In 1988 Aixtron acquired an exclusive technology transfer and license package from Philips for the Planetary Reactor, and since then has further developed the concept, registering a raft of intellectual property rights around the original Philips patents. The first AIX 2000 Planetary Reactors for industrial production of compound semiconductors were delivered to Philips Eindhoven in 1990 and to Hewlett Packard in 1991.

In 1992 Aixtron shipped its first AIX 2400 system, which has an enlarged capacity of 5 × 4 inch wafers, to Bandgap Corporation. In the same year, the company started to develop the world's largest MOCVD reactor, the AIX 3000, which has a capacity of 95 × 2 inch wafers (or equivalents in larger sizes) and is widely used by manufacturers of solar cells.

In 1996 Aixtron shipped its 200th system and also doubled the size of its assembly facility in Aachen. Around this time the first blue LEDs were developed, promoting intense worldwide activity in this new field. Through in-house and collaborative R&D programs, Aixtron developed GaN growth technology and in 1996 shipped its first GaN MOCVD systems to Northwestern University and to the Fraunhofer Institute in Freiburg, Germany.

In 1997 Aixtron went public, establishing the capital foundations for its anticipated rapid and profitable future growth and to be able to invest in further joint R&D programs.

The period from 1998 to 2000 saw rapid growth in Aixtron's business and markets. The facilities in Aachen were expanded again in 1998, and in 1999 the group was enlarged by acquiring Thomas Swan Scientific Equipment Ltd of Cambridge, UK, and a 70% stake in Epigress AB of Lund, Sweden. These acquisitions allowed Aixtron to offer a wider product portfolio, including vertical reactor technology and SiC growth systems.

In 2000, Aixtron completed its new state-of-the-art assembly and test facility at Herzogenrath, Germany, and now has the capacity to build and test more than 400 systems a year. The company also created its Global Service Organization to further strengthen its round-the-clock customer support in all the major world markets. In 2001, Aixtron delivered its 500th MOCVD system, and in the same year was invited to be the first (and only) MOCVD equipment provider to occupy space in the Hsinchu Science-based Industrial Park in Taiwan. Also in 2001, to support the rapid growth of business in Asia, Aixtron GSO opened offices in Japan, Korea and Taiwan, and in 2002 a representative office was opened in Shanghai, China.

According to VSLI, the Aixtron Group had a 67% share of the global MOCVD equipment market in 2002, up from 58% in 2001. The company says that it has invested more than $200 million in R&D and engineering in the past 20 years, and generated revenues of more than $800 million.

Although demand from some compound semiconductor markets is limited at present, ongoing developments in the silicon industry are opening up new markets. "Aixtron's knowledge and experience in gas-phase deposition has created opportunities to take this core competency into new areas of scientific and commercial interest," said Paul Hyland, Aixtron's president and CEO. "Over the last 10 years, the group has been steadily building its capabilities in several emerging market sectors, including strained silicon, SiGe, III-Vs on silicon, high-k dielectrics, ferroelectrics and OLED technologies."

Hyland says that the introduction of multiple new materials into silicon and compound semiconductor manufacturing schemes, coupled with the development of new display technologies, presents Aixtron with some unique challenges and opportunities. "As a company with extensive experience in providing complex material solutions, Aixtron is very well positioned to address upcoming customer needs during what some industry observers are calling 'the decade of materials'," said Hyland. "The company's focus on maximizing those opportunities indicates the determination of management to leave this difficult economic period far stronger than it went into it."

A longer version of this article is on our website at http://compoundsemiconductor.net/magazine – see the July 2003 issue.

Equipment sales

● **Riber** has announced multiple orders for its MBE equipment. **ALPS Electric**, based in Tokyo, Japan, has recently placed an order for an Epineat MBE system for research on ZnO-based electronic devices.

Two Compact 21 systems have been sold to Japanese customers; **Kwansei Gakuin University** in Kobe will use its system to grow III-V nanostructures, while the **Nippon Institute of Technology (NIT)** in Minami-Saitama will be researching GaN deposition, with both plasma source and on-surface-cracked ammonia for N species generation.

The National Cheng Kung University, Taiwan, and **Instituto Politecnico Nacional** in Mexico, have each ordered a Compact 21 to conduct research in the field of GaN-based materials. The **Institute National des Sciences Appliqués (INSA)** in Rennes, France, has ordered its third Compact 21 to pursue studies of quantum nanostructures on InP substrates.

