

COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

October 2004 Volume 10 Number 9



MANUFACTURING **Cree outlines five-year expansion program**

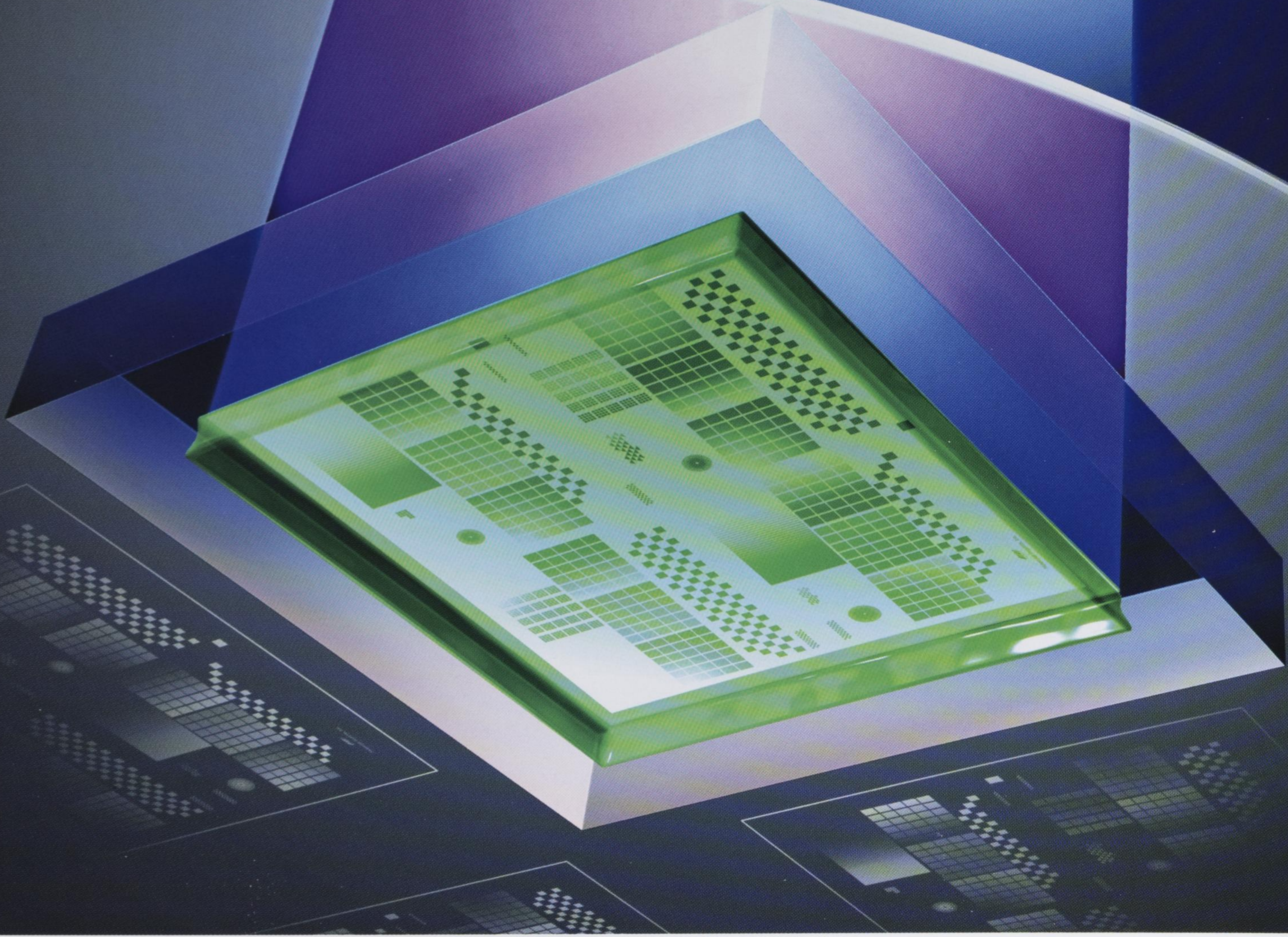
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raise their game**

**Japan sets targets
for white LEDs**

**Etched facets cut
diode-array cost**

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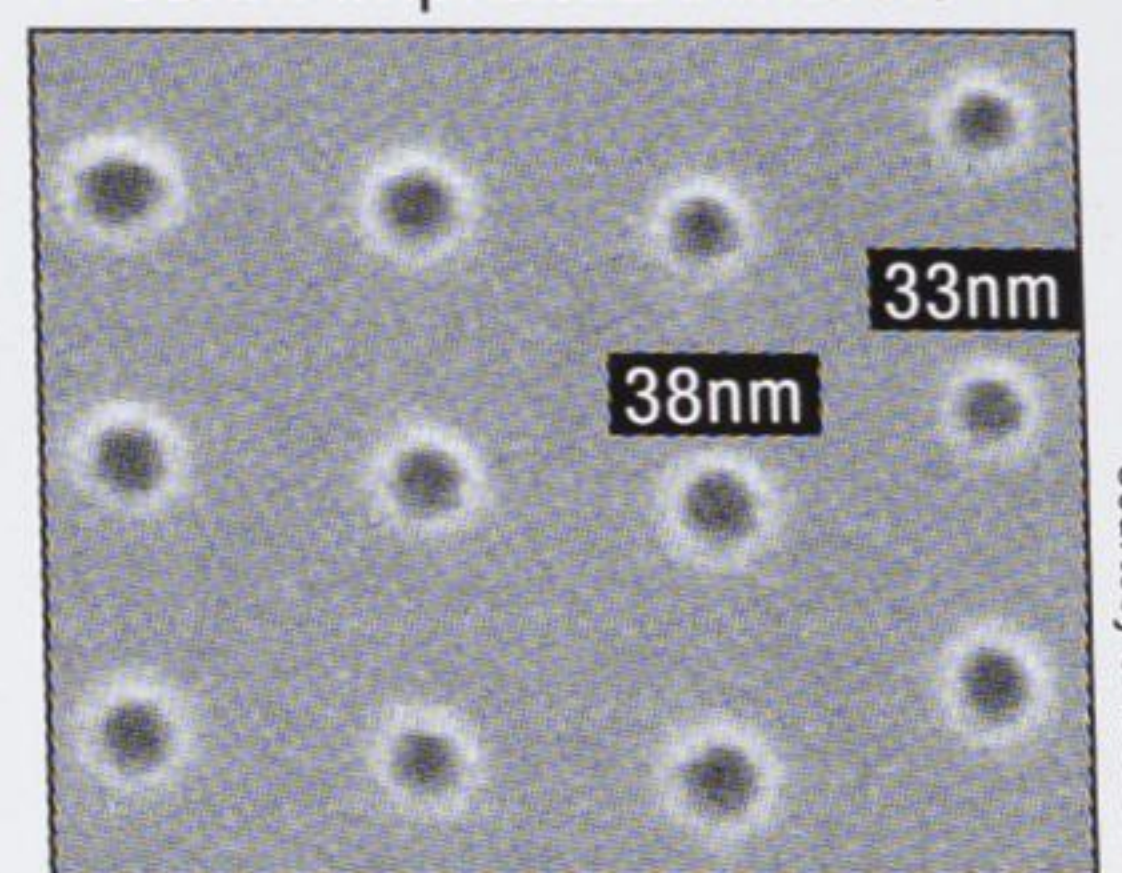


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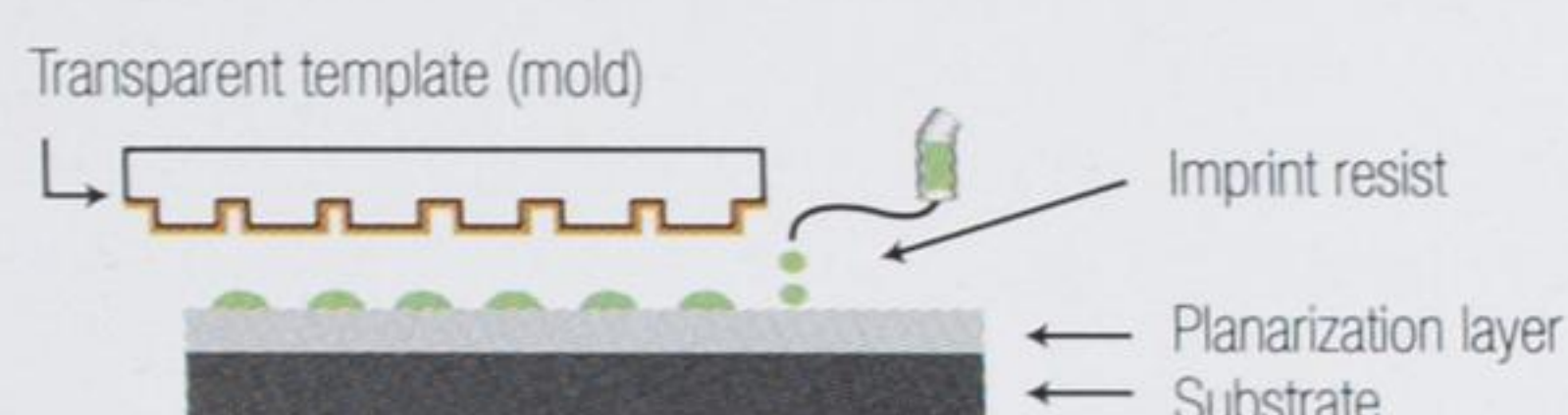
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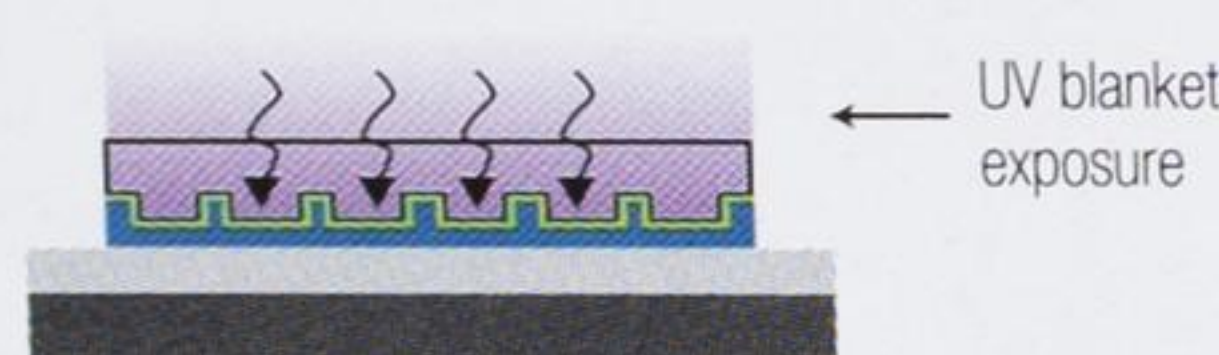


