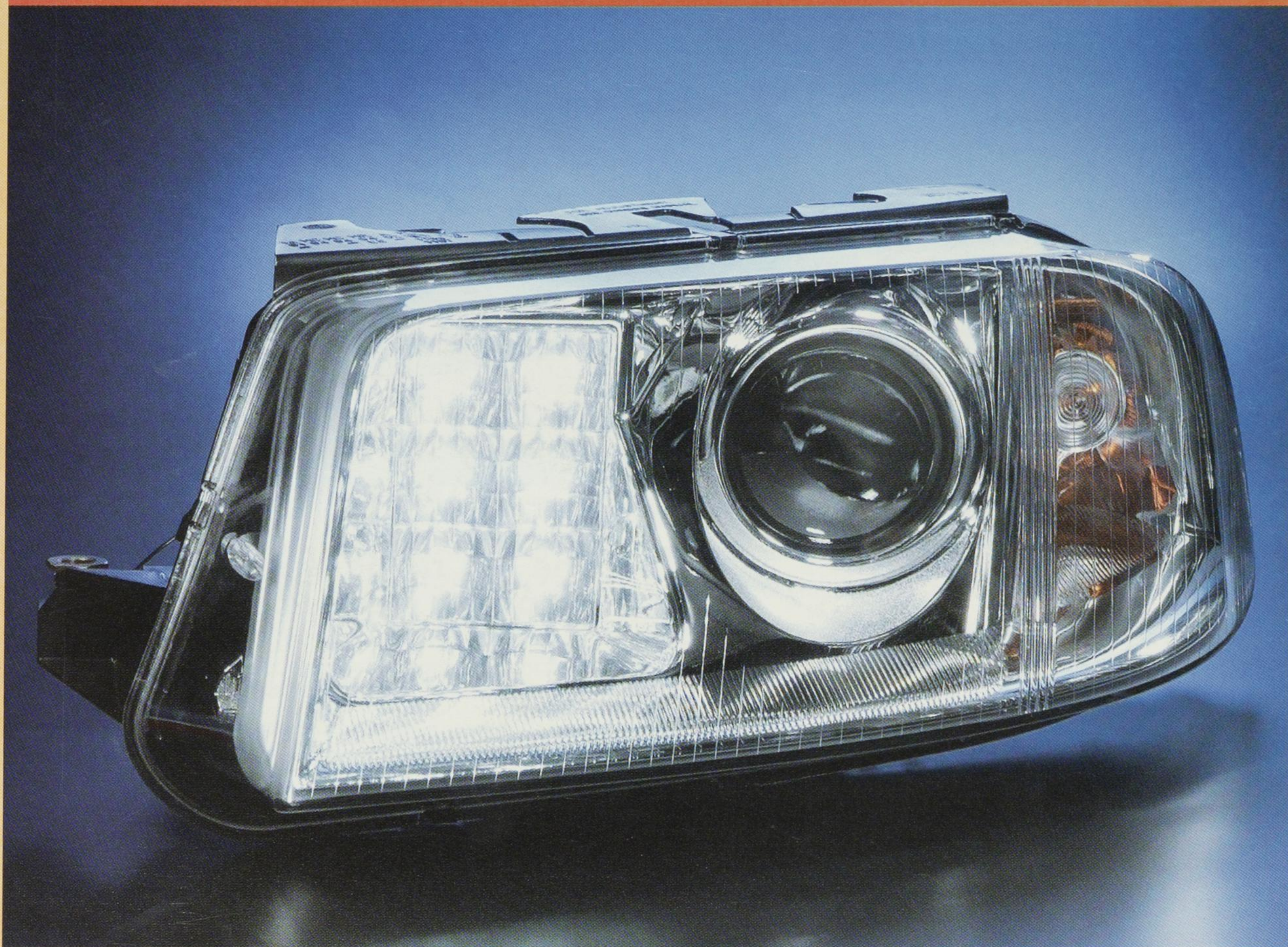


COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

December 2003 Volume 9 Number 11



LIGHT-EMITTING DIODES
**Solid-state lighting presents
targets for future development**

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**Device makers
consolidate further**

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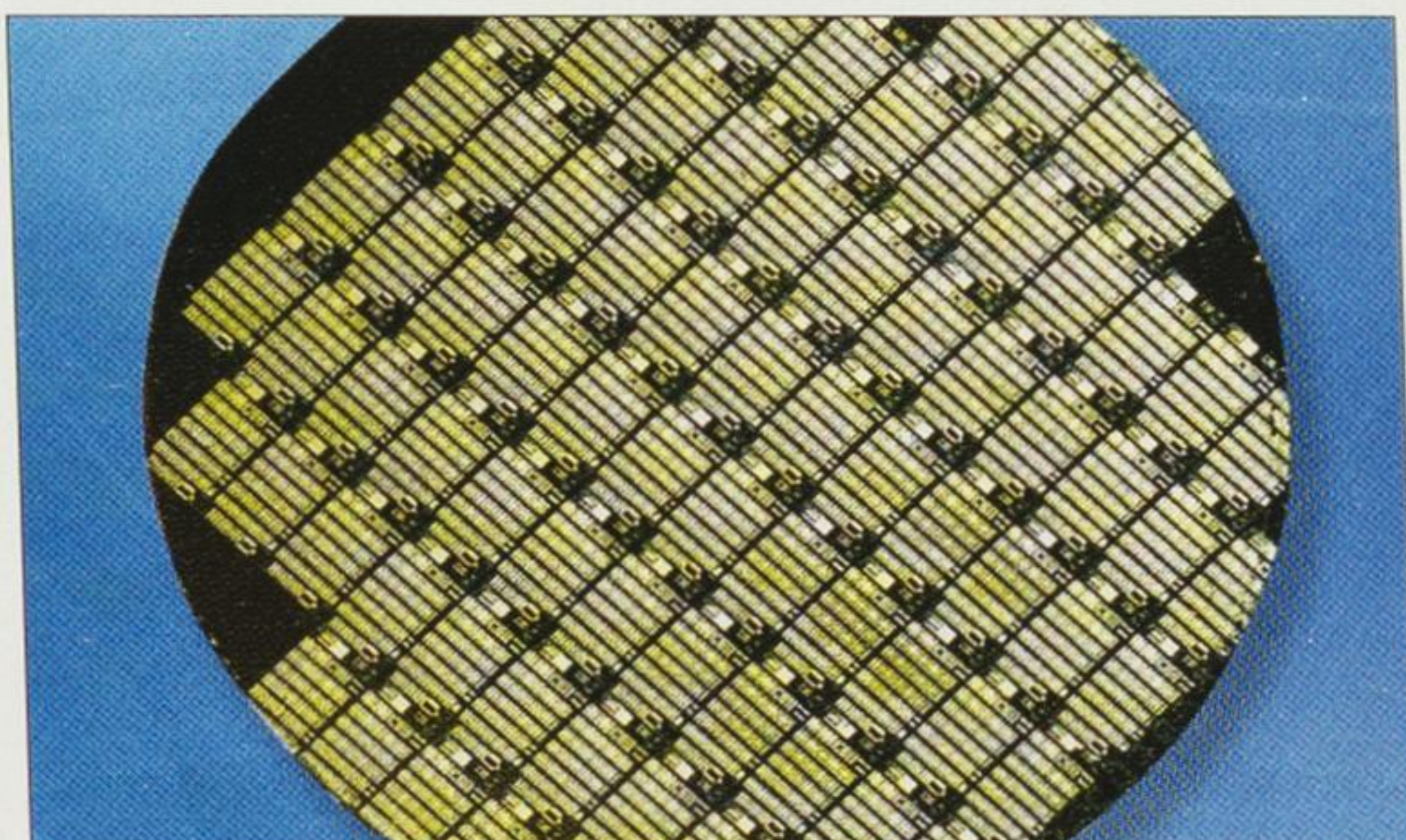
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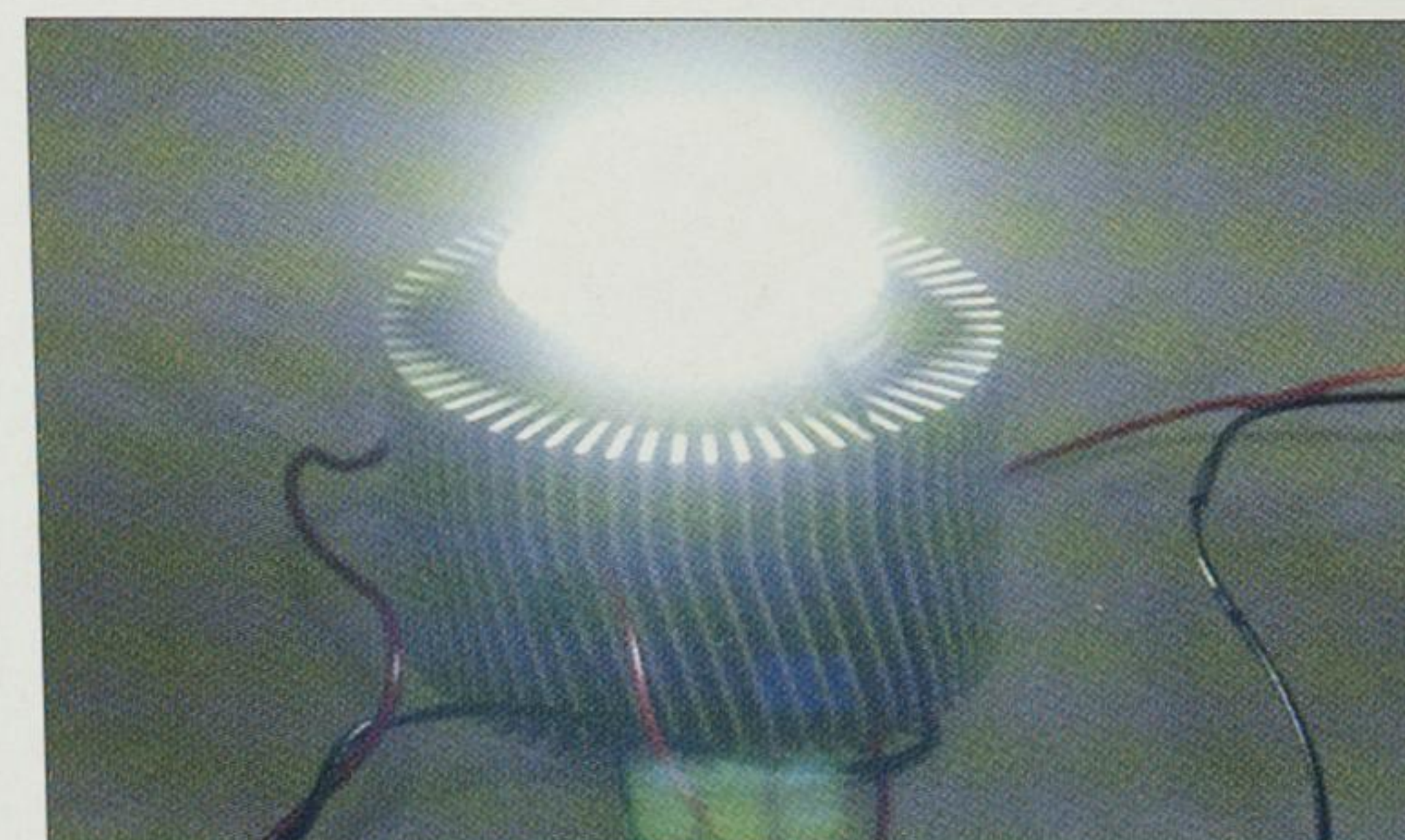
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Institute of Physics PUBLISHING

Editorial

Foundries gain ground as consolidation continues



Recent weeks have seen more examples of consolidation among compound semiconductor device manufacturers. Two foundry companies, GCS of the US and GCTC of Taiwan, are joining forces to form Global Compound Semiconductor Corporation (GCSC), which is likely to be the industry's largest foundry company. Offering a range of electronic and optoelectronic device wafers together with access to a state-of-the-art 6 inch GaAs fab that is also capable of producing SAW devices, the company hopes to emulate the success of giant foundries such as TSMC and UMC in the silicon industry.

Meanwhile, both Raytheon and Celeritek recently decided to quit the commercial GaAs business, concentrating instead on defense markets. Raytheon sold its commercial GaAs business, including its stake in another Taiwanese foundry, WIN Semiconductors, to Fairchild. Both Raytheon and WIN will now provide foundry services to Fairchild.

At another level of the industry, two fiber-optic component manufacturers concentrating on integrated InP-based devices have also merged. ThreeFive Photonics of the Netherlands was effectively saved from bankruptcy by its merger with the New Jersey start-up ASIP. Interestingly, ThreeFive's original venture capital backers were sufficiently impressed with the potential of the merged entity that they provided it with further funding, although they hadn't been prepared to continue to support ThreeFive on its own.

A new editor

This editorial column, which is only the second I have written in more than four years as editor of *Compound Semiconductor*, is also my last. At the start of 2004, Michael Hatcher takes over as editor of the magazine. Michael is an excellent journalist who has written extensively for our sister publication, *Opto & Laser Europe*, on a range of subjects. I'm sure that this magazine will benefit from Michael's fresh approach, and that he will continue to keep *Compound Semiconductor* in its pre-eminent position as the industry's leading source of news and information.

Tim Whitaker

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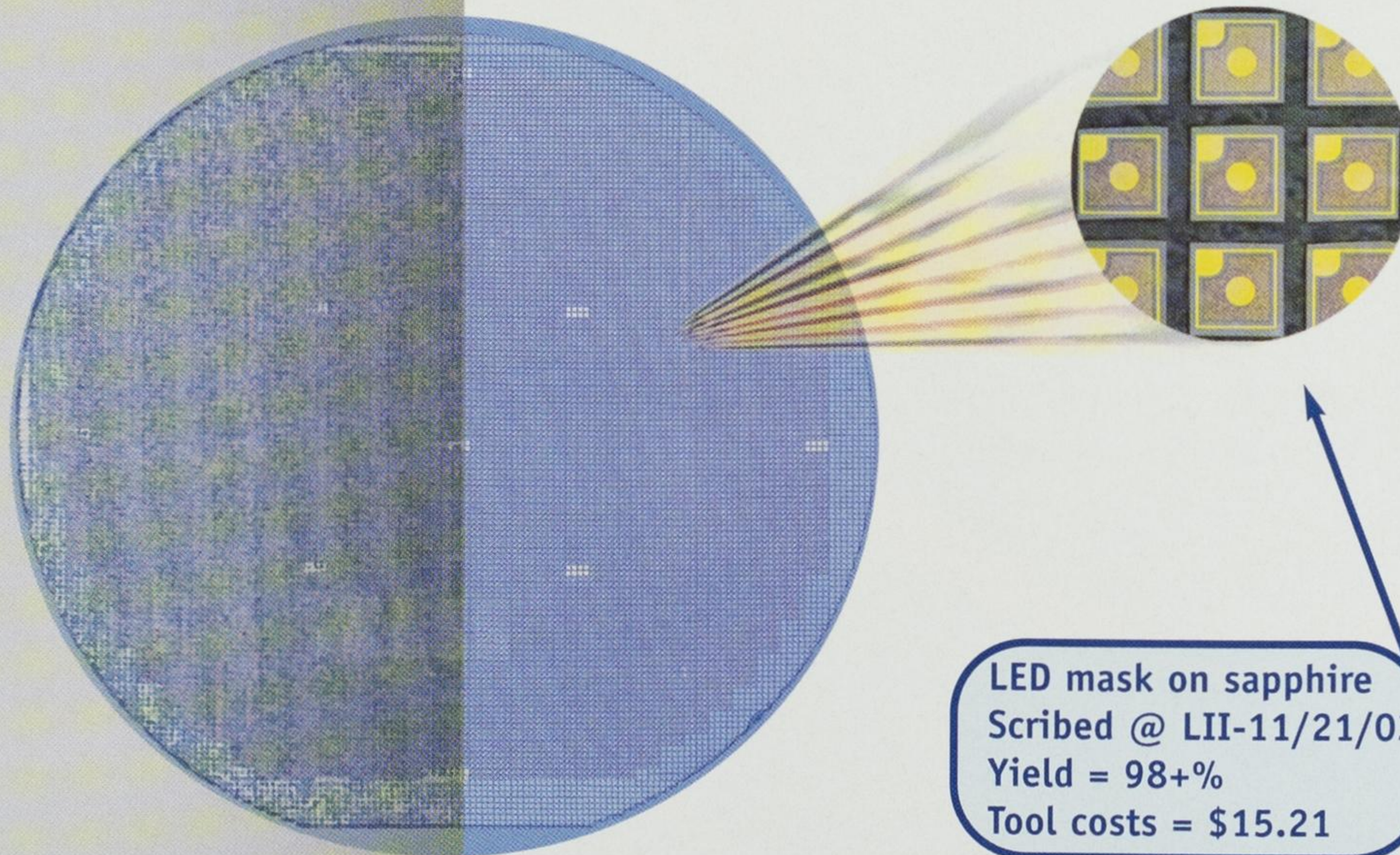


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GCS and GCTC form III-V foundry giant

By Tim Whitaker

Two of the leading compound semiconductor foundry companies in Taiwan and the US are to join forces. Global Communication Semiconductors, Inc (GCS), a wafer foundry based in Torrance, CA, and Global Communication Technology Corporation (GCTC), a III-V foundry company based in Hsinchu, Taiwan, will combine their operations to form the industry's largest foundry service provider.

The new company, Global Compound Semiconductors Corporation (GCSC), will be formed once the deal closes in early 2004. The boards and shareholders of both companies have already approved the agreement.

GCS and GCTC say that their merger combines a high-volume, low-cost 6 inch manufacturing facility in Taiwan while maintaining the Torrance facility, known for cutting-edge technologies, and will therefore meet the demands of various technology-driven, high-

performance markets.

The GCS facility in Torrance is ISO 9001:2000 certified and offers foundry services for InGaP HBT, InP HBT, SAW and PHEMT processes. It also provides optoelectronic foundry services for QWIP detectors, modulators and *pin* diodes used in the surveillance, security and fiber-optic communication markets. GCS says that several major compound semiconductor device manufacturers, on three continents, have qualified its facility for volume manufacturing programs.

Meanwhile, GCTC operates an ISO 9001-certified facility in Hsinchu comprising a state-of-the-art, cassette-to-cassette, fully automated 6 inch wafer processing plant with a Class 1 cleanroom.

"The low cost of labor and overhead associated with Taiwan, and GCTC's location in the Hsinchu Science-Based Industrial Park, enables foundry customers to take advantage

of the mature infrastructure of related testing and packaging companies clustered around Hsinchu," said Don Brooks, recently elected chairman of the board of GCSC.

"This is a very exciting time in compound semiconductor foundry services and I am reminded of my experience in Taiwan during the formation of the silicon foundry industry," continued Brooks. "Like silicon in the early 1990s, we are now seeing growth in III-V foundries fueled by the expanding telecommunications and wireless markets and the growth of fabless design companies."

Sam Lee, currently CEO of GCS, will become CEO of the newly formed GCSC. Lee said: "GCSC customers will have immediate access to the broadest process portfolio, latest technologies, a worldwide customer service organization, high-volume, low-cost 6 inch manufacturing and one-stop supply chain management."

ASIP and ThreeFive merge and receive funding

By Michael Hatcher

Two leading developers of InP-based integrated optoelectronic components, ASIP and ThreeFive Photonics, have merged and at the same time received \$7.5 million in funding. ASIP, which is headquartered in Somerset, NJ, is developing products based on its Asymmetric Twin Guide (ATG) technology, a highly scalable platform for monolithic photonic integration.

ThreeFive Photonics BV, a Netherlands-based fabless developer and supplier of monolithically integrated InP-based optoelectronic chips, filed a "suspension of payments" request with a Dutch court in July 2003. This is the equivalent of a Chapter 11 bankruptcy filing in the US. As a result of the merger with ASIP, the suspension of payments proceedings have been successfully concluded.

The combined company will be known as ASIP, Inc, with ThreeFive Photonics BV operating in the Netherlands as a wholly owned subsidiary. ASIP currently employs 33 people, 11 of whom are based at ThreeFive.

At the same time as the merger, ThreeFive's existing investors, Atlas Venture and Gilde IT Fund, made a combined investment of \$7.5 million in ASIP. The new investment completes ASIP's Series C financing, bringing the round to \$23.5 million. The company's

total funding to date is \$31 million.

ASIP spokesperson Yassi Moghaddam told *Compound Semiconductor* that the merger brings together the transmission expertise of ASIP with the receiver side that ThreeFive has concentrated on. ASIP will continue to target subsystem and transceiver manufacturers with its uncooled 1310 nm electroabsorption-modulated lasers (EMLs) for 10 Gbit/s applications in the short term. The next products to emerge from ASIP, said Moghaddam, will be 1550 nm EMLs for SONET applications.

Looking at the longer term, Moghaddam said that the receiver components developed by ThreeFive would be integrated to make more sophisticated EMLs and to enable smaller transceiver modules.

ASIP says that the \$7.5 million will fund product development and manufacturing infrastructure, allowing the company to ramp up production if necessary. ASIP already has growth capability and processing equipment.

ASIP customers will now have access to an expanded product platform that includes critical optical building blocks such as distributed feedback lasers (DFBs), electroabsorption modulators (EAMs), high-speed photodetectors (*pin*, APDs), semiconductor optical amplifiers (SOAs) and ultra-low-loss arrayed waveguides (AWGs).

Mike Decelle will continue as president and CEO of ASIP. Wouter Deelman, formerly CEO of ThreeFive Photonics, will become ASIP's general manager, Europe, and managing director of ThreeFive Photonics BV.

"This merger joins two of the industry's most powerful innovators of optical integration technology," said Decelle. "ThreeFive is the acknowledged leader in the development of InP-based AWGs, and combining this experience with ASIP's ATG platform will enable new classes of integrated devices that will dramatically reduce the cost of building next-generation fiber-optic systems."

Commenting on the state of the still-depressed telecom market, Moghaddam said that there were signs of growth in the enterprise sector, with some investment trickling down to the component level.

Late news

Cree raises estimates

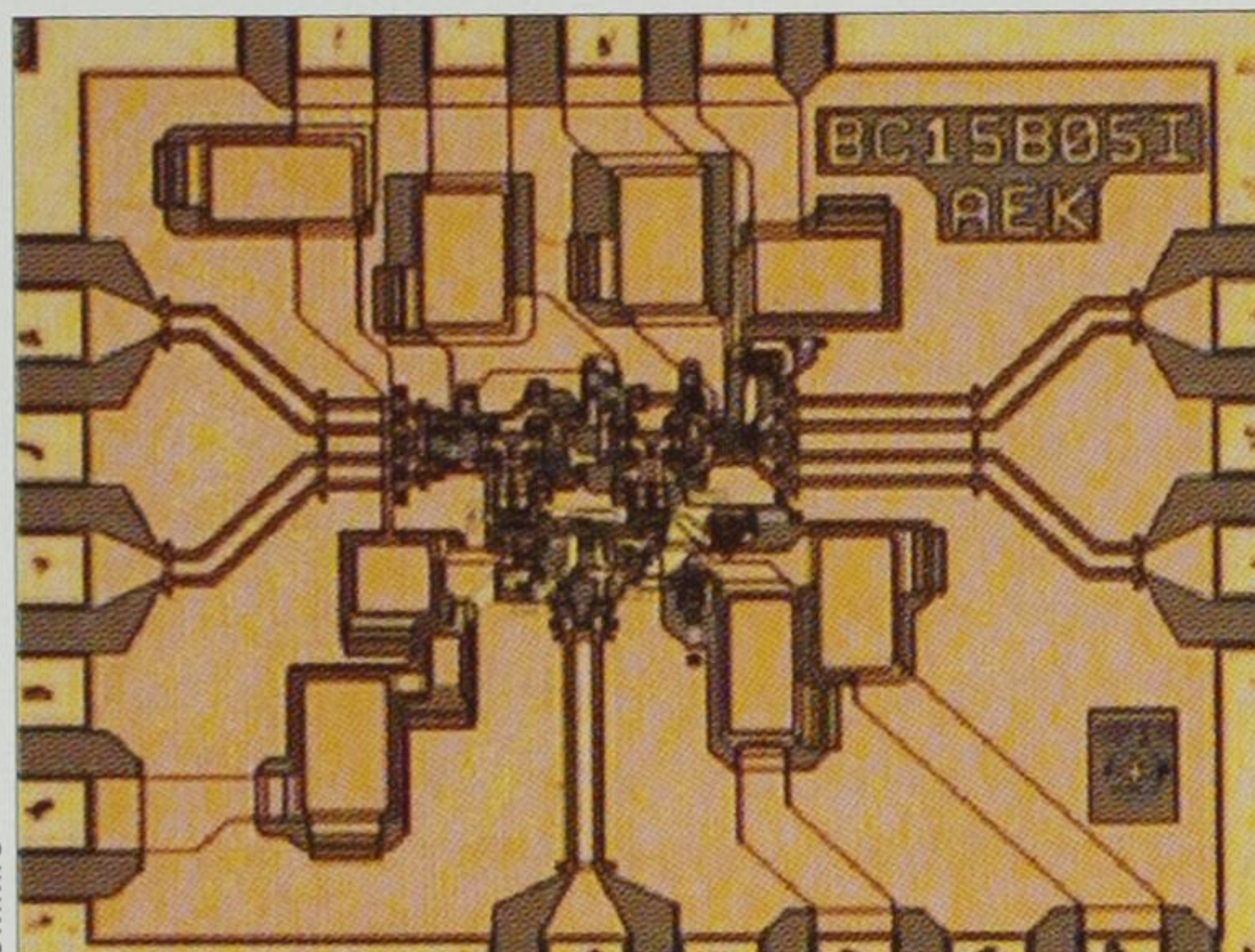
Citing increased demand in its LED business, Cree raised its revenue target to \$72-73 million for the quarter ending December 28, 2003, compared with its previous target of \$70 million.

Alcatel transfers InP HBT technology to Ommic

Ommic will become Europe's first InP HBT foundry after the transfer of Alcatel's InP-based HBT technology to the Paris-based MMIC and epitaxial wafer supplier. Ommic, which already runs high-frequency GaAs PHEMT and MHEMT processes, says that the agreement will complete its commercial portfolio of III-V technologies. "This InP DHBT process fits in exactly with our strategy and technology roadmap," said Marc Rocchi, Ommic's CTO and COO.

The InP technology was developed at Alcatel's Research & Innovation department. The process uses a double HBT structure, which offers a cut-off frequency of more than 200 GHz and a breakdown voltage of over 5 V. Alcatel says that it has already developed prototype 40 Gbit/s chip sets based on the DHBTs with record-breaking performance. These circuits include full-rate D-type flip-flops, multiplex drivers and voltage-controlled oscillators.

Following the transfer, Alcatel designers will have access to a qualified source to develop 40 Gbit/s transmission systems for core networks. Joelle Gauthier, VP of Alcatel



A reshaper IC manufactured using InP HBT technology, now licensed by Ommic.

Research & Innovation, said: "To prepare for the deployment of 40 Gbit/s systems, Alcatel has to secure the industrial availability of all required technologies, and we feel InP DHBT is one of them. Ommic's commitment to develop the process is very good news for us."

Ommic now joins Vitesse, Northrop Grumman and Global Communication Semiconductors as one of the few companies in the world offering InP HBT foundry services.

DMG and Adtech Technologies form optoelectronics foundry

DMG Technologies, a manufacturer of optical subassemblies used in telecom, datacom, CATV and instrumentation systems, and Adtech Technologies, a designer of semiconductor-based optoelectronic devices, have formed a partnership in order to establish Netchip, an optoelectronic chip foundry.

Netchip, based in Los Angeles, CA, will initially produce distributed feedback (DFB), Fabry-Perot, and coarse wavelength-division multiplexing (CWDM) lasers, as well as avalanche photodiodes (APDs). While some of the production is designated for use in DMG's line of optical subassemblies, Netchip is already filling subcontract orders for other international laser manufacturers.

The new firm will utilize DMG's packaging, marketing and distribution resources, according to DMG's CEO, Malcolm McLean. "Netchip will make high-performance, high-quality, low-cost optoelectronic chips," he

said. "In fact, we intend to deliver what the market demands – Japanese quality, American service, and Chinese pricing."

McLean says that Netchip will be able to control prices at the chip level. "Control of the chip cost allows DMG to have tighter control of the module cost," he explained. "This means further production savings, which we fully intend to pass on to our customers."

Toshi Makino, recently appointed CTO of DMG, will also act as CTO of Netchip. "Netchip has assembled an outstanding team of semiconductor design and process engineers from such firms as Nortel, Agere, Fujitsu and Hitachi," he said. "We are confident that we can deliver superior technology at an affordable price."

DMG Technologies was founded in August 2003 when it acquired the assets and IP rights of the Demeter Module Group from fiber-optic equipment supplier Finisar.

Bridgestone set to produce SiC wafers

Bridgestone, the Japanese company best known for its range of tires and other rubber products, is joining the growing number of businesses to offer SiC substrates. The company says that it has been developing SiC bulk growth technology and can now produce high-quality SiC wafers, which it plans to begin sampling to customers in 2004.

The company is using a powder sublimation growth method and is now producing wafers with fewer than 10 micropipe defects per cm². Currently Bridgestone's pilot line can produce up to 1000 2 inch wafers per month, but it expects to be able to expand this to 10,000 per month by 2010 as demand for SiC substrates takes off. It is also developing 3 and 4 inch wafers, which are required by SiC device manufacturers as they seek to reduce their production costs and compete more effectively with Si-based high-power devices.

The market for high-power devices is currently dominated by Si, but as SiC devices mature and become more readily available at lower prices, SiC will begin to grab market share. Bridgestone says that SiC devices will account for 20% of the total market for high-power electronics by 2010, at which point it expects its SiC substrate sales to be ¥10 billion (\$91 million) per year.

DVD Forum OKs blue laser format

The 220-member DVD Forum of electronics manufacturers and movie studios has adopted a next-generation recording format based on blue laser diode technology, according to Japan's *Nihon Keizai Shimbun* newspaper. The format, which has been advocated by the Japanese firms NEC and Toshiba, is a rival to the Blu-ray disc format already being marketed by fellow electronics manufacturer Sony and supported by a small group of companies including Philips and Samsung.

The NEC-Toshiba standard is designed to record high-definition (HD) digital broadcasts. Unlike Blu-ray, the format is said to be compatible with existing DVD drives. According to the developers, it will be able to record 2 h of high-resolution broadcasts onto a disc.

Toshiba will start marketing a HD-DVD recorder in December 2004, while NEC plans to sell HD-DVD drives for PCs in late 2005.



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Lighting workshop sets tough targets for LEDs

By Tim Whitaker

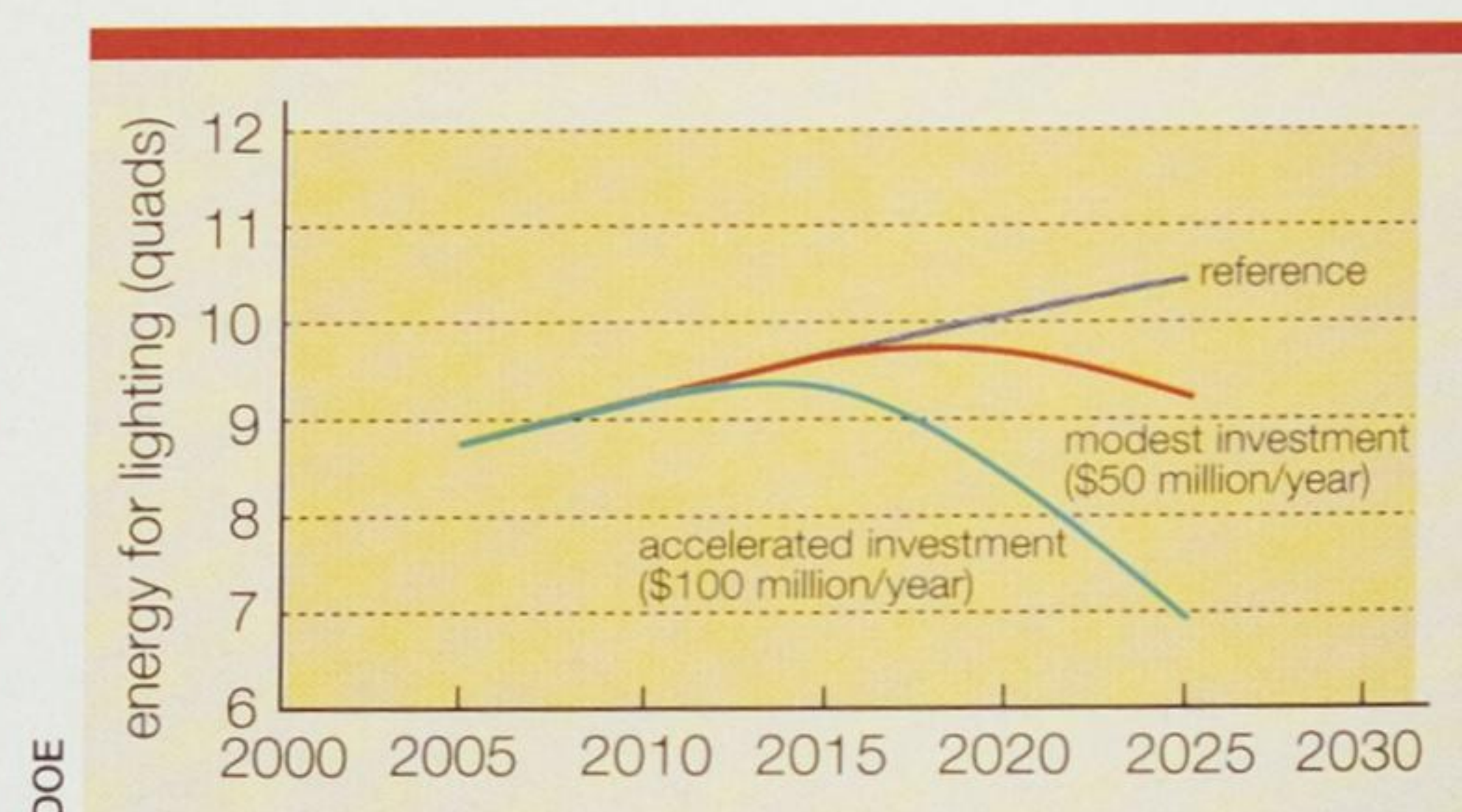
The US Department of Energy (DOE) has set aggressive targets for solid-state lighting (SSL) that should lead to massive reductions in energy consumption in the future, as well as enhancing the quality of electrically lit environments. By 2015, it plans to develop advanced SSL technologies that, compared with conventional lighting technologies, are much more energy efficient, longer-lasting and cost-competitive. The DOE is targeting a product system efficiency of 50% with lighting that accurately reproduces the full spectrum of sunlight.

These goals were announced in November at a workshop in Washington, DC, sponsored by the DOE's Building Technologies program, which was attended by experts from industry, universities, research institutions, trade associations and national laboratories.