● **Rensselaer Polytechnic Institute (RPI)** has purchased an AIX 200/4 RF-S MOCVD system from **Aixtron** for research in the field of GaN ultra-high-brightness LEDs covering the range from green to deep UV. Aixtron has also joined the Future Chips Constellation research thrust at RPI.

Veeco buys AFM probe technology business

Veeco Instruments has purchased the atomic force microscope (AFM) probe business of NanoDevices, Santa Barbara, CA. The terms and conditions of the transaction were not revealed. "This strategic technology acquisition will help Veeco provide its customers with probes designed specifically to maximize the performance of Veeco's AFM instruments," said Don Kania, president of Veeco.

ISO certification for Unaxis

Unaxis Semiconductors has been awarded ISO 9001:2000 certification for its manufacturing facility in St Petersburg, FL, meaning that all Unaxis Semiconductors manufacturing sites are now ISO 9001:2000 certified. At the same time, Unaxis Semiconductors also received ISO 14001:1996 certification, which relates to environmental management systems.

Matheson Tri-Gas expands gas manufacturing facility

Matheson Tri-Gas plans to double its manufacturing capacity for arsine and phosphine at its plant in New Johnsonville, TN. New purification methods will be incorporated to enable the plant to even further reduce the level of critical impurities. The company says it sees continued growth in the MOCVD market, coupled with a demand for higher purity and consistency of gases.

Cascade Microtech in RF license agreement

Cascade Microtech, a manufacturer of wafer probe cards and probe stations for testing of semiconductor devices, has licensed essential RF measurement technology to Tokyo Seimitsu of Japan, a supplier of manufacturing equipment and measurement instruments for the semiconductor industry.

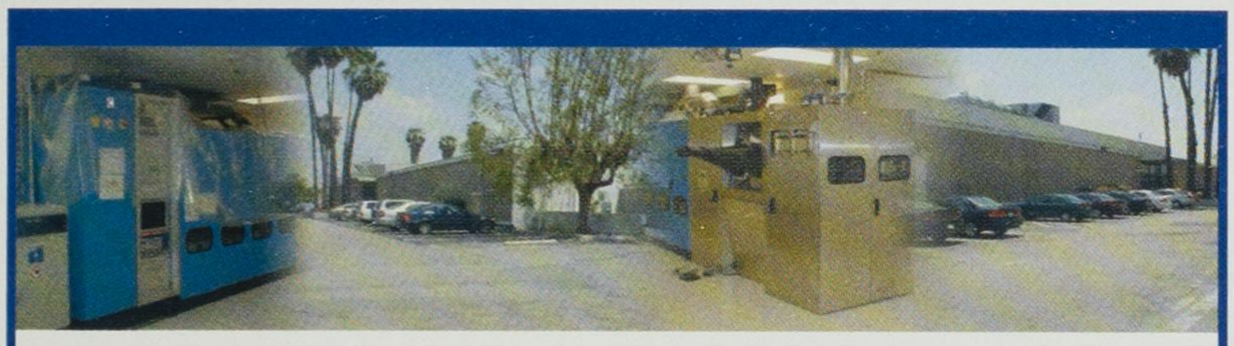
Equipment sales

- **Bede** of Durham, UK, has received orders from Taiwan totaling about $1.25 million for three D1 X-ray diffractometer systems. The systems will go to the **Industrial Technology Research Institute (ITRI)**, **Arima Optoelectronics** and the **National Chiao Tung University**.

- **Suss MicroTec** has received a follow-on order for its LithoFab200 lithography cluster from **Osram Opto Semiconductors** for the production of LEDs.

- **Emcore** has sold a second E300 MOCVD GaNzilla production tool to **EpiPlus** of Korea, a manufacturer of blue, UV and green high-brightness LEDs.

- **Tekcore** of Nantou, Taiwan, a manufacturer of GaN-based LED wafers, has recently ordered two 24 × 2 inch AIX 2600G3 HT reactors from **Aixtron**.



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Boston Laser moves to upstate NY

By Tim Whitaker

Earlier this year, Boston Laser, a manufacturer of high-power laser diodes and subsystems, acquired the assets of the bankrupt laser maker Semiconductor Laser International (SLI). Since the deal closed at the end of March, Boston Laser has vacated its plant in the Boston area and has relocated to the SLI facility in Binghamton, NY.