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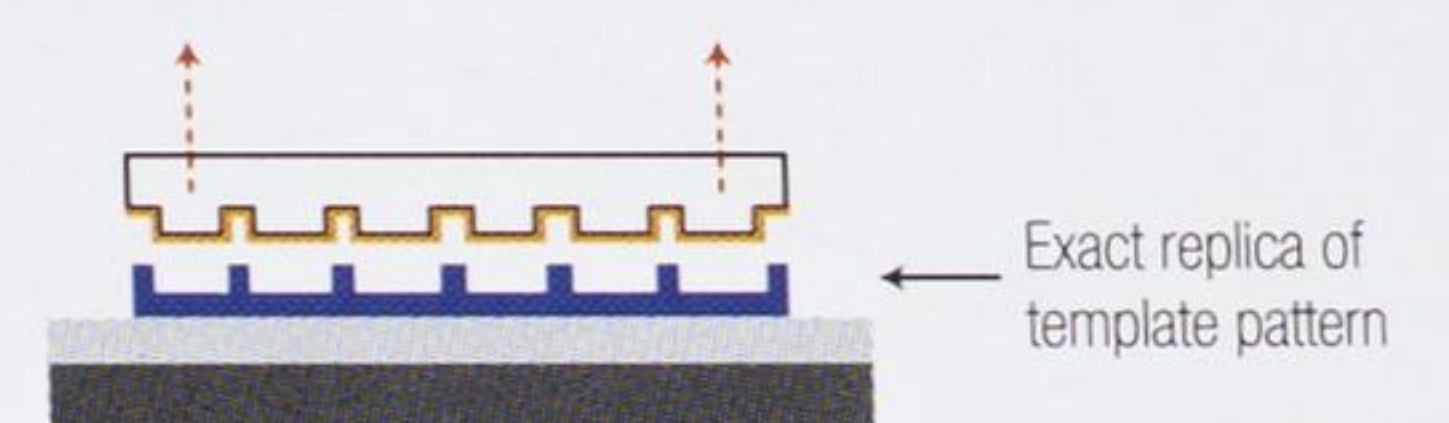
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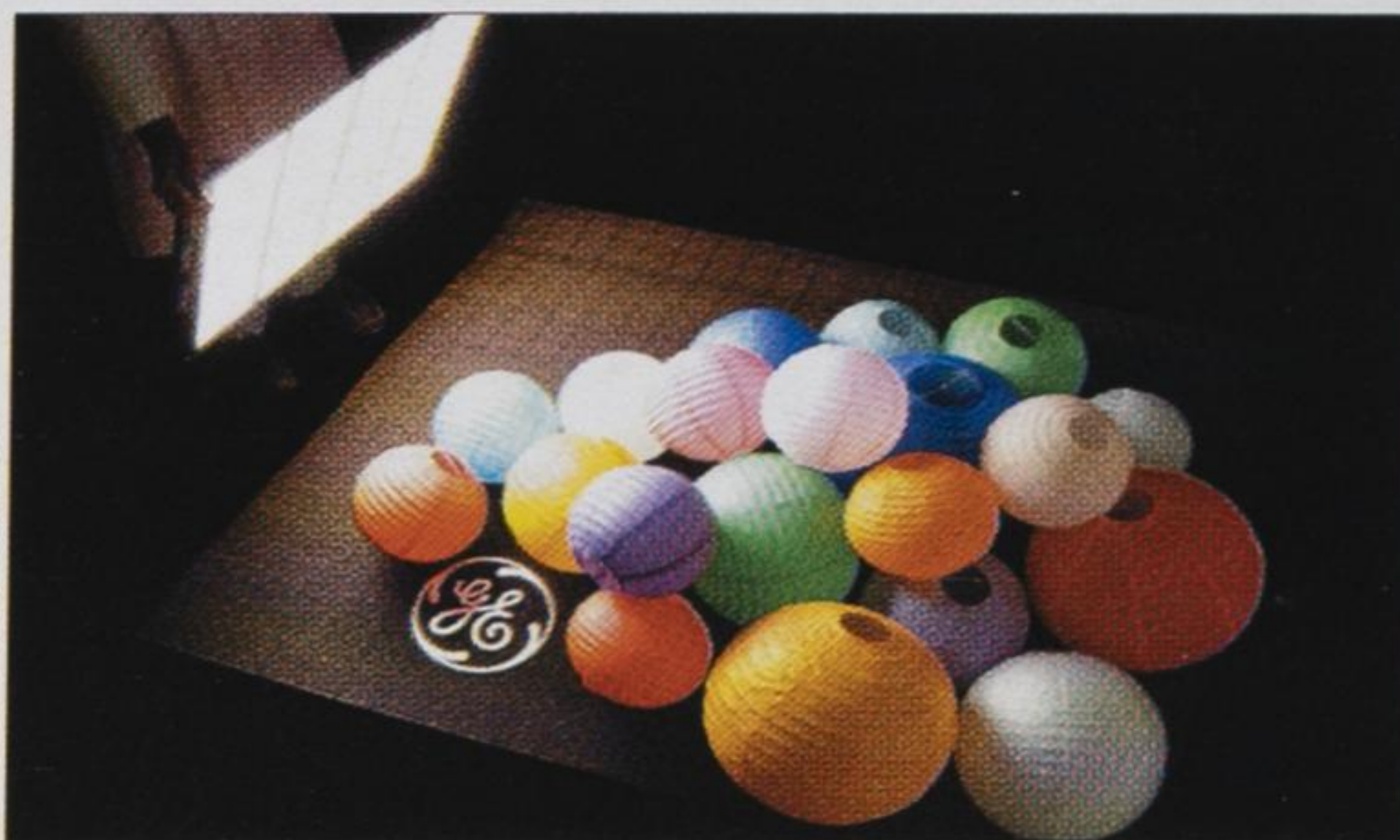
Three-Fives and Silicon Heterostructures

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- 27** **Native substrates spar with the established technology**
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On the cover: US LED maker Cree details plans for expanding its chip-making facilities and its new range of LED-based lighting products. See pages 11 and 25. Credit: Corbis.

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Editorial

Manufacturing: learn from the best in the business at CS-MAX



For the CS-MAX 2004 technical program, we've signed up speakers from all sides of the industry. From GaAs HBTs to blue-laser diodes; from source materials and substrates to back-end processing, we've done our best to cover the whole supply chain.

For example, the CS-MAX plenary session – scheduled for the morning of Wednesday October 27 – includes coverage of all of the major compound semiconductor manufacturing sectors. Speakers include Michiro Chiba from Sony's laser-diode manufacturing division. With a monthly manufacturing output exceeding 20 million units, Sony is a serious laser-diode producer, and Chiba is sure to give CS-MAX delegates a rare insight into the Japanese firm's high-efficiency production processes and future plans to make GaN-based blue emitters in high volumes.

Production of high-brightness LEDs is the hot topic in the industry currently, and delegates will learn about key issues of safety and energy efficiency in a presentation by Zelkjo Spika from the leading LED manufacturer Osram Opto Semiconductors. Head of the company's InGaN production, Spika will focus on the new energy-efficient manufacturing facility in Regensburg, Germany.

The RFIC industry will also be represented strongly. Sam Lee, CEO of US-based GaAs foundry Global Communication Semiconductors, will focus on the strong emergence of wireless LAN and Wi-Fi applications and the implications for GaAs device manufacturing. Tom Rogers, director of RF Micro Devices' MBE operation, will tell how the leading GaAs HBT maker has developed world-class manufacturing techniques.

Completing the CS-MAX plenary session will be Dave Reamer from key equipment supplier Veeco Instruments. Reamer's talk will focus on the lessons that compound semiconductor device manufacturers can learn from the silicon industry, with a look at how these two industries are converging.

To sign up for CS-MAX, check the registration details on page 10 of this issue – it's your chance to learn about high-volume manufacturing from some of the very best in our community.

Michael Hatcher

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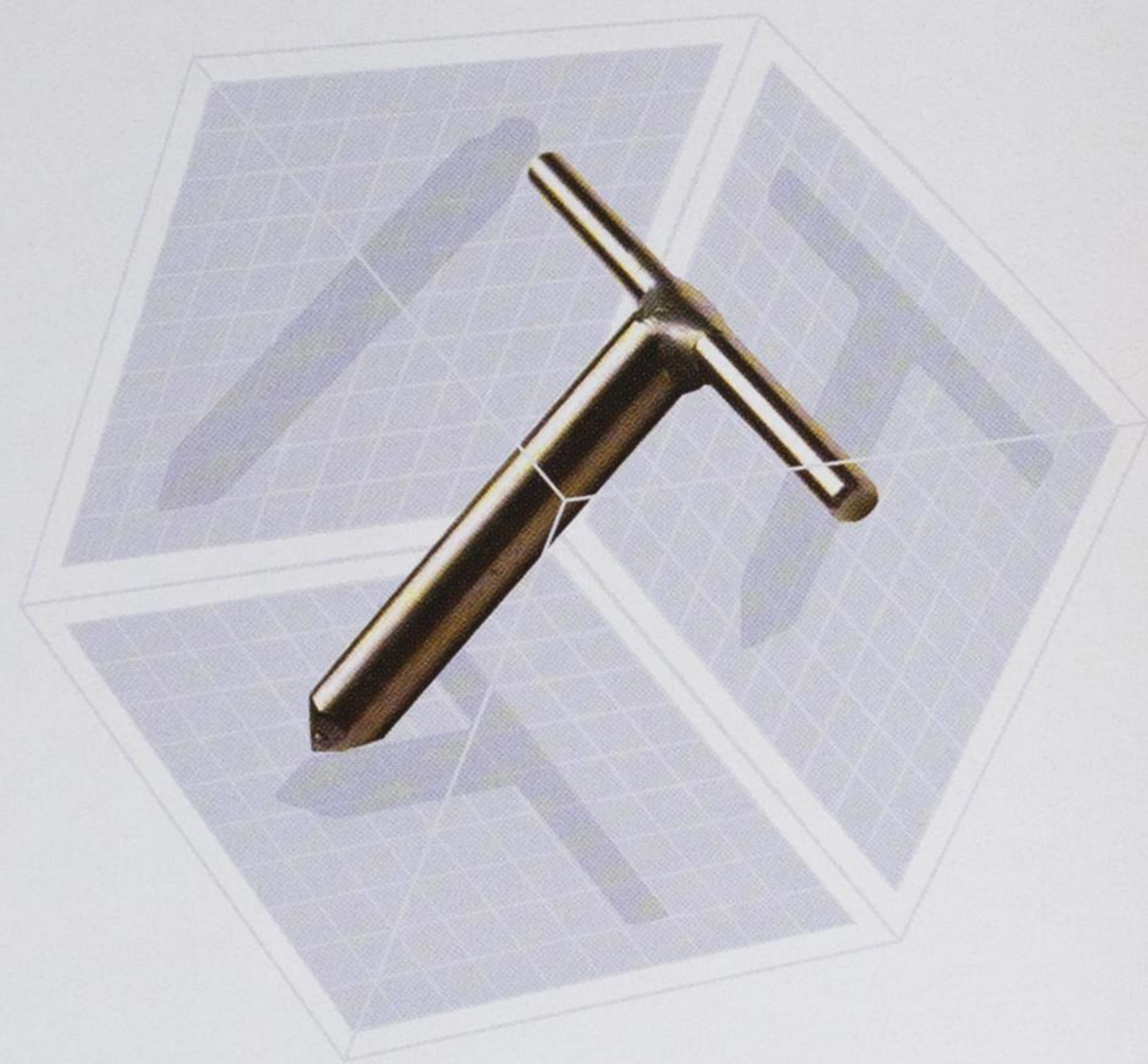
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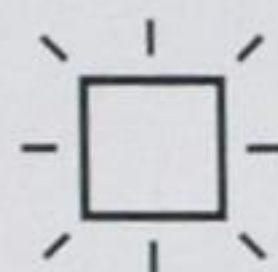
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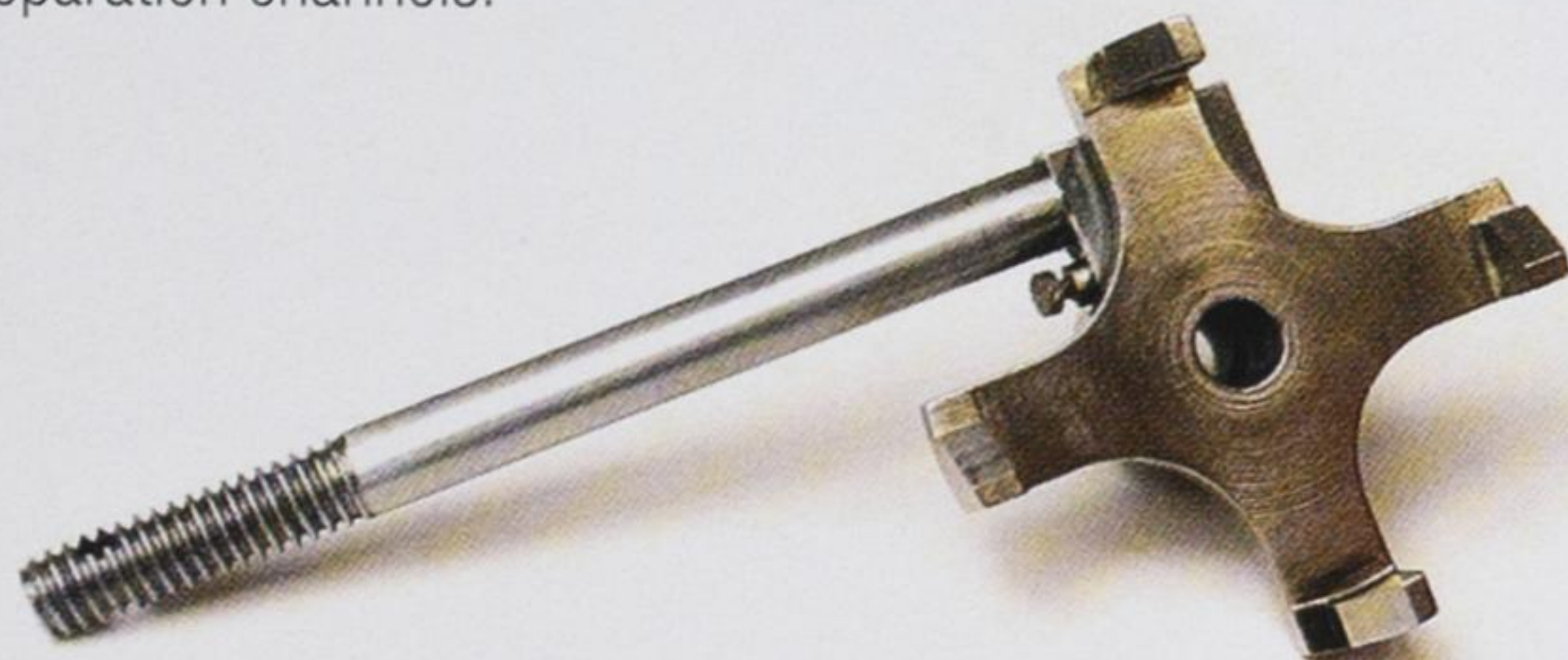
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BOOKHAM TECHNOLOGY