The workshop was held to launch a concerted effort by DOE to accelerate advances in SSL technology using both LEDs and OLEDs. The DOE will consist of a Core Technology Research thrust, involving academia, national laboratories and research institutions, and a Product Development thrust, conducted by industry. A government-industry partnership will also be established to identify core technology needs. As a precursor to this, various sessions were held at the workshop to clarify and prioritize research needs and objectives. The DOE, which already funds a number of R&D projects relating to both LEDs and OLEDs, expects to release competitive solicitations in the near future.

At the workshop, David Garman, assistant secretary for renewable energy and energy efficiency, released two new DOE reports authored by Navigant Consulting. One study analyzes the energy savings that can be achieved by using LEDs in a range of niche applications, such as traffic signals and automotive, while the other estimates the potential future energy savings from the use of SSL in general illumination.

Garman said that lighting currently accounts for 8% of US energy consumption, and 22% of the electricity. If SSL achieves its price and performance targets over the next two decades, this will remove the need for more than 30% of the estimated lighting energy consumption.



An investment of \$100 million per year in solid-state lighting could result in a drop of one-third in the amount of energy consumed by lighting in the US by 2025.

In turn, this will represent billions of dollars of savings for consumers.

According to the niche applications study, energy savings to date from LEDs exceed the power produced from one large electric power plant – more than 8 terawatt-hours (TWh). The use of LEDs in automotive lighting applications saves 41 million gallons of gasoline and 142 million gallons of diesel fuel annually. However, if the entire fleet of automobiles, trucks and buses were to convert to LED lighting, 1.4 billion gallons of gasoline and 1.1 billion gallons of diesel fuel could be saved each year. In gasoline, that is the energy equivalent of 30 days of oil flow in the Alaskan pipeline at full capacity; and, in diesel, it represents 12 days of national consumption.

When SSL technology penetrates the general illumination market, the savings become even more significant. The report considers two scenarios – one where the technology receives a moderate national investment of \$50 million per year, and an accelerated scenario based on an investment of \$100 million per year. SSL achieves different cost, efficiency and durability targets under each scenario.

Under the moderate investment scenario, in 2025 the energy saving associated with SSL will total approximately 114 TWh, or the equivalent electrical output of about 14 large power plants. Under the accelerated investment scenario, in 2025 the total energy saving is nearly three times higher, at 326 TWh.

From 2005 to 2025, the cumulative energy savings under the moderate and accelerated scenarios are 505 and 1848 TWh, respectively. This latter figure equates to electricity bill savings of more than \$120 billion.

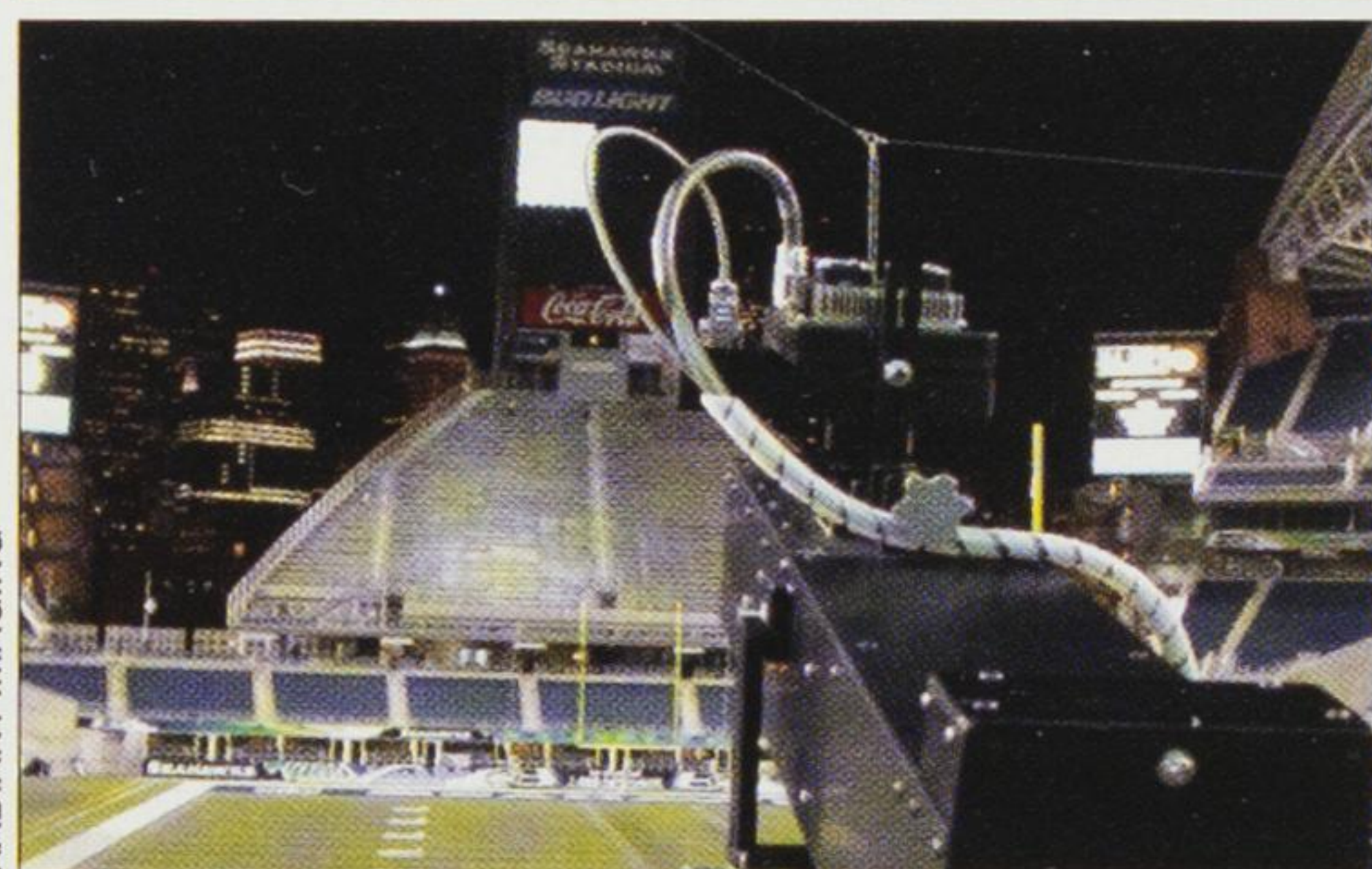
VPEC ships first WB-LED chips

VPEC has started to ship high-brightness AlGaInP chips wafer-bonded to a silicon substrate, marking the first time that the Taiwanese epiwafer supplier has shipped chips to its customers. Michael Yang, CEO of VPEC, said: "We are responding to customers' strong demand to continuously increase the brightness and life for higher-performance applications. VPEC is now in the process of expanding its production capacity."

VPEC's wafer-bonded LED (WB-LED) is based on the company's patented technology in which the AlGaInP LED is bonded to a silicon substrate with a metal surface, and the original GaAs substrate is subsequently removed. VPEC says that the metal mirror has

a higher effective reflectivity and broader reflectivity angular bandwidth than the alternative using a multilayer DBR, and reflects the light towards the front surface to significantly improve the total light emission efficiency of the LED. Moreover, since the thermal conductivity of the silicon substrate is higher than that of GaAs, heat dissipation has been greatly improved.

VPEC's first WB-LED product is a 625 nm red LED with more than 4 lm of total flux and a forward voltage of less than 2.4 V at 70 mA. More new products are expected in 2004. Yang expects the WB-LED to become VPEC's second major product, alongside its HBT epiwafers.



Radiant Imaging Inc has developed a system, based around a CCD imager, which is capable of carrying out on-site calibration and correction of large LED screens such as this one in the Seattle Seahawks football stadium (the screen measures 12 x 14 m; only a quarter of it is illuminated in the photograph). The company described its work at the recent Intertech LEDs 2003 conference in San Diego (see p20).

UEC claims record red RCLED efficiency

United Epitaxy Company (UEC) has announced a new 650 nm high-power resonant-cavity (RC) LED for plastic optical fiber (POF) applications. The company claims that, with epoxy encapsulation, the devices gave a record high wall-plug efficiency of 12% and also yielded an output power of more than 3.5 mW at 20 mA.

The device has an emission window with a diameter of 84 µm, which allows the output to be easily coupled into the POF. Data links using POF are being employed in automotive applications, as well as to connect multimedia devices. UEC says that the devices are suitable for transmitting data at a rate of 250 Mbits/s over 100 m. The power variation between 20 and 85 °C of the POF-coupled emission was approximately 2 dB at 20 mA forward current.

The company also says that the RCLED has a long lifetime in a high-temperature environment. UEC started to ship this product during the fourth quarter of 2003.

Sandia UV LEDs emit record high power

Researchers at Sandia have demonstrated two record-breaking deep-UV emitters, one producing 1.3 mW of optical power at a wavelength of 290 nm, and the second producing 0.4 mW at 275 nm. Both devices emit light in CW mode under DC operation. The devices are based on AlGaN structures grown on sapphire, and the 275 nm device contains layers with about 50% aluminum. Increasing the aluminum content shortens the output wavelength, but makes the devices harder to grow.

A flip-chip packaging approach was used with emission through the substrate. This prevents light from being blocked by the opaque top contacts, and also permits more efficient heat sinking.

Sandia's work was funded by DARPA's Semiconductor Ultraviolet Optical Source (SUVOS) project. The LED devices are already being supplied to DARPA program participants making both non-line-of-sight (NLOS) covert communication systems and bio-sensor test beds.

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GaN HEMT features high power density

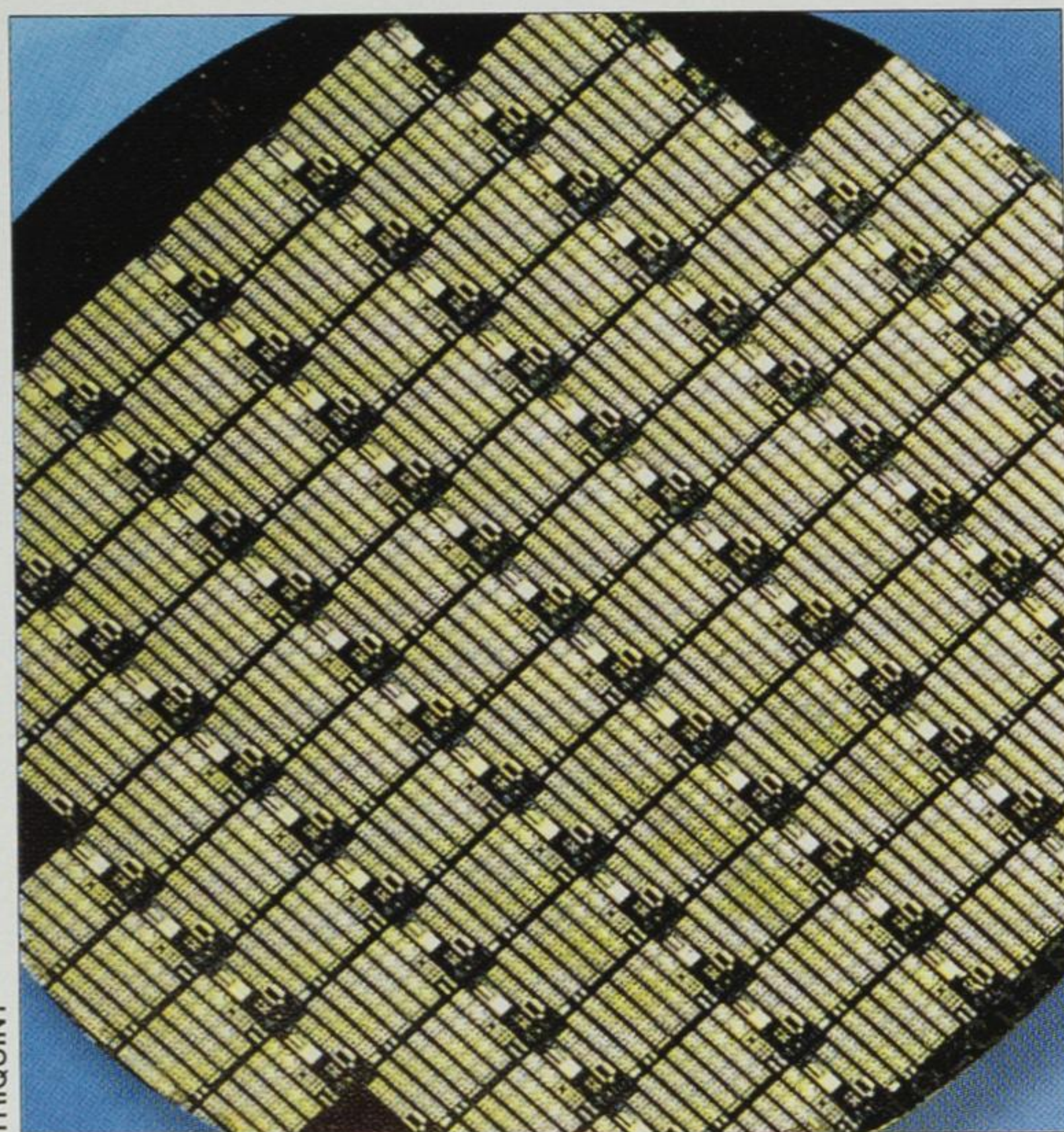
A GaN HEMT developed by TriQuint and Lockheed Martin has achieved record values of power density, power-added efficiency and RF lifetime, say the companies.

The high-performance transistor, which was fabricated using an "advanced gate process", features nearly 12 W/mm CW power and more than 50% power-added efficiency at 10 GHz.

The improved performance and reliability should enable significant size and weight reductions in radar-based defense applications.

Gailon Brehm, TriQuint's military business unit manager, said: "GaN has capabilities from L-band up to W-band, making it a very exciting technology for the future of millimeter and microwave applications."

The device's increased power density could simplify radar power distribution in large systems and greatly reduce operational electrical current. This may lead to significant



A 2 inch GaN on SiC wafer fabricated using TriQuint's proprietary advanced process. The wafer consists mostly of large FET transistors for test and evaluation purposes.

weight and size reductions in shipboard systems and land-based applications.

TriQuint says that its proprietary process increases GaN HEMT power density 50% beyond that of more conventional E-beam T-gate devices. In addition, power-added efficiency is 10–15 points higher, allowing the devices to function with reduced power dissipation and at a lower operating temperature.

Improved RF lifetime has also been demonstrated with the advanced high-voltage gate structure, thanks to reduced gate leakage and a lower electric field in the drain region.

Mahesh Kumar, director of research and technology for Lockheed Martin Maritime Systems and Sensors, said: "GaN will redefine what is possible by giving our customers the reliable, compact, high-powered technology they need to field solid-state phased array radar, space systems and missiles to protect against emerging threats."

APA Optics aims for commercial production of GaN-based devices

APA Optics of Minneapolis, MN, is set to move into commercial production of GaN-based photodetectors and transistors following its purchase of an MOCVD reactor.

The Veeco system (following Veeco's recent acquisition of Emcore's MOCVD product line) is capable of handling six 2 inch diameter wafers at a time.

Anil Jain, APA's CEO, said: "MOCVD material growth capability is at the heart of the company's activities in GaN, and the acquisition represents APA's commitment to move from the R&D mode to commercialization of GaN-based products." He added

that the acquisition will make APA a "fully viable, competitive supplier in this market".

The new reactor will increase production capacity for wafers used in APA's SunUV ultraviolet light monitor as well as the company's HFET power transistor wafers.

According to APA, wafers grown to the company's specifications had very good performance regarding mobility, which was as high as $1900 \text{ cm}^2/\text{Vs}$, and a carrier concentration of $1.14 \times 10^{13} \text{ cm}^{-2}$. These results, prior to any on-site optimization, approach the best results achieved with the current reactors making one wafer at a time, says APA.

Nitronex releases high-voltage GaN devices

Nitronex says that it has achieved new performance levels with its GaN-based RF power transistors. The devices, which have a higher linearity and operating voltage than conventional silicon transistors, are being targeted at power amplifier designers in the 3G wireless market.

Based on Nitronex's patented Sigantic technology, devices for 3G applications with an operating voltage of 34 V are available for sampling. These will be available in 10 and

20 W versions (W-CDMA Power). Devices operating at 38 V will be released in the near future, says the company.

"The higher operating voltage characteristics that we are now seeing promise to bring a new dimension in the design of RF power amplifiers," said Paul Williams, Nitronex's managing director for Europe. "Increased operating voltage allows designers to take advantage of design techniques not possible with traditional devices."

ATMI reduces GaN wafer defect density

Materials supplier ATMI, Inc of Danbury, CT, says that it has shipped improved 2 inch diameter GaN substrates to "major consumer electronics companies".

The company says that unlike other GaN wafer products that only have a low dislocation density in select regions, its new free-standing GaN substrates have a uniform dislocation density of 10^6 cm^{-2} .

"We've delivered our GaN wafers into every major semiconductor region in the world, and the early feedback is very good, with customers obtaining improved device performance on our substrates," said George Brandes, director of ATMI's GaN venture.

"We are confident that GaN wafers will help to allow full realization of the enormous benefits of blue laser capabilities, and we are producing [these] wafers in large volumes," said Bob Vaudo, manager of ATMI GaN Substrates.

"Our improved growth process reduces dislocation density by an order of magnitude. The wafers now meet the critical parameters needed to extend laser lifetime and performance. In high-performance electronics, we have developed semi-insulating GaN wafers and are beginning to offer them to select R&D customers in engineering quantities."

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Soitec installs SSOI toolsets

Silicon-on-insulator (SOI) specialist Soitec of France has expanded its manufacturing capability to ensure broad industrial availability of strained SOI (SSOI) wafers. The company is installing epitaxial equipment in its pilot line facility and a full strained-SiGe-on-insulator (SGOI) and SSOI manufacturing line at its Bernin II site in France.

SGOI production is due to commence in the fourth quarter of 2004. At full capacity, the new line will run more than 60,000 200 mm-equivalent wafer starts per year.

"SSOI appears to offer the greatest potential for improving the performance of ICs at 65 nm and below," said Andre Auberton-Herve, Soitec's president and CEO. "Adding these new capabilities, particularly the epitaxy process in our own production facility, will help ensure that we can rapidly deliver volume quantities of high-quality SSOI wafers."

Through its partnership with ASM International, Soitec is fine-tuning the epitaxial processes to accelerate time-to-market for 200 mm and, ultimately, 300 mm SSOI wafers.

Communicant SiGe project collapses as funding dries up

After months of uncertainty surrounding the future financing of Germany-based SiGe foundry Communicant Semiconductor, it seems that the company will be disbanded.

Communicant was set up with investment from Intel, Dubai's Airport Free Zone Authority, the Brandenburg regional government and the German federal government. Construction of the company's fabrication plant in the Brandenburg region has now stopped.

The venture's principal investors in Dubai appear to have been unwilling to put the necessary funds into Communicant. Dubai is currently planning major investment in semiconductor manufacturing infrastructure within its own borders at the so-called Dubai Silicon Oasis. The very slow review process required by the European Union has also been cited as a reason for investors getting cold feet.

AmberWave sublicenses Agere's patents

Strained Si specialist AmberWave Systems has secured exclusive rights to sublicense nine strained Si patents from Agere Systems.

One patent covers methods for growing low-defect-density SiGe buffer layers onto which strained Si channels can be formed for high-mobility FETs. This patent was granted in 1991 to a team of scientists working at Bell

Labs, including Gene Fitzgerald, one of AmberWave's founders.

"By combining patents from Agere, patents licensed from MIT and our own IP, AmberWave offers the industry a true end-to-end technology solution for strained Si wafer manufacture," said Richie Faubert, president and CEO of AmberWave Systems.

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A Research Unit of **PennWell**

Blue Sky Research releases first red laser diodes manufactured in house

California-based laser manufacturer Blue Sky Research has released three new 635 nm red laser diodes, the first to be made at its in-house semiconductor foundry.

Available in 5, 10 and 15 mW versions, the BRLD-635 family of semiconductor lasers feature low operating current, a wide operating temperature range, and an estimated MTTF (mean time to failure) of more than 150,000 h at 25 °C. Each laser is housed in a compact DVD-grade 5.6 mm TO can with integrated monitor photodiode, hermetically sealed for high reliability. Applications for the BRLD-635 include construction and alignment equipment, biomedical and metrology instrumentation, and bar code readers.

"The release of our BRLD-635 laser diode marks a significant expansion of capabilities," said Al Shugart, chairman of Blue Sky Research. "[Blue Sky] is one of a select few US-based



Blue Sky Research says that it and Hitachi are the only two companies currently making 635 nm laser diodes in house.

laser manufacturers with integrated facilities for everything from semiconductor fabrication and optical systems development, to control system design and electronic packaging."

Blue Sky says that the BRLD-635 red laser

diodes employ a unique design and structure that maximizes power output over lifetime while increasing device reliability via low operating current.

Test results demonstrate 5, 10 and 15 mW power output at operating temperatures up to 50 °C with a minimum MTTF of 10,000 h. This equates to more than 150,000 h at 25 °C.

"We can now develop customer-specific lasers quickly, fab the chips internally, and integrate them into any platform the client requires. Combined with our partnerships with high-volume manufacturers, we are able to cost-effectively span the range between limited quantity, R&D volumes, or large OEM quantities," said Shugart.

Blue Sky Research says that it will continue to expand its in-house laser capabilities to include wavelengths from visible to near-infrared.

nLight Photonics wins \$5 million DARPA contract

nLight Photonics of Vancouver, WA, has been awarded a \$5 million research and development contract by the Defense Advanced Research Projects Agency (DARPA) as part of its super-high-efficiency diode source (SHEDS) program. The contract will enable nLight to take a dramatic step forward in high-power laser diode efficiency, and follows a similar award of \$3.9 million to Alfalight under the same program (*Compound Semiconductor* November 2003 p19).

The aim of SHEDS is to continue the improvement of laser diodes with a goal of converting more than 80% of their input electrical power into output optical power. This level of efficiency will enable lasers with up to 100 kW of output power to be deployed on mobile military platforms.

"This program will enable nLight to take a quantum leap forward in high-power laser diode performance," said Jason Farmer, vice-president of advanced technology at nLight.

"Both output power and reliability of high-power laser diodes are critically dependent on operating temperature. With current packaging technologies, every watt of heat generated corresponds to a particular rise in operating temperature. The key issue for reliable high-power laser diodes is therefore optimizing the ratio of optical power generated to heat deposited in the package. Today, this ratio is roughly 1:1. The technology to be developed on this program will increase the ratio to 4:1."

UK firm acquires Cornell VCSEL technology

BTG, a technology commercialization company based in London, UK, has acquired the exclusive rights to license strain-compensated multiple quantum well (MQW) VCSEL technology developed at the Cornell Research Foundation in Ithaca, NY.

"The telecoms market is looking for a next-generation technology that will replace costly, low-yield devices, such as distributed feedback (DFB) lasers at 1300 and 1550 nm," said Jay Kshatri, vice-president of BTG's Semiconductors and Optoelectronics business unit. "We believe that the strain-compensated

VCSEL is that technology, and we are actively seeking licensees who are interested in integrating this technology into their commercial products."

The Cornell-developed devices overcome the critical thickness constraint on the quantum wells used in conventional VCSELs by using strain compensation. This allows many quantum wells to be stacked to form the gain medium without undue strain build-up, which is said to dramatically improve the performance of the VCSEL.

VCSEL-based transceivers operating at

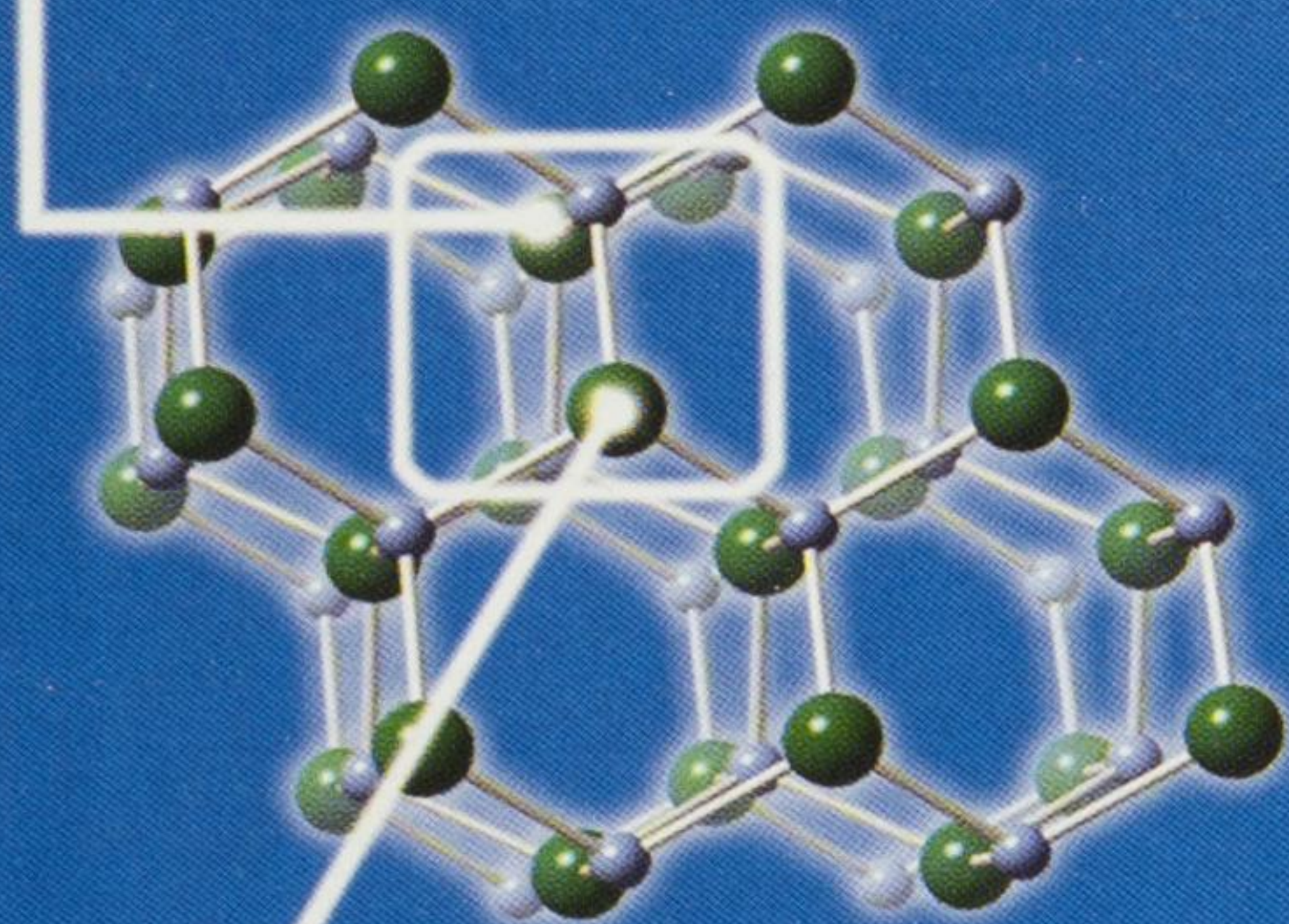
850 nm have become the dominant source for high-speed, very-short-reach optical interconnects, such as Gigabit Ethernet and Fibre Channel.

With the advent of longer-wavelength VCSELs operating at 1300 and 1550 nm, the sources may increasingly appeal to companies developing transceiver products for short and intermediate reach SONET/SDH and fiber-to-the-home applications.

Parallel VCSEL transceivers are said to be particularly attractive for back-plane interconnect applications.

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UK start-up firm eyes silicon optoelectronics

By Jon Newey

Another company has joined the race to develop and commercialize light-emitting devices based on silicon. Si-Light Technologies, a start-up company in Guildford, UK, was founded by academic staff from the University of Surrey. It is investigating the low-cost applications of its patented dislocation engineering technology, which enables 1.1–1.6 μm light emission from silicon.

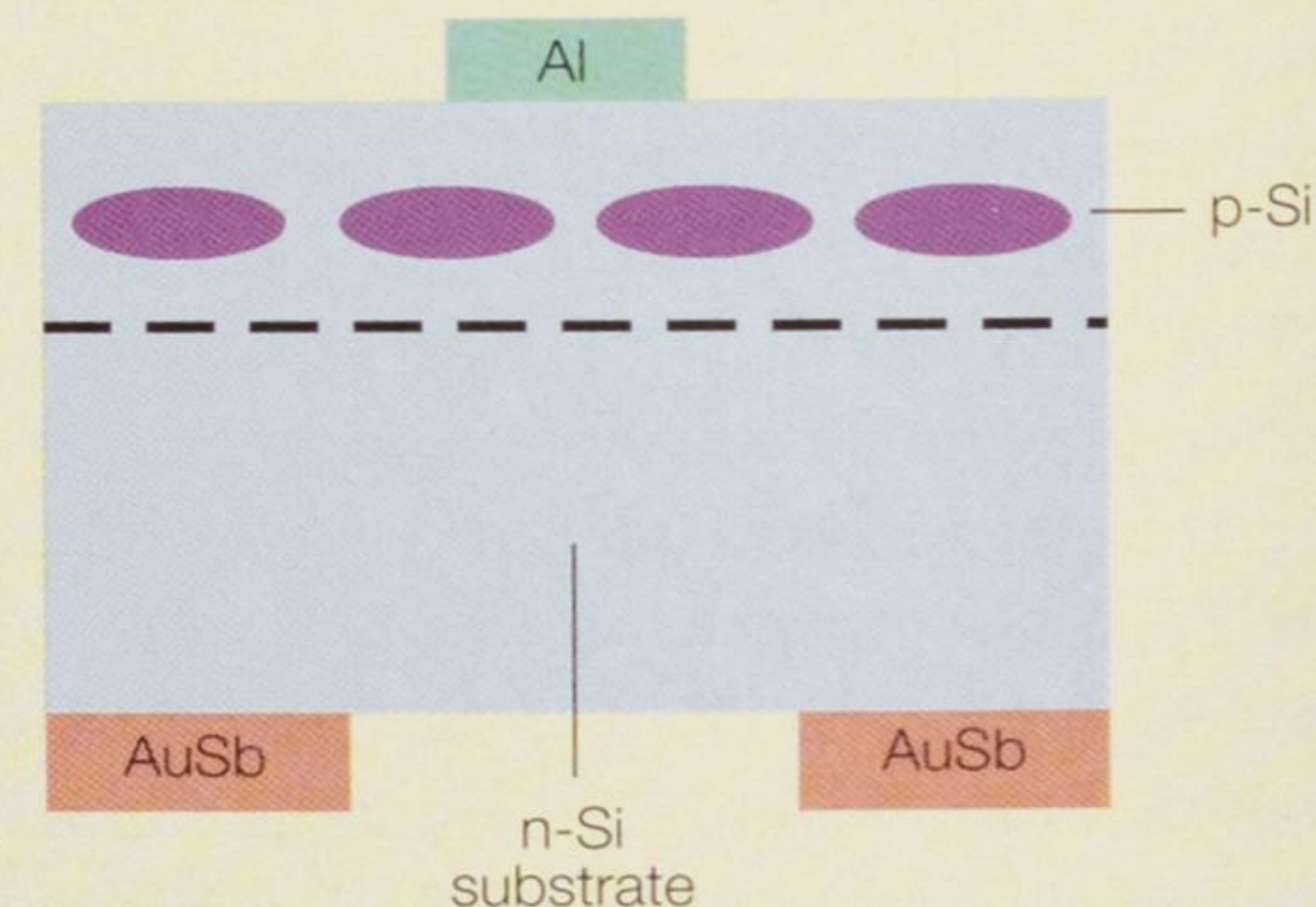
Si-Light Technologies plans to exploit its intellectual property through a mixture of consultancy, licensing and fabless manufacture of products for niche markets as and when these are identified. The company is receiving financial backing from the UK government's Department of Trade and Industry to evaluate potential applications and to conduct an early partner search for commercialization routes. Potential applications include IC optical interconnects, silicon-based optoelectronic ICs, MEMS, lab-on-a-chip, and sensor systems, with the benefit of significantly reduced manufacturing costs compared with conventional hybrid III-V/silicon approaches.

Si-Light says that its light-emitting devices have efficiencies comparable with those achieved in conventional III-V devices, and that in contrast to alternative approaches for fabricating light-emitting devices in silicon, its devices are robust and highly reliable, requiring low drive potentials. The company also claims that its devices are wavelength-tunable. "Our devices are essentially forward-biased p-n junctions, so they turn on at under 1 V and we can inject large currents without difficulty," said Russell Gwilliam, one of the academic staff from Surrey University who set up Si-Light Technologies.

In October 2002, ST Microelectronics announced that it had developed silicon light emitters using a technology in which silicon-enriched SiO_2 is implanted with rare earth elements. ST expects to have an all-silicon optocoupler on the market in 2004. Given that ST's devices require pumping of the active region through a resistive oxide, the drive potentials of its devices are likely to be significantly above Si-Light's figure of 1 V.

In silicon, carrier diffusion to point defects is the non-radiative recombination route that dominates over radiative recombination. Si-

Loop LED device



Si-light believes that its silicon-based light emitters could find applications in optical interconnects, MEMS and sensors.

Light's technique enhances the radiative recombination route by suppressing carrier diffusion. By introducing dislocation loops through boron implantation, a localized three-dimensional strain field is introduced into the material. This strain causes band bending, which introduces a blocking potential that confines the carriers, allowing them to recombine radiatively.

Non-radiative recombination in semiconductors is thermally driven, so that radiative emission is suppressed as temperature increases. Decoupling the radiative combination from the non-radiative route has the benefit that as temperature increases the emission intensity also increases, becoming most efficient at about room temperature.