After accumulating at least $20 million in losses as a public company (see box), SLI was under Chapter 11 bankruptcy protection for about two years. After inviting other bids, the bankruptcy court approved the sale of SLI's assets to Boston Laser for a fee of $1.5 million. Financial backing was provided by a group of European investors.

Boston Laser acquired all of SLI's assets, including its building, equipment, technology and product lines. Perhaps more importantly, says Boston Laser's CEO Aharon Meytahl, the company hired many of the people that had previously worked for SLI. "We now have about 30 people; about 20 are former SLI employees and the others are senior people that moved from Boston," he said.

Boston Laser was founded by Meytahl in early 2000, and acquired Polaroid's laser diode business. Since then it has been housed in a facility rented from Polaroid in Norwood, MA.

Meytahl says that there were two main reasons for the acquisition of SLI's assets. "Aside from this being a good business deal, we don't have to pay rent in Binghamton, while the rent in Boston was very high." The second reason, he says, is the availability of a large pool of talent in the Binghamton locality, including former SLI employees and staff of a large IBM facility that is now closed.

The processing and packaging lines in Binghamton, which have already been re-qualified, primarily use equipment transferred from Boston Laser's former facility. "Boston Laser is an industrial company, whereas SLI was more like a laboratory," said Meytahl.

The one significant addition to Boston Laser's capabilities is an MBE machine. The company uses external epiwafer vendors, primarily IQE, for its production requirements, and Meytahl says that outsourcing will continue as it offers significant economic advantages. However, the in-house MBE capability will allow the company to design and grow test wafers with a very short turnaround time, which will assist development efforts.

BOSTON LASER

The Litening II pod, shown mounted beneath an F-15 fighter, contains infrared and CCD detectors to identify targets and a laser designator for precise delivery of munitions.

As part of the acquisition, Boston Laser took over an exclusive license to certain patents relating to Al-free lasers owned by Northwestern University. "We believe in time this will become an important technology," said Meytahl. "However, any Al-free product will have to match standards for reliability and lifetime of lasers that contain aluminum."

Products and markets

Boston Laser makes high-power lasers in the wavelength range of 635–1550 nm, with key products at 660, 808, 915, 980 and 1100 nm. The company specializes in high-power, high-brightness multimode lasers and offers single emitters at 808, 915 and 980 nm rated at 8 W. As well as pigtailed modules, Boston Laser also manufactures Milon modules, which combine the output of six multimode lasers into fiber with a coupling efficiency of 75%.