Bookham Technology, the InP optoelectronic device manufacturer, switched its corporate home from the UK to the US on September 21. Its shares are now listed exclusively on the Nasdaq stock market under the ticker name "BKHM".

Japanese giants size up blue-laser production

A raft of major Japanese electronics firms will begin mass production of blue laser diodes next year, claims the Tokyo-based *Nihon Keizai Shimbun* business newspaper. The firms listed in the report include NEC, Toshiba, Matsushita, Sony, Sharp and Sanyo.

Until now, fellow Japanese company Nichia, which has a licensing agreement with Sony, has had a stranglehold on the blue-laser market. Nichia itself has a new building already primed to meet the expected increase in demand for the devices in next-generation data-storage applications.

Compound Semiconductor understands that Sony will begin volume manufacturing the devices this year, and that the company will sell them on the open market as well as using them internally.

The report says that NEC Compound Semiconductor Devices will begin sample shipments in the first half of 2005, with lasers manufactured by NEC Kansai and assembly outsourced to another company in Japan.

Meanwhile, Toshiba is reported to have

developed production technology to bring the cost of a blue-diode-laser unit to about \$46. It is believed to be starting mass production of lasers in the first half of next year as a supply line for its next-generation DVD recorder.

Matsushita, which said earlier this year that it planned to manufacture devices on GaN substrates, recently released a DVD recorder featuring a blue laser made by Nichia. It plans to introduce products featuring its own lasers next year, says the report.

Find out more about Sony's laser diode production at CS-MAX. See registration details on p10

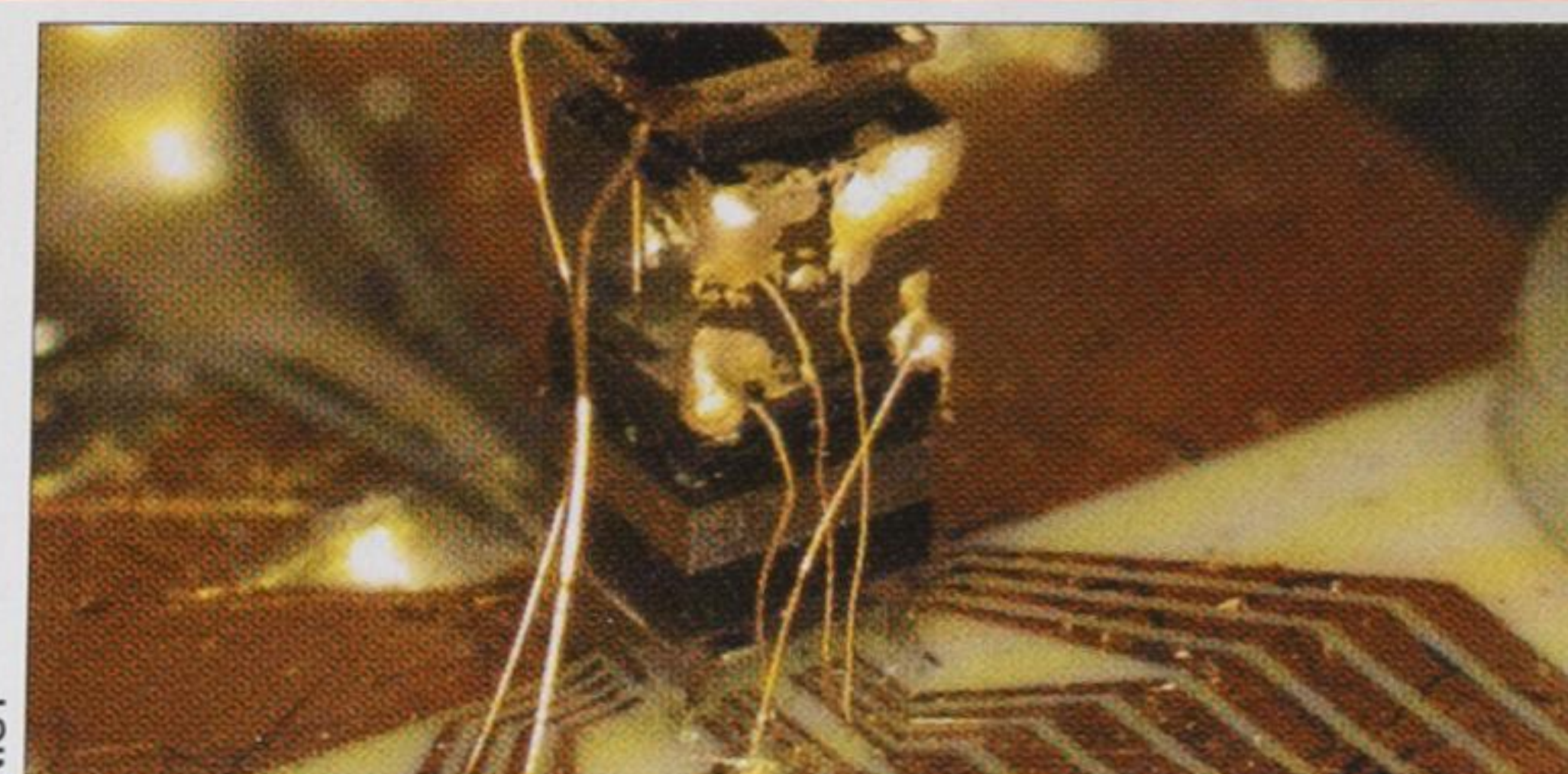
VCSEL-based clock is 'world's smallest'

By Oliver Graydon

A team at the National Institute of Standards and Technology (NIST) in Colorado says that it has made the world's smallest atomic clock by exploiting MEMS fabrication technology and a vertical-cavity surface-emitting laser (VCSEL) chip. As a result, the precision of

atomic-clock timekeeping could soon be coming to handheld devices such as cell phones, radios and GPS receivers.

The chip-scale clock contains a 852 nm VCSEL, a lens, an optical attenuator, a polarizing waveplate, a cell containing cesium vapor and a photodiode. The ease with which the NIST design can be built potentially opens the door to low-cost mass-production of miniature atomic clocks that can easily be integrated with electronics.



NIST

Small time: a VCSEL with precise emission wavelengths is one of the key components in this chip-scale atomic clock.

Anadigics scores Chinese design wins as RFMD sees revenue fall

US-based InGaP HBT maker Anadigics has scored three design wins from Chinese cell-phone handset manufacturers. The Warren, NJ, company is shipping production volumes of power-amplifier (PA) products to Lenovo, Truetel and Ningbo Bird.

All three customers have ordered the same component, the AWT6108 quad-band PA module. Lenovo is using the module, which supports GSM850, GSM900, DCS and PCS bands, in its new V858 model camera phones.

Truetel, which makes a range of products – including wireless terminals – is employing the

same PA modules, which Anadigics claims simplify handset calibration and shorten development time. GSM handset maker Ningbo Bird will use the AWT6108 in its V5600 phones.

Anadigics, which has announced plans to raise \$30 million through the issue of convertible notes, says that the Chinese business results partly from the company's "Asia-centric" strategy – Anadigics has technical support centers in Shanghai in mainland China, and Taipei, Taiwan.

Anadigics' rival RFIC manufacturer, RF Micro Devices (RFMD), recently stepped up

its own presence in China through the opening of a sales and customer support office in Shenzhen. However, Greensboro-based RFMD has been forced to warn investors of an expected shortfall in revenue for the quarter that ended on 30 September. The company blamed "short-term inventory adjustments" caused by excess inventory levels in the supply chain, primarily at Asia-based handset makers, as it predicted an 8–12% sequential decline in revenue to \$146–152.5 million. It had previously expected revenue in the period to be \$166 million.