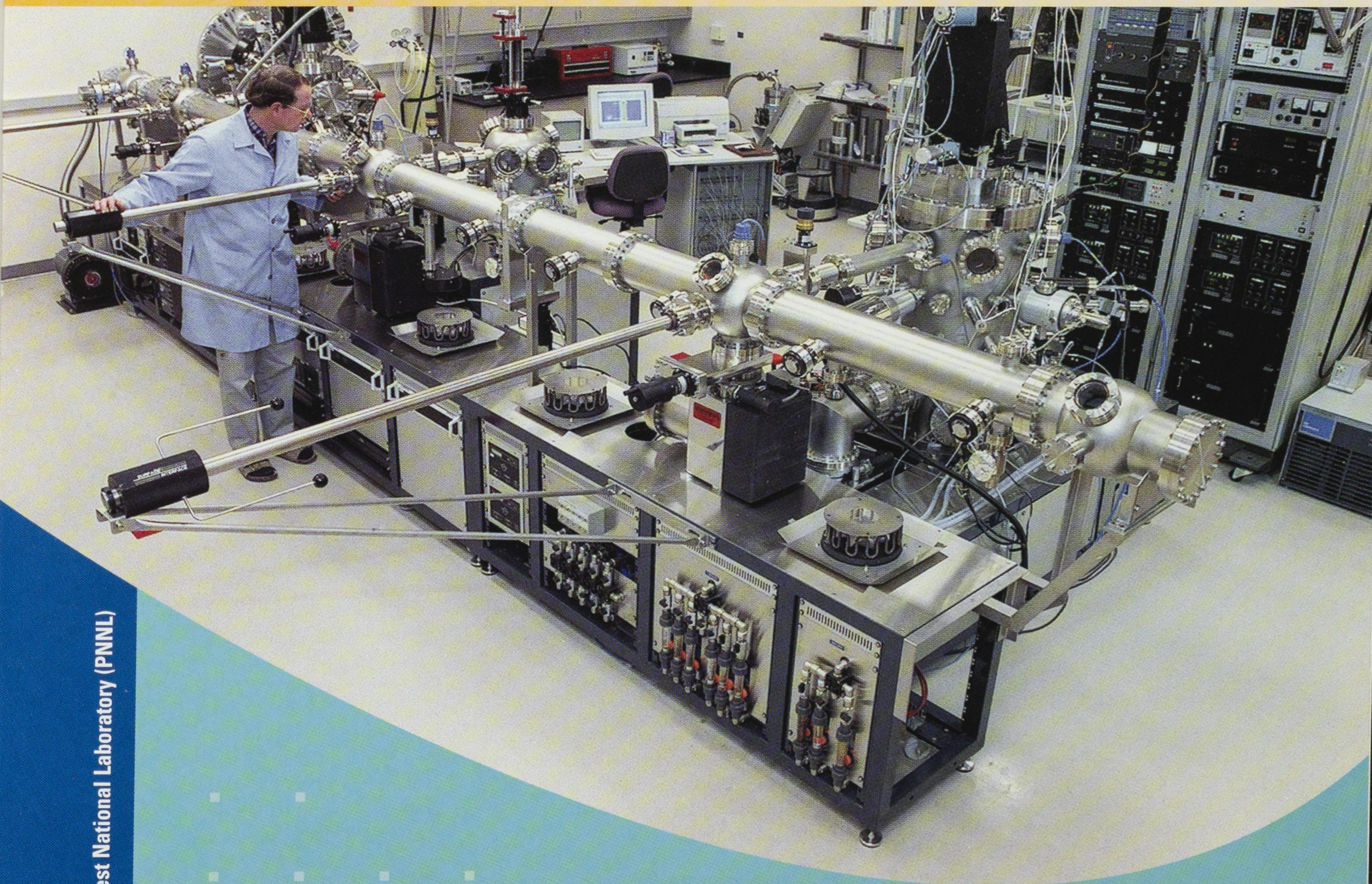
Implanting boron into n-type silicon performs two functions — introducing the dislocation loops and creating the required p-n junction. An alternative route is to use CVD to deposit the required doped silicon layer onto a silicon substrate to form a p-n junction, before implanting with silicon to create the dislocation loops. Both methods are wholly compatible with the tools and methods used for standard silicon processing.

Correction

In the November issue of *Compound Semiconductor*, we incorrectly stated that Nanosemiconductor (NSC) had fabricated a 1.5 μm QD VCSEL. NSC's 1.5 μm QD laser is in fact an edge-emitting device. We apologize for this error.

Spintronics Research

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

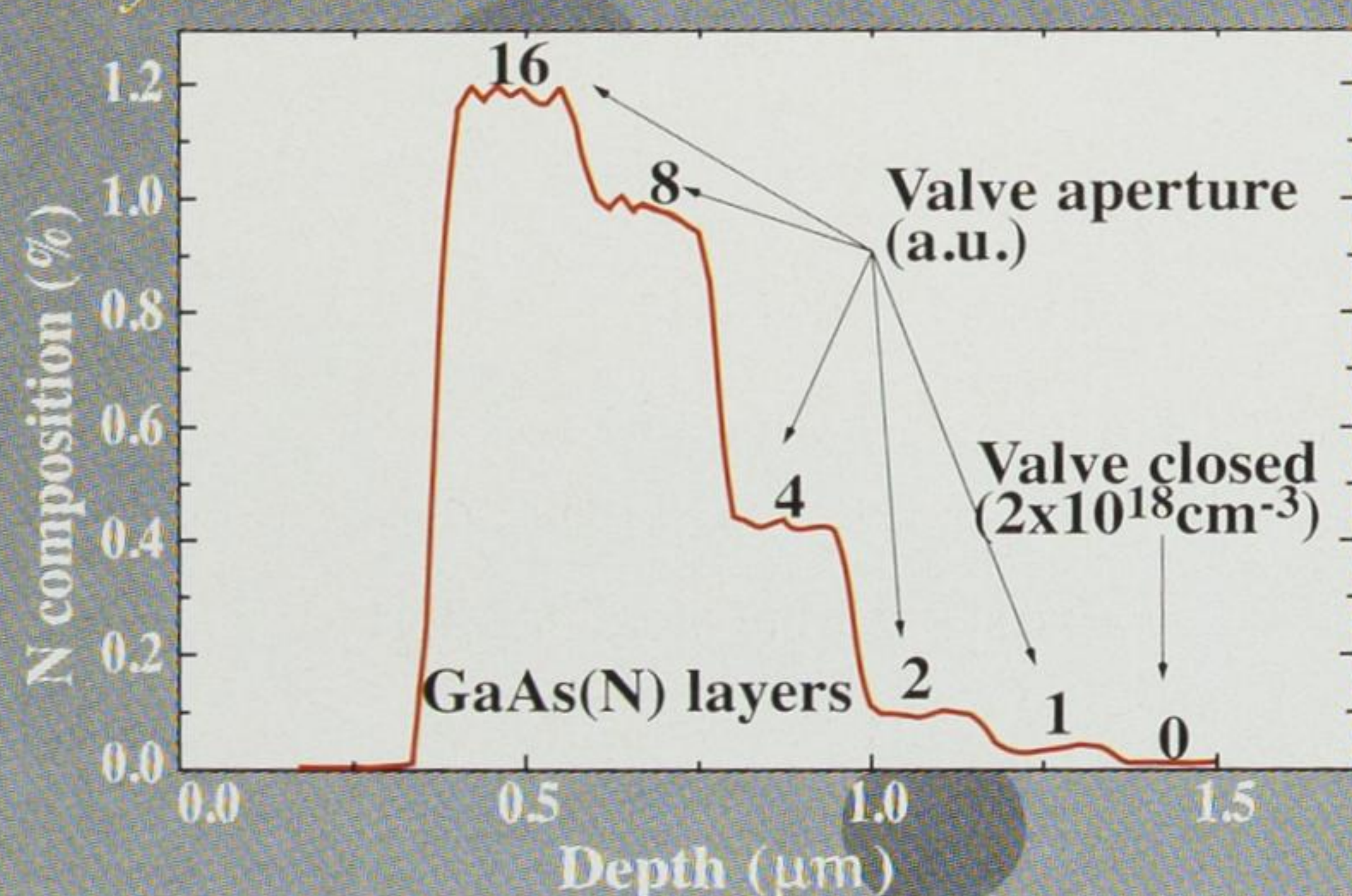
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NEWS FROM ASIA

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Mitsubishi ramps up DVD laser diode production

Mitsubishi Electric plans to increase its red laser diode production by 40%, according to Japan's *Nihon Keizai Shimbun* newspaper. The report says that although the company has already ramped up production from 1 million to 3.5 million units per month this year, this is insufficient to meet the demand created by the rapid adoption of recordable DVD drives.

From next March, Mitsubishi will produce

5 million units per month. The diodes will be packaged by a Taiwanese firm before shipment to optical pick-up module manufacturers. Mitsubishi estimates that it currently holds around a 70% share of the global market for lasers used in recordable DVD drives. It expects to achieve sales of around ¥20 billion (\$183 million) from its DVD laser business in fiscal 2004.

Mitsubishi Cable Industries licenses UV LED technology

Taiwan's P&U Group, which includes memory chip manufacturer Powerchip Semiconductor, has signed a memorandum of understanding to license manufacturing technology for UV LED chips from Mitsubishi Cable Industries. The licensed technology was developed under Japan's Light for the 21st Century program, which was funded by NEDO, and relates to substrates, epitaxy and chip processing.

A spokesperson for Powerchip told *Compound Semiconductor* that "there will be an independent new company to produce LEDs", and that details of the business model are currently being developed.

Lite-On purchases packaging equipment from Fairchild

Lite-On Technology has purchased a large amount of packaging equipment from US company Fairchild Semiconductor, which is closing its factories in Wuxi, China, and Kuala Lumpur, Malaysia. The acquisition will allow Lite-On to increase its production capacity for infrared modules, optocouplers and alphanumeric LED displays.

Lite-On is now the world's second largest producer of optocouplers and the largest producer of alphanumeric displays. The equipment will be moved to Lite-On's factories in Thailand and China. In a separate agreement, Lite-On will manufacture the three different types of component for Fairchild.

In brief...

● Nichia is developing a blue-violet CW laser with an output of 100 mW, according to news released at the Ceatec Japan 2003 show. The product will replace mercury lamps used in the manufacture of high-density PCBs.

● New Japan Radio has launched a 2.1 GHz LNA GaAs MMIC designed for use in W-CDMA handsets. Incorporating inverter circuitry, the product permits switching between high-gain and low-gain modes. The current consumption is 2 mA in the high-gain mode, with 1.6 dB noise and 14.7 dB gain, while the low-gain figures are 2 μ A current consumption, 4 dB noise and -4 dB gain.

● InGaAs laser diodes have been used as the light source in laser-welding robots developed by two Japanese companies, Marubun and Yaskawa Electric. The laser system has a power output of 1.6 kW and an efficiency of 35%, and is being used as a braze welder for manufacturing automotive bodies and motorcycle gas tanks.

● Chinese telecommunications companies are to begin high-speed 3G cellular phone services in major cities next spring, and will expand the services throughout China by the end of 2004. China already has more than 250 million users of cell phones, and this number will double by 2008, with half the total using 3G services.

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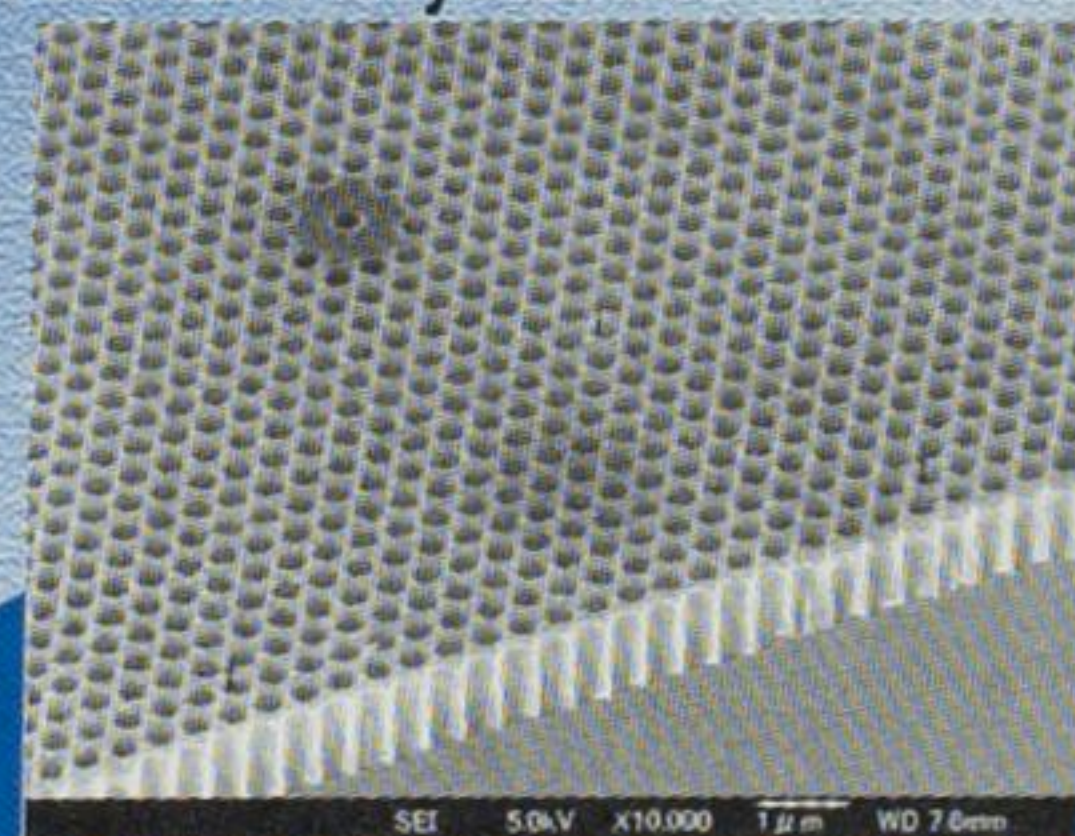


Photo Courtesy of Baba Research Lab,
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Symposium considers market recovery

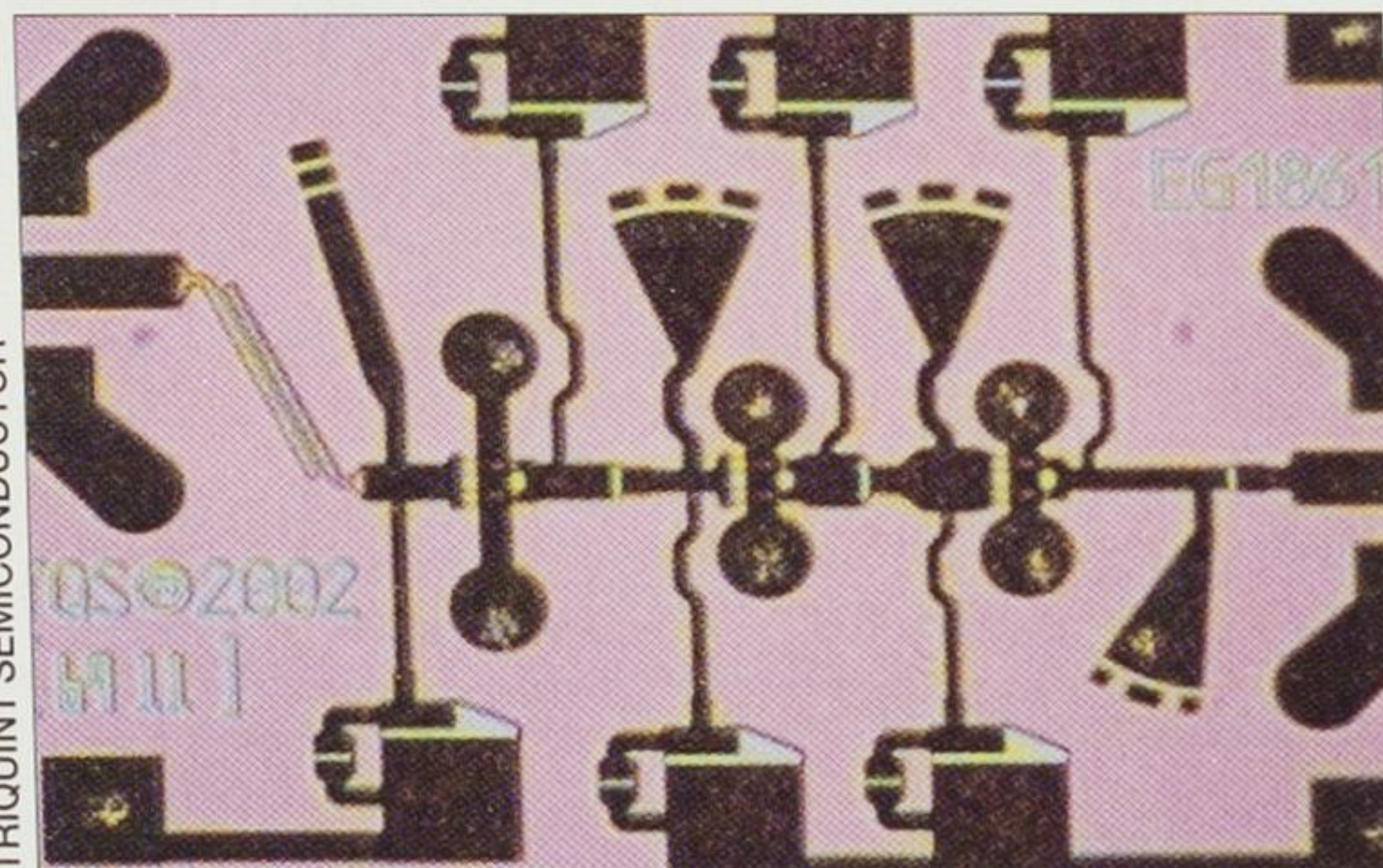
By Michael Hatcher and Tim Whitaker in San Diego

The big question that industry analyst George Bechtel was considering in his GaAs IC Symposium plenary talk was one of the key themes at a quieter-than-usual event – market recovery. Bechtel estimated that the market for GaAs ICs was worth around \$3 billion in 2003, and he predicted that it should grow to around \$4 billion in 2006. Signs of a market recovery were mixed, he said. On one hand, the general semiconductor market was up (recent figures from the Semiconductor Industry Association show a 23.3% rise in semiconductor sales from October 2002 to October 2003), but on the other hand, telecom carrier debt is still high and restricting spending. “In 2004, the recovery may begin,” was as much as Bechtel would speculate.

Driving any recovery in the wireless market will be two key applications, said Bechtel. The most important is wireless handsets, and the emergence of 3G networks in Japan this year is fueling hope that the advanced technology will soon spread throughout the world. The second driver will be wireless networks in the home. Bechtel expects 30% compound annual growth in this application sector over the next few years, but he warned that the home WLAN market would never be as large as the cellular market. Other applications holding out some hope for beleaguered device manufacturers are millimeter-wave automotive radar systems and smart military sensors.

Also in the plenary session, Phillip Smith of BAE Systems reported the first multiwatt metamorphic HEMT MMIC PA. The 3 W, 32 GHz Ka-band device represents a significant advance in power-added efficiency (39%) over current GaAs PHEMTs, said Smith. He added that the high gain per stage (20 dB power gain) was another record, meaning that the two-stage MHEMT PA offers a gain equivalent to a three-stage PHEMT. Higher indium content in the MHEMT channel (53%) means that it must be operated at a lower voltage.

Robert Eye from TriQuint Semiconductor reported an improved 77 GHz low-noise amplifier (LNA) based on a three-stage microstrip GaAs PHEMT. The device is designed for automotive radar applications. Although active cruise control and collision-avoidance radar are now available in high-end models, Eye said that his team's latest LNA



This GaAs-based low-noise amplifier could reduce the cost of automotive radar.

could allow the technology to be incorporated into lower-cost vehicles. This is because the LNA developed by TriQuint allows a simpler radar design. “MMICs will support the high volumes and low costs that will make this safety and convenience feature available for average-priced automobiles,” said Eye. He added that the TriQuint LNA had a smaller die size, better output power and higher sensitivity than devices used in a typical radar front-end. At slightly under 4 dB, the noise figure, at 77 GHz, is thought to be the best to date.

In the “late news” session, two teams reported record speeds for frequency dividers. The first was based on InP/InGaAs double HBT devices from NTT Photonics Laboratories. The dynamic divider IC, which had a record operating speed of 150 GHz, was based on a clocked-inverter feed-forward configuration. It was fabricated using InP DHBTs with an f_t of 240 GHz and an f_{max} of 370 GHz.

Meanwhile, researchers at the IBM TJ Watson Research Center in New York reported a static frequency divider based on SiGe bipolar technology. The device featured an f_t of 210 GHz and operated at 96 GHz, the fastest speed yet reported for an SiGe static divider.

Among the talks on emerging technology was a presentation by Mark Rosker from DARPA on the promise of antimonide technology. With a lattice spacing of around 6.1 Å, antimonide-based devices feature very high mobilities and other important features, and have already been used to demonstrate ICs with very low power consumption. Rosker described DARPA's Antimonide-Based Compound Semiconductors (ABCS) program, which has three major contractors; HRL Laboratories, Northrop Grumman Space Technologies (NGST) and Rockwell Scientific Company (RSC). Major challenges include

the development of a suitable low-defect substrate; the integration of 5000 devices per circuit; and circuit design to achieve low noise performance at 0.5 V operation.

Earlier this year, RSC, in collaboration with the University of California at Santa Barbara, demonstrated the first AlSb/InAs HEMT-based MMIC. A more recent result from HRL is a D-mode HEMT with an f_t of 308 GHz, a record for an InAs channel device (see Research Review, p36).

According to Roger Tsai of NGST, HEMTs with InAs channels have demonstrated 5–10 times lower power dissipation for equivalent f_t over conventional InAlAs/InGaAs lattice-matched HEMTs and MHEMTs. NGST grows its AlSb/InAs structures by MBE on 3 inch GaAs substrates, using a 2 µm AlSb buffer. The growth technology was transferred from the Naval Research Laboratory. NGST has fabricated HEMTs with 0.1 µm metal gates, f_t values above 200 GHz, and f_{max} values approaching that figure. Very-low-power X-band (12–14 GHz) LNA MMICs have been fabricated, with a record peak gain of more than 7 dB per stage for a DC power dissipation of only 6 mW/stage. NGST expects Sb-based ICs to significantly reduce the size, weight and cost of millimeter-wave phased-array receiver systems.

News in brief

Dutch center allies with UMS and WIN

Taiwan-based GaAs RFIC/MMIC foundry WIN Semiconductors and United Monolithic Semiconductors (UMS) of France are both teaming up with the Netherlands Organization for Applied Scientific Research (TNO).

WIN and TNO have signed a memorandum of understanding to co-operate on design services for third-party customers, coupling WIN's process technologies with TNO's expertise in MMIC design.

Meanwhile, GaAs foundry services and MMIC specialist UMS has set up a strategic alliance with the lab to focus on improving the performance and functionality of MMICs.

IBM expands foundry services at chip manufacturing facility

IBM is to offer foundry services for three new process technologies for wireless applications through its chip manufacturing facility in Burlington, VT. Called CMOS 7RF, BiCMOS 7WL and BiCMOS 7HP, the new processes span CMOS and SiGe-based bipolar technologies and extend down to the 180 nm level.

Chips can be designed in these processes for use in applications such as cell phones, wireless networks, automotive radar sensors and storage devices. Industry analyst iSuppli estimates the market for RF and mixed-signal ICs to be worth more than \$30 billion in 2003, and predicts that it will command an 18.8% share of the total semiconductor market by 2007.

IBM says that its CMOS 7RF process is ideal for low-cost wireless applications such as Bluetooth, handsets and RF identification tags. The transistors support analog RF-compatible models. This technology offers a wide range of optional passive features to

enable analog designs.

The BiCMOS 7WL process uses IBM's SiGe technology with deep trench isolation and a partially self-aligned bipolar structure. The technology is best suited for higher-performance wireless applications such as local-area networks and cell phones. Copper wiring at the first metal level and aluminum wiring at the remaining metal levels reduces the product complexity and processing time compared with standard BiCMOS products.

IBM's BiCMOS 7HP process incorporates a high-performance SiGe bipolar device optimized for high-speed or low-power applications. It includes a fully self-aligned structure, a buried n+ doped subcollector and a base profile optimized for maximum operating frequencies. It is ideally suited for 40–100 GHz applications such as fiber-optic transceivers, test instrumentation and proximity sensors for automobiles.

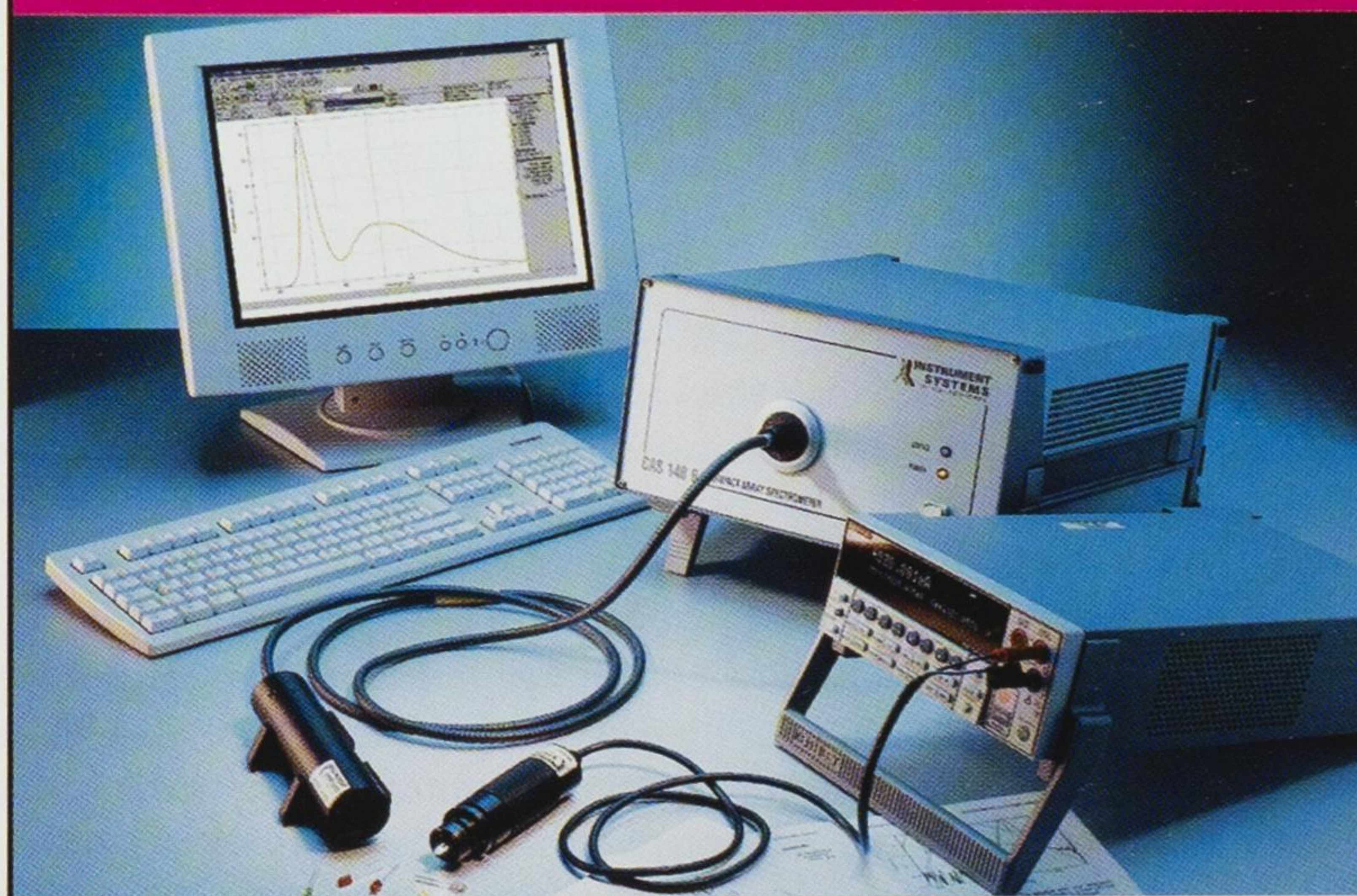
Mimix Broadband raises additional \$8 million in funding

Fabless wireless ICs supplier Mimix Broadband of Houston, TX, has secured an additional \$8 million investment in its second round of institutional financing. Cash from Gefinor Ventures and individual investors completed the latest round, with ongoing support from 3i and First Capital Group.

Gefinor Ventures managing director Greg Carlisle will now join Mimix Broadband's board of directors. "We have been impressed by the quality of the Mimix team, their MMIC technology, and key customer wins in the competitive microwave semiconductor market," said Carlisle, a 20-year veteran of high-technology start-ups, software development and consulting.

● Mimix has also been recommended for registration to the ISO 9001:2000 quality standard by Det Norske Veritas (DNV) Certification, Inc.

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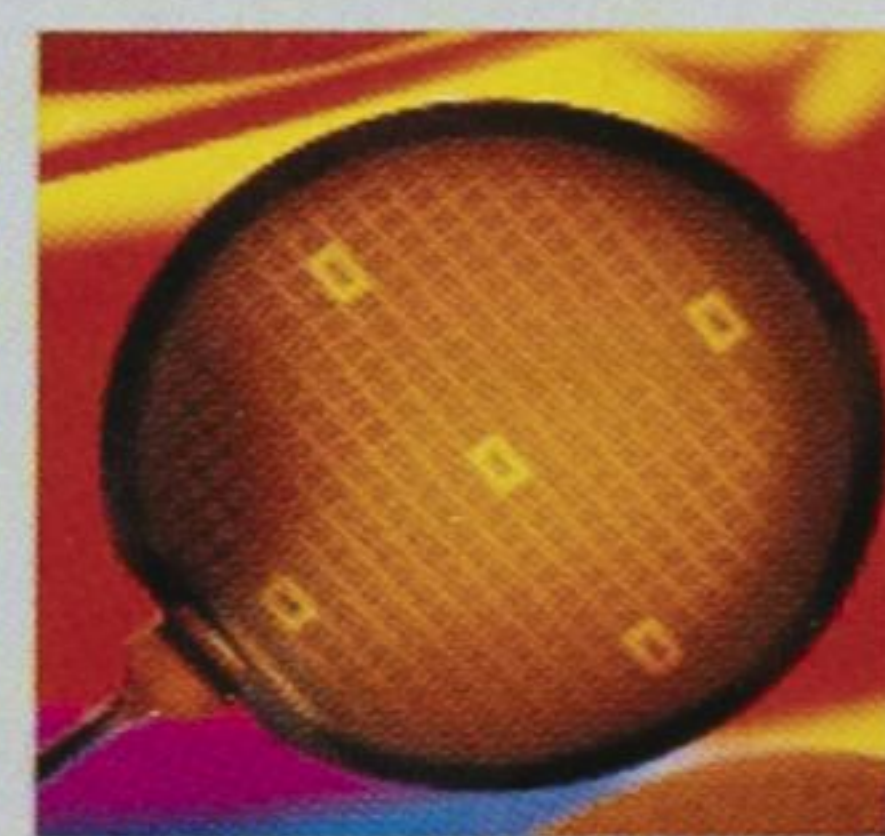
- Luminous intensity (candela)
- Luminous flux (lumen)
- Dominant wavelength (nm)
- Color coordinates (x, y, z)
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Backlights, airports and ve

As chip manufacturers continue to improve the performance and reduce the cost of their products, new applications in areas such as airport lighting and car headlamps continue to emerge.

Tim Whitaker reports from the Intertech LEDs conference.

The LED market continues to expand, driven not only by existing applications such as signage and backlights for mobile appliances, but also by the emergence of new applications. Examples such as car headlamps, airport lighting and dental curing tools were among the many subjects covered at the recent LEDs 2003 meeting, which also included details of the progress being made by leading device manufacturers.

Backlighting drives market growth

According to Jagdish Rebello of market research company iSuppli, the total LED chip market will reach \$3.4 billion in 2003, compared with \$3 billion in 2002. Rebello also said that the compound annual growth rate (CAGR) will be 12% between 2002 and 2007, and the market will exceed \$5 billion by the end of that period. The high-brightness (HB) segment (iSuppli defines HB-LEDs as having an output of more than 500 mcd) will be about 45% of the total market in 2003, and about 57% in 2007.

In a number of applications, long lifetime is a key factor in the adoption of LEDs. However, while there may be a high initial demand for LEDs, their long lifetime means that LED-based products have a long replacement cycle, which can slow market growth. Therefore, says Rebello, it is imperative for LEDs to continue to find new applications in order to stimulate further growth in the overall market.

Figure 1 shows the 2002 LED market by application. Backlighting and signage comprised 17% and 10.3% of the total LED market respectively, and these segments, which mainly use HB-LEDs, offer the highest growth potential. The largest segments for standard-brightness LEDs were for status indicators and alphanumeric displays (37.5% of the total market) and IR transmitters (21.3%).

Rebello says that LEDs are particularly well suited for backlighting small LCD panels in

cell phones, PDAs, digital cameras and camcorders. The market for larger panels – tablet PCs, laptop screens – is several years out, with the barrier being uniform illumination across large areas. The human eye requires a color uniformity of at least 95%.

iSuppli estimates that the backlighting market for LEDs will grow at a CAGR of 18% from around \$500 million in 2002 to more than \$1.1 billion in 2007. The market should be around \$700 million in 2003. In handsets, the average number of LEDs per display is decreasing as LED performance improves; however, some phones now have more than one screen. The introduction of higher-quality cameras in phones might reduce the demand for stand-alone digital cameras, which would in turn reduce the demand for LED backlights in the latter application.

Osram's thin-film technology

Numerous techniques have been developed to enhance the extraction efficiency of LEDs, and several of these rely in part on the emission from the sidewalls of window layers and transparent substrates. In some cases, notably Lumileds' TIP-LED and Cree's XBright device, the chips are shaped. Sidewall emission becomes less effective when the chip area is increased, so that in larger chips the extraction efficiency and hence the luminance (which correlates to brightness) is reduced. Osram Opto Semiconductors has developed a new approach that does not rely on sidewall emission, and allows the luminance to be scaled with chip area.

Osram's "Thin Film" technology involves bonding the LED structure to a metallized carrier substrate, after which the original epitaxial growth substrate is removed by laser lift-off (*Compound Semiconductor* June 2003 p29). The company has manufactured prototype 5 mm radial blue (460 nm) LEDs with an output of 16 mW at 20 mA.