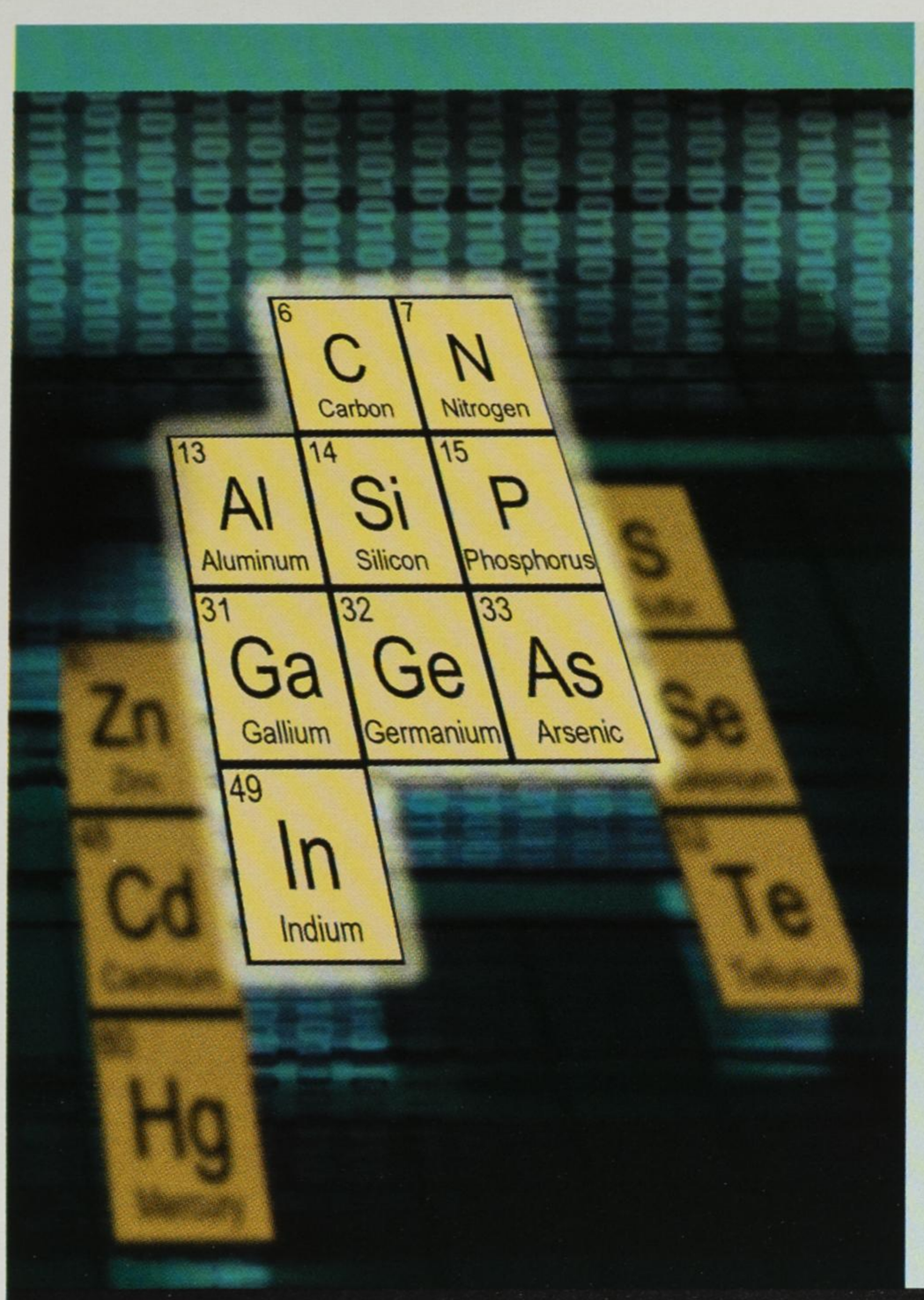
Polaroid originally set up a laser diode manufacturing capability to supply components for a printing product. Today, printing is one of Boston Laser's principal markets; the company supplies lasers to Heidelberg, the world's largest printing press manufacturer, and various Japanese companies.

The military market is also important for Boston Laser. The company recently announced that its lasers made in Binghamton had been re-qualified by Northrop Grumman and Rafael for use in the Litening II laser designator pod (see photo).

Following the SLI acquisition, Meytahl says that Boston Laser hopes to achieve sales of about $10 million in the next 12 months. He believes that SLI was unsuccessful for the same reason that a number of small companies in the industry struggled. "It's a very long road from making 100 pieces to full industrial production," he said. "SLI probably didn't spend its money very intelligently and also lacked industrial experience, which Boston Laser certainly has."

The inglorious history of SLI

SLI was founded in 1993 to manufacture high-power diode lasers. In 1996, the company went public and also received a license to make and sell lasers based on Northwestern University's patents relating to Al-free material. SLI's share price peaked at over $10 in mid-1996, but fell steadily to below $1 in mid-1998. The company was delisted from the Nasdaq exchange in May 1999 and was investigated for possible violations of securities regulations. SLI applied for bankruptcy protection in 2001. As a public company, it failed to make significant revenues, never had a profitable quarter, and generated cumulative losses of at least $20 million.



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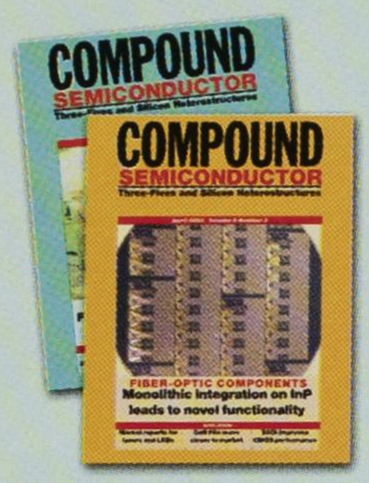