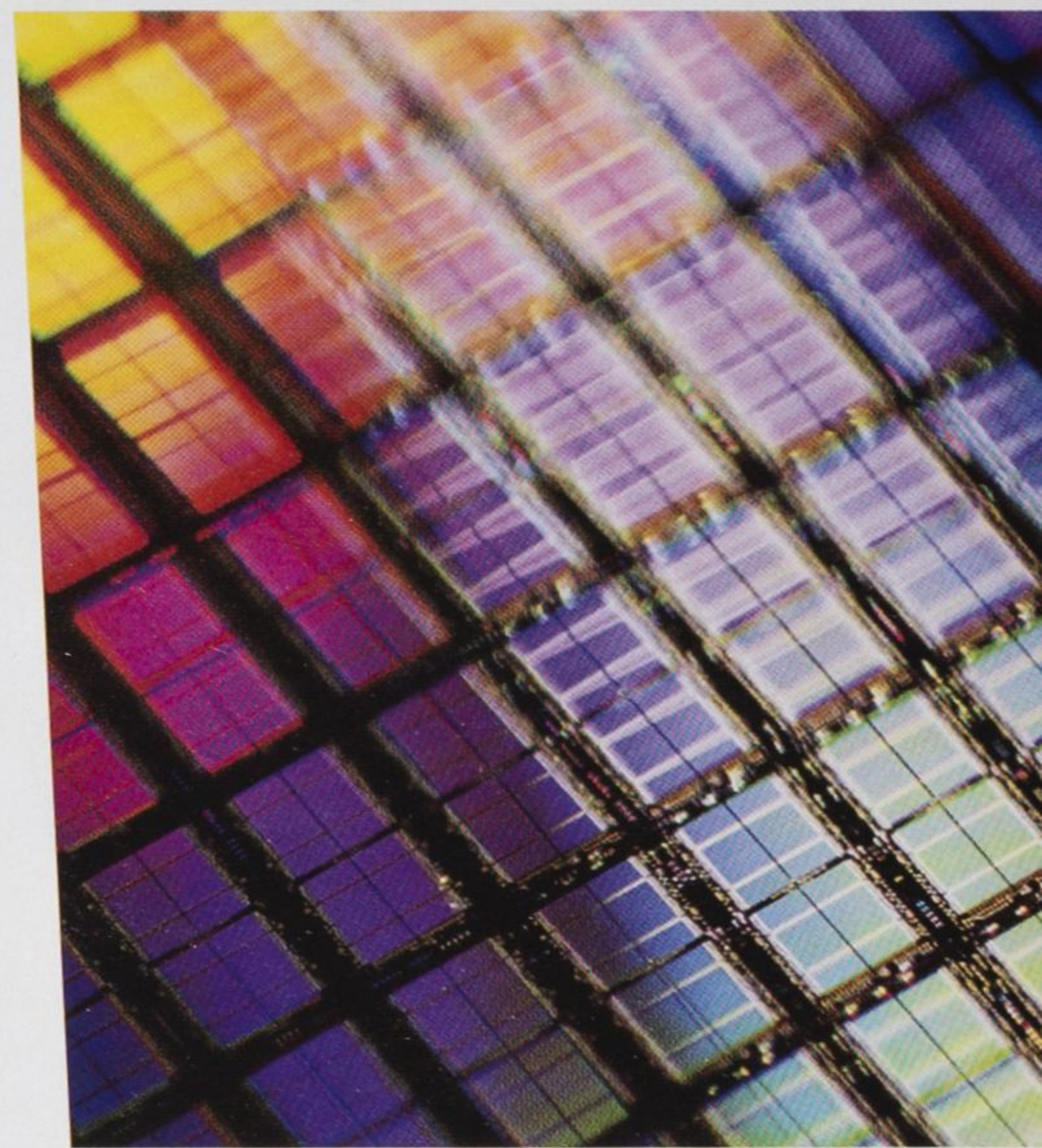


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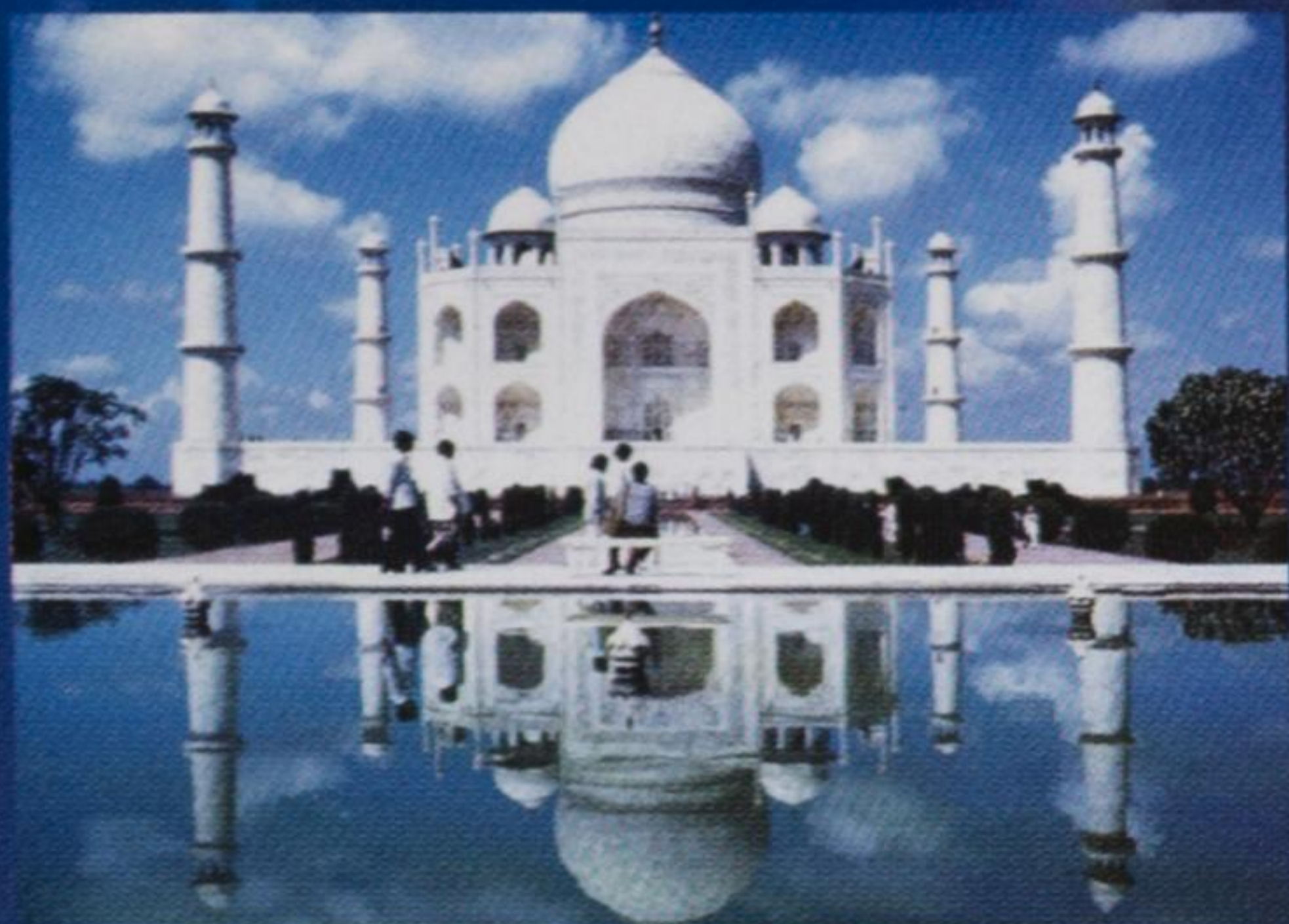
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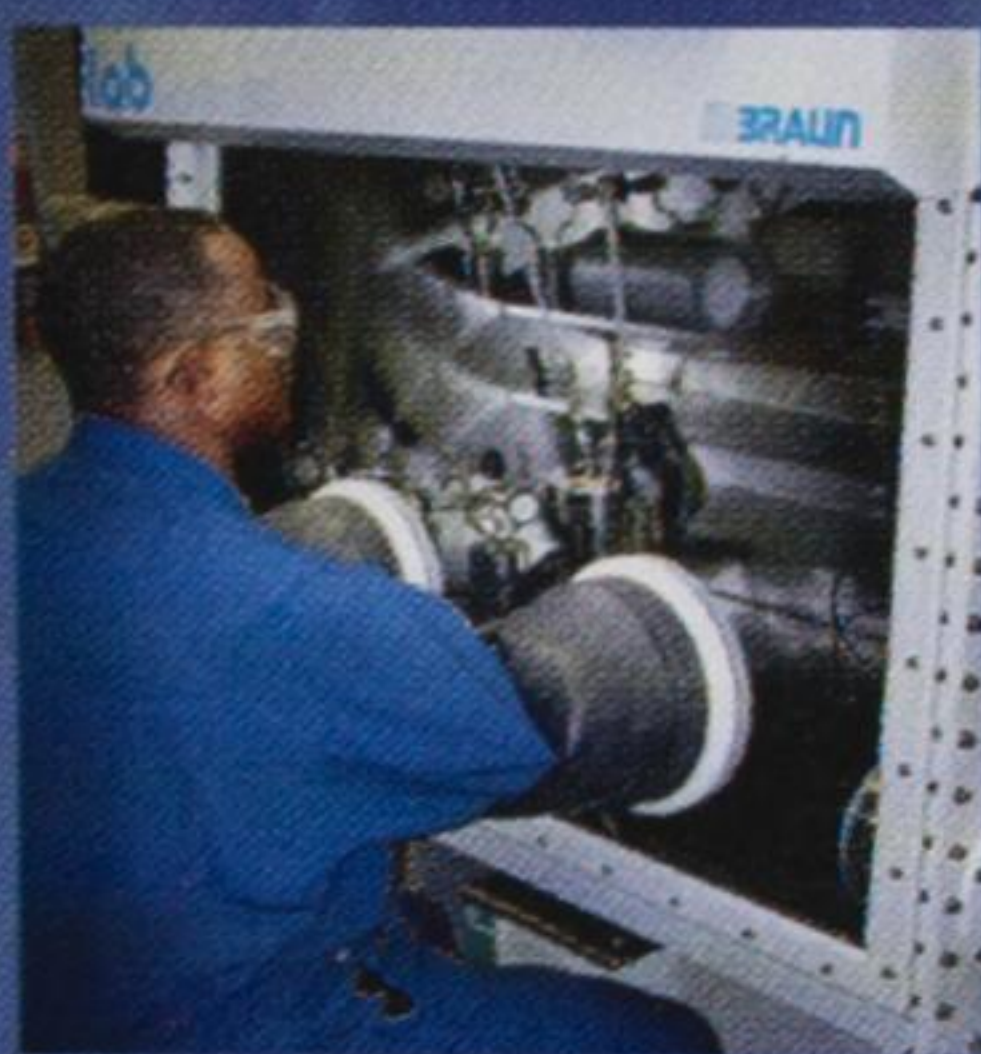


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GaAs IC market expected to reach \$3.7 bn in 2008

By Richard Stevenson

Market research firm Strategy Analytics predicts that the global GaAs device market will grow from \$2.7 billion in 2003 to \$2.9 billion in 2004 and \$3.7 billion in 2008.