At the conference, Osram's Klaus Streubel

2002 LED chip market

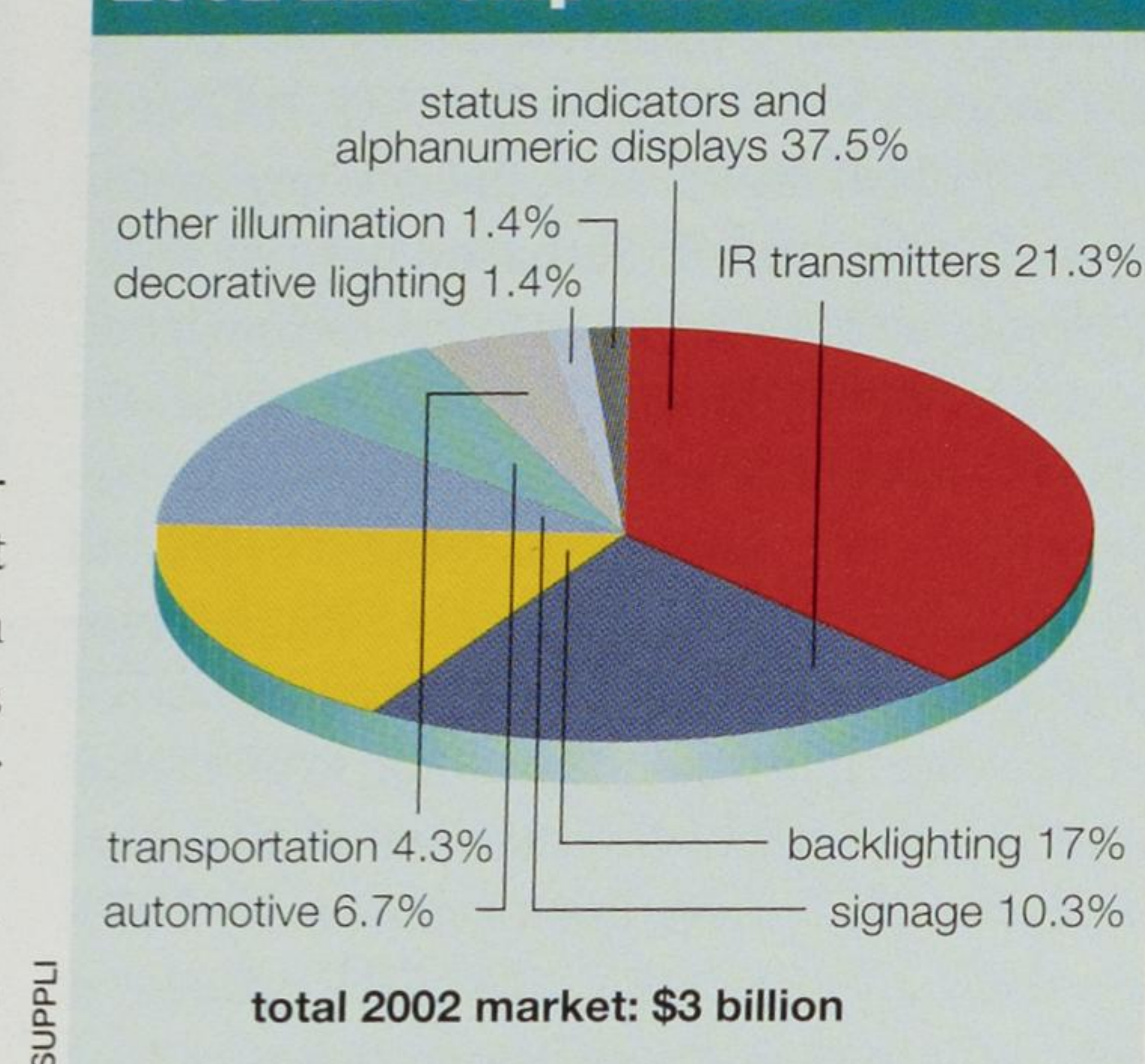


Fig. 1. Indicators/alphanumeric displays and IR transmitters, the largest LED chip markets, are served by standard-brightness devices, while backlighting and signage are the biggest markets for HB-LEDs.

described the fabrication of AlGaInP Thin Film devices, a process carried out using 4 inch wafers. After growth, microprisms are etched into the epitaxial layer structure, and the surface is coated with isolation and metallization layers. This structure is bonded to a metallized carrier before removal of the original GaAs substrate. In the final device structure, shown in figure 2a, a p-contact is formed at the top of each microprism. Light emission takes place from the active layer within each microprism, but does not take place in the area directly underneath the n-contact bond pad. Furthermore, the geometry of the microprisms causes light to be efficiently reflected towards the top surface. As shown in figure 2b, each device contains a number of microprisms.

According to Streubel, 618 nm Thin Film devices have demonstrated an extremely high luminous efficacy at 20 mA of 96 lm/W, with a wall-plug efficiency of 33%. At 10 mA, the efficacy was slightly higher at 98 lm/W. The $300 \times 300 \mu\text{m}^2$ devices had an output of 12 lm at 70 mA. Streubel also reported yellow LEDs (595 nm) with an efficacy of 49 lm/W at 20 mA and an output of 7 lm at 70 mA.

In comparison, Lumileds has reported an efficacy of 100 lm/W for its 605 nm TIP-LED chip, which has a much larger size of $1 \times 1 \text{ mm}^2$.

The above results have been generated with

vehicles boost LED market

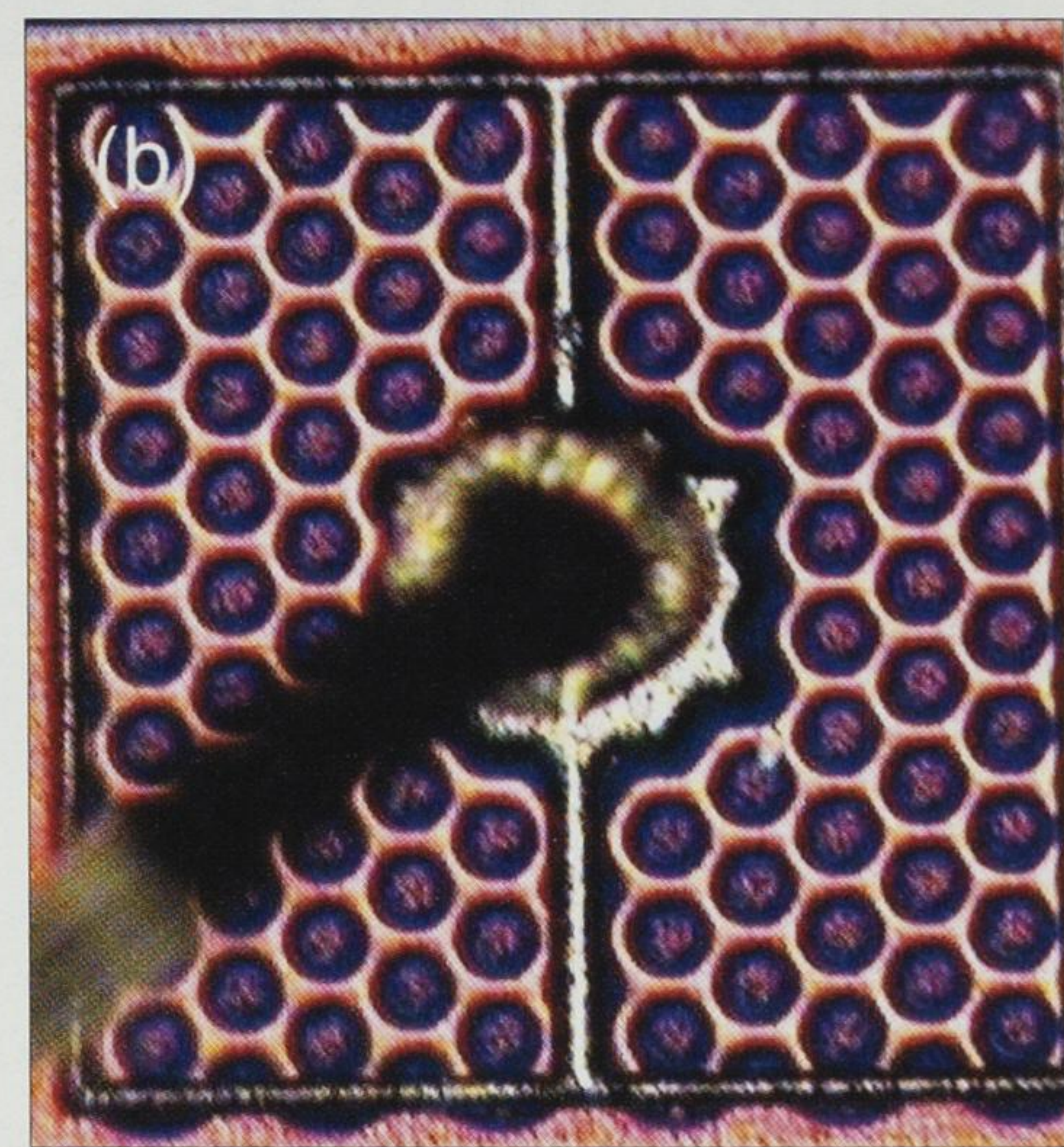
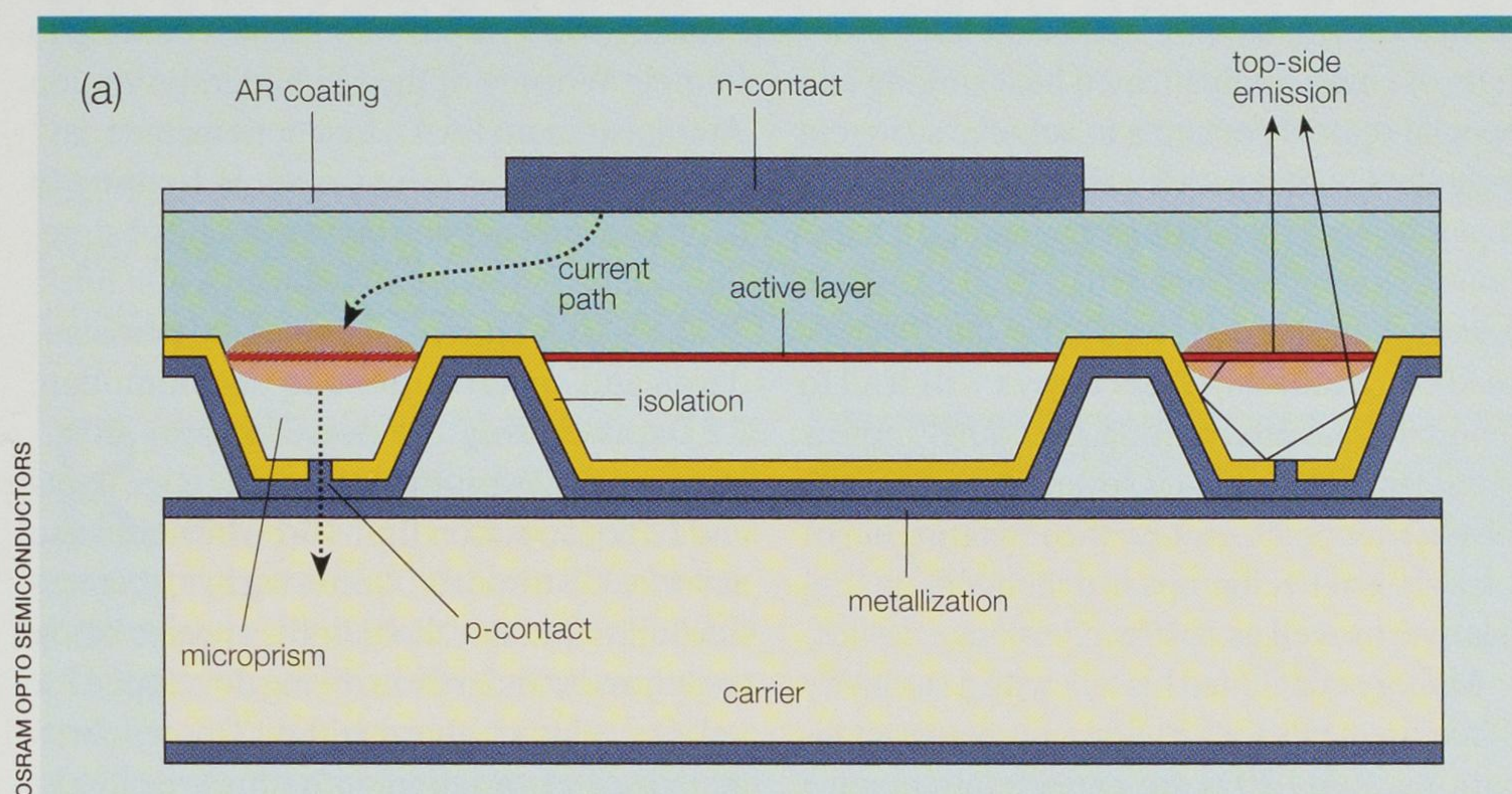


Fig. 2. Cross-section of Osram's third-generation Thin Film device (a), and a top view of the chip measuring 320 μm per side (b). The hexagonal areas in the chip photo are the microprisms, the only regions from which light emission takes place.

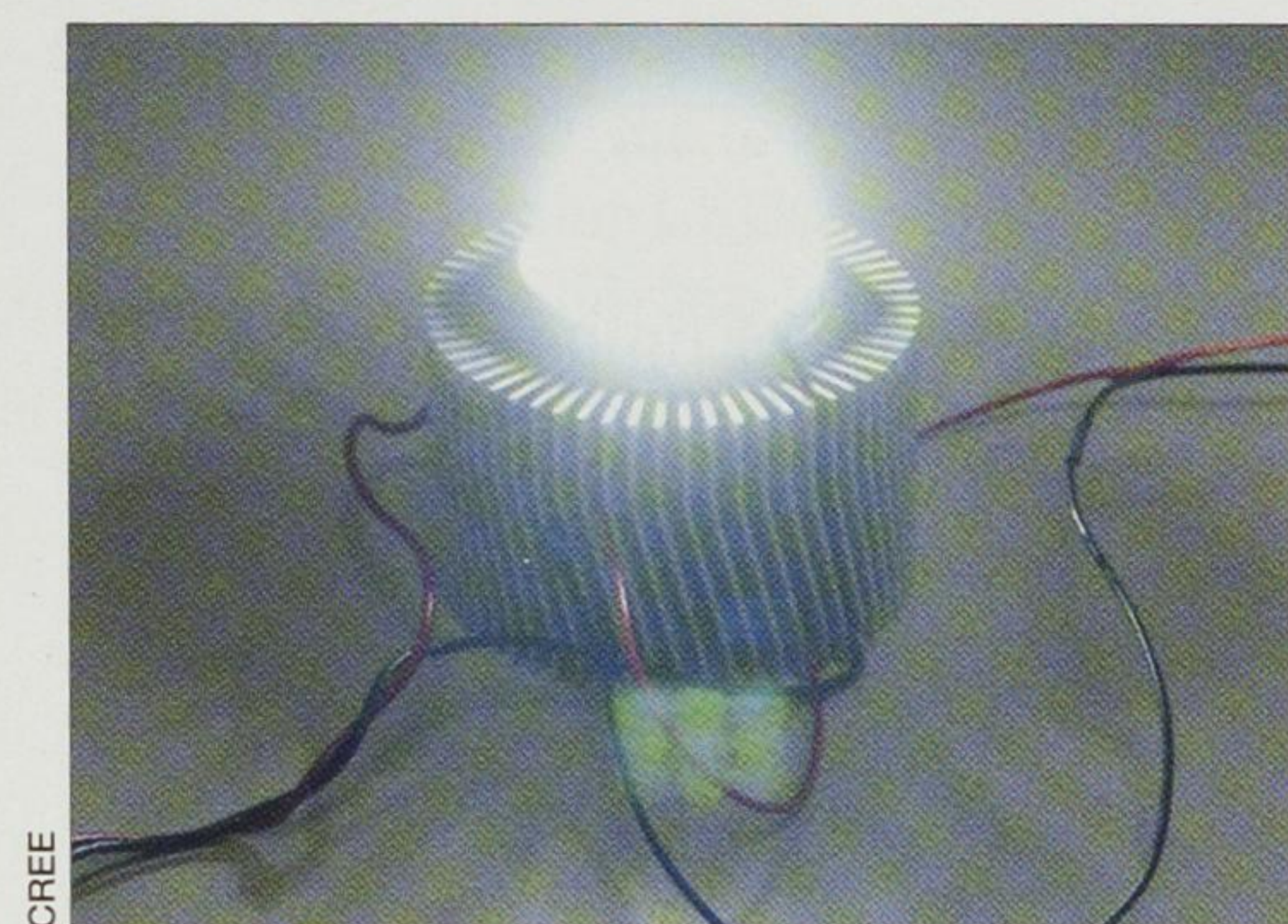
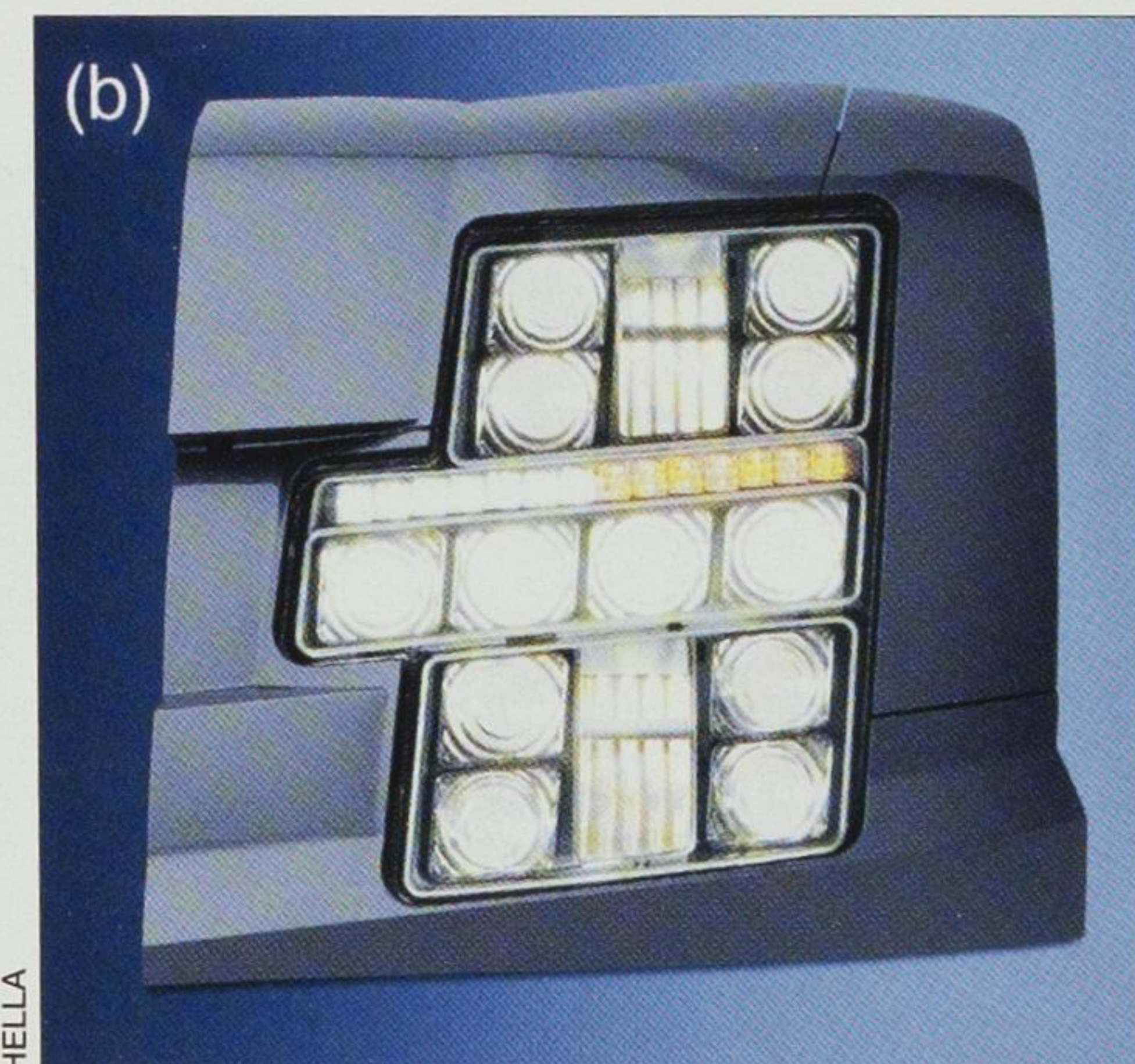


Fig. 3. This white lamp produced 1200 lm, about the same as an incandescent bulb, but with twice the efficiency.



Fig. 4. White LEDs are now being used to provide daytime running lights within headlamps (a), while full headlamp prototypes have also been developed (b).



Osram's third-generation Thin Film devices, while first-generation devices have been commercially available for about a year. At a current of 600 mA, large first-generation devices measuring $1 \times 1 \text{ mm}^2$ generated an output of 44 lm at 615 nm.

Cree pushes white LEDs to limit

Cree continues to make improvements to its blue LEDs, and Bernd Keller described blue (460 nm) LEDs that have an output of 19 mW when driven at 20 mA, with 35% quantum efficiency and 29% wall-plug efficiency. These chips enable very-high-efficiency white LEDs that provide 4.7 lm when driven at 20 mA, with an efficacy of 74 lm/W.

Keller reported that Cree is working to increase the efficiency, operating power den-

sity and yield of its LEDs, and to move to larger wafer diameters (LEDs are currently produced by Cree on 2 inch SiC wafers). "The industry is now capable of producing about 300 times the number of lumens per wafer compared to the first commercial blue LEDs," he said. "By 2010 this factor is anticipated to increase by about 15,000 times, i.e. 50 times from today." The actual lumen/wafer value is dependent on packaging and other factors.

Cree has also been developing high-flux LEDs that measure $900 \times 900 \mu\text{m}$ and have an output of 250 mW when driven at 350 mA. These blue chips have been packaged with a commercially available phosphor to make white LEDs with an output of up to 48 lm at a color temperature of 6000 K, and an efficacy of 40 lm/W. Further increases in the flux per

chip can be made by increasing the operating power, which in turn increases the need for innovative packaging solutions that minimize thermal resistance and remove heat from the LED junction.

Keller also described an R&D lamp module that has an output exceeding 1000 lm. The multichip lamp (figure 3) produced 1200 lm when driven with an electrical power of 37.5 W, giving an efficacy of 32 lm/W; this is about twice the efficiency of incandescent lamps with a similar lumen output.

Automotive applications

LEDs are already established in some aspects of the automotive lighting market. Derek Mallory, representing automotive lighting supplier North American Lighting, estimated

LIGHT-EMITTING DIODES

that in the North American market around 40% of CHMSLs (center high-mounted stop lights) and 2% of rear combination lamps (RCLs) use red LEDs. Around 500,000 RCLs will be installed on North American cars in 2004, while a much smaller number of amber LEDs are currently being utilized.

As performance improvements continue, LEDs should be able to penetrate all the lighting applications in vehicles, even front headlamps. Karsten Eichhorn of Hella, a German supplier of automotive lighting and electronic parts, described the use of white LEDs in headlamps. Examples ranged from daytime running lights (DRLs; figure 4a) to full headlamp prototypes (figure 4b). These have already appeared on a number of concept cars displayed at motor shows around the world.

LEDs offer design and styling options as well as long lifetime which leads to low or zero maintenance. Other factors valued by vehicle OEMs are space savings and efficiency, while customers appreciate added safety, higher performance, cost reduction and reliability.

White LEDs are already being used as park-

ing lights and as DRLs within headlamps. Eichhorn described a DRL that employs five LED chips each producing 30 lm; by 2006, this is expected to migrate to two chips at 70 lm each. Other applications such as fog lamps and the main headlamp function are even more demanding, requiring large numbers of chips, sophisticated heat sinking and special optical concepts to achieve stringent light distribution patterns. Eichhorn estimated that low-beam headlamps can require a luminous flux ranging from 350 to 1000 lm, which means about 45 LED chips today, and 19 chips in 2006. Multichip LED arrays will lead to headlamps incorporating functions such as the ability to illuminate around corners as the vehicle turns. However, the introduction of LED-based headlamps is dependent on legislative, as well as cost/performance, issues.

Mallory concluded his talk with a summary of requirements for LEDs in automotive applications. Red LEDs are expected to reach a luminous flux of 100 lm at a cost of less than \$2, while amber needs to reach 240 lm at less than \$4. White LEDs need to reach targets of 150 lm and 100 lm/\$; other speakers at the

conference indicated that the latter figure is around 10 lm/\$ today.

LED lights for airports

A number of other applications for LEDs were discussed at the conference, one of the most exciting being airport lighting. According to Pamela Whitley of the US Federal Aviation Administration (FAA), functions include navigational aids for pilots, airfield lighting to delineate runways and taxiways, and obstruction lights for towers and transmission lines.

The FAA is currently developing new standards and specifications to accommodate LEDs, including the power supply infrastructure. LED-based blue runway edge lights and red obstruction lights are already in use at some US airports. Green taxiway centerline lights and threshold lights are also being tested, and standards are being developed for yellow runway guard lights. Color, chromaticity and variation with time are closely controlled by FAA regulations, and airport lights must also operate in extreme weather conditions and under exposure to hazards such as snow ploughs and de-icing fluid.

Models

flow dynamics heat transfer
mass transport gas-phase and surface chemistry

Output

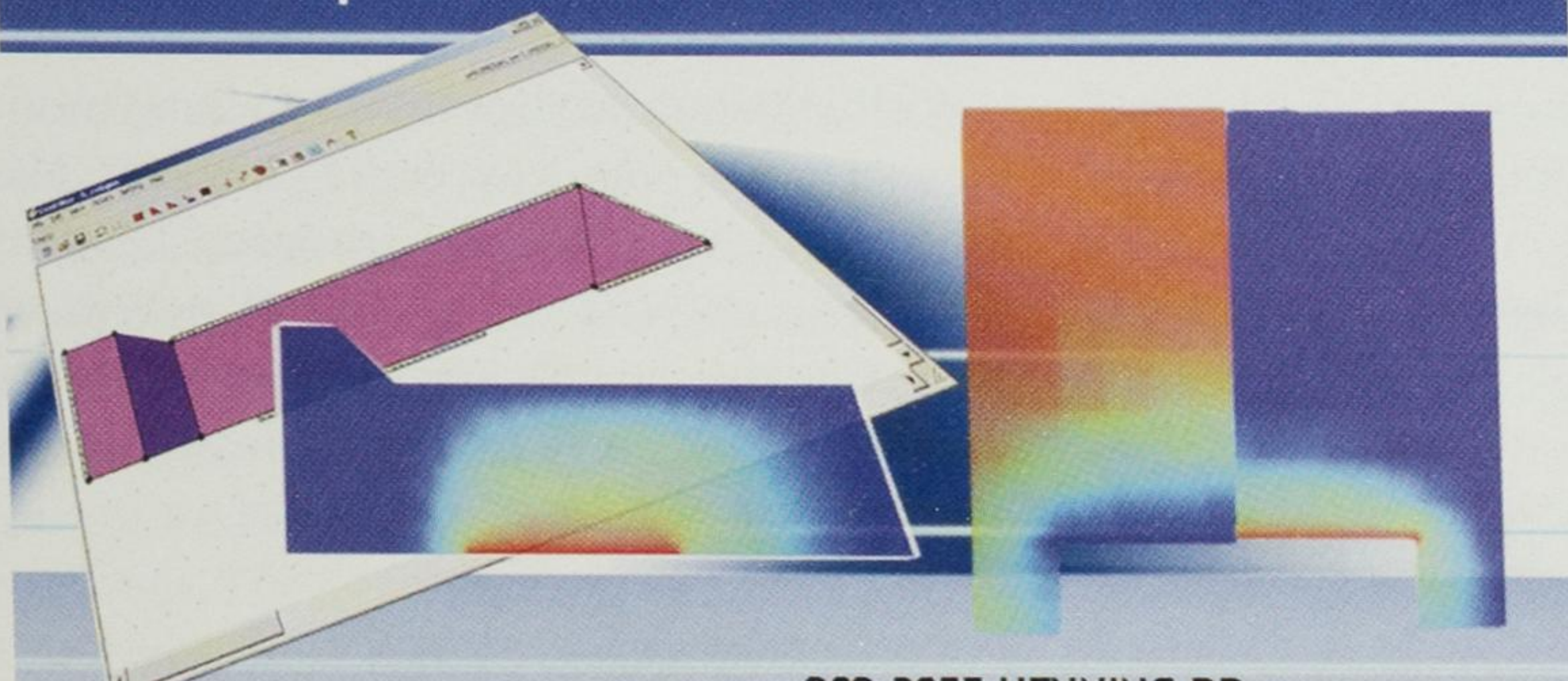
flow pattern temperature distribution
film composition growth rate

Materials

GaAs, InP, AlGaAs, InGaP,
GaN, AlGaN, InGaN ...

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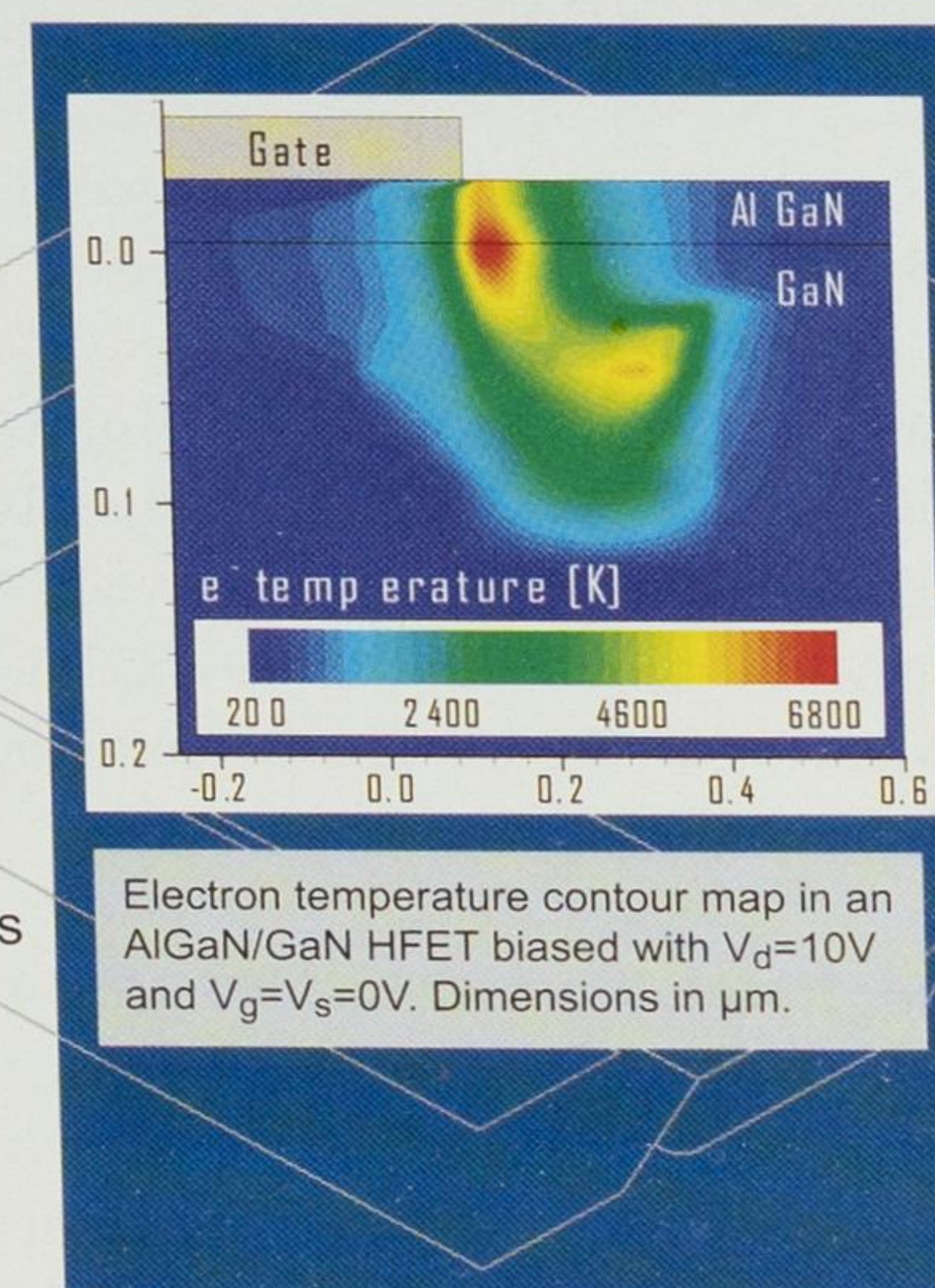


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LIGHT-EMITTING DIODES

HB-LEDs: the market drive towards solid-state lighting

Growth in the high-brightness LED market will be fueled increasingly by illumination applications over the next five years as the price/performance characteristics of devices improve. **Bob Steele** of Strategies Unlimited analyzes the development of the solid-state lighting marketplace.

Rapid advances in high-brightness LED (HB-LED) technology have opened up the possibility of using LEDs as sources of general illumination in the not-too-distant future. Remarkable progress in LED efficiency, lifetime and total lumen output has enabled an early market in niche lighting applications, and has given encouragement to those who believe that LEDs could have a significant impact on the lighting market within the next 10 years.

Reflecting the enthusiasm surrounding this technological progress, national programs to promote and develop LEDs for lighting (generally known as solid-state lighting) are underway in the US, Japan, Taiwan, Korea and China. Because lighting accounts for approximately 20% of total electricity consumption, the main motivation for these programs is large-scale energy savings, along with the associated benefits of reduced oil imports, lower greenhouse gas emissions, and lower energy costs to consumers.

The development and commercialization of solid-state lighting is dependent on a robust HB-LED industry that can generate the revenues and profits to support the R&D required to improve LED performance and lower the costs. Despite a flattening in 2001 due to the worldwide economic slowdown, the history of the HB-LED market shows a CAGR of more than 47% from 1995 through 2002. It reached \$1.8 billion in 2002, and is forecast to exceed \$2.5 billion in 2003.

Current HB-LED applications

The current HB-LED market can be conveniently divided into six major application categories, and associated subcategories. These are given in Table 1 along with figures showing the size of each market in 2002.

As Table 1 shows, the use of HB-LEDs in illumination applications (solid-state lighting) accounted for just 5% of the market

Current applications of high-brightness LEDs

Application	Market size in 2002	Typical uses
mobile appliances	\$716 m (40%)	cell phone screen and keypad backlights; PDAs; digital cameras
signs	\$422 m (23%)	single-color (highway VMS, moving message panels); full color (large video screens)
automotive	\$332 m (18%)	car interior (instrument panel lighting, map lights); car exterior (CHMSL, stop, turn, tail); truck and bus exterior (marker, stop, turn, tail)
illumination	\$85 m (5%)	machine vision; architectural lighting; specialty lighting; channel letters; contour lighting; flashlights; marker lights, etc.
signals	\$44 m (2%)	traffic signals; pedestrian crossings; railroad; aviation
other	\$221 m (12%)	indicator lamps in commercial, industrial and consumer electronics; entertainment; indoor displays; miscellaneous

Table 1. Mobile appliances like cell phones and PDAs currently dominate the market for HB-LED applications, with illumination responsible for just 5% of the overall revenue base.

(\$85 million) in 2002. However, it is one of the fastest-growing applications, and the one that is driving a great deal of the current interest in HB-LED technology.

The current and potential future market for LEDs in lighting applications exists only because LED technology offers real, often quantifiable, benefits in these applications. Whereas LEDs have several years of history in some lighting applications, such as machine vision and architectural/theme/retail applications, in many other areas lighting system designers are just beginning to understand their properties and experiment with LEDs as new lighting tools.

Designers are attracted by the design flexibility accorded by a directional light source that is capable of saturated color, and most applications in lighting to date have been for colored LEDs. The combination of red, green and blue LEDs provides a far greater selec-

tion of color and grayscale (16.7 million variants) than any other light source. Approximately 80–90% less energy is consumed than with conventional filtered white-light sources, and the light beam produces no heat.

Compact solution

The solid-state compact nature of HB-LEDs is one of the primary drivers behind their use. Compact, digitally addressable LED arrays can be assembled so that a large variety of colors can be produced using programmable controls. Similarly, long linear strips of LEDs can be assembled for use in contour lighting and channel letter lighting.