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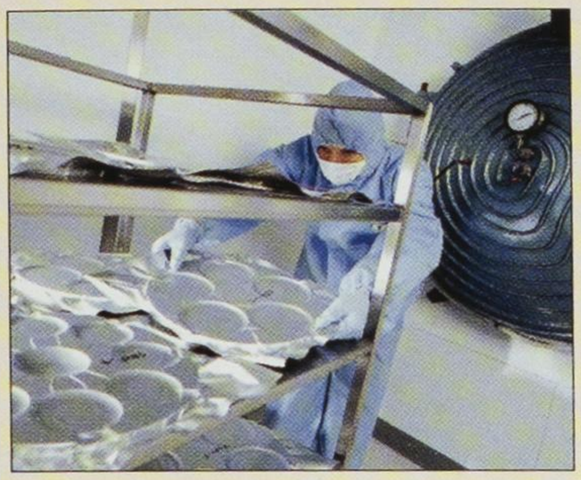

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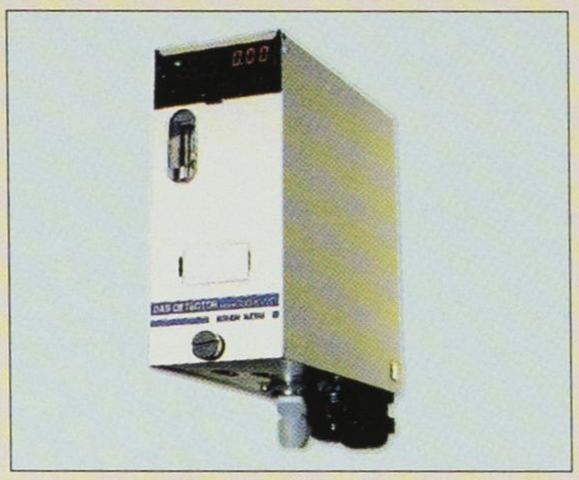

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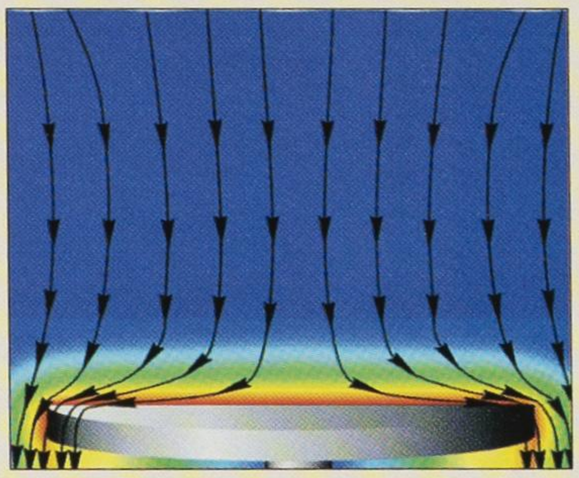
STR CVD-Module

Semiconductor Technology Research, Inc (STR, Inc)

STR, Inc has developed a new software product – STR CVD-Module. This product is aimed at efficient and predictive modeling of chemical vapor deposition. The unique features of the tool are built-in reactor geometries and chemical models combined with a simple and convenient graphical user interface. STR CVD-Module is an add-on to the well known CFD-ACE+ package. This simulation tool is expected to be very useful in providing guidelines to growers during the design and optimization of III-V, III-nitride and SiC deposition processes.



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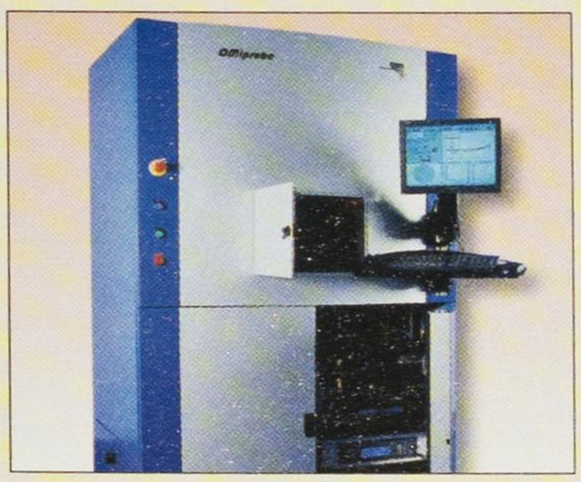

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Emcore clarifies InGaN V-defects

Solid-phase indium incorporation during the InGaN growth by MOCVD required for blue and green LED epiwafers remains poorly understood, but is known to be strongly dependent on variables including the gas-phase In mole fraction, growth rate and temperature, ammonia overpressure and carrier gas composition. The so-called V-defect is a commonly reported morphological feature of InGaN/GaN QW heterostructures that consists of a threading dislocation terminated by a pit in the shape of an inverted hexagonal pyramid with $(10\bar{1}1)$ sidewalls. Two papers to be published by Doru Florescu and colleagues at Emcore, Somerset, NJ, have helped to clarify the numerous reports of contradictory results and interpretations regarding the V-defect occurrence, propagation, and correlation with In incorporation. Further complicating the matter, inclusions embedded within V-defects originating at the first InGaN/GaN interface have been observed under certain growth conditions.