Mobile phones will continue to be the dominant application area: "The cellular market represented over 41% of the total demand for GaAs devices in 2003, and will still account for at least 33% in 2008," said Asif Anwar, director of the analyst firm's GaAs service.

Demand for non-cellular applications is expected to increase, with Anwar forecasting double-digit annual growth in automotive radar applications through 2008.

He expects device demand from the wireless market to peak in 2006, with a continuing decline in the average selling price (ASP) offsetting any increases in handset shipping volumes. "There is a constant battle to get the price down for GaAs ICs, with price erosion typically [being] 8–12% per annum."

Anwar thinks that the effect of the weakened US dollar on the market "has already been felt", pointing out that exchange rates have been relatively stable for quite a few months.

Competing technologies, such as SiGe, are expected to take market share from GaAs, but in the power-amplifier market GaAs is expected to remain the dominant technology for the foreseeable future.

Anwar believes GaAs will continue to

dominate future high-power, high-frequency applications, but that SiGe devices may compete in applications requiring lower power.

Strategy Analytics' GaAs IC market forecast is markedly different from that produced by rival market research firm The Information Network (TIN). In July of this year TIN predicted that the GaAs IC market for 2004 will be worth \$3.9 billion, even higher than Strategy Analytics' 2008 figure.

Anwar could not account for the discrepancy, but said: "We have a high degree of confidence in our figures. It's not just a case of being conservative. We are being realistic."

Compound Semiconductor contacted Robert Castellano of TIN, who stands by the figures quoted in July: "We are confident in our analysis. We see continued strong demand in cellphones and an increased customer demand for both wireless LAN and cable infrastructure products."

Castellano expects a downturn in sales of silicon ICs due to excess capacity and lower ASPs resulting from "excessive build-outs and capacity expansion in late 2003 and 2004".

In contrast to Strategy Analytics' forecast, TIN says that there will not be a GaAs IC downturn in 2006. "These technologies are not influenced by overexpansion problems, but more by macroeconomic issues (GDP, employment, etc) and there are really no signs of recession anywhere in the world."

News In brief

● GaAs device manufacturer **TriQuint Semiconductor** has reduced its financial guidance for its current quarter and for fiscal year 2004. Having previously expected \$92–94 million revenue in the period ending September 30, TriQuint now predicts only \$88–90 million.

The company has also revised its full-year forecast down slightly, but at \$362–367 million the new fiscal 2004 estimate is still well up on the \$312 million recorded last year.

● US-based **Fairchild Semiconductor** has released the RMPA0965, an RF power amplifier optimized for CDMA2000-1X applications in the 824–849 MHz frequency

band for today's handset requirements.

● **RF Micro Devices** is the world's seventh-largest global wireless communications semiconductor supplier, according to the analyst firm Gartner Dataquest.

● **Mimix Broadband**, of Houston, TX, has introduced the 40BRFM0058 GaAs MMIC fundamental balanced mixer, which has been optimized for use as a down converter.

"The combination of broad frequency coverage and high linearity is achieved through the use of 'cold FET' mode mixers in a balanced configuration," commented Jim Harvey, CTO of Mimix Broadband. "This makes the device useful in a variety of radio and instrumentation applications."

Surge in handset sales could dent 2005 growth

Mobile-phone handset sales are continuing to soar, but the excess growth witnessed recently may produce a hangover at the beginning of next year, US analyst Gartner has warned.

With 35% year-on-year growth and more than 300 million units sold in the first half of 2004, Gartner projects full-year sales to be around 620 million units. However, it warned that there could be trouble ahead if the current momentum is maintained and unit sales reach 650 million by the end of the year.

"If mobile phone sales exceed 650 million units this year, it could result in excess inventory that could harm sales in the first half of 2005," said Gartner.

Around half of the high-brightness LEDs produced in the world end up in phone handsets, as do an even higher proportion of GaAs-based power-amplifier devices.

Gartner cited "spectacular" growth in

emerging markets, particularly Latin America, as phone sales hit 156.4 million in the second quarter of the year.

Consumers upgrading to camera phones spurred growth in Western Europe and North America, while sales in the Asia/Pacific region dropped slightly on the previous quarter as the Chinese government tried to rein in the country's rampant economic growth.

In another recent survey of the market, Strategy Analytics said it believed that handset sales would reach 670 million this year.

Nokia, Finland, remains the market leader, with a 29.7% share, up slightly on the first quarter of the year thanks to heavy discounting, but down from 35.6% one year ago.

US-based Motorola's recovery saw its market share increase from last year, although it remains under pressure from Korea's Samsung, whose market share grew to 12.1%.

US-based RFIC manufacturer Anadigics is shipping production volumes of its InGaP HBT power amplifier (PA) for 450 MHz CDMA applications. The firm claims that this PA gives handset makers a low-power quiescent current mode to reduce power drain on the system battery, resulting in longer talk time. Anadigics' vice-president of wireless products, Ali Khatibzadeh, said: "The AWT6136 expands our broad CDMA product portfolio to cover the emerging 450 MHz CDMA 1X/1xEV-DO markets in Europe and the greater Asia-Pacific regions." Anadigics' InGaP PAs are also in camera phones made by Samsung (inset) and Taiwanese handset maker Asustek.

increasing demand" for handset and wireless LAN applications.

"GCTC is extending its low-cost manufacturing prowess to higher radio frequencies and higher value-added applications," the company said in a statement.

The capital investment that has been earmarked is expected to increase GCTC's production capacity of 6 inch GaAs wafers to 1200 units per month.

The firm, which is based in Hsin-Chu Science Park, has a 6 inch GaAs fabrication facility and recently released its 0.25 μm PHEMT process technology.



ANADIGICS/SAMSUNG

Foundry wins \$5.6 m funding

By Michael Hatcher

Taiwan-based pure-play GaAs and surface acoustic-wave-filter foundry Global Communication Technology Corp. (GCTC) says it will increase HBT and PHEMT production following a successful financing round.

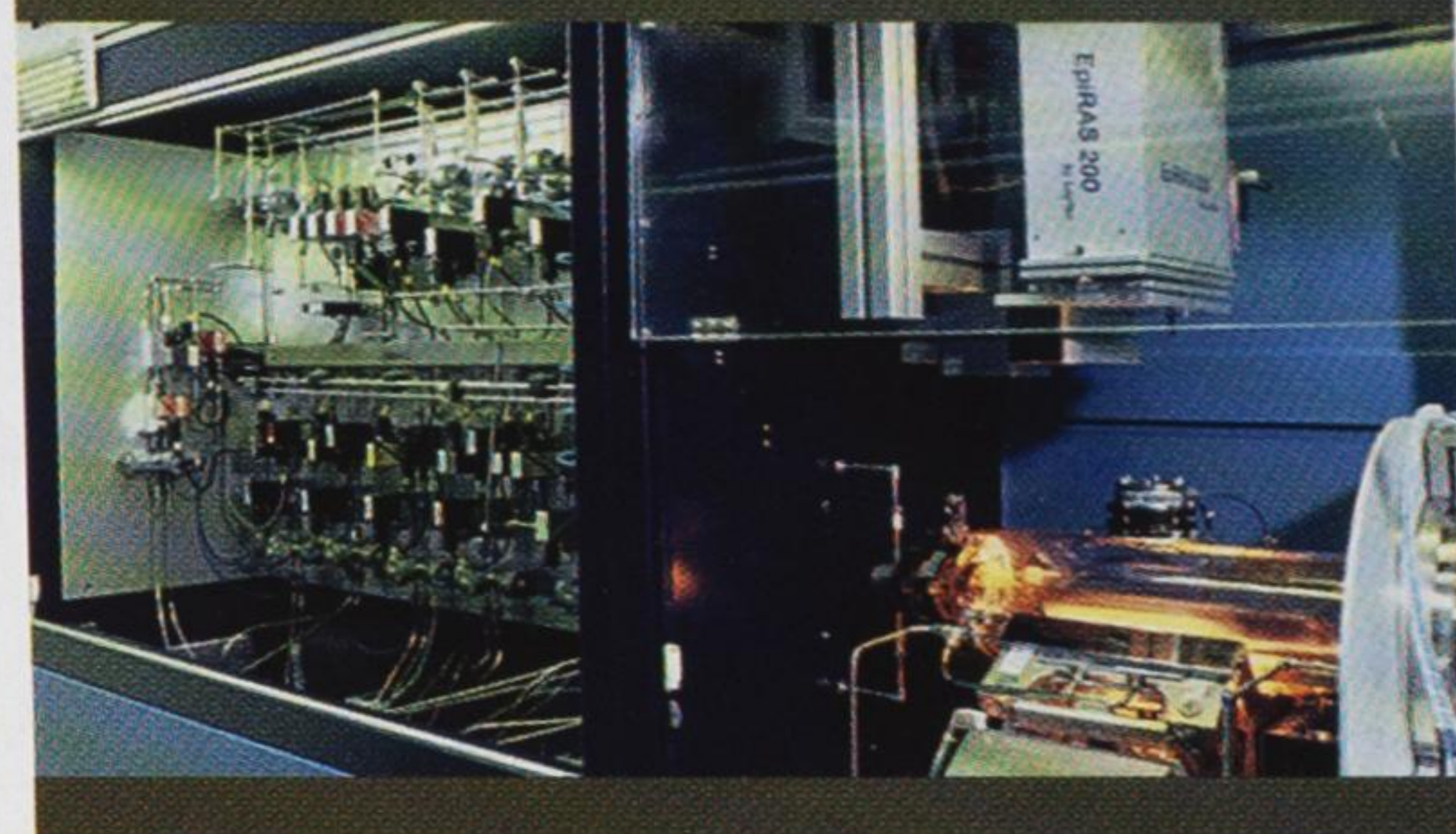
Having raised NT\$190 million (\$5.6 million), the company says that it will inject the cash into RFIC production to meet "rapidly

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Cree plans to stimulate LED lighting

Having established itself as a leading supplier of blue- and green-LED chips to packaging firms, Cree recently changed its business strategy and in July launched a range of packaged LED products under the name XLamp.

The 7090 XLamp series has a footprint of 7×9 mm and is designed to operate at 350 mA. Blue, cyan, green and white XLamps are based on Cree's InGaN-on-SiC XB-900 chip, while red and amber products incorporate chips from external suppliers. The 4550 series has a smaller footprint of 4.5×5 mm and operates at 125 mA.

A key feature of the XLamp LED is its surface-mount package, which is compatible with automated pick-and-place manufacturing equipment and reflow soldering.

Tim Whitaker spoke with Norbert Hiller, vice-president of Cree Lighting, about the company's new XLamp product range.

Tim Whitaker: Why did Cree choose to enter the lighting market?

Norbert Hiller: In the past, when Cree has introduced chips we have seen a fast response from customers in bringing the chips to market in their packaged products. With our power chips it took a long time for products to emerge, so we decided that we needed to stimulate the market by introducing our own packaged products.

TW: Is there a risk of conflict with your chip customers?