The long lifetime of LEDs relative to conventional light sources has been a key attribute in their adoption, especially in applications where a high premium is placed upon reliability, or where maintenance costs are high. For example, in machine vision, the cost of

LIGHT-EMITTING DIODES

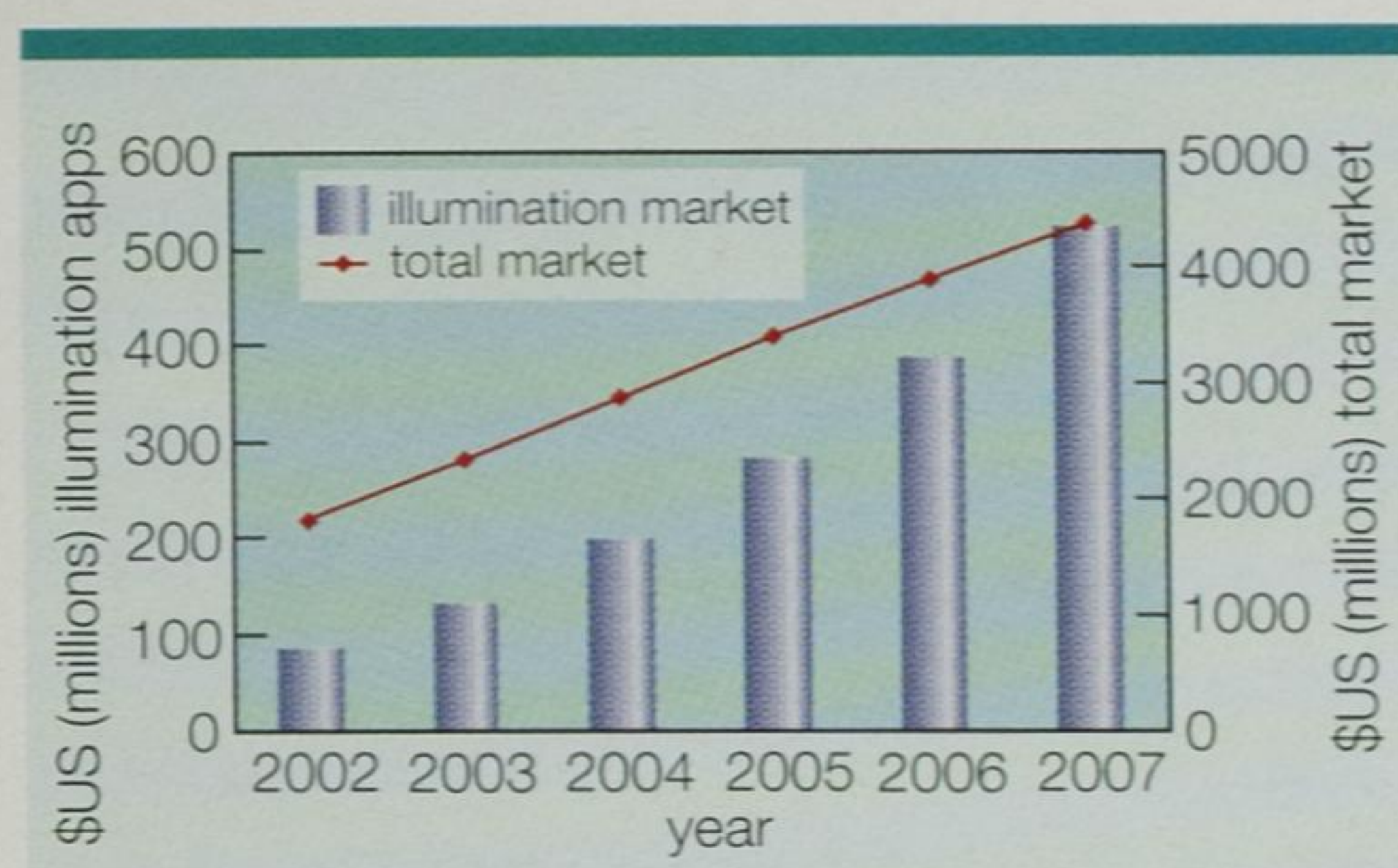


Fig. 1. According to Strategies Unlimited, the illumination applications sector will make up an increasing proportion of the overall HB-LED market over the next five years, rising to \$522 m (12%) in 2007.

downtime on a manufacturing line due to lamp failure is much higher than the cost difference between LEDs and conventional sources.

In white-light applications, LEDs are more than twice as efficient as low-wattage incandescent and halogen lamps, and the best white LED technology is significantly more efficient than standard 60–100 W incandescent lamps (17 lm/W). White LEDs demonstrated in the laboratory are now approaching the efficiency of fluorescent lamps (80 lm/W) (see *Compound Semiconductor* June 2003 p31).

The main disadvantages of LEDs are their much higher cost than conventional light sources, and their low lumen output per device. Both of these problems are being vigorously addressed by the LED industry, and dramatic progress has been made in the past few years. For commercial white LEDs, using large-area chips and special packaging has increased the lumen output per package by a factor of 100. The cost per lumen has decreased by a factor of five. Even greater performance and cost improvements are imminent in products that have been announced, but are not yet fully commercial.

Much additional progress must be made before LEDs can effectively penetrate the large-scale general illumination market, but substantial penetration into lighting applications can still be expected in the next five years, based on the attributes described above.

Near-term illumination markets

The key to the near-term adoption of HB-LEDs in lighting applications is not to use them in applications where traditional light sources (fluorescent, halogen and incandescent) are firmly entrenched, much lower in cost, and where maintenance and replacement costs are low. The greatest driving force in the illumination market for LEDs is their use in

Current illumination applications of LEDs

- **Channel letter/contour lighting**
- **Architectural/retail/theme**
“architainment”
uplighting
downlighting
color wash
neon replacement
decorative outdoor
- **Machine vision**
- **Consumer portable**
flashlights
key lights
novelty items
- **Maintenance retrofit**
socket-compatible
replacement lamps
- **Safety/security**
exit signs
emergency lighting
- **Accent/marker/decorative**
colored accent lamps
marker lights
path lights
string lights
- **Specialty illumination**
aircraft interior lighting
task lights
low-wattage applications

The main disadvantages of LEDs are their much higher cost than conventional light sources, and their low lumen output per device.

new applications where traditional lighting has significant disadvantages and where LEDs provide some true added value, or where a factor such as reliability is particularly important.

The major uses of LEDs in lighting applications currently are listed in the box above. These niche applications are being developed primarily by lighting systems companies that are manufacturing lighting fixtures (luminaries) or other products, including control electronics and optics, using the devices provided by the LED manufacturers to address a specific lighting task. By and large, these companies are not the mainstream lighting system manufacturers (although there is some participation by such companies), but smaller, specialized companies focused on the development of LED lighting. Such companies include pioneers in the field such as Color Kinetics, TIR Systems, Permlight Products, Boca Flasher, and many others.

However, mainstream lighting companies are beginning to evaluate the potential of LEDs and a number of them have even developed LED-based products. At lighting industry trade shows – such as LightFair, the largest in North America – a significant number of exhibit booths have displayed LED-based products in recent years.

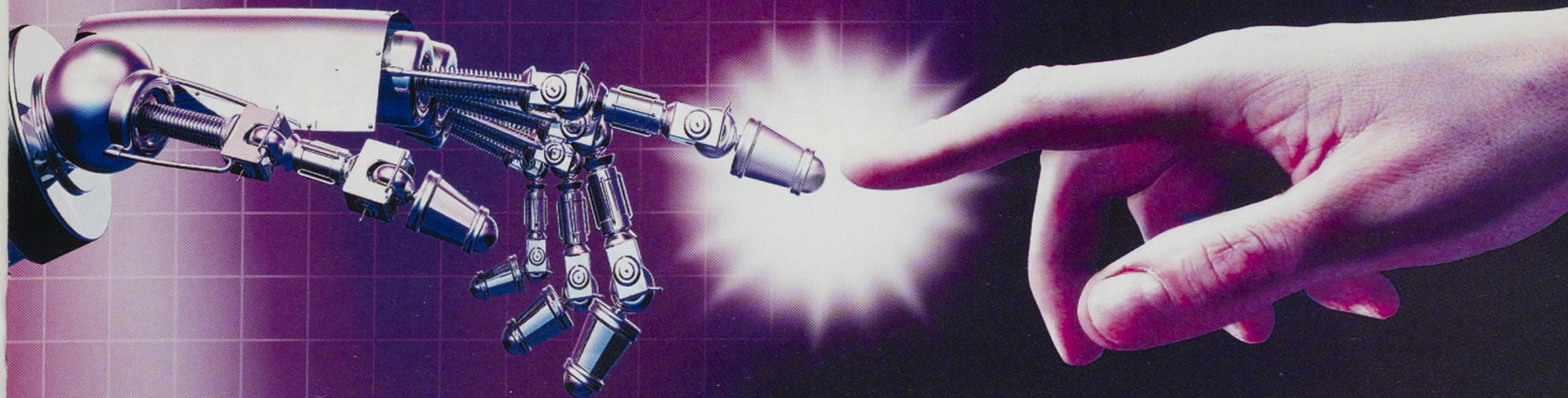
These specialized lighting applications rep-

resent one of the fastest-growing markets for HB-LEDs. While they are relatively limited compared with the \$12 billion general illumination market (for all types of lamps) that is envisioned as the “holy grail” of the HB-LED industry, they nevertheless constitute a transition stage that will provide a point of entry into this larger market. Moreover, these applications are being developed based on the current price and performance characteristics of LEDs, whereas the development of the general illumination market will require much lower prices and much higher performance than is available today. As the price/performance characteristics of HB-LEDs continue to improve, and as the lighting industry becomes more familiar with the attributes of LEDs, this market will continue to expand.

Future forecast

Figure 1 shows Strategies Unlimited’s forecast for the overall HB-LED market and that for HB-LEDs used in the illumination sector. The overall market is forecast to grow at an average annual rate of 21% to reach \$4.7 billion in 2007. Meanwhile, the market for HB-LEDs in illumination is forecast to grow at 44% per year, double the overall rate, to reach \$520 million in 2007. In that year, illumination applications are projected to account for 12% of the HB-LED market, compared with just 5% today. Beyond 2007, the market for HB-LEDs in illumination is expected to continue to grow, resulting in the capture of a significant fraction of the world lighting market after 2010.

Robert V Steele is director of optoelectronics at Strategies Unlimited, 201 San Antonio Circle, Suite 205, Mountain View, CA 94040, USA. E-mail rsteele@strategies-u.com.



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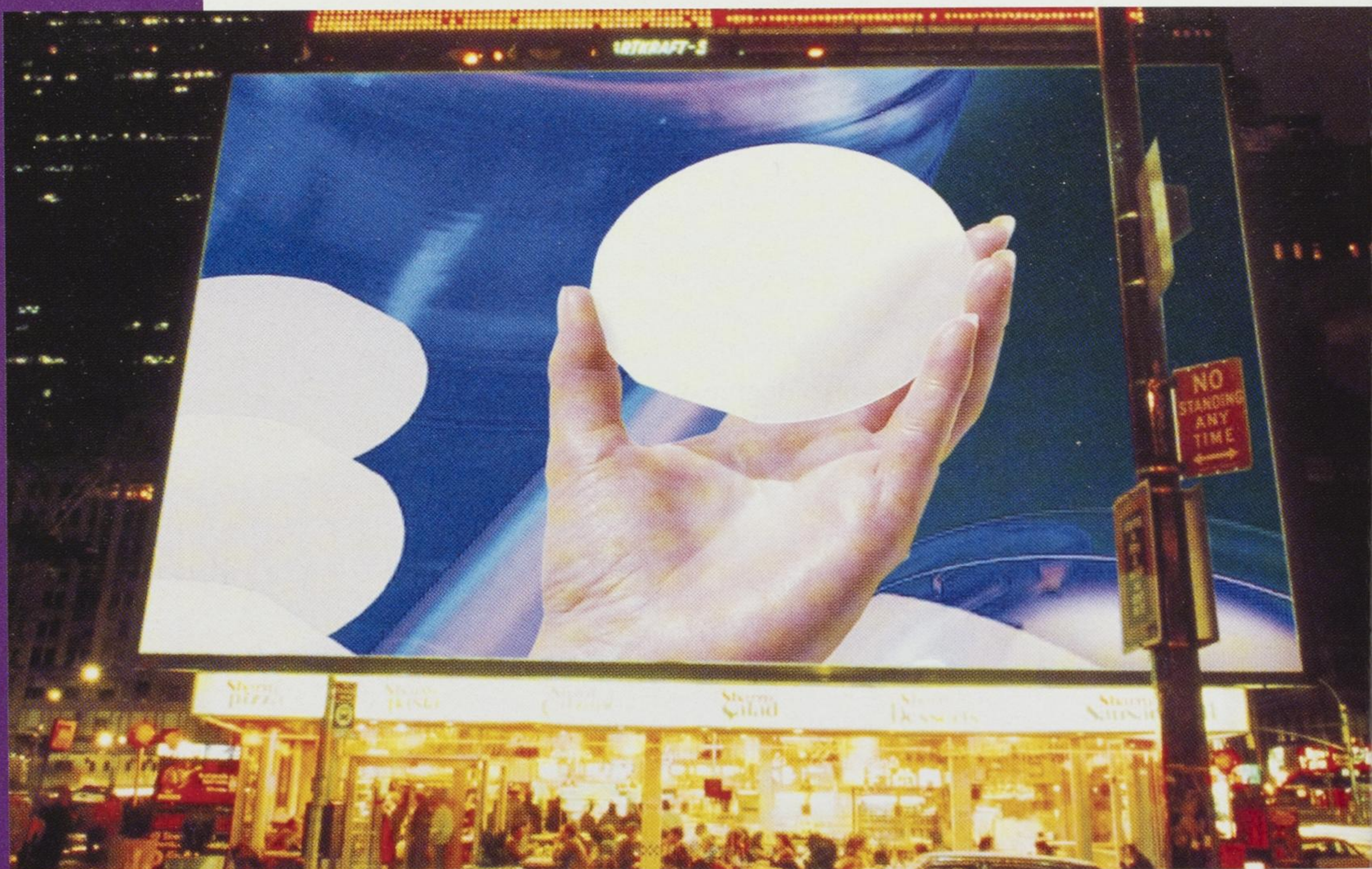
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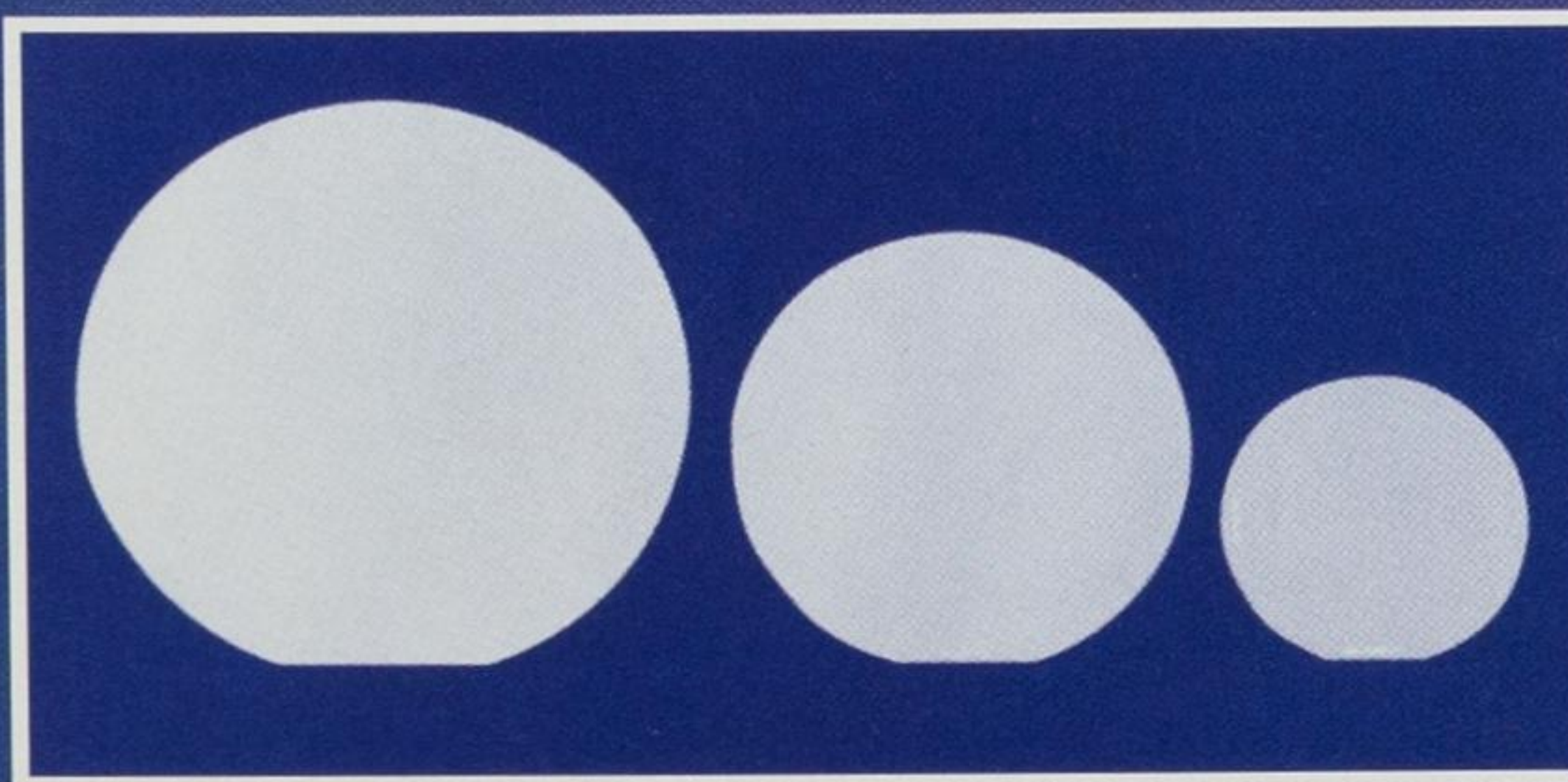
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LIGHT-EMITTING DIODES

Any color, as long as it's white

It is widely believed that general lighting will one day become a huge market for white-light LEDs. **Bill Kennedy** describes some of Toyoda Gosei Optoelectronics' recent technological progress.

Why use LEDs in general lighting? The problem with incandescent lamps is well documented. Their efficiency, in terms of photon propagation, isn't very good. They produce maybe 15 lm per W of input power, with a high degree of wasted energy given off as heat. And while fluorescent bulbs can produce up to 100 lm/W, their high operating voltages require expensive transformers. At peak efficiency, fluorescent sources also produce poor color rendering, while their mercury content is an environmental concern.

LEDs offer the best of all worlds: ultra-efficient, environmentally friendly, low-power lighting. Many countries are now recognizing LEDs as a "strategic technology", as evidenced by Japan's Light for the 21st Century program, the US Government's Next Generation Lighting Initiative (NGLI), and similar schemes in Europe, Taiwan and Korea.

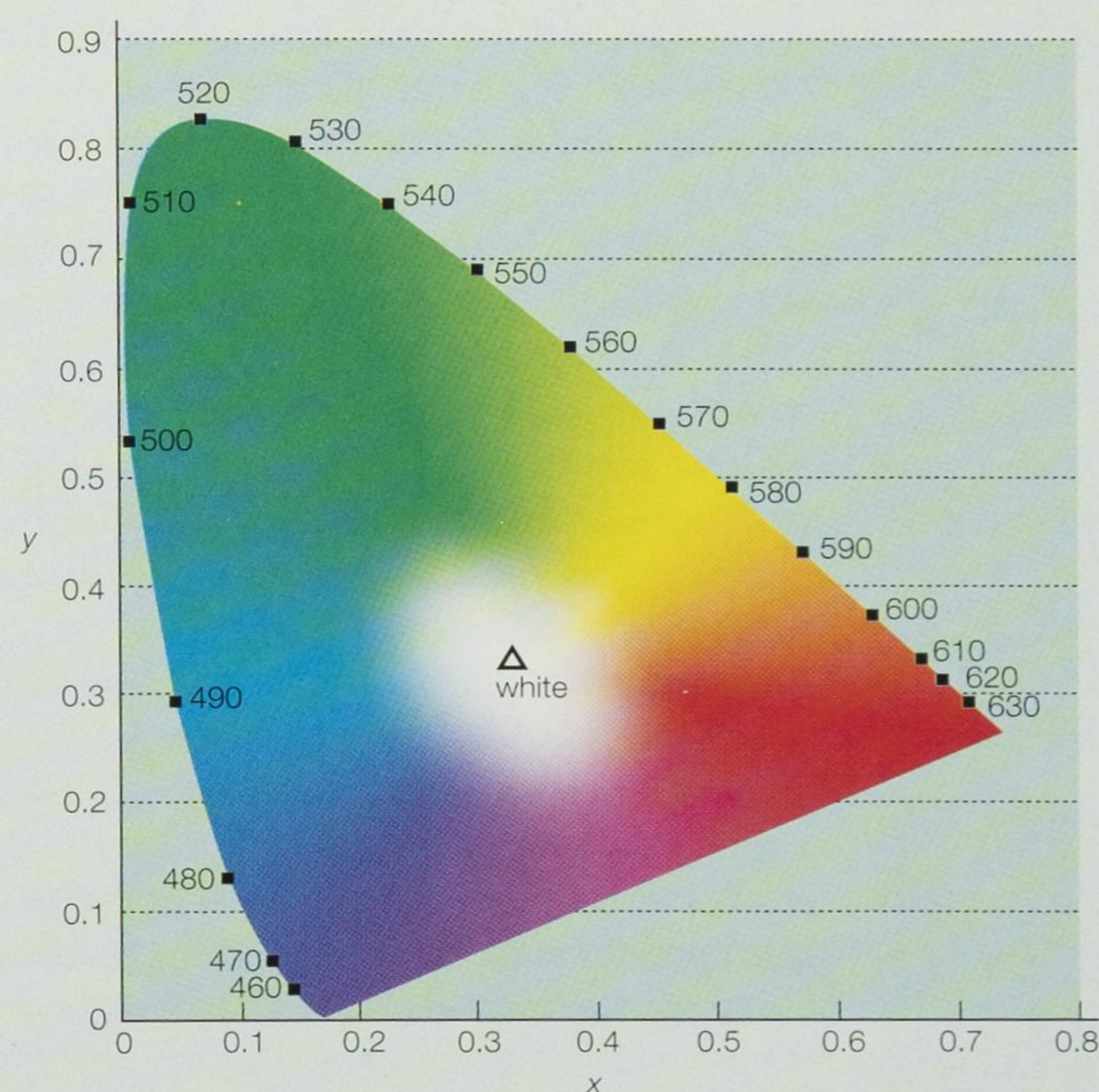
For these programs, white-light LEDs are the key technology. But what exactly is white light? Light possesses no specific "color" until it is processed by the human brain. What we call "white light" is a sensorial phenomenon that doesn't exist until it is processed and is perceived by the individual. There is no single kind of white light – there are in fact many kinds, each with a subtly different hue (see the table "Types of white light", right). With LEDs a whole new type of light source has become available; one that can both mimic many of the characteristics of older lighting technologies and provide a wealth of new lighting capabilities.

Degrees of "whiteness"

Technically, the color temperatures detailed in the table only apply to blackbody sources, and, as such, the figures are a specification of both the degree of "whiteness" and the spectral composition of the source. However, the term "apparent color temperature" is often used to specify the degree of whiteness of all types of light sources, including LEDs.

All possible colors, including all types of white light, can also be designated on the chromaticity chart established by the International

Which white do you need?



Types of white light

Type of "white" light	Black-body temperature (K)
sunlight (EEW)	5400
candle/fire	1700
low-wattage tungsten lamp	2000
incandescent lamp	2600–3000
TV studio floodlight	3100–3400
"warm" fluorescent light	3000
"cool" fluorescent light	4000
"daylight" fluorescent lamp	7000
"analog" white-light LED	6500–7000

Commission on Illumination (CIE) in 1931 (above in box). The x/y chart, which was based on a number of research programs dating from at least as early as Maxwell's work in 1854, defines the color-matching characteristics of a standard observer. It has established a framework for the specification of colors in coordinates defined for virtually all wavelengths associated with visible light.

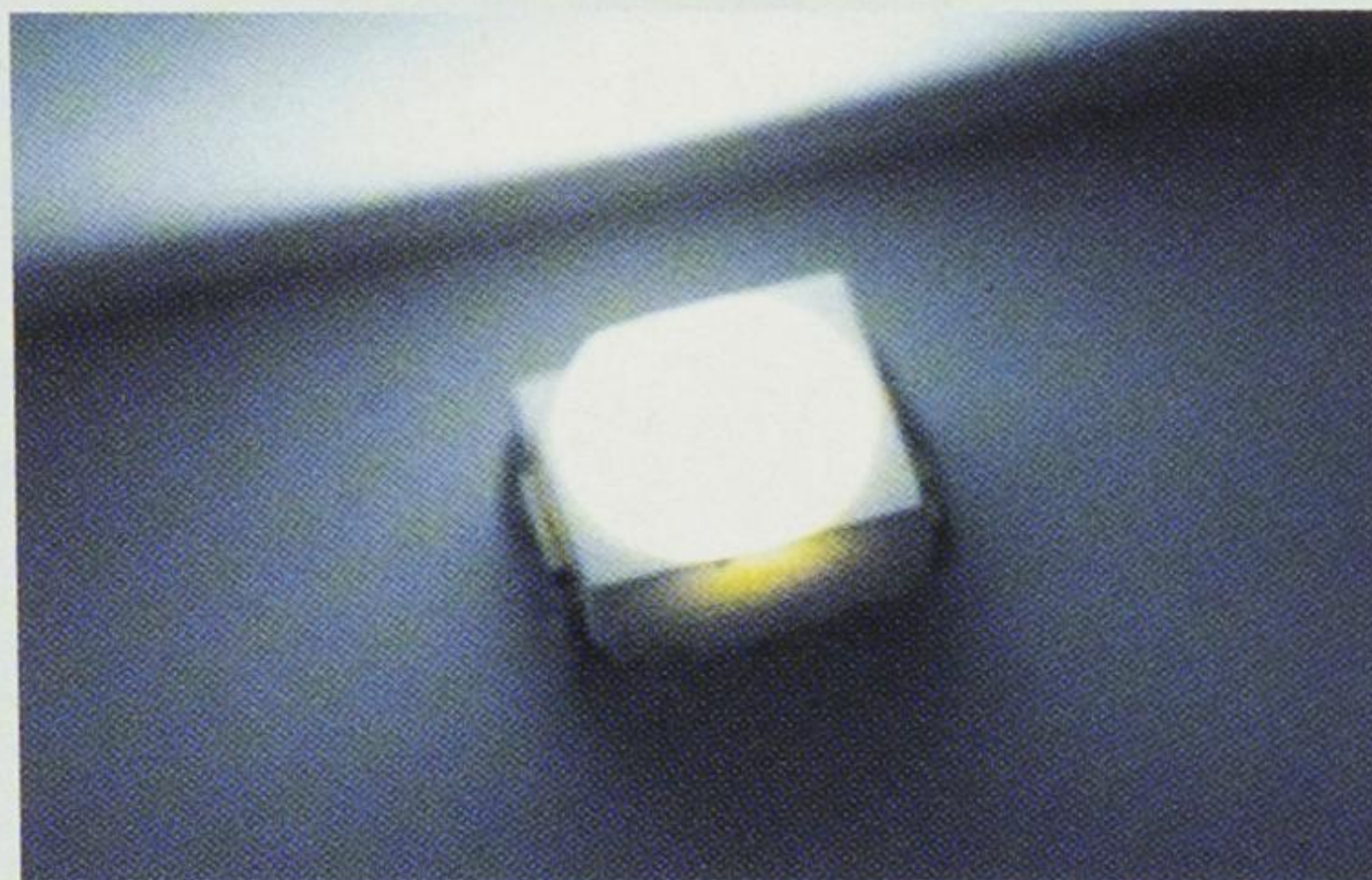
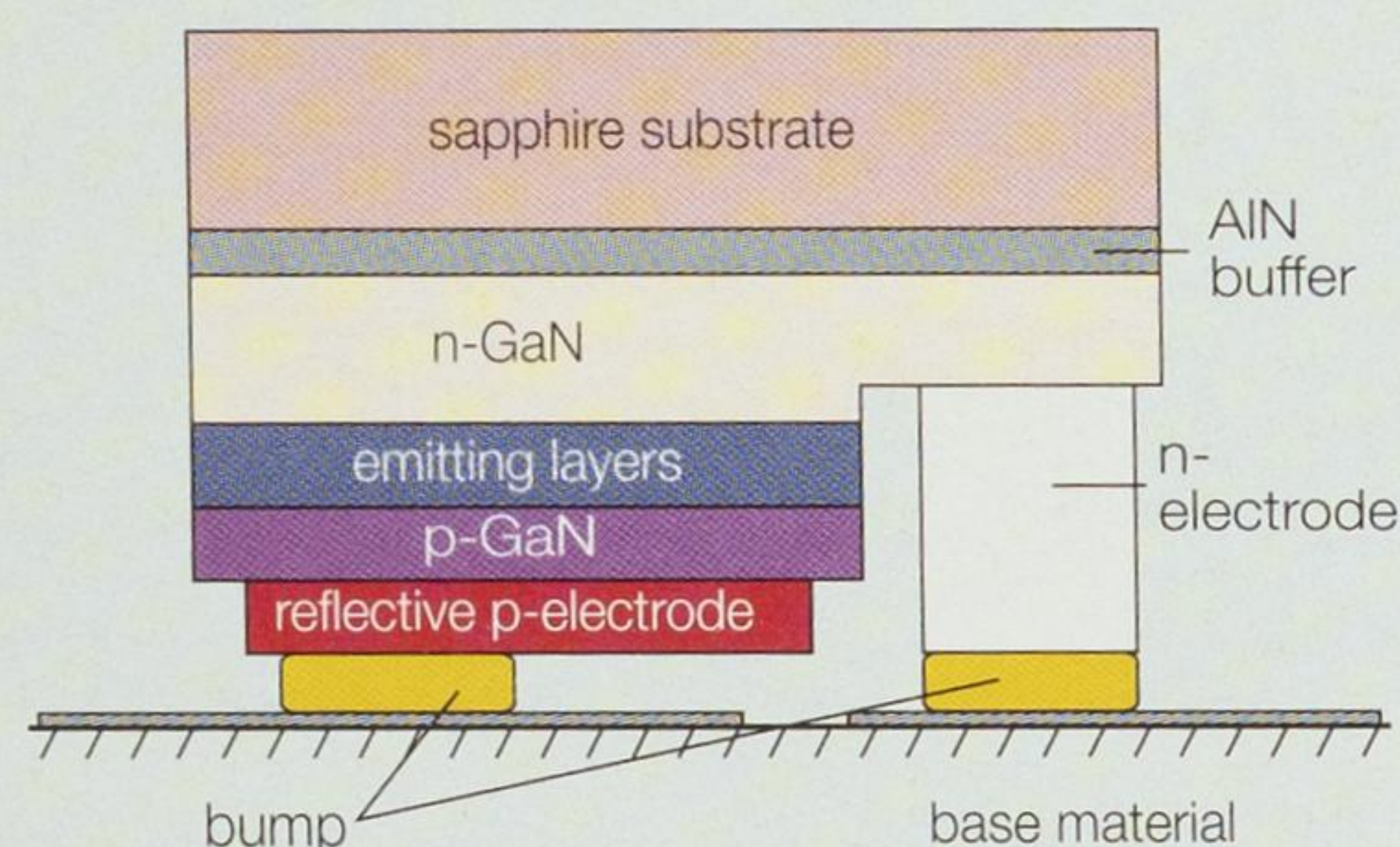
Superimposed upon this chart is the

Plankian Curve (black-body locus), which is also used to establish a definition of white light, including equal-energy white (EEW), through x/y plotting. The information collected for this chart includes pure spectrum colors. This chart is the lighting and LED communities' standard tool for the definition of chromaticity, including the many different shades of white light.

The development of high-brightness white LEDs has already led to new approaches for

LIGHT-EMITTING DIODES

Toyota Gosei's recent white LED developments



Left: TG's flip-chip GaN-on-sapphire LED leads to improved thermal management and package designs. **Right:** the full-spectrum polychromatic white LED technology, the first of its kind in the industry, is based on a purple LED and an RGB phosphor.

2001

● TG White Hi: based on high-brightness blue LED and new yellow phosphor, giving a more consistent color uniformity and a higher luminosity.

comprising red, green and blue phosphors all illuminated by a purple flip-chip LED. Provides greater color-control and stability despite temperature variations.

2002

● TG White MP: a trichromatic white source,

● True-White Hi: has much higher optical power

(265 mcd) than the White Hi. Also powered with a flip-chip purple LED. Produces a broadband white light similar to EEW, and virtually eliminates off-angle color variation and halo effects. Currently available in sample quantities, it emits 1–2 lm per package.

lighting, and will eventually significantly affect the type, style and quality of general illumination. The key here is that most traditional light sources never really provided a close approximation to EEW. Among the common types of non-solar white light that people encounter are: the cool “bluish” white from fluorescent lamps ubiquitous in many office buildings; incandescent “yellowish” white seen in residential lighting; the brilliant “blue-white” of mercury vapor and metal halide lamps seen in most warehouses, manufacturing, assembly and repair facilities; and the “yellow-white” of high-pressure sodium street lamps.

With white LEDs, emissions that approximate incandescent, fluorescent and – more importantly – EEW, can be produced. Indeed, the whole definition and quality of such light can be changed and/or redefined by LEDs.

LEDs offer a number of solutions to creating white light, ranging from bichromatic (two-color) to full-spectrum polychromatic sources. The two basic techniques for LED white-light propagation can be described simply enough, but to really define this technology, we must look at the two in more detail.

The first technology is “analog white”. This is the term used to describe white light produced by efficient blue or violet GaN-based LEDs coupled to phosphors. Analog white

products that provide bichromatic, trichromatic and full-spectrum polychromatic white light are in production.

Color combinations

The first “white” LED, introduced in 1996, featured a blue LED in combination with a yellow phosphor. In this device, blue LED light combines with the yellow light that it stimulates in the phosphor to generate a whitish light. Now available from many suppliers in a standard “T” type package, this source is typically powered by a 460–470 nm LED thinly coated with a cerium-doped YAG (yttrium aluminum garnet) phosphor composition that emits around 598 nm.

In the human vision system, these two colors combine to create the perception of white light. The devices have color temperatures ranging from 6500 to 7000 K (± 500 K) and are provided in various formats and chromaticity binning regimens. Many users think of this type of LED as a “standard” and the only alternative to obtaining a true “white LED”, but in actual fact the bichromatic spectrum of white light created by these devices is insufficient in many regions to generate a good color rendering index (CRI): near-UV (<430 nm), cyan-green (480–540 nm) and deep red (>640 nm) are all absent from their

emission spectra.

Bichromatic analog technology gives a typical on-axis color rendering index of 60–70. However, the “whiteness” of the emitted light changes due to variations in LED optical power, peak emission wavelength, drive current, temperature and symmetry, as well as the thickness of the phosphor coating and the phosphor quality. Depending on these variables, the actual color produced can appear too blue or too yellow.