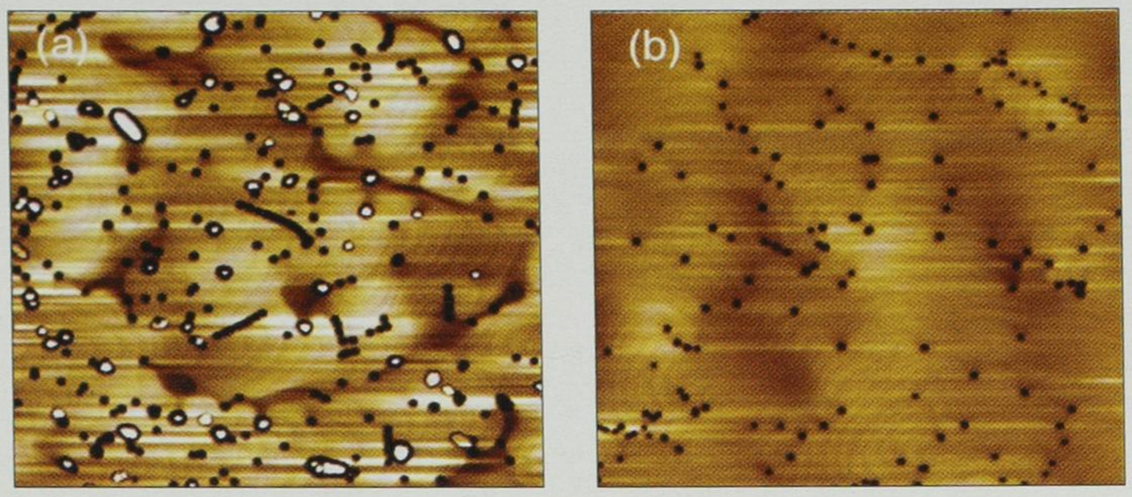

Fig. 1. 5 × 5 μm AFM images of InGaN/GaN MQWs grown (a) without and (b) with hydrogen. The vertical scale range is 20 nm.

In the reported work at Emcore, the morphology of InGaN/GaN heterostructures was found to be extremely sensitive to the process tradeoffs made in order to facilitate In incorporation. GaN barrier growth at reduced temperatures (~800 °C) in an H_2-free environment promotes V-defect formation and propagates inclusions (to be published in *J. Appl. Phys.* 2003 **94(3)**). Striking morphological differences were noticed in AFM scans of material grown with and without an H_2 ambient (figure 1). A higher density of pits with a wider range of pit diameters was seen for the H_2-free growth when compared with the MQW growth in an H_2 ambient under identical barrier growth temperatures. In addition, the typical inclusions embedded within the pits, characteristic of low-temperature, H_2-free GaN barriers, are seen in figure 1a as bright, irregular features. The correlation between inclusion density and accelerated post-growth thermal degradation strongly suggests that the inclusions are In-rich or promote In segregation. The addition of H_2 suppresses inclusion propagation and thermal degradation without sacrificing wavelength (figure 1b).

Combining AFM with high-resolution SEM/cathodoluminescence (CL) performed at the University of Central Florida provided evidence that some V-defects occur as a direct result of barrier growth temperature. There are additional V-defects associated with In-rich regions, which act as sinks for further In segregation during the MQW growth. Both types of V-defects have a tendency to promote inclusions during low-temperature (800 °C) GaN barrier growth in an H_2-free environment. There was clear correspondence of significant features in the CL and SEM images, with 60–70% of the inclusion-filled pits appearing to display a brighter CL signal when compared with areas between these pits. Adding H_2 or raising the temperature (~900 °C) during the GaN barrier growth reduces the V-defect formation and suppresses inclusion propagation entirely, rendering a uniform nanoscale CL signal (*Appl. Phys. Lett.* 2003 **83(1)**).

Applying the principles and observations discussed, a thermally robust 525 nm LED with an unpackaged chip-level output power in the 2.5–3.0 mW range, forward voltage of <3.2 V at 20 mA, and breakdown characteristics of <–20 V at –10 μA was recently achieved.