NH: We will continue to sell our standard and power chips to anyone who wants to buy them, without restrictions. We had discussions internally and with customers, and we don't see it as a source of conflict. Cree Lighting is focused on high-power packaged LEDs, and is separate from Cree's chip business.

TW: What are the potential applications for XLamp?

NH: The first markets to give a positive response to XLamp are those of architectural lighting, task lighting and specialty lighting, such as flashlights. In the mid-term, we expect to see interest from the automotive industry and from the display market where LEDs can be used as backlights for large LCD screens.

We introduced red XLamps primarily for customers that want to build RGB products and need a red package with the same form-factor as blue and green [devices], without hav-



21st century light: In launching the XLamp range of high-power packaged LEDs, Cree has entered the general-lighting market that many of its chip customers are targeting.

ing to switch between component suppliers.

TW: What technology is used to produce white emission?

NH: Our white LEDs use a blue-chip emission around 470 nm with a down-conversion phosphor. We would have liked to use our own UV chip, which is one of the most efficient in the market, but we haven't yet found a UV-pumped phosphor as efficient as the combination that we're using in production.

TW: What are the performance characteristics of the white XLamp?

NH: The white XLamp produces about 30 lm at 350 mA. This is at least as bright as – and in many cases brighter than – the upper end of competing products already in the market.

Currently, the color temperature is in the 5000–6000 K range. Various markets are also asking for warmer whites, and we are looking

into developing these products using different phosphor blends. Unfortunately there is a trade-off in lumen output when moving to a warmer white as the phosphors are less efficient.

TW: Why did you choose a surface-mount package?

NH: From the beginning, we designed the device to address major issues identified by different customers and market requirements. We decided that providing a surface-mount device would mean a big advantage for our customers, who can use reflow soldering and standard, automated machines rather than hand assembly or custom-built equipment.

Another major issue is thermal management; we chose a design and materials that support an easy way to transport heat away from the chip. The chip itself is mounted junction-side down, which gives the shortest possible path for heat dissipation.

TW: What is the significance of your modular package design?

NH: We think that we have chosen a robust, straightforward design that combines the chip on a submount with a lens, reflector, heat sink and baseplate. Not only is this design compatible with high-volume manufacturing, but also we have the flexibility to make modifications to the different components. This allows us to optimize performance and cost, depending on the demands of our different customers and end markets.

TW: Where is XLamp manufactured?

NH: Initial production is being performed at Cree's headquarters in Durham, NC, alongside our chip-manufacturing operation. It's possible that Cree may decide to invest in an overseas production facility in the future.

*Tim Whitaker is editor of LEDs Magazine, a new publication for the LED industry.
E-mail: tim.whitaker@ledsmagazine.com.*

**John Palmour
spells out Cree's
manufacturing
strategy on p25**

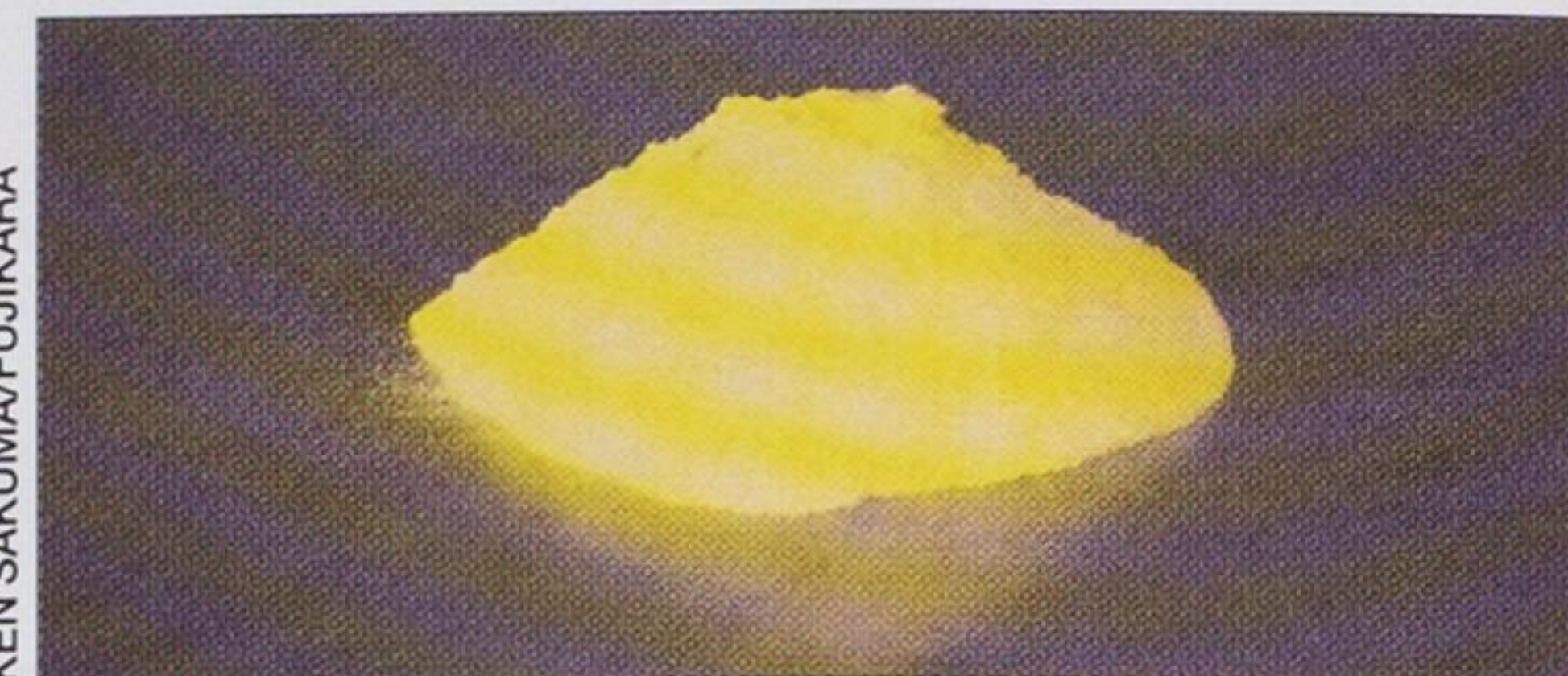
Yellow-orange phosphors mimic incandescent lamp

A Japanese collaboration between Fujikara and the National Institute for Materials Science has produced a warm-white LED – a promising candidate for next-generation solid-state lighting – by using a yellowish-orange phosphor pumped by a blue LED chip (*Optics Letters* 2001 29).

Ken Sakuma, a member of the Fujikara team, says that emission from the device – comparable to that of an incandescent lamp – cannot be produced by commonly used phosphors. The color temperature for an incandescent lamp could be reached by blending different phosphors, although the problem with this approach is reduced emission efficiency.

The device produced by Sakuma and co-workers incorporates an InGaN-based LED as the primary light source, and a ceramic phosphor (divalent-europium-activated α -SiAlON) dispersed in a transparent epoxy resin. The LED chip is coated in the phosphor-resin mixture, which is then heat-cured.

Driven with a forward-bias current of 20 mA at room temperature, the LED had a peak-emission wavelength of 454 nm, and an efficacy of 25.9 lm/W, which is superior to that typical of an incandescent lamp (16–18 lm/W). The associated color temper-



KEN SAKUMA/FUJIKARA

Phosphor stability: pumped by a blue LED chip, the yellow-orange phosphor developed by the Japanese team shows excellent thermal and chromatic stability.

ature of 2750 K meets the requirements of the incandescent lamp color defined by Japanese Industrial Standard Z 9112.

Sakuma says that the α -SiAlON phosphor exhibits excellent thermal stability. The chromatic stability of the Japanese team's device was compared with that of LEDs containing a standard phosphor (P46-Y3) at temperatures of up to 200 °C. The α -SiAlON phosphor proved to be more than three times as stable as a standard phosphor, in terms of the change of chromaticity with temperature.

Sakuma said: "I hope that our work will accelerate the coming era of solid-state lighting. Our SiAlON warm-white LED will be a rival to conventional incandescent lamps."

Epitech ramps GaN and AlGaInP epiwafers

Taiwan-based epiwafer supplier Epitech Corporation has placed orders for another seven MOCVD mass-production tools from German equipment supplier Aixtron.

The company is adding more large-scale planetary reactors for the mass production of AlGaInP-based red, orange and yellow-green ultrahigh brightness (UHB) LEDs.

The purchase order also includes close coupled showerhead reactors for the mass production of GaN-based blue, green, UV and white UHB LEDs. All of the recently purchased epitaxy systems will be installed at Epitech's new MOCVD plant located in the Tainan Science-based Industrial Park.

The additional capacity resulting from the purchase is expected to further strengthen Epitech's position in the market as a high-end LED epiwafer supplier. It offers a complete spectrum of UHB LEDs, from the deep-red to the UV range, including power LEDs for

white lighting applications.

Simon Chen, the president of Epitech, commented: "Demand for our leading-edge UHB LED products, produced solely on MOCVD systems from the Aixtron group, continues to increase very strongly, especially overseas. Epitech sales have doubled year on year.

"Corresponding to our long-term expansion plan, we will start up the new systems to ramp up production in our new factory building as soon as possible. This is mandatory to cover the demand for virtually all of our products," added Chen.