The most common problems for this type of LED system are the “halo” and “blue center” effects, where the LED emits blue light in the center and along the package axis preferentially and the phosphor emits yellow light in a more isotropic fashion. In addition, these products suffer from package-to-package variations. Reliability and durability also vary greatly with manufacturer. Radiation from the blue LED causes degradation of epoxy encapsulants, die-attach adhesives and phosphor binder materials, shortening the useful lifetime of the lamp. Some suppliers bin and test each individual white LED to ensure compliance, while others offer limited or no binning options.

Despite these problems, this “standard” white LED has carved out a successful market and the momentum is growing. Many new types of bichromatic, trichromatic and full polychromatic analog white LEDs are now available, each offering distinct attributes. Today there are a variety of new bichromatic white LEDs available from several companies, and being licensed to others, including “warm white” devices (rated at 2500–3500 K) that are being marketed to mimic the old standard as “the incandescent lookalike”. Other white LED products include specialized devices for corporate clients who want a specific Pantone color.

The second technology is called “digital white”. In this scheme, light from monochromatic LEDs is combined to make high-brightness and dynamically adjustable white and other color sources. Bichromatic, trichromatic and full-spectrum polychromatic white-light products based on this technology are also in production and can be found in many formats.

The digital solution offers many advanced technical features and performance parameters when compared with the analog technology described above, including wide dynamic color control with white-point tuning and full dimming capability without color variation. Bichromatic versions that exhibit metameric (i.e. colors that look identical but have differ-

LIGHT-EMITTING DIODES

ent spectra) white color are now in full production, with the technology extending to RGB trichromatic and full polychromatic white lighting. The packaging formats offered are also proliferating, with a variety of 2-in-1, 3-in-1 and higher counts available to lighting designers and integrators. A similar development of elegant broadband or RGB sensors, LED drivers and address and control devices support "color management" in these versions of the technology.

Power increase needed

However, for GaN-based LEDs to become more competitive with traditional lighting sources, an increase in optical power is needed. Both internal and external quantum efficiency improvements are being vigorously pursued by the industry at large. Many innovative new epitaxial processes, designs and materials are being developed to achieve higher internal quantum efficiencies. Die fabrication, finishing, shaping and wafer-bonding processes are also being developed to enhance external quantum efficiencies.

One of the biggest new changes is the GaN-on-sapphire flip-chip LED pioneered by Toyoda Gosei (TG), as well as the addition of many new flip-chip sizes both smaller and larger than the 320 μm standard. GaN flip-chip technology provides a new way to optimize thermal efficacy and improve package designs with regard to space saving and optics.

Larger LED die sizes are also proving quite popular. Producers are supplying larger die formats and developing more complex geometries to accomplish this. Other technical issues receiving attention include eliminating encapsulant degradation through "epoxy-free" packaging and increasing phosphor efficiency in the red spectrum. Increasing the optical efficiency of packaging and advancing thermal management to enable higher LED drive currents in a variety of device formats, including advanced surface mount device (SMD) designs suitable for automated assembly techniques, are also under investigation.

For comparison, a typical 5 mm GaN white LED lamp contains a 340 μm LED die, has a thermal resistance of 150 $^{\circ}\text{C}/\text{W}$, and an output of 1 lm/package. In contrast, the new high-power "True White" LED from TG (introduced at the CEATEC show in Japan in October), uses a 1000 μm die flip-chip packaged with superior optics and thermal management in an SMD format. It yields 20 lm/package with a color rendering index

of 90. These powerful lamps benefit designers and manufacturers by requiring far fewer LEDs and occupying less space.

Market share

LEDs have a long way to go before they command a big market share. However, a 10% share looks like a realistic figure later in this decade. LEDs that solve color rendering and color temperature differences that are commonly found with competing technologies have been demonstrated, and these are now in production. Color consistency issues and extended lifetimes are also being resolved. Specialized varieties of "white" light LED that mimic traditional lighting sources are in production. LED efficiencies are also increasing while their cost is decreasing quickly.

The benefits of LED-based lighting include energy savings and greatly increased reliability and durability. However, the speed with which LED technology is adopted depends on the general lighting industry, legislation and funding issues. Standards are being developed, and industrial, societal and governmental organizations such as the National Electronic Manufacturers Association, the Underwriters Laboratory, the National Institute of Standards and Technology and others are defining more appropriate qualification procedures. Psychophysical researchers are investigating the new technology and beginning to understand how it can be used in a variety of applications ranging from color blindness to inducing sleep. Designers and integrators are taking a closer look at how best to apply LEDs as compared with conventional light sources. This key area, more appropriately defined as "do not integrate an LED in the same way as you do a lightbulb and expect low-cost, high-brightness, long-life product solutions", needs concentrated industry, association and government attention, focus and change as compared with utilizing conventional solutions.

At last year's LightFair International, the lighting industry's leading showcase, at least 10% of some 600 exhibitors featured LED lighting devices (*Compound Semiconductor* July 2003 p23). Market penetration looks certain to increase at next year's LightFair exhibition, which is scheduled to take place at the end of March in Las Vegas.

Bill Kennedy is General Manager of Optoelectronics for Toyoda Gosei Co., Ltd. in North America.

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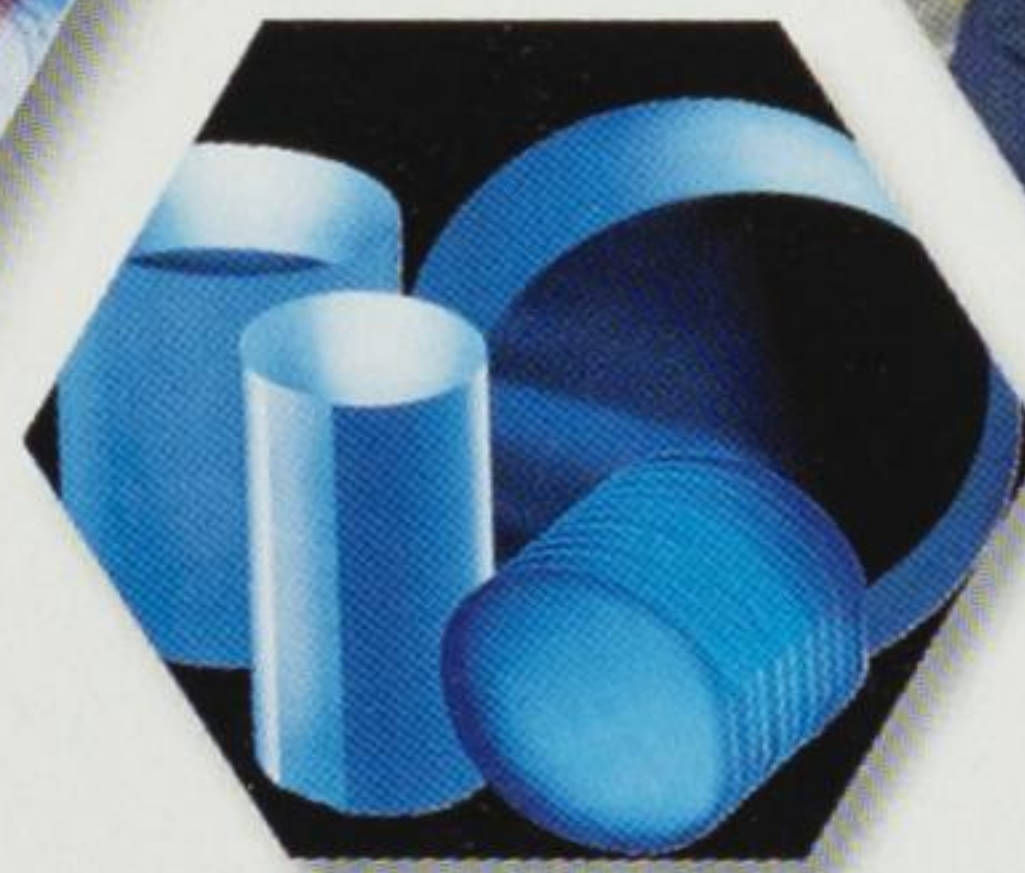
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LIGHT-EMITTING DIODES

Mirror adhesion technique boosts LED chip brightness

Donald Huo and colleagues from Epistar Corporation describe a new mirror adhesion technique for producing high-brightness and high-power AlGaInP LED chips.

One of the main reasons that high-brightness LEDs have yet to penetrate a variety of new applications is that the cost per lumen is still too high. There are two ways to expand the market: improving the external light efficiency; or reducing the manufacturing cost.

Improvements in epitaxial growth and device processing have pushed LED internal quantum efficiencies close to the limit, particularly for AlGaInP devices. Extracting more internally generated light from the device is the major challenge for the future.

There are many ways to improve extraction efficiency in AlGaInP devices. These include replacing the absorbing GaAs substrate with a non-absorbing substrate such as GaP, changing the chip geometry, using surface texturing or growing a semiconductor DBR.

Although DBR layers can reflect most of the light normal to the incident direction, they are non-reflective at oblique angles of incidence, which results in optical losses.

Besides such light trapping issues, AlGaInP and AlGaInN LED epitaxial films are grown on GaAs and sapphire substrates, respectively. These are poor materials for thermal dissipation, limiting the device's drive current and its resulting light output.

In 1994, Hewlett-Packard introduced the first commercial AlGaInP LED on a transparent GaP wafer fabricated using direct wafer bonding. Since then, several interesting metal-bonding techniques have been successfully developed by Osram, Sanken, Oriol, VPEC and UEC. These involve the transfer of epitaxial layers to an electrically and thermally conductive substrate.

However, very few of those devices are in mass production and commercially available. The problems may be due to the difficulties in preventing reactions between the reflector metals, the solder materials and the epitaxial layers, while at the same time overcoming adhesion problems.

Comparison of wafer-bonding techniques

	<i>Direct wafer bonding</i>	<i>Eutectic metal bonding</i>	<i>Omnidirectional mirror adhesion (OMA)</i>
bonding temperature	high	relatively high	medium
bonding agent	none	soldering metal	organic dielectric
film bonding pressure	high	high	high
substrate	GaP	conductive silicon	silicon
reflector	none	metal	metal
reaction between reflector and bonding agent	n/a	possibly	no

Table 1. Epistar's OMA technique uses an organic bonding layer to prevent problems that can occur in alternative eutectic metal bonding processes.

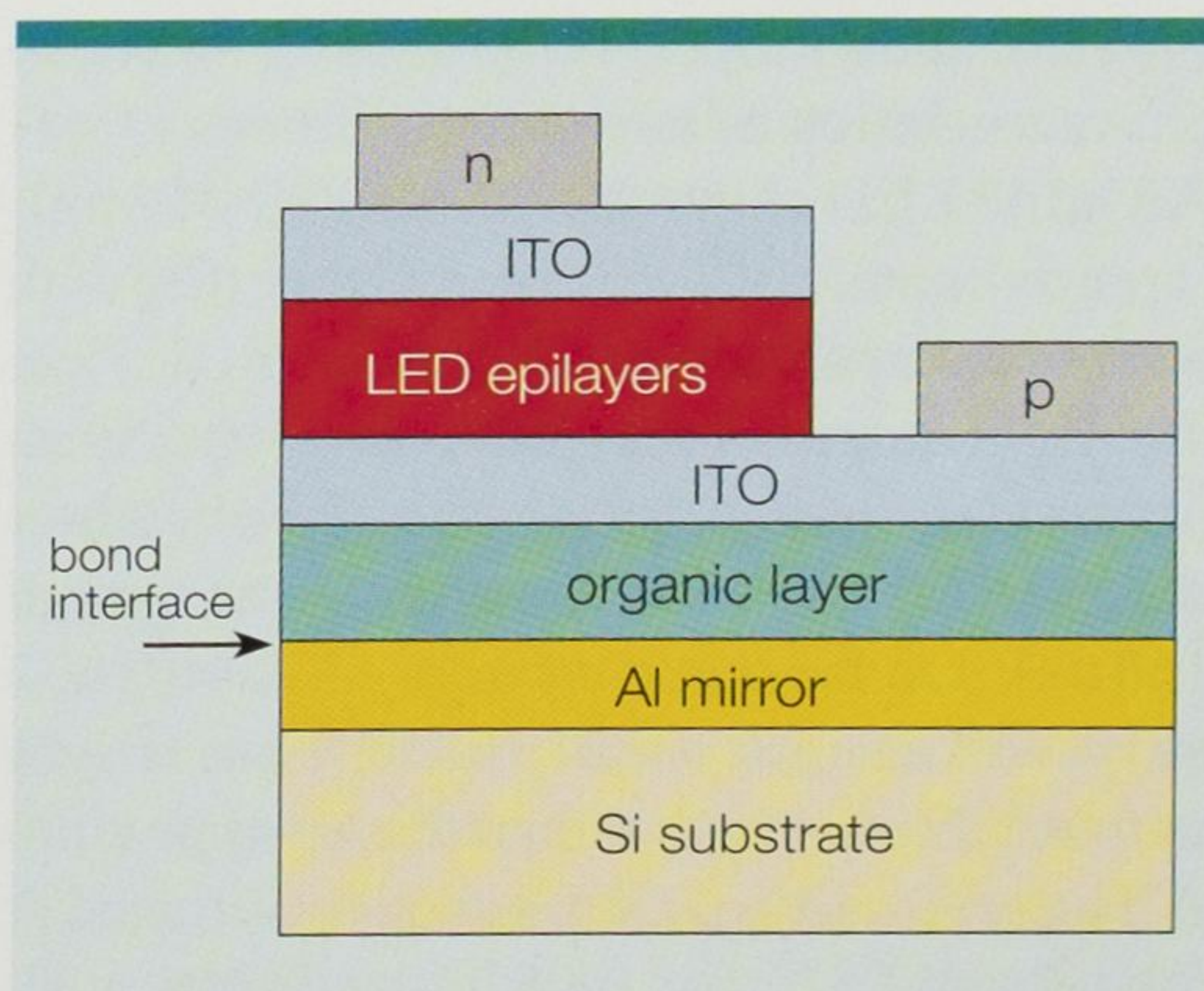


Fig. 1. Cross-sectional view of the AlGaInP high-brightness OMA chip.

Omnidirectional mirror adhesion

Epistar Corporation has recently developed a novel technique, omnidirectional mirror adhesion (OMA), to mass-produce a new type of AlGaInP LED. The extraction efficiency of the new device is improved by reflecting the downward light using a metal mirror. OMA LEDs are made using existing equipment and there is virtually no restriction on output capacity.

To eliminate the chance of reactions between the reflector metal and the solder materials, a high-temperature stable organic film is used as the bonding agent instead of a solder metal. Also, n and p ohmic contacts are fabricated on the same side of the chip to pro-

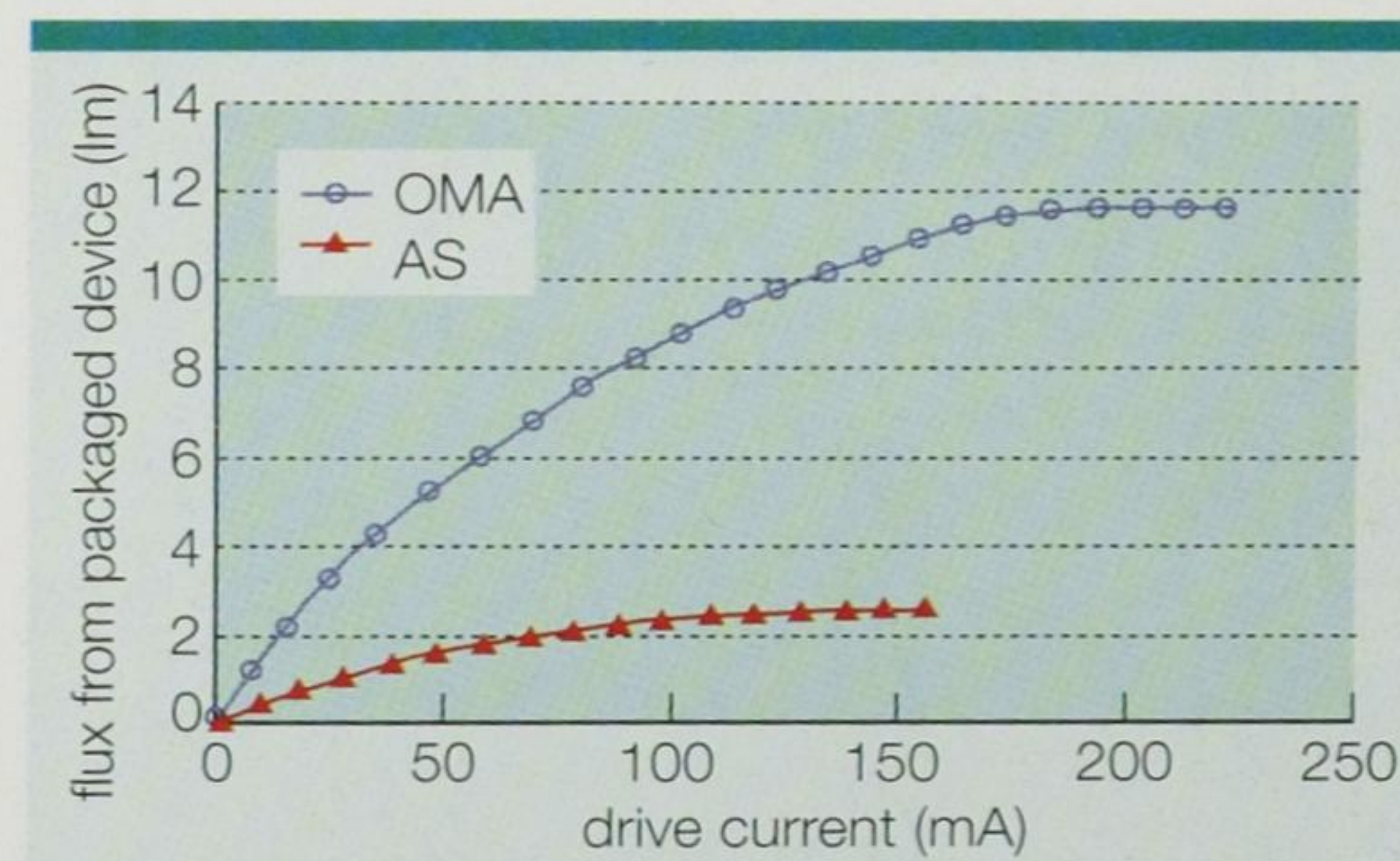


Fig. 2. L-I characteristics of the 615 nm high-brightness AlGaInP OMA chip, compared with a standard absorbing-substrate (AS) device. Both chips measure $12 \times 12 \text{ mil}^2$ (approximately $300 \times 300 \mu\text{m}^2$).

vide more freedom of substrate selection and to build a platform for flip-chip applications.

Table 1 compares direct wafer bonding, eutectic metal bonding and OMA techniques. One of the key advantages of OMA is the relatively low bonding temperature.

Figure 1 shows an OMA high-brightness AlGaInP LED chip. To fabricate the device, an ITO film with a thickness of $3000 \text{ \AA}$ is deposited on top of the AlGaInP-on-GaAs epi-wafer. Then a film of commercially available organic material is laid on top of the ITO layer. This wafer is then bonded to a silicon substrate covered with an Al layer that acts as the reflector. After bonding, the light-absorbing GaAs

LIGHT-EMITTING DIODES

High-power OMA AlGaInP LEDs

LED size		Light output		Saturation
(mil)	(μm)	Flux (lm)	Forward current (mA)	current (mA)
12 × 12	300 × 300	6.5	70	200
22 × 22	560 × 560	14.4	150	550
40 × 40	1020 × 1020	44.5	500	1500

Table 2. Epistar's production $300 \times 300 \mu\text{m}^2$ devices produce 6.5 lm, while larger devices have been developed with a much higher light output.

substrate is removed by chemical etching, and a $3000 \text{ \AA}$ thick ITO film is deposited to form the n-side transparent electrode. The p contact area is then patterned and etched to stop at the ITO layer. The p and n ohmic and bonding metals are then deposited. After probing, the bonded device wafer is sawn into individual discrete devices.

The advantage of the OMA technique is that the reflectivity of the metal mirror is extremely high, even after bonding and ohmic contact formation. With metal bonding, on the other hand, the reflectivity of the mirror may be reduced during the bonding process. As a result, OMA improves the light extraction efficiency.

Device characterization

Figure 2 shows the L-I (luminosity-current) characteristics of a high-brightness OMA AlGaInP LED chip with a size of $12 \times 12 \text{ mil}^2$ (approximately $300 \times 300 \mu\text{m}^2$) together with a standard absorbing-substrate (AS) device. The light output of the OMA chip, which saturates at around 200 mA, is 3 times brighter than the AS type, which saturates at around 160 mA. On the other hand, an AlGaInP LED chip with a semiconductor DBR has a light output 1.7 times higher than the AS-type chip.

The reliability of OMA chips was tested at 50 mA and 55°C for 1000 h; the results were comparable to standard AS-type chips with only slight changes in light output after 1000 h operation. Epistar has also performed harsh thermal cycle testing for evaluation of the bonding interface. The results indicate that despite the use of an organic adhesion layer, the bonding interface is very robust and no failures have been observed.

Large-area chips

Recently, large-sized power LED chips have also attracted lots of attention. They have found applications in outdoor signage, traffic signals, automotive exterior lighting, and medium- to large-sized LCD backlighting. They will eventually be used in general illumination. Epistar has just completed the development of two different sizes of LED

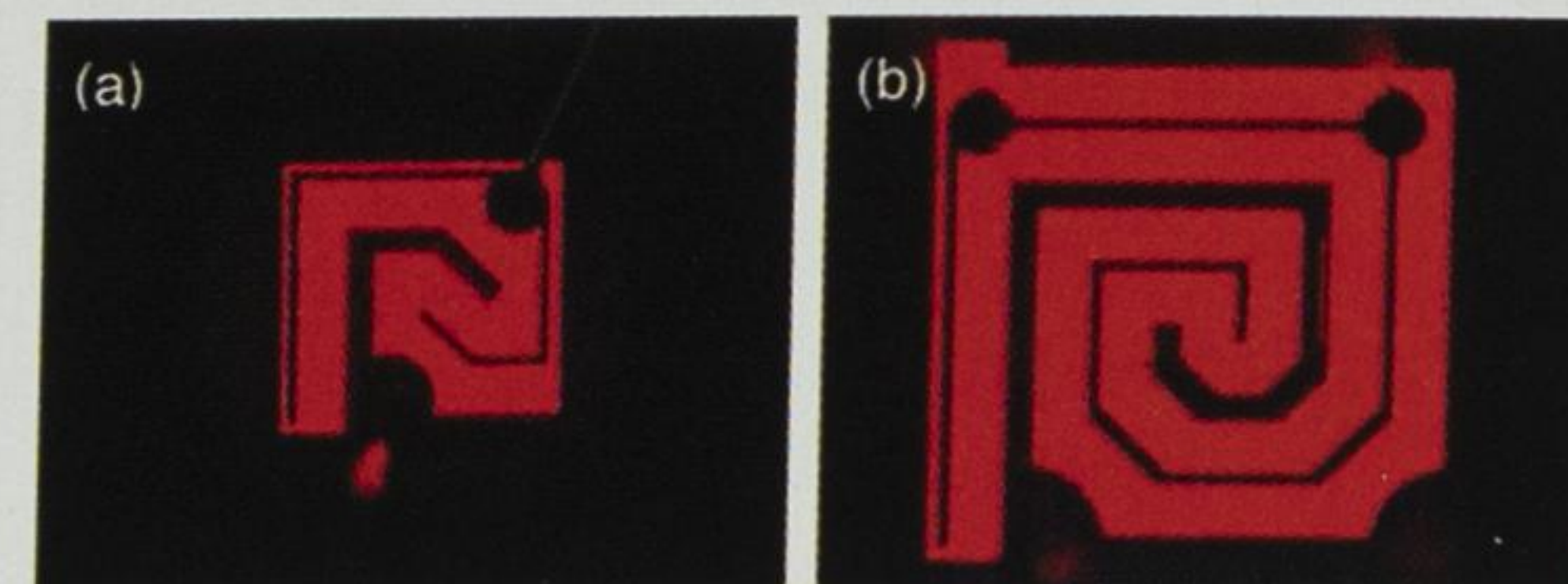


Fig. 3. Top view of two large AlGaInP high-brightness OMA chips. (a) A $22 \times 22 \text{ mil}^2$ chip driven at 0.2 mA. (b) A $40 \times 40 \text{ mil}^2$ chip driven at 1.0 mA. Low drive currents were used in order to demonstrate the quality of the illuminated areas of the chips.

chip with areas of $22 \times 22 \text{ mil}^2$ (approximately $560 \times 560 \mu\text{m}^2$) and $40 \times 40 \text{ mil}^2$ (approximately $1 \times 1 \text{ mm}^2$). Figure 3 shows the top view of two OMA high-power AlGaInP LED chips, driven with a low current to show the quality of the lighting areas.

Table 2 shows the luminosity of the high-power AlGaInP LEDs at three different chip sizes. The largest chip ($1 \times 1 \text{ mm}^2$) generated a light output of 44.5 lm at a drive current of 500 mA, and had a saturation current of 1.5 A. In reliability tests, the $22 \times 22 \text{ mil}^2$ OMA high-power chips were driven at 150 mA on a PC board at 25°C for 1000 h. The results again showed excellent behavior, with the light output dropping to 95% after 100 h operation and to about 92% after 1000 h.

Future work

Having successfully developed this high-power AlGaInP LED chip technology, Epistar commenced mass production of the devices in the fourth quarter of 2003. To further improve the drive current limitation, the company has modified the OMA technique to replace a large portion of the silicon substrate with plated copper; this improves the thermal conductivity for higher-power applications. The new AlGaInP high-power LED devices with copper-plated silicon substrates will be ready for sampling in early 2004.

Donald Huo, M-H Hsieh, W-H Lin, T-F Tseng, J-S Wang and M-J Jou are with Epistar Corporation, Hsinchu, Taiwan. Web: www.epistar.com.tw.

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ICSCRM underlines good progress in SiC technology

This year's ICSCRM highlighted the significant steps that have been taken recently towards broadening the range of SiC devices available off the shelf. **Jon Newey** reports.

The recent International Conference on SiC and Related Materials (ICSCRM 2003) illustrated very well that two years is a long time for a fledgling technology. Many of the 500 delegates gathered in Lyon, France, over October 5–10, 2003 were at the last ICSCRM in Japan in 2001, when Infineon and Cree had just begun to compete as the first two companies to commercialize SiC Schottky diodes. Since then, successive generations of SiC Schottkys have been released, handling greater levels of power. Rohm is just about to enter into SiC Schottky production, and Cree and Rockwell Scientific have released commercial SiC MESFET products. Behind the scenes there has been rapid progress in SiC R&D labs. Bulk and epitaxial material quality has improved, something that device developers have taken full advantage of, and new processing strategies are helping to overcome old barriers to progress.

Given the still limited commercialization of SiC devices, the fact that so many delegates attended illustrated the strong level of funding being invested in SiC R&D. The funding given to SiC and other wide-bandgap semiconductors by the US Department of Defense was perhaps reflected in the fact that more than 100 delegates were from the US, with Japan having a similar number, and France and Germany accounting for 90 and 60 respectively. As well as established SiC players such as Cree, II-VI and Okmetic, the exhibit featured some new faces, including SemiSouth, Bandgap Technologies and Dow Corning, which acquired SiC substrate manufacturer Sterling Semiconductor in January 2003.

Micropipes are history

Cree's Don Hobgood gave the opening talk of the conference, bringing the audience up to date on the state of the art in SiC substrates, the impact this has had on devices, and the issues that are now being tackled. Micropipes have been the main issue for substrates for some time, but recent progress is changing

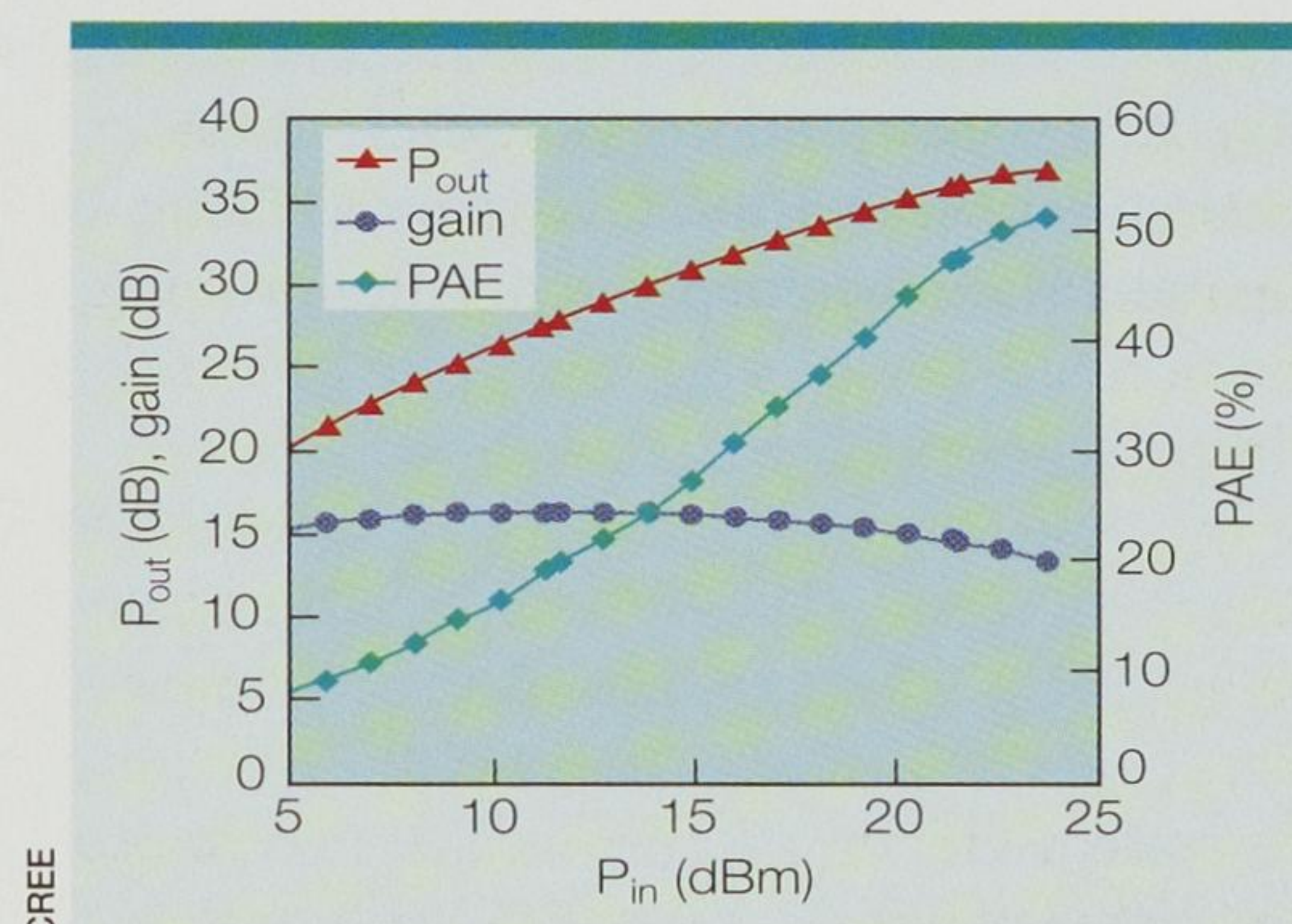


Fig. 1. Cree's AlGaIn/AlN/GaN HEMT uses field plate technology and an AlN barrier which increases mobility in the GaN channel. Operating at 4 GHz and V_d of 82 V, the maximum output power density is 20.4 W/mm with 51% PAE.

this. Cree's best result was a 75 mm 4H wafer with just 10 micropipes. To put this in perspective, 10 A Schottky diodes fabricated using 75 mm wafers with a micropipe density of $0.45/\text{cm}^2$ would have a yield of 97%, and the yield for larger 100 A devices would be 79%. The current best micropipe density for 100 mm 4H-SiC wafers is $22/\text{cm}^2$. While 10 A device yield on such a wafer would drop to 67%, it would still provide 970 good devices, far more than the very best 3 inch material. The economics of manufacturing may well dictate that large-area wafers with more micropipes are good enough for many device types, although material scientists might not be happy until micropipes are a thing of the past.

Given the problems of forward voltage drift in bipolar devices (see "Bipolar devices" overleaf), basal plane dislocations are replacing micropipes as the enemy on the battlefield. The density of these defects in current best material is 10^3 – $10^4/\text{cm}^2$, and their presence in epilayers has been linked to the formation of stacking faults in the thick epitaxial drift layers of bipolar devices under stress conditions.

The best-performing AlGaIn/GaN HEMTs have been those fabricated on SiC substrates

thanks to their high thermal conductivity and closer lattice match to GaN than sapphire or Si substrates. Highlighting the link between good substrates, high-quality epitaxy and device performance, Hobgood described some impressive figures from an AlGaIn/AlN/GaN HEMT grown on a 75 mm semi-insulating SiC wafer. The sheet resistance of the epi structure grown onto a Fe-doped buffer was $280 \Omega/\square$ with less than 1% standard deviation across the wafer. The HEMT, fabricated using a field plate on the gate electrode and an AlN barrier layer above the GaN channel, operated at 4 GHz and had a current density of 20.4 W/mm with 51% PAE at 82 V (figure 1). If GaN-based devices can handle such power density, why is there such interest in SiC? John Palmour, Cree's executive VP of advanced devices, put the case for SiC succinctly in the Industrial News session: "SiC is very reliable at high powers, but the reliability curves for GaN devices are still horrible. We are interested in both materials, but in the meantime we need to sell something."

MOSFETs and channel mobility

The development of SiC MOSFETs has been hampered by poor oxide reliability and low channel mobility. The low channel mobility is mainly the result of a high density of interface states near to the conduction band, which trap or scatter the carriers. The subject of MOSFETs and the oxide/SiC interface was widely discussed and fortunately reflected some good progress since ICSCRM 2001.

Dietrich Stephani of SiCED in Germany gave a plenary talk reviewing the progress, outstanding issues and current state of MOSFET development at SiCED, which has resulted in the demonstration of a vertical device with a blocking voltage of 3 kV. In blocking mode, the normally off device showed a leakage current of $<10 \mu\text{A}$ at 3 kV and $<10 \text{ nA}$ at 2 kV. The on resistance of the 2.4 mm^2 device was 3Ω at 25 °C, rising to 4.9Ω at 150 °C where such a device would be

likely to operate.