Ultra-violet LEDs make rapid progress at 325 nm

Moving LED emission deeper into the UV requires active regions containing higher Al fractions. Quantum efficiency strongly depends on the material quality of the active region, and therefore on the quality of the buffer layers between the substrate and active layers. Also, weak carrier confinement in the active region leads to deep-level assisted radiative recombination, reducing the carriers available for injection into the QWs and diminishing the LED output power.

Mohammed Asif Khan's group at the University of South Carolina has reported key improvements to epilayer growth and design that have yielded 325 nm emitters with a record optical power of 10.2 mW at a pulsed pump current of 1 A (*Appl. Phys. Lett.* 2003 **82(16)** 2565). This represents considerable improvement in the space of a year since the group published data for a 324 nm LED with 4 mW of optical power for a 0.9 A pulsed pump current (*Jpn J. Appl. Phys.* **Pt.2 (4B)** L450).

The main difference between the new structure and those grown previously is the growth of a high-quality AlN buffer layer and AlN/AlGaN strain relief superlattice using the pulsed atomic layer epitaxy (PALE) technique developed by the group (*Compound Semiconductor* March 2002 p25) and an electron blocking layer above the active region. After the buffer and strain relief layers were deposited by PALE, the active device layers were grown by LP-MOCVD.

LED die measuring 200 × 200 μm^2 were fabricated and showed an emission peak at 325 nm with a big reduction in the unwanted 340–230 nm emission band seen from previous epilayer designs. This emission band is thought to originate from deep-level recombination in p-AlGaN layers. The 15 nm Mg-doped $Al_{0.42}Ga_{0.58}N$ blocking layer grown above the active region confines the electrons to the MQW region and, coupled with the lower defect material, reduces the broad longer-wavelength emission band.

The LED IV characteristics showed a sharp turn-on at 5 V with a series resistance of 24 Ω. To reduce the series resistance and operate the device at high DC current, four chips were packaged and operated in a parallel array. This configuration offers advantages over a single emitter of the same area, as it reduces the effect of current crowding, thus minimizing resistance. In this case the IV curve for the array was considerably steeper than for the single device, as the resistance was reduced from 24 to 11 Ω. The four-element array showed a DC power of 1 mW at 100 mA pump current before saturation due to device and package heating. The researchers suggest that considerable improvement on this can be expected if more attention is given to thermal management. For pulsed operation, the pump power increased linearly up to 1 A drive where the record 10.2 mW power was measured.