Solid-state lighting conference: read our report on p20

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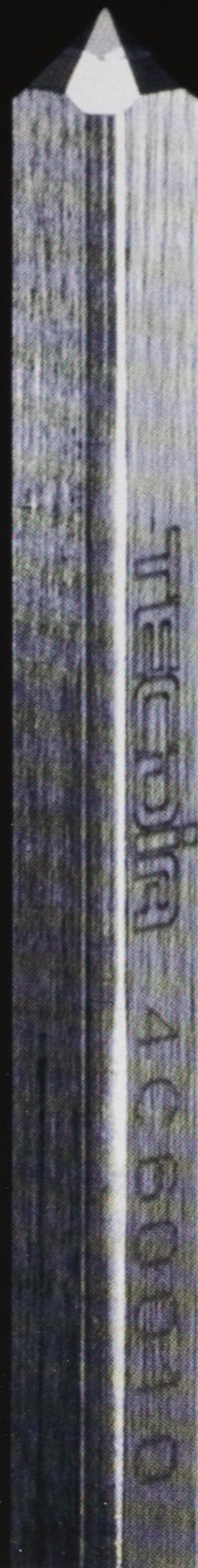
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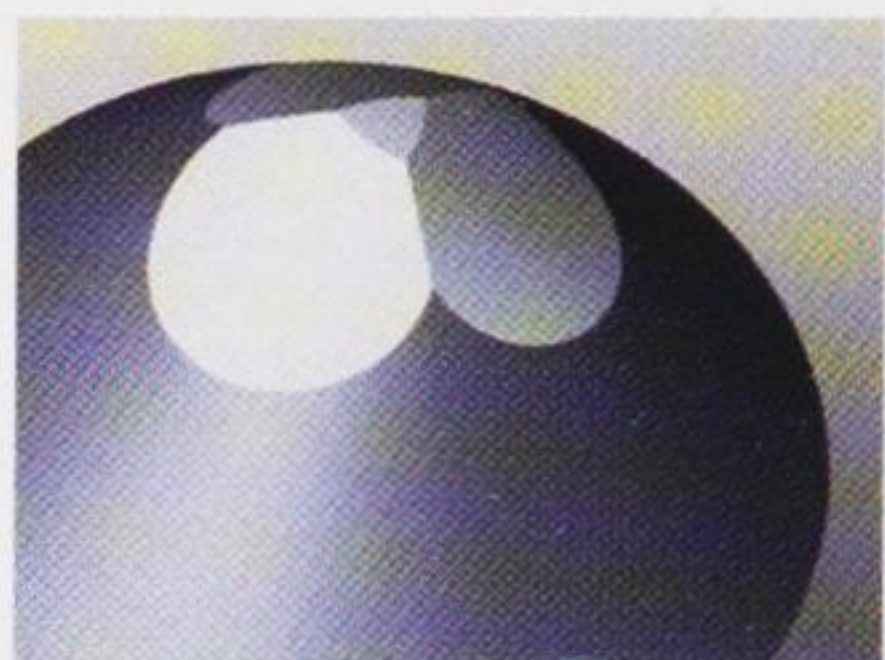
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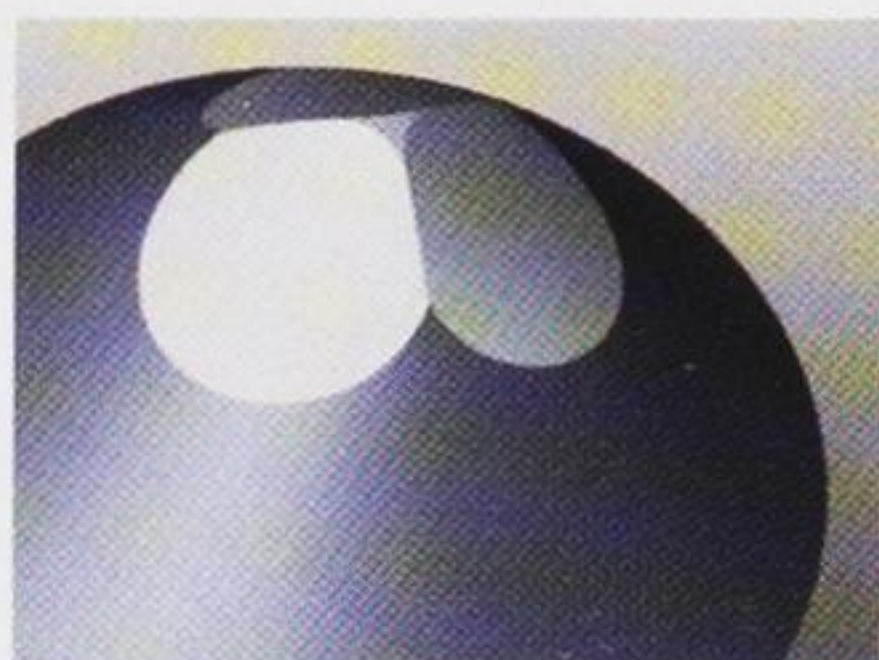
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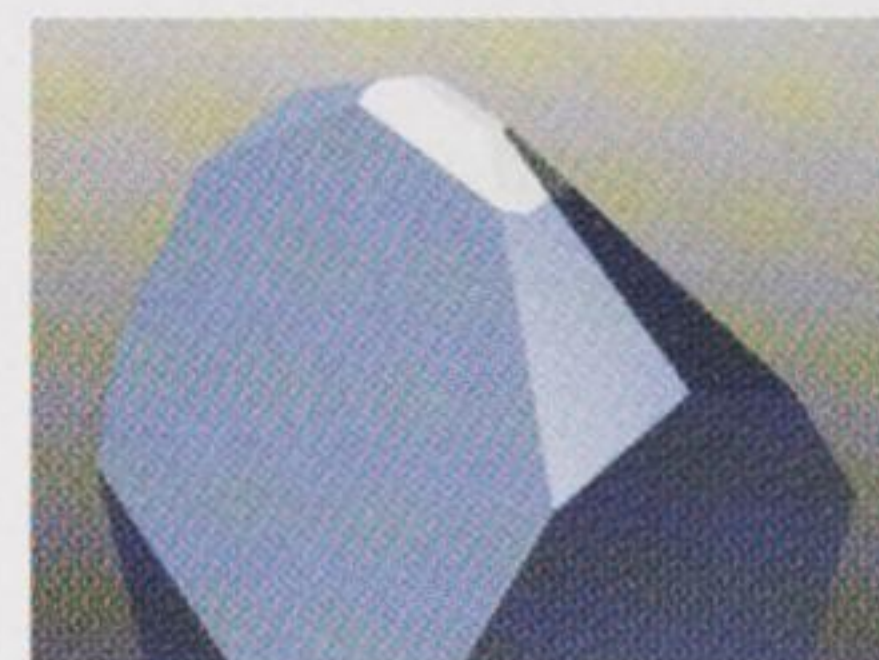
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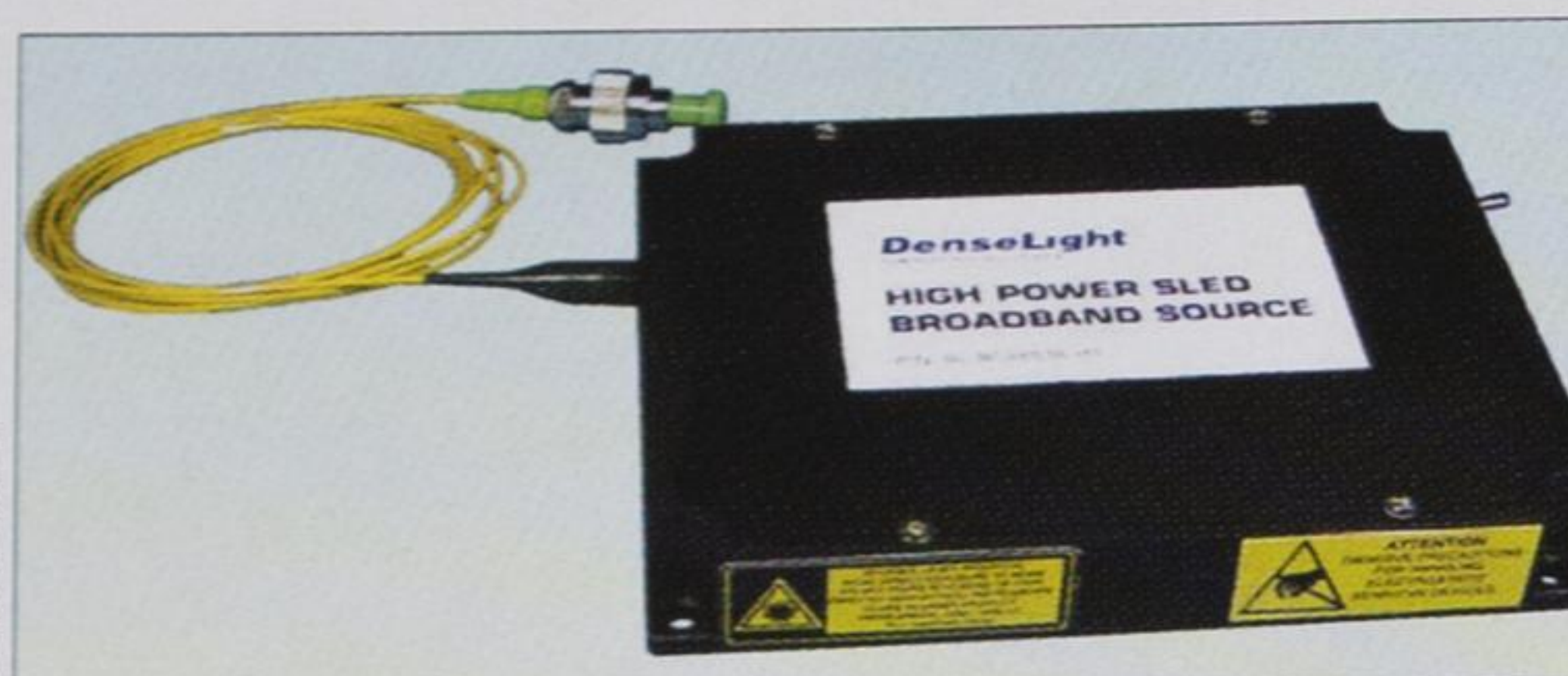
Denselight Semiconductors, the InP optoelectronic chip manufacturer based in Singapore, claims to have produced the most powerful superluminescent LED (SLED) ever.

The company believes that the device, which emits 120 mW at 1550 nm, could penetrate applications such as medical imaging, security and industrial sensing.

"We believe that this high-powered chip can totally change the way broadband [optical] sources are used and deployed today," said Denselight's Derek Leong. "This is a disruptive technology. It has the benefits of high-output broadband light, [but] at miniature chip dimensions and lower power consumption."

Denselight was originally set up with a view to targeting the fiber-optic communication market, and the source emits in all of the important bands used for long-haul transmission. The company has some components operating in live networks, and says that it has shipped "tens of thousands" of its Telcordia-qualified SLEDs worldwide.

But the company believes that many other applications will now be possible. "In many application areas – like test and measurement,



DENSELIGHT

High-power superluminescent LEDs from Denselight Semiconductors look set to improve early detection of cancers.

fiber-optic sensors, optical coherence tomography and communications – increased power can certainly extend the range of such systems," said Denselight's vice-president of engineering, Etsuji Omura.

Optical coherence tomography (OCT) is a relatively new medical imaging technique that requires a broadband optical light source. The higher power of Denselight's SLED ought to produce improved images of tissue structures and allow faster scanning for real-time imaging. The technique has had to rely on either expensive laser-based light sources or 810 nm semiconductor emitters until now. The chief constituents of living tissue that absorb light

(water and haemoglobin) are both significantly more transparent at the longer wavelength.

Having improved the SLED output power from 25 to 120 mW in just a year, Denselight has further improvements planned: "It is on our roadmap to release even higher-powered SLEDs over the next few months, with an aim to reach 500 mW soon," continued Omura.

According to Leong, the chip's optical gain was increased by optimizing its cavity length and improving the thermal diffusion efficiency. He says that the high power output will have a number of benefits: "Signal-to-noise will improve dramatically. This will reduce image acquisition time. Images will be more stable, sharper and have higher resolution. Real-time images are now a possibility and greater penetration depths can be reached."

Meanwhile, the Japanese company NTT has launched its own commercial SLED. It too is targeting the OCT application. The NTT device emits at the slightly shorter wavelength of 1310 nm. As well as allowing deeper imaging of internal organs, which ought to help with early detection of cancers, the device is said to be compatible with endoscopes.

Optical mice master intractable terrain

Logitech has launched a new optical mouse that uses a laser to track its position.

Made by Agilent Technologies, the infrared laser sensor used in the mouse is said to improve the trackability of surfaces that typically cause LED-based optical mice to falter.

According to Logitech, the greater precision of the laser tracking system means that it



LOGITECH

Logitech's laser-based mice can cope with painted metal and polished wood surfaces.

can track mouse movement on painted metal, polished wood and glossy paper – all surfaces that cause problems for LED-based mice.