Cree's Mrinal Das discussed recent advances in MOS device performance that have come about through oxidation techniques and post-oxidation N_2O or NO anneals. Nitridation is thought to increase mobility through the passivation of interface states. Post-oxidation nitridation anneals also result in the oxidation of the underlying SiC surface, and eventually the passivation effect is offset by increased disorder at the SiC-oxide interface. Das described the development at Cree of what he called "pure nitridation", whereby the oxidation of the SiC is suppressed. This has resulted in the density of interface traps (D_{it}) falling below $10^{11}/eV/cm^2$. Lateral MOSFETs fabricated on the (0001) face using the pure nitridation process showed greatly enhanced performance over those with the standard N_2O nitridation. This included lower threshold voltages and a channel mobility of $73 cm^2/Vs$. Das expects that a further optimization of the nitridation now under way will result in a mobility figure of $100 cm^2/Vs$. Accelerated lifetime tests on MOS capacitors using this process indicated >100 years of reliable operation at $300^\circ C$.

Continuing the nitridation theme, Einar Sveinbjornsson of Chalmers University in Sweden discussed the development of a 4H-SiC device with channel mobilities up to $150 cm^2/Vs$. The oxide was grown in an N_2O ambient and devices without the N_2O -grown oxide were also made for purposes of comparison. D_{it} figures extracted from C-V curves for the two types of devices showed that the oxide growth in N_2O halved the D_{it} . It was unclear if the growth in N_2O passivated the traps or if it lowered the probability of traps forming. Interestingly, the group observed that a post-oxidation anneal in N_2O increased D_{it} , perhaps backing up the theory of increased disorder at the SiC-oxide interface mentioned in Das's talk. D_{it} was also seen to increase following the RTP of ohmic contacts, although a later slow anneal had no effect. The fast temperature ramp in the RTP possibly has a detrimental effect on the SiC-oxide interface. Devices without the RTP of the contacts showed up to $150 cm^2/Vs$ mobility, but the contact resistivity was two orders of magnitude above that of contacts formed using a normal RTP step. The group is now working to simultaneously achieve the high mobility figure and good ohmic contacts.

Apart from nitridation, processing devices on alternative crystal faces to the normal (0001) has been shown to increase mobility

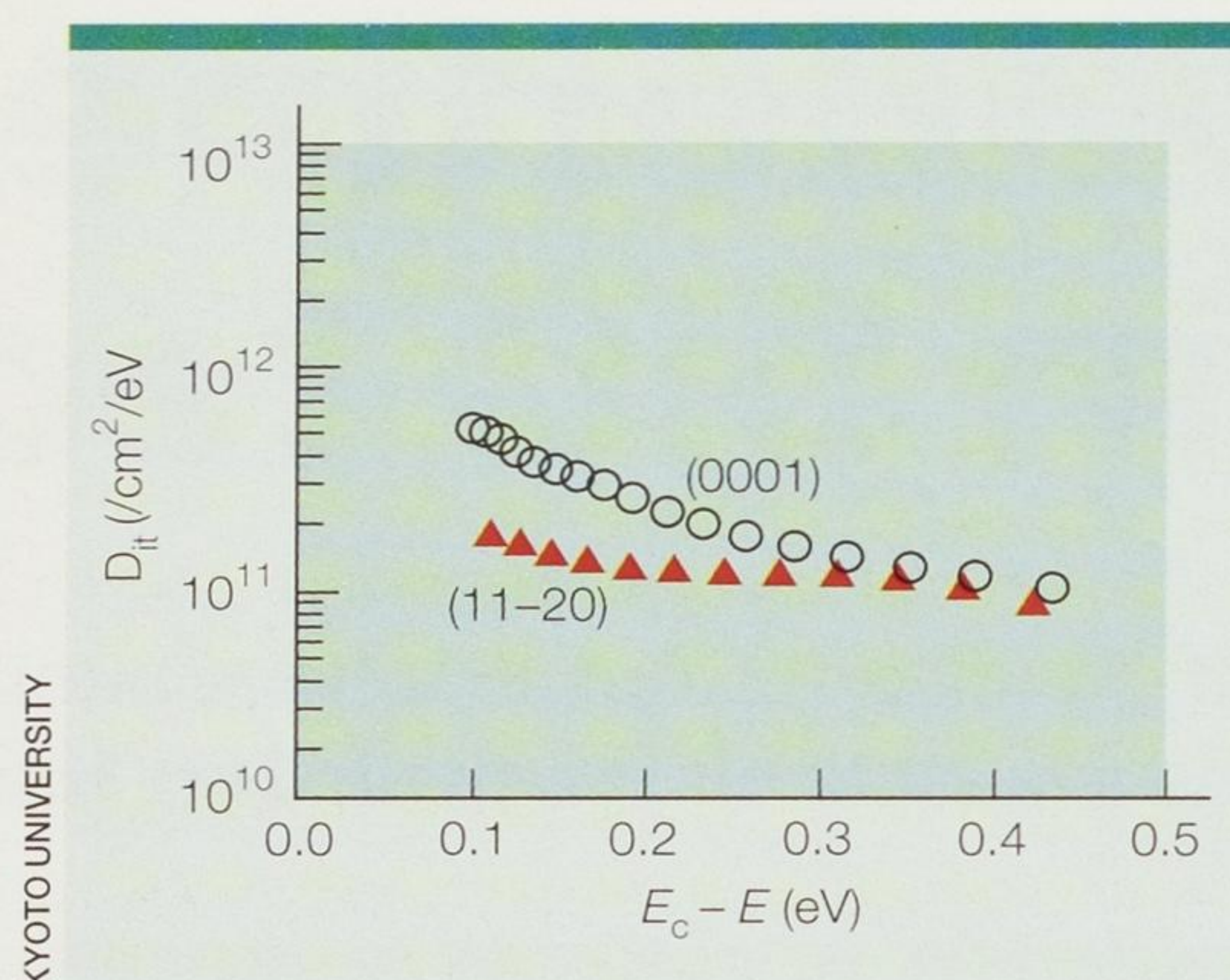


Fig. 2. The distribution of interface state density (D_{it}) for 4H-SiC (0001) and (11 $\bar{2}$ 0) n-type MOS structures.

One of the outstanding issues facing bipolar devices and a key to their commercialization is reliable junction termination.

through the reduction of interface traps (figure 2). Much of this work has been on low-doped material with mobilities over $200 cm^2/Vs$ reported. Y Kanzaki of Kyoto University described his group's studies on 4H-SiC (11 $\bar{2}$ 0) channels combined with N_2O annealed oxide and using highly doped material which is required for high-power devices such as the 3 kV devices described by Stephani. MOSFETs were made on (11 $\bar{2}$ 0), (0001) and (000 $\bar{1}$) epilayers with p-type doping in the $7 \times 10^{15} - 2 \times 10^{17}/cm^3$ range. In (0001) channels mobility was low at 17 and $8 cm^2/Vs$ for doping of 10^{16} and $10^{17}/cm^3$. In contrast, the 11 $\bar{2}$ 0 devices showed high mobility even for high doping, with mobilities of 70 and $54 cm^2/Vs$ for doping at 10^{16} and $10^{17}/cm^3$ respectively. It is thought that electron trapping and scattering is more pronounced at high doping levels, meaning that the much higher D_{it} near to the conduction band in (0001) material results in much lower mobility than for the (11 $\bar{2}$ 0) material, which exhibits fewer interface states near to the conduction band.

Epitaxial growth

Epitaxial growth featured in three dedicated sessions. Phil Neudeck of NASA gave the delegates an update on his group's development of atomically flat on-axis epitaxial layers

using a mesa and cantilever growth method. This is now producing step-free mesa surfaces up to $0.4 \times 0.4 mm^2$. A Shoji of the Kyoto Institute of Technology in Japan discussed the growth of 3C-SiC on silicon using pendeo epitaxial growth, a technique already established for growing high-quality GaN on non-native substrates.

While off-axis growth has become well established for high-quality epitaxy, it is not ideal as fewer off-axis substrates can be cut from a boule, and the high density of growth steps on the surface of an off-axis substrate increases the probability that the epilayer will copy crystal faults in the substrate. Christer Hallin of Linköping University in Sweden reported on the development of a method for on-axis growth of SiC on 4H- and 6H-SiC substrates, which has resulted in $30 \mu m$ thick epilayers on 4H and 6H material with comparable surface quality to layers grown on off-axis substrates.

Bipolar devices

One of the outstanding issues facing bipolar devices and a key to their commercialization is reliable junction termination. Good edge termination means that a thinner i-layer (drift layer) can be used to withstand a given blocking voltage. Igor Sankin of SemiSouth Laboratories in Starkville, MS, reported on work to fabricate 4H-SiC *pin* diodes with junction termination extensions (JTEs) formed by implantation of B^+ or Al^+ .

The diodes had $10 \mu m$ epitaxial drift layers and p^+ epitaxial anodes. Devices with 100 and $200 \mu m$ JTEs were fabricated. Both B- and Al-implanted JTEs showed sharp breakdown with yields above 80% at over 1.7 kV. Current density was $1.2 kA/cm^2$ at a forward voltage (V_f) of 5 V, and $6.5 kA/cm^2$ at 8 V. The reverse leakage current at low to medium voltages was proportional to the perimeter of the JTE region. At higher voltages ($<1000 V$), the leakage became a function of the entire device diameter. The performance of Al JTE devices with various epitaxial layer parameters matched simulated results, indicating the reproducibility and scalability of the JTE process.

Great advances have been made in the quality of the epitaxial layers required to grow drift layers up to $200 \mu m$ thick in high-voltage *pin* diodes. High-quality epitaxy results in better V_f stability, reduced reverse leakage and higher carrier lifetimes. Cree's Das discussed the problems of V_f drift, widely accepted to be the result of stacking fault generation and

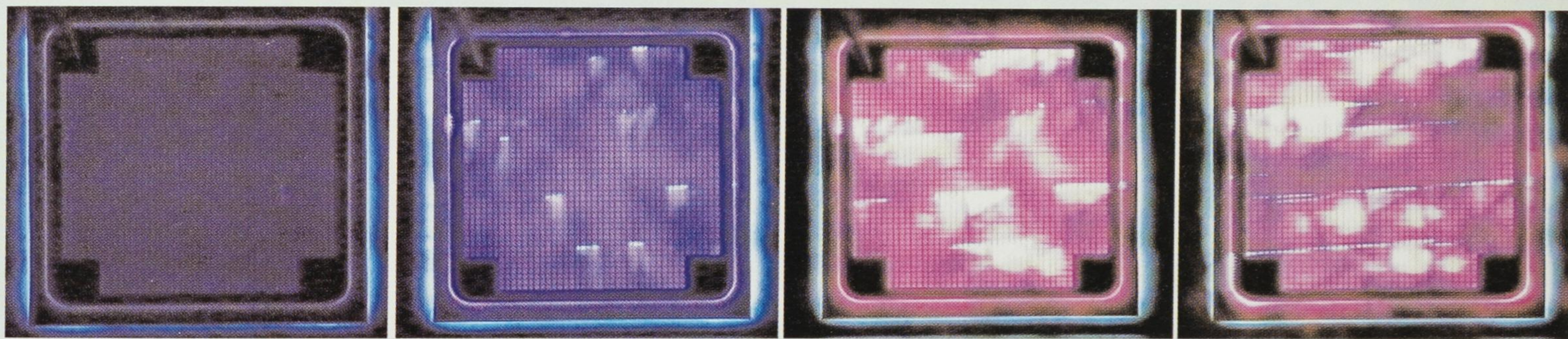


Fig. 3. Electroluminescence of stacking fault generation during the turn-on of a *pin* device with a 100 μm drift layer. The images from left to right represent start-up, 0.25, 0.5 and 0.8 A and the forward voltage drift is 6–12 V.

propagation through the drift layer, which increases resistance and therefore results in a higher voltage drop (figure 3). He described devices with high-quality 100 μm drift layers and 2 μm p^+ anode layers, and B-implanted JTEs on (11 $\bar{2}$ 0) and (0001) material. The (11 $\bar{2}$ 0) devices under 100 A/cm^2 stress for 100 h showed a V_f drift of less than 100 mV, but breakdown strength of material on this orientation is poor. Large-area 7.5 A devices on (0001) material gave 10 kV blocking voltages. At 7.5 A the forward voltage was a record low

at 3.74 V. Packaged devices were stressed for 50 h with 20% of the devices exhibiting V_f drift of less than 100 mV.

Epi quality and stacking faults came under further scrutiny from Bob Stahlbush of the Naval Research Laboratory in Washington, DC. The origin and development of stacking faults was tracked using light emission images under low-current conditions (0.1 A/cm^2), with each image taken after 0.2 s periods of stress at 34 A/cm^2 . Stahlbush showed a movie of the formation and development of these

faults, and from a careful analysis of the image was able to draw conclusions on the mechanism for propagation. An important conclusion was that stacking fault growth is driven by the response of dislocations to internal stresses, and not by the lowering of electronic energy as the stacking fault grows, as has been previously suggested. The observation from the images that the faults move at different rates was attributed to their natural response to mechanical tensile and compressive stresses in the SiC. ●

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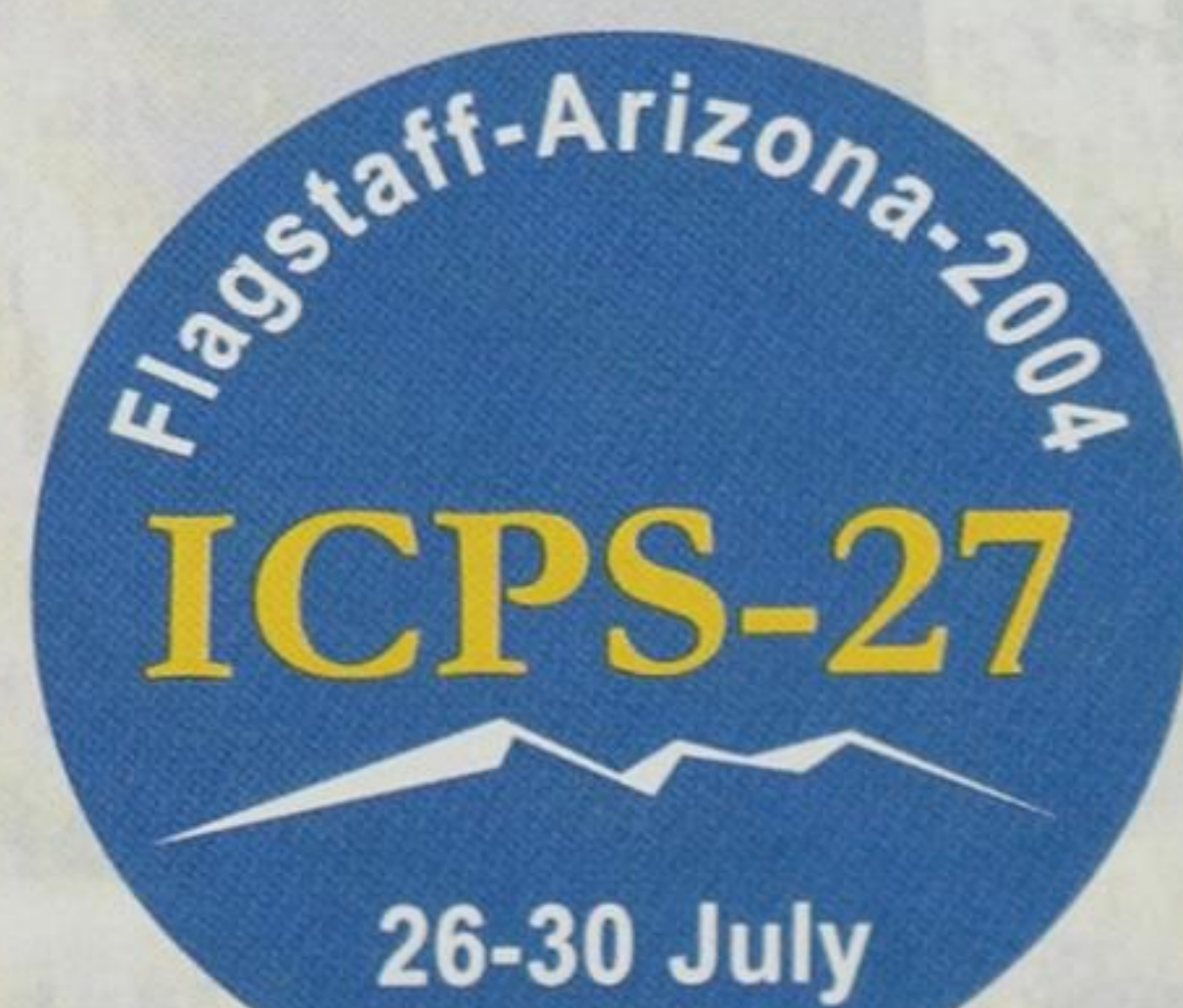
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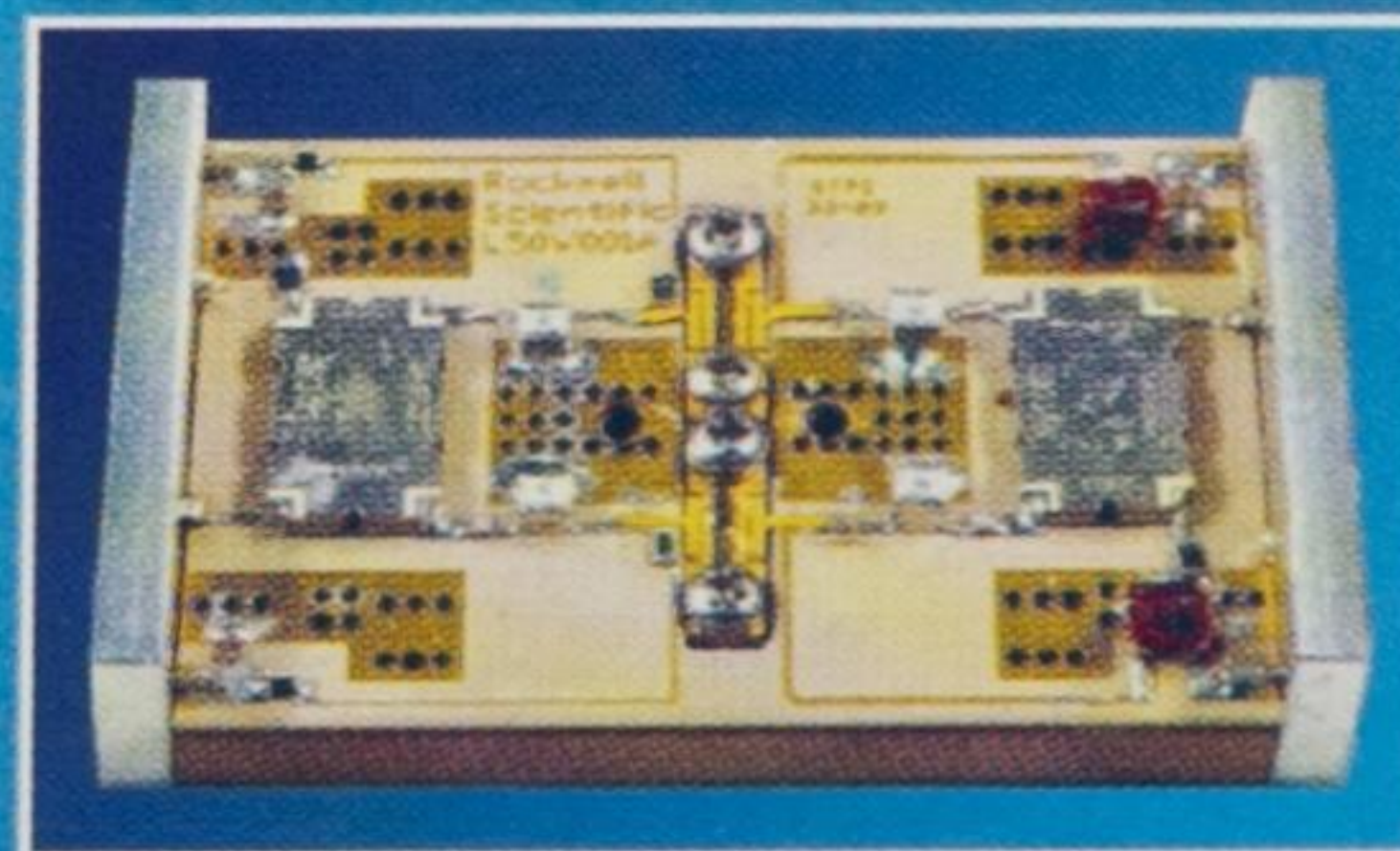


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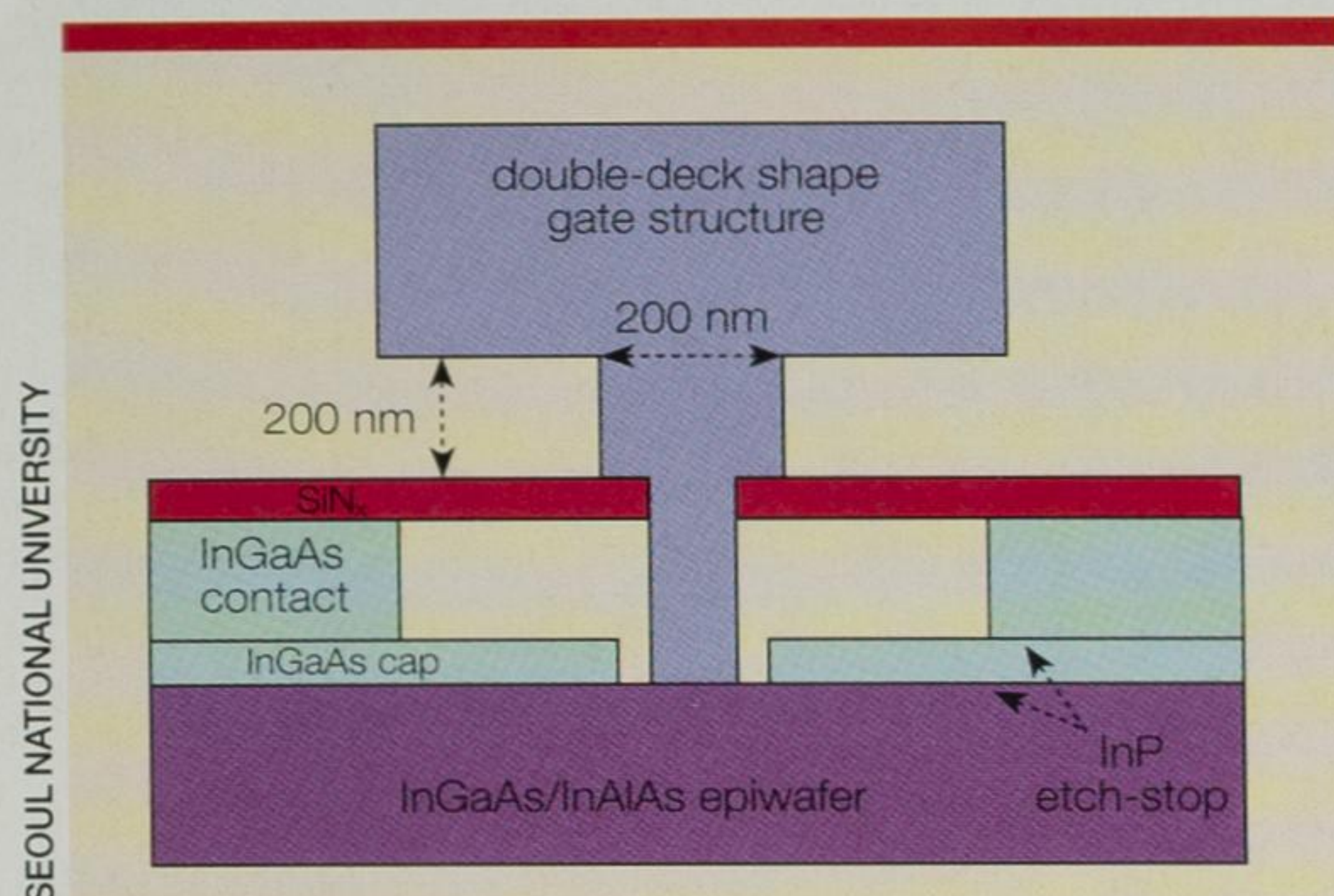


Fig. 1. The double-deck gate structure in this HEMT reduces gate fringing capacitance by heightening the gate foot.

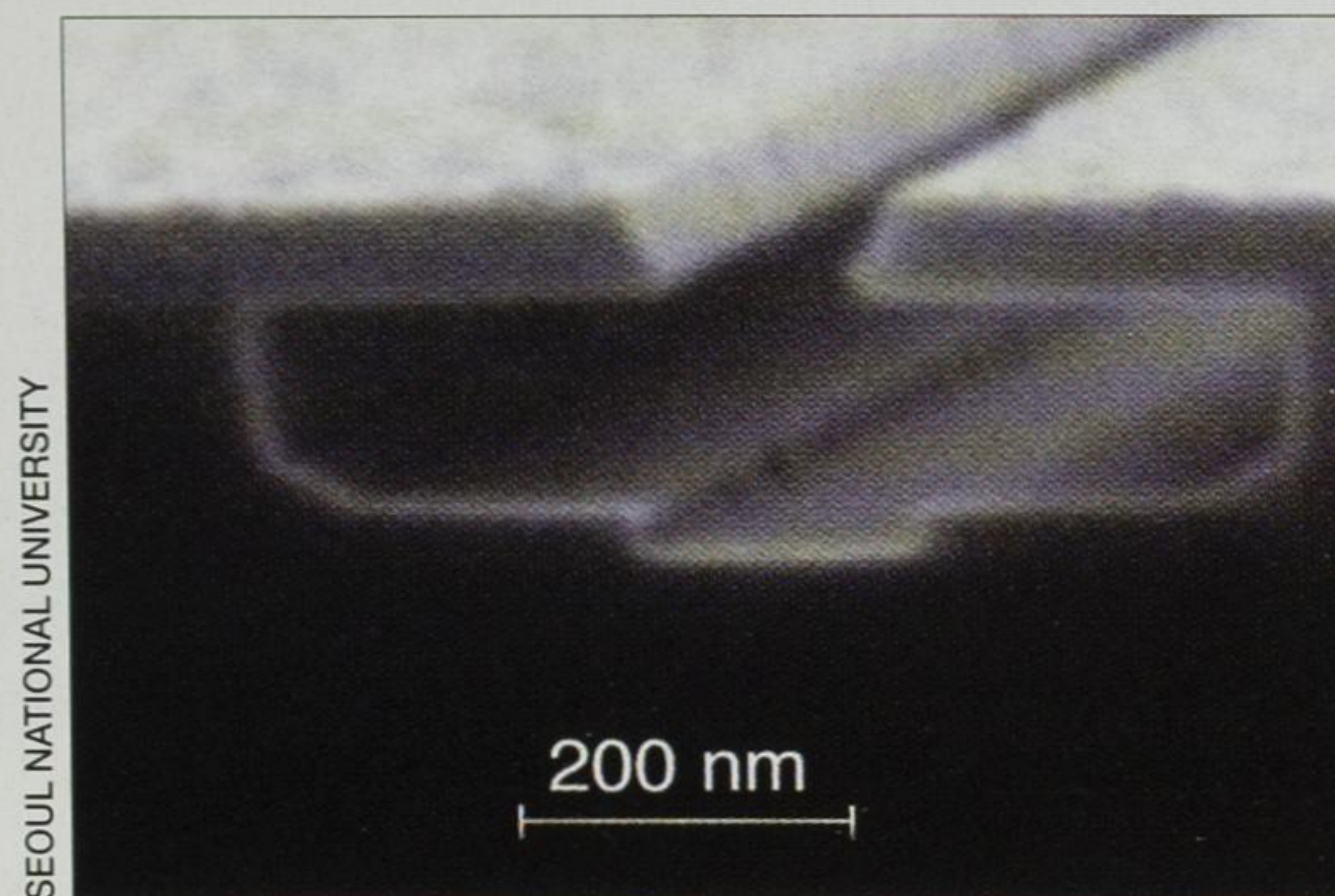


Fig. 2. An SEM image of the etched gate recess with overhanging SiN layer shown before the metal gate is formed.

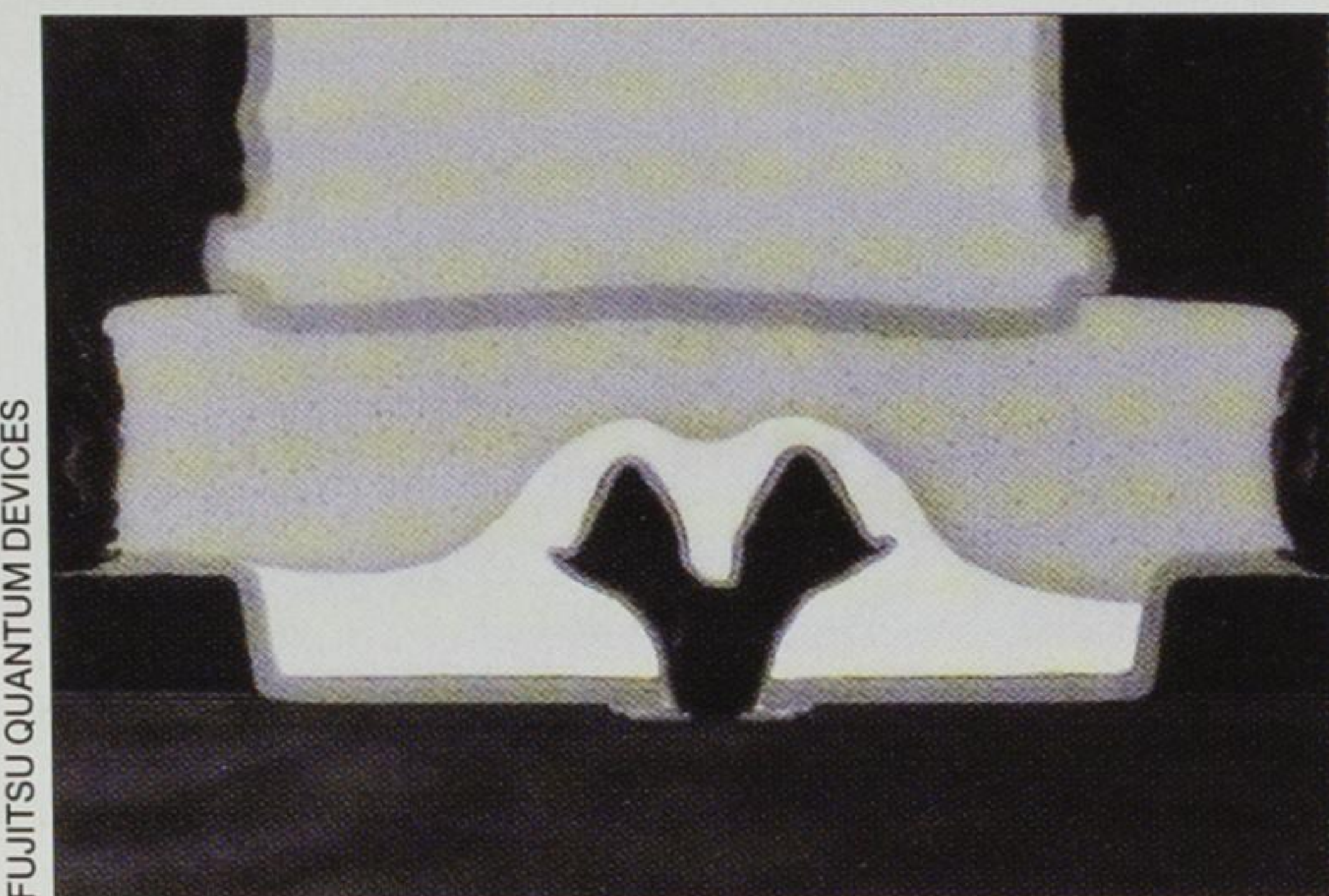


Fig. 3. A TEM cross-section of the cave-structure HEMT with the dielectric removed from around the gate.

Although dominated by papers covering advances in silicon-based devices, the International Electron Devices Meeting (IEDM), held December 8–10 in Washington, DC, also included contributions from the III-V and III-nitride communities.

Researchers are paying particular attention to the elimination of parasitics in III-V HEMTs as the reduction of gate length on its own is no longer enough to keep the performance of these devices advancing. There were two papers devoted to the subject which put forward novel HEMT architectures for minimizing parasitics in sub-0.15 μm devices. A paper from Dae-Hyun Kim and colleagues from **Seoul National University** in South Korea described a double-deck 0.13 μm T-gate HEMT which significantly reduced gate fringing capacitance. This was achieved by making the pedestal of the T-gate higher through the etching of an additional 200 nm InGaAs capping layer which was deposited on top of the usual 20 nm InGaAs cap with 4 nm InP etch-stop layers above and below it (figure 1). The thick cap was covered in SiN before being etched to create a SiN overhang (figure 2). By etching through the lower InP etch stop, the device could be made to work in a quasi enhancement-mode which suppressed the gate-hole current generated by impact ionization. The low gate-hole current resulted in an increase in on-state breakdown voltage. Compared with InGaAs/InP devices with a standard gate design, the reduction in gate fringing capacitance in the double-deck structure resulted in a 22% improvement in f_t to 220 GHz.

Kozo Makiyama and colleagues from **Fujitsu Quantum Devices** also tackled gate parasitic capacitance to improve the operating speed of an InAlAs/InGaAs-based flip-flop circuit. To do this, the dielectric material that usually surrounds the gate electrode was removed, leaving the 0.1 μm gate in a cave of empty space bridged by the source and drain interconnect dielectric (figure 3). As a result, the gate-drain and gate-source capacitance that results from the gate encapsulating dielectric is significantly reduced. Compared with the standard structure, it was estimated that gate capacitance was 50% lower in the cave structure, which resulted in a 10% improvement in f_t to 270 GHz. A flip-flop IC using 100 HEMTs with the cave structure operated at 90 GHz, a more than 10% improvement over the same IC fabricated using conventional 0.1 μm HEMTs.

HEMTs with InAs channels are candidates for low-voltage MMICs and logic devices because of the high electron mobility and velocity in InAs. Y Royte and colleagues from **HRL Laboratories** reported a new

structure which has yielded a peak f_t of 308 GHz (the highest yet reported for InAs devices) at $V_{ds} = 0.7$ V. The metamorphic structure, grown onto an InP substrate, allowed lattice-matched growth of an InAlAs barrier layer before the InAs channel was grown. Using such barriers improves hole confinement compared with the AlSb barriers normally used, leading to higher breakdown voltages and output conductance.