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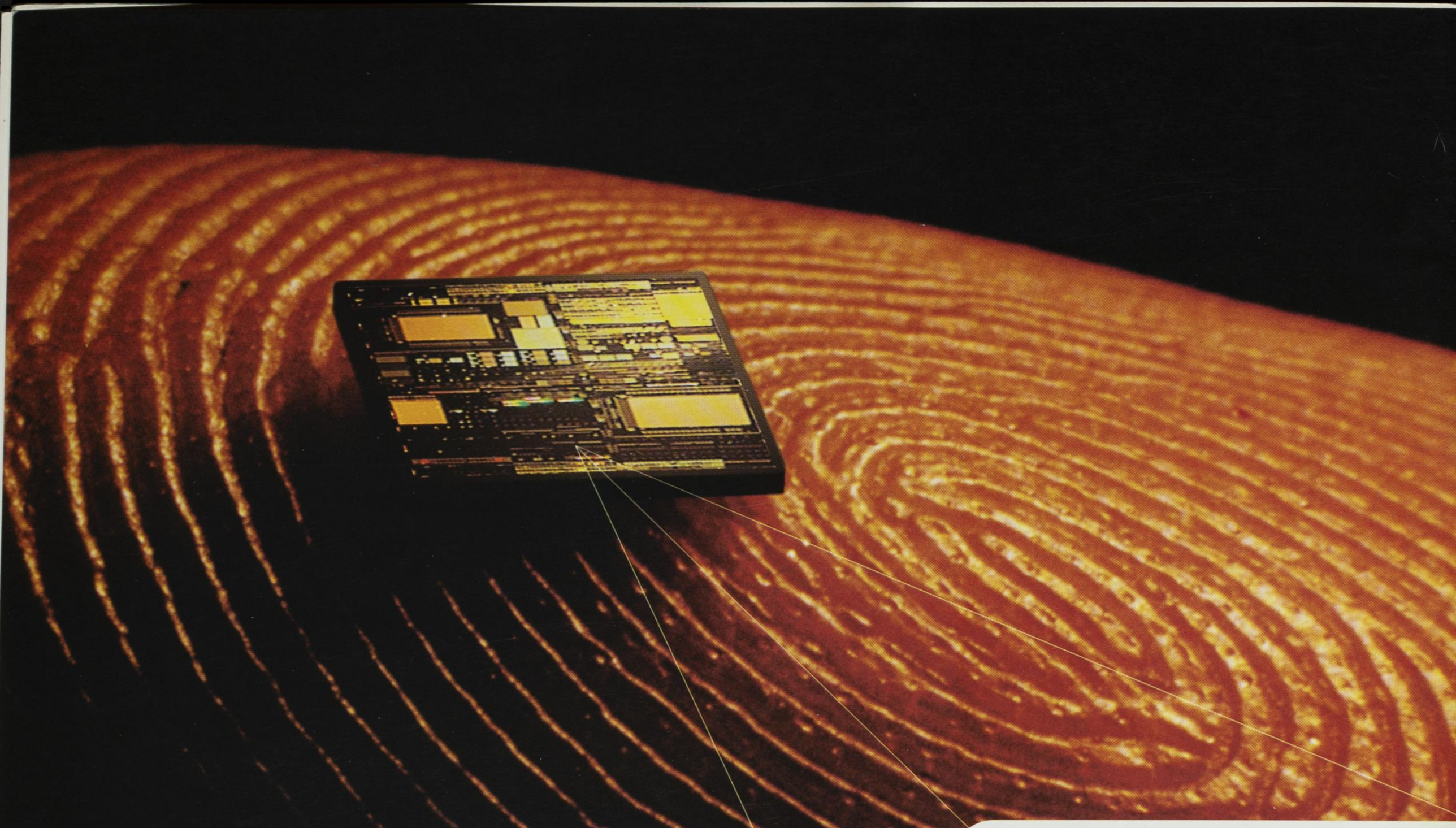

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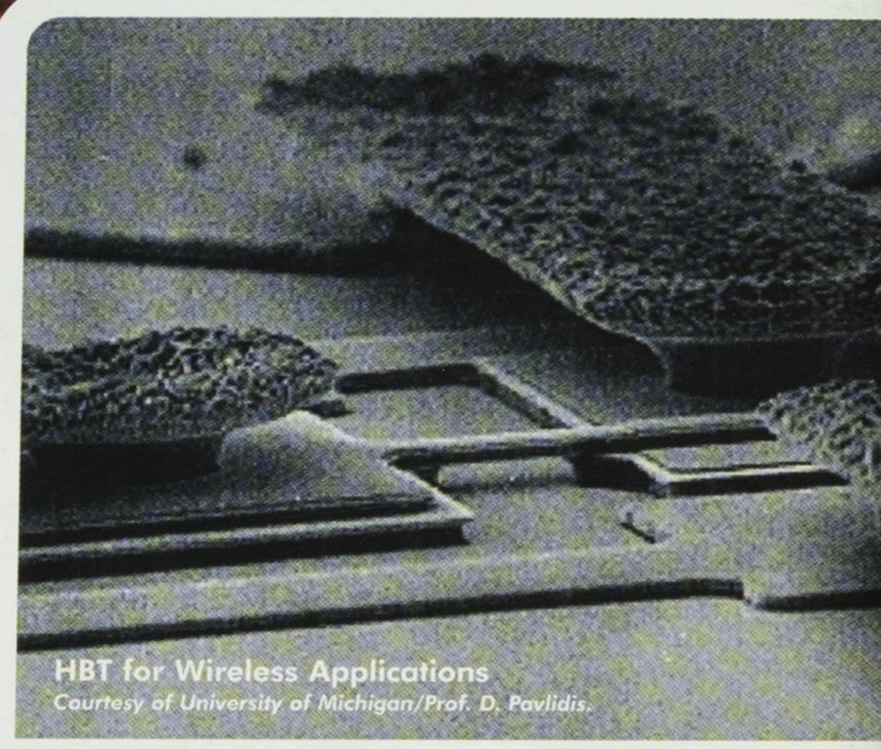

HBT for Wireless Applications
Courtesy of University of Michigan/Prof. D. Pavlidis.

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