More speed and power from III-nitrides

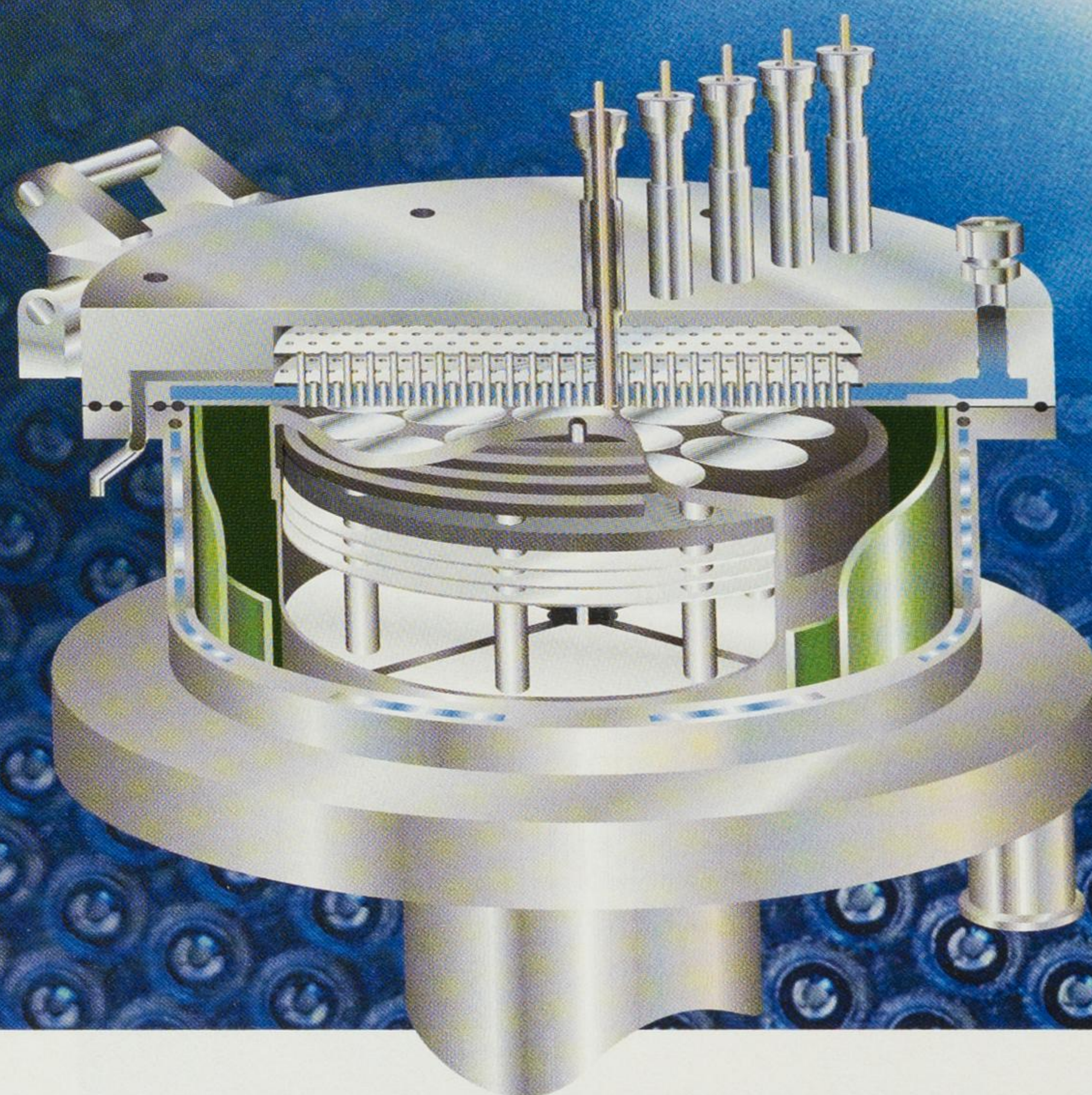
New device structures are also pushing up the performance of AlGaIn/GaN HEMTs. Field-plate structures have helped to increase the breakdown voltage of these HEMTs, but at the expense of gain due to increased capacitance (*Compound Semiconductor* August 2003 p21). Ando and colleagues from **NEC** in Japan reported a field-plate structure with the gate recessed into the AlGaIn layer, which helped to maintain the gain figure and also improved transconductance. For comparison, planar field-plate devices were also fabricated. Transconductance in the recessed device was 200 mS/mm compared with 130 mS/mm in the planar device. Power measurements for 1 mm wide packaged devices showed that the recessed device at 2 GHz with a drain bias of 66 V had a saturated output power of 12 W/mm with linear gain of 21.2 dB and a PAE of 48.8%. The 12 W/mm is thought to be the highest yet reported for GaN-based FETs at this frequency. The planar device at the same bias had a saturated output power of 10.3 W/mm, gain of 18 dB and a PAE of 47.3%. Gain was 3–7 dB higher for the recessed device over the entire range of drain bias (~10–66 V).

There is increasing effort being devoted to AlGaIn/GaN devices operating at frequencies well above those required for cellular base stations (*Compound Semiconductor* November 2003 p38). Ruediger Quay and colleagues from the **Fraunhofer Institute** in Germany discussed how AlGaIn/GaN HEMTs on SiC are showing early promise for operation in the V-band (50–75 GHz). The idea is that GaN can step in at these frequencies for applications where the output power of GaAs and InP devices is insufficient. The Fraunhofer group has developed dual-gate AlGaIn/GaN HEMTs with 150 nm gate lengths, optimized for V-band operation. At a drain-source voltage of 8 V, the transconductance was 371 mS/mm and the maximum drain current was 1300 mA/mm. At 60 GHz, the dual-gate devices had gains of between 13.5 and 12.5 dB for gate widths between 0.18 and 0.27 mm at a V_{ds} of 14 V. A 0.18 mm wide gate device at a V_{ds} of 15 V operating at 60 GHz had an output power density of 0.5 W/mm with an efficiency of 4.2%.

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IQE raises \$32 m in share placement

Wafer supplier IQE plc has raised £18 million (\$32 million) through a placement of 125 million new ordinary shares.

Despite suffering "poor visibility" in current trading conditions, the UK-based company says that it has seen recent signs of progress and secured several important contracts. In November, two major Asia-Pacific customers for laser epiwafers for optical storage applications (both CD and DVD) placed orders with IQE Europe for initial pilot pro-

duction quantities, and have indicated a production ramp through 2004.

IQE also said that while the optoelectronics market for communication devices has remained depressed for a considerable period, a number of customers are now indicating that inventory burn will be largely complete by the middle of 2004. Re-ordering is expected to begin in that time frame.

IQE's US subsidiary, IQE Inc, has been qualified over the last 12 months by four key

players in the wireless component supply chain that supply directly to handset manufacturers. However, visibility throughout the supply chain still remains relatively poor.

IQE's substrate manufacturing subsidiary, Wafer Technology, is seeing increasing demand for higher-margin products such as InP and InSb, and is currently expanding some parts of its manufacturing organization.

● Each of the four IQE subsidiary companies has now achieved ISO 9001:2000.

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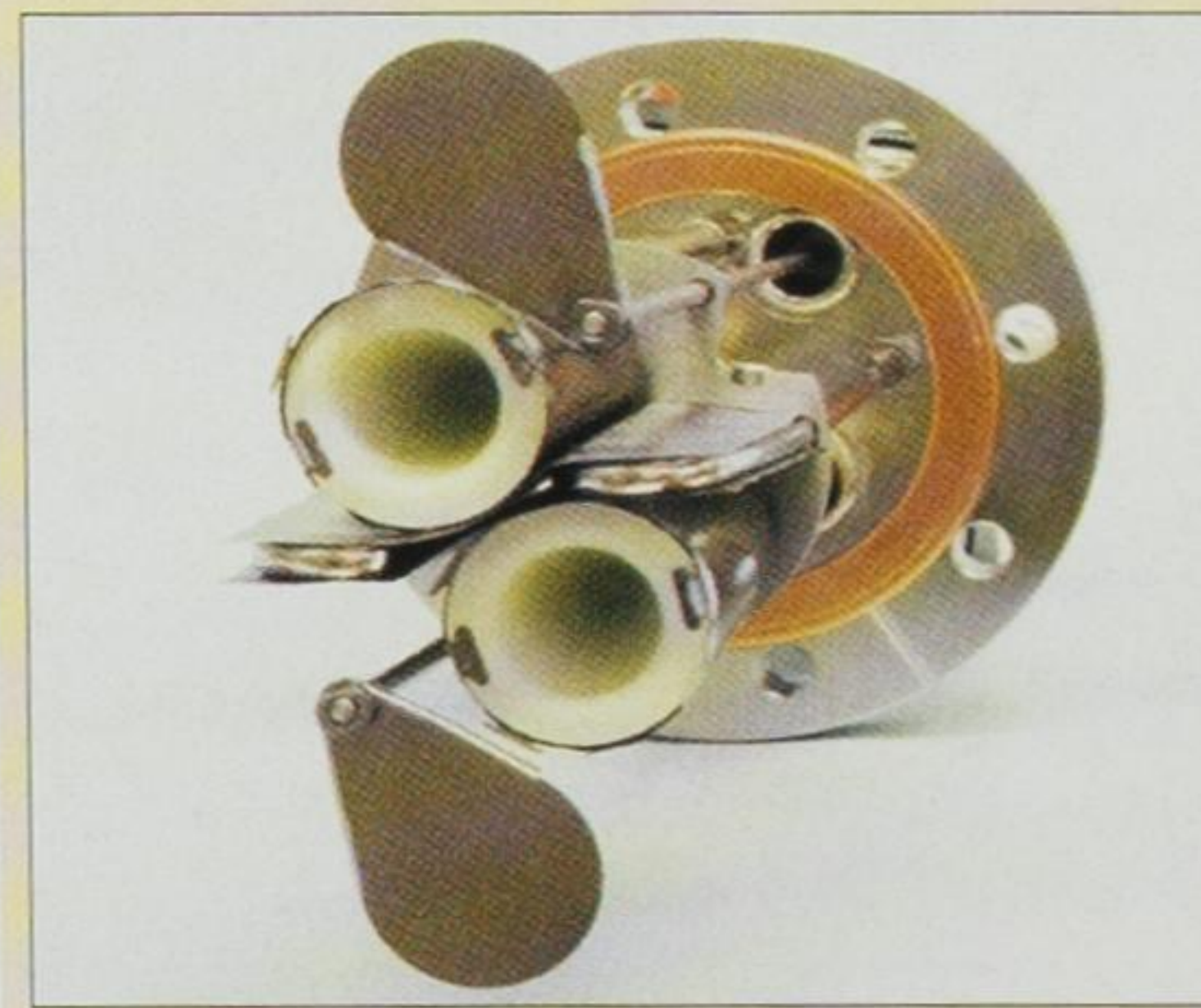
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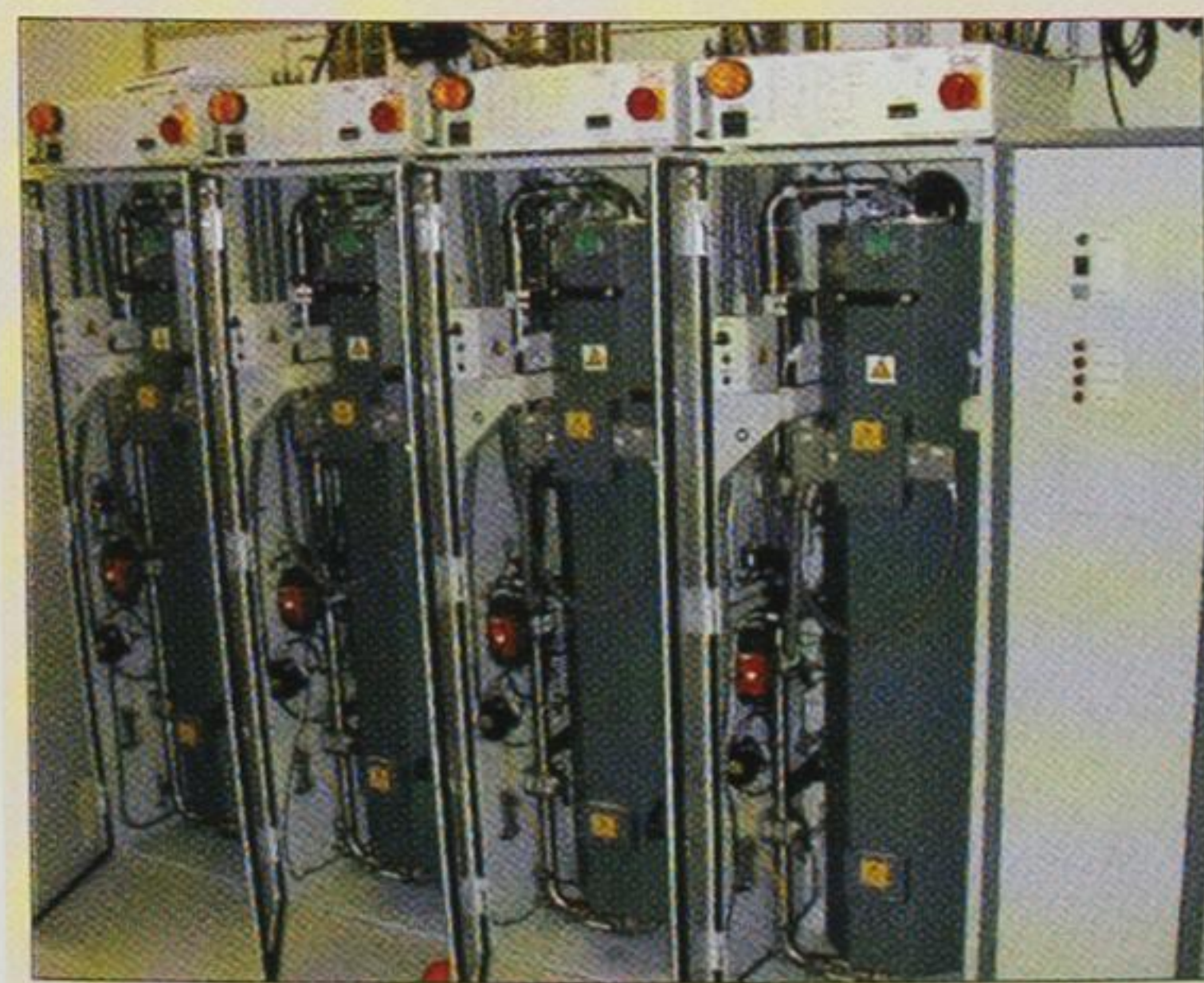


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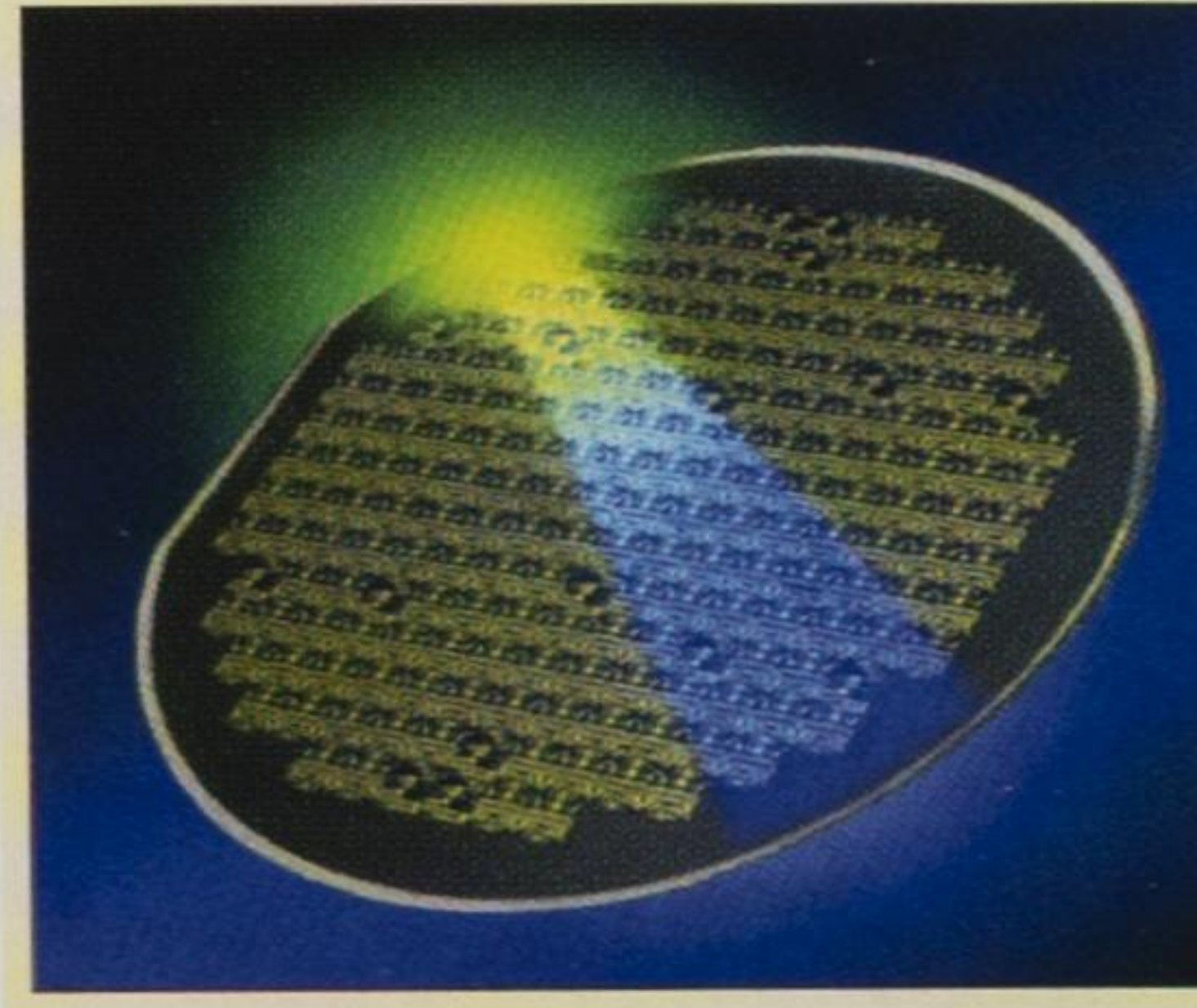


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EV Group and SiGen in bonding venture

EV Group (EVG), a manufacturer of MEMS and semiconductor wafer-processing equipment, and Silicon Genesis Corporation (SiGen), a developer of silicon-on-insulator and other engineered substrate technologies, have announced a wide-ranging co-operation in the field of low-temperature wafer bonding based on a license of SiGen's NanoBond patents and process technologies.

The companies will combine their exten-

sive experience to commercialize production-proven, next-generation low-temperature bonding equipment and processes.

EVG has developed low-temperature and dry-activated bonding equipment over the last 15 years. SiGen has developed plasma activation for ultra-clean bond applications and is contributing its plasma-bonding intellectual property portfolio and related process technologies to the agreement.

KLA-Tencor and Soitec join forces

KLA-Tencor and Soitec have announced a partnership to improve the quality, yield and cost of SOI wafers used to produce low-power-consumption ICs. The program is expected to provide wafer and IC manufacturers with the industry's first wafer inspection system specifically optimized for SOI and meeting the sensitivity requirements for the 90 nm and 65 nm nodes.

Tegal targets atomic layer deposition

Tegal is to purchase the assets of Simplus Systems, a privately held developer of nanolayer deposition (NLD) cluster tools and processes for barrier, copper seed and high- κ dielectric applications. Simplus offers a multichamber tool incorporating its patented NLD and plasma-enhanced NLD processes that are similar to atomic layer deposition, but with much higher throughput.

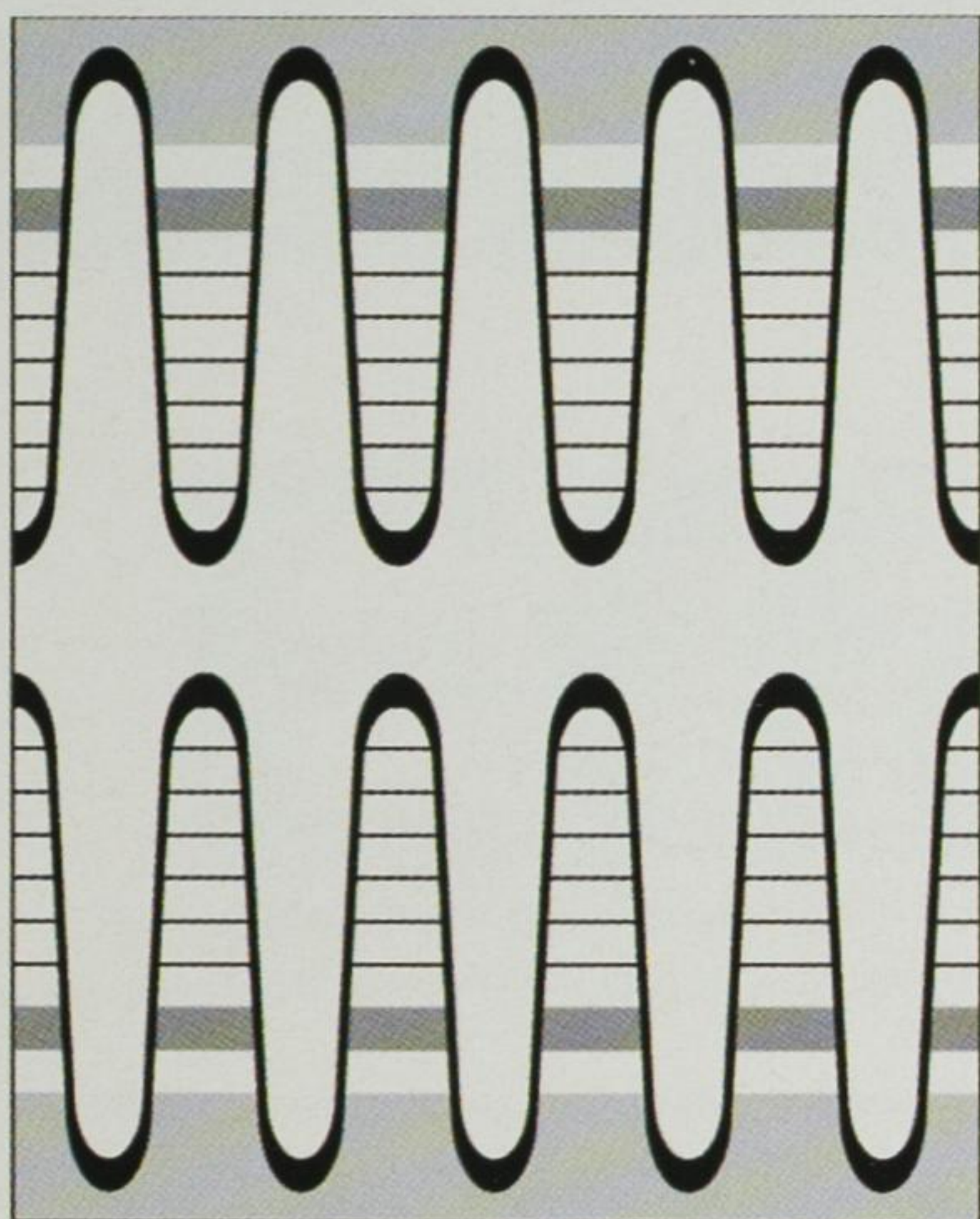
Equipment sales

● Epiwafer supplier **Intelligent Epitaxy Technology, Inc** (IntelliEPI) has ordered another Riber 6000 multiwafer production MBE reactor.

● **West Virginia University** (WVU) has ordered an AIX 200/4 RF-S MOCVD system from **Aixtron**. The machine will be used to develop nitride-based materials, UV emitters and detectors, biological sensors and HEMTs.

● The Department of Physics of the **State University of New York at Buffalo**, NY, has ordered a second Riber MBE 32 P system to grow photonic materials and ferromagnetic heterostructures.

● The **Ioffe Technical Institute**, located in St Petersburg, Russia, has also ordered an AIX 200. It will be used to grow InGa(As)Sb material for mid-IR light sources and detectors.



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- Molecular Electronics: Devices, Materials and Contacts
- Epitaxy for Devices
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- Non-Destructive Testing and In-Situ Monitoring and Control
- Epitaxy: Growth, Metamorphic and Templates (other areas)
- Semiconductors: Processing and Oxidation
- Point and Extended Defects in Mismatched Materials
- Si-Based Heterojunctions and Strained Si: Growth, Characterization, and Applications
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- Silicon Integration: Alternative Dielectrics, Thin Oxides, Ferroelectrics, Metal Gates, and Epitaxial Oxides
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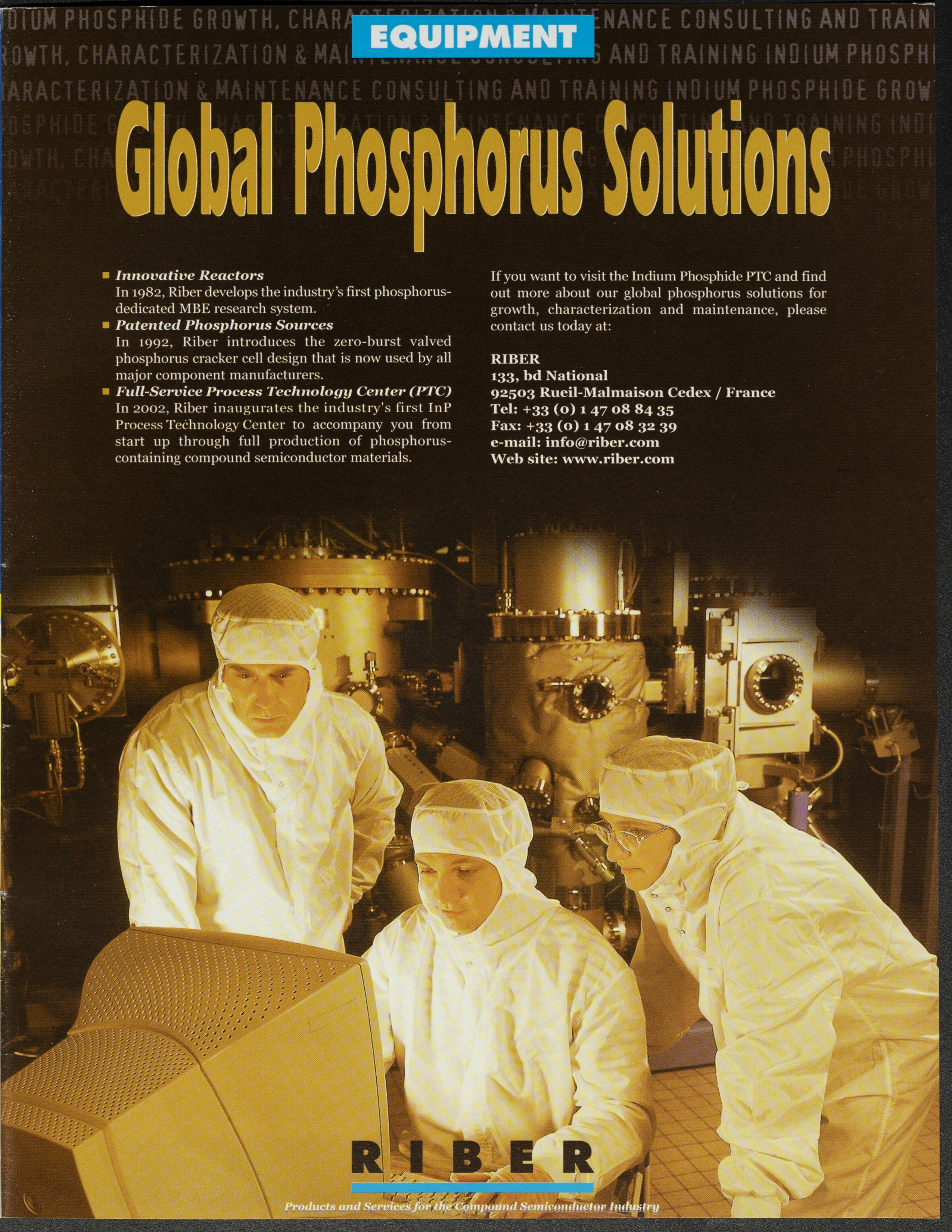
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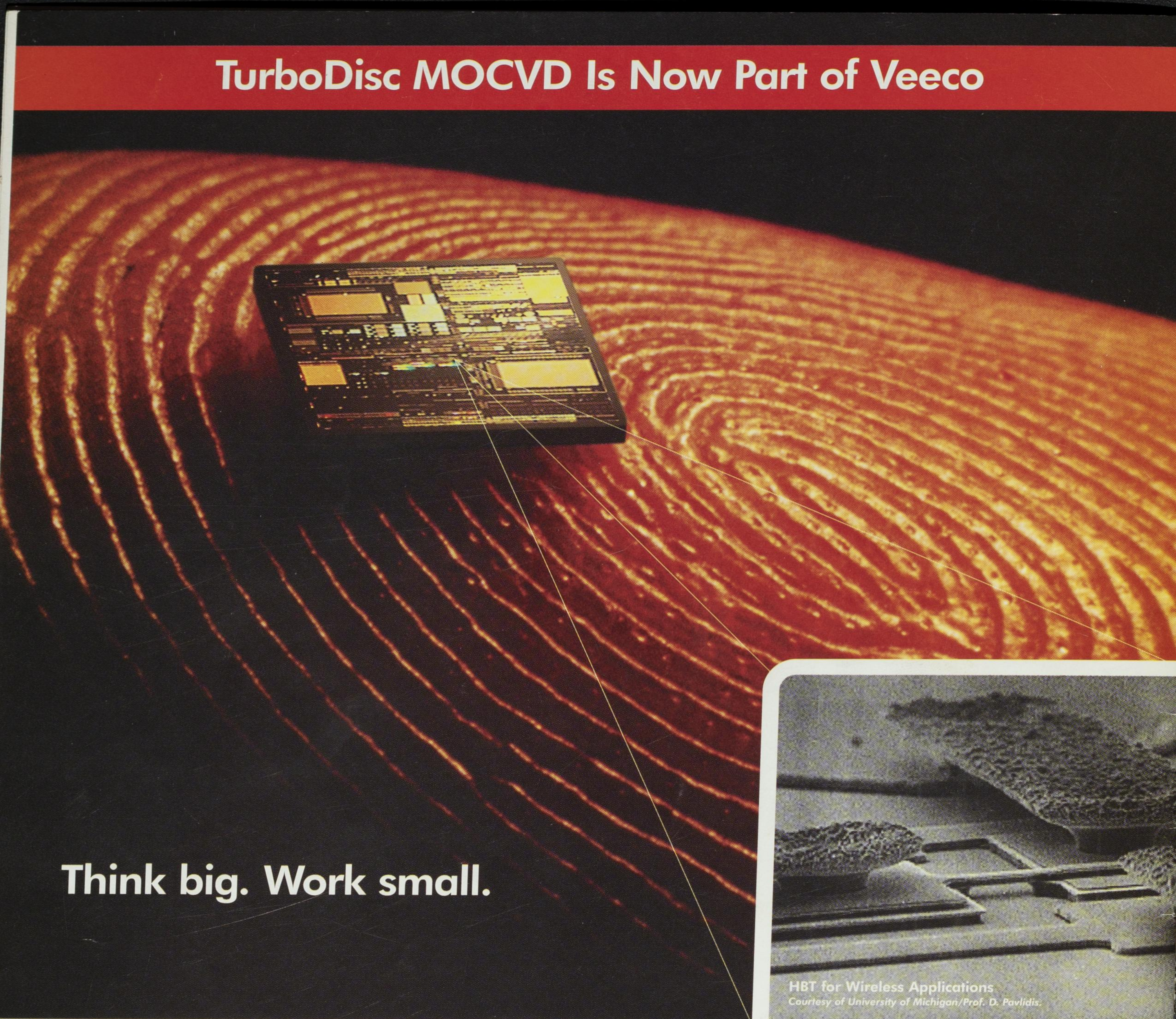
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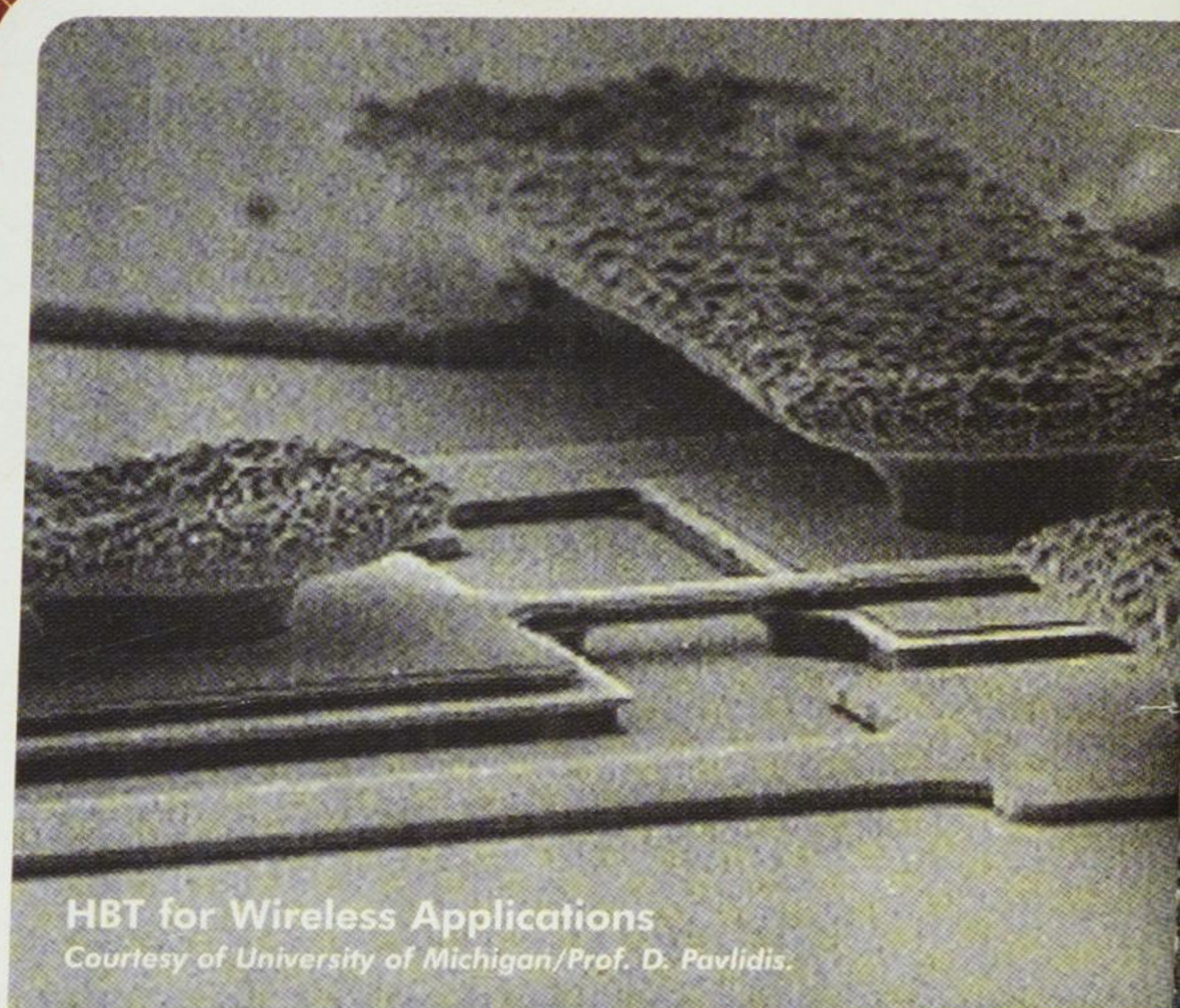
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