Logitech believes that the new design will render LED-based mice obsolete. Agilent, which developed both the laser- and LED-based sensors and supplies them to all of the major mouse manufacturers, agrees. Jason Hartlove, general manager of Agilent's sensor solutions division, said: "We expect this technology to replace the LED-based optical mouse sensor."

News in brief

- UK-based optoelectronic chip manufacturer **Intense Photonics** has appointed Iain Robertson and Christopher Snowden as non-executive directors.

Robertson is currently chairman of the power semiconductor company Cambridge Semiconductor, and Snowden, a part-time academic at Leeds University, is also joint CEO of the communication components and systems firm Filtronic.

- **Eblana Photonics**, an Irish manufacturer of laser products for high-speed

broadband-access and enterprise networks, is commencing shipment of edge-emitting laser diodes that feature circular, non-astigmatic far-field emission patterns.

"The consistent performance and non-astigmatic emission of these products break the complexity and total-cost barrier for broadband transceiver manufacturers," said James O'Gorman, Eblana's CEO.

- **APA Optics**, which makes GaN-based materials for UV photodetector applications, has changed its name to APA

Enterprises. After radically shifting its focus in recent years through the acquisition of various non-optical businesses, as well as ceasing optics manufacturing at its own site, the name change better reflects the company's activities.

- **Sanyo** intends to join the ranks of next-generation DVD-format suppliers, aiming to release a HD DVD player in Japan by fall 2005, according to the Japanese newspaper, *Nihon Keizai Shimbun*.

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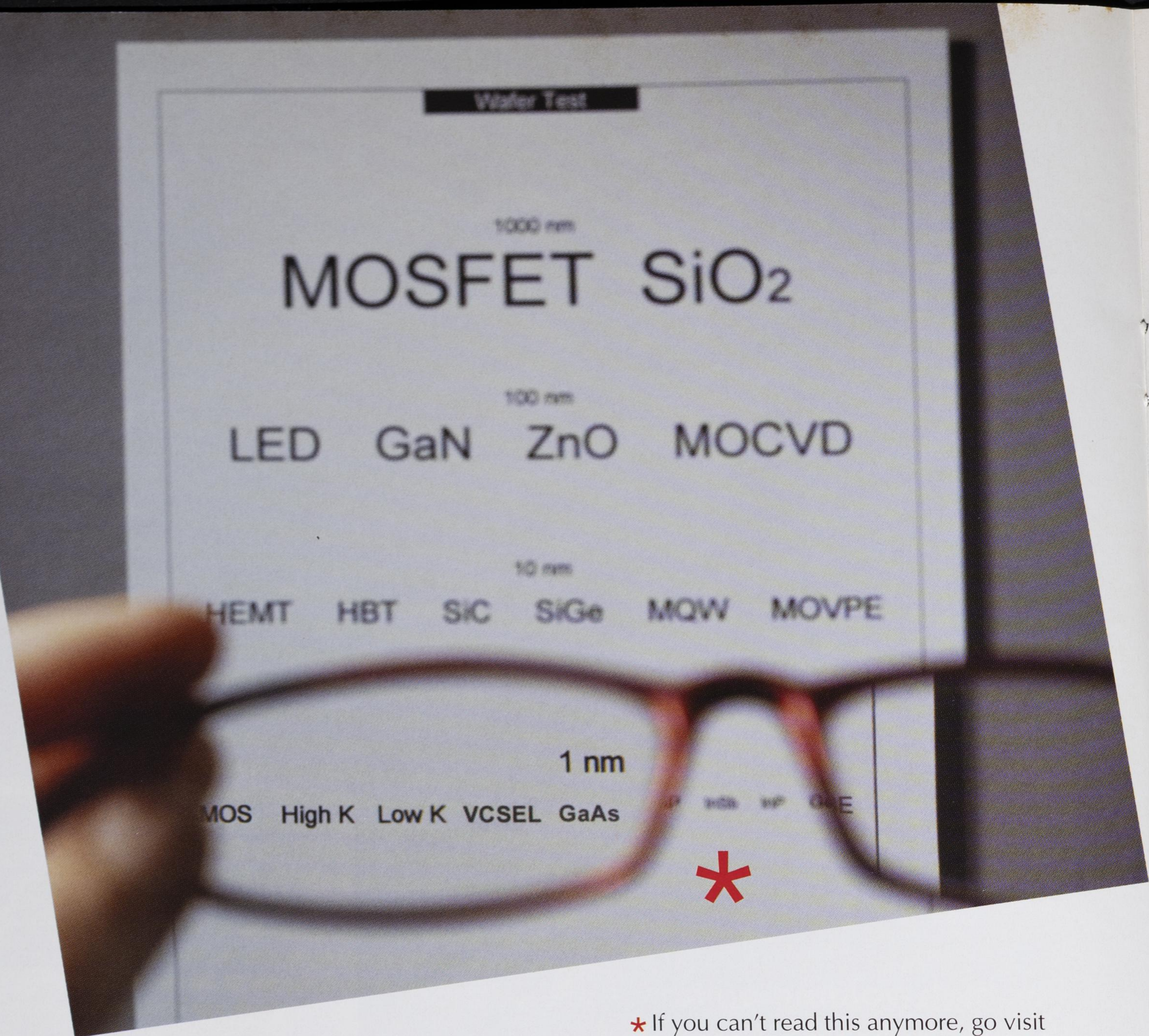
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Fujitsu plots commercialization of quantum dot lasers in 2007

A collaboration between Fujitsu and the University of Tokyo, Japan, has developed a quantum dot (QD) laser for use in next-generation broadband telecommunications.

The partnership hopes to put the new device to practical use by 2007, citing low manufacturing costs and high efficiency as the main benefits of the technology.

The GaAs-based device, containing 10 layers of 10 nm diameter InAs dots, emits at 1.3 μm and can operate at speeds of up to 10 Gb/s. However, the key breakthrough is that the QD device is temperature insensitive and requires no current adjustment at 20–70 °C. The team plans to extend this range to 0–85 °C through further device development.

Using epiwafers based on n-type GaAs supplied by Germany-based QD specialist NL Nanosemiconductor, the Japanese team claims that its breakthrough will “open the way for

low-cost transmitters and trigger the introduction of QD lasers to real optical networks”.

Nikolai Ledentsov (NL Nanosemiconductor’s chief scientist, and to whom the “NL” in the company name refers) says that another key attribute of the lasers is that their output power is maintained when the modulation speed is increased to 10 Gb/s. This is a distinct advantage of QD technology over InP-based lasers featuring strained quantum wells, whose output power is dramatically reduced at high modulation speeds.

“The technology will pave the way for compact, low-cost, low power consumption optical transmitters for metro, access and high-speed optical LAN applications,” said a Fujitsu spokesperson. A post-deadline paper detailing the research was presented at the recent European Conference on Optical Communication held in Stockholm, Sweden.

Magnolia touts high-speed VCSEL links

By Michael Hatcher

Magnolia Optical Technologies of Woburn, MA, has developed what it believes to be the first 120 Gb/s fiber-optic transmitter and receiver modules.

The modules feature 12 parallel channels, each operating at 10 Gb/s. The transmitter uses 850 nm vertical-cavity surface-emitting laser (VCSEL) sources, while the receiver element features a PIN diode array.

With funding from the US Army’s Tank and Automotive Command division, it’s no surprise that the initial applications of the technology will be in combat systems. As well as providing a high-speed local area network (LAN) for ground vehicles, the 120 Gb/s modules could be used in next-generation warplanes, such as the Joint Strike Fighter, to connect missile systems with logic processing.

Magnolia president and co-founder Ashok Sood told *Compound Semiconductor* that the links could have a number of commercial applications too, although these are not expected to materialize for some years – until the modules are made sufficiently rugged and their cost drops considerably.

For instance, the transfer of medical images that carry a very high data burden (such as MRI scans) could be one such application. “These images are stored in a network, and

[our] modules would be very useful for delivering them from a central hospital computer around the local network at a very high speed,” explained Sood.

One of the key technological difficulties that the Magnolia team has overcome is that of parasitic capacitance. Sood says that when increasing the speed of each parallel channel from 2 to 10 Gb/s, parasitic capacitance becomes a critical issue, suppressing the frequency response of the overall module. “The packaging scheme used to house and align the various components becomes critical when it comes to maintaining signal integrity at these high speeds,” Sood explained.

At the moment, the use of 850 nm VCSELs limits the range of such links to LAN use. Magnolia’s next goal is to incorporate 1310 nm VCSELs into its module design, which ought to extend the link range to several kilometers.

Set up in May 2000, Magnolia had initially planned to manufacture VCSEL sources in-house. However, it scrapped these plans after expected venture funding dried up following the telecoms bust.

Sood and colleagues decided to operate the company as a fabless enterprise and source VCSEL chips from vendors including Honeywell (now Finisar) and Germany-based Ulm Photonics.

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Malibu lab eyes X-band with GaN-based MMIC

HRL Labs in Los Angeles, CA, says that it has made two GaN-based amplifier HFET MMICs with “unprecedented” performance.

The first, a 33 GHz (K_a -band) power amplifier MMIC, outputs up to 2.8 W with a power-added efficiency of 27%. K_a -band devices can be used in two-way broadband satellite communication links (see *Compound Semiconductor* July p33).

“To our knowledge, this is the first reported K_a -band millimeter-wave MMIC demonstrated in GaN technology,” said HRL. “[As well as having] numerous applications in communications and sensing, the MMIC represents a new stepping stone to even higher frequencies of operation.”

HRL’s GaN team has also developed a low-noise amplifier MMIC operating at 3–18 GHz that features 20 dB gain and a minimum noise value of 2.4 dB. These represent world-best figures for GaN MMIC gain over more than an octave of bandwidth.

Often touted as suitable devices for next-generation cellular base-station amplifiers, GaN HFETs offer higher outputs and breakdown voltages compared with their GaAs

counterparts. “Low-noise amplifiers like these could be an enabling technology for multi-function RF receivers such as those envisioned by the US Navy for future shipboard applications,” HRL said.

According to HRL, the K_a -band development should also pave the way to significant improvements in “X-band” power amplifiers (operating at 8–12 GHz), beyond the 43% efficient, 20 W amplifier performance reported by HRL in 2000.

The latest MMICs from the company were grown using MBE on a SiC substrate. HRL has developed two different MMIC architectures, whose cost and performance can be tailored to a specific application.

Currently fabricated on a 3 inch diameter semi-insulating SiC substrate, HRL says that the demonstration MMICs could be transferred to a 4 inch wafer process. This would substantially reduce device cost, provided there is volume demand for the advanced MMICs. The firm says that it will “productize” MMICs over the next two years, and that it has sufficient manufacturing capacity to supply the devices in volume if necessary.

TriQuint researchers announce record GaN-on-Si HEMT power

The record for the world’s most powerful AlGaIn/GaN HEMTs fabricated on a silicon substrate has been claimed by researchers at TriQuint Semiconductor.

Deep Dumka and colleagues at the company’s Richardson, TX, research facility reported that their device has a continuous-wave output-power density of 7 W/mm at 10 GHz (*Elec. Lett.* **40** 1023).

“The results suggest that GaN-on-Si has evolved to a level that is attractive for medium-to high-power transistors,” Dumka said. “A prospective application could be X-band power MMICs or even higher frequencies.”

While it is cheap, silicon is not the first choice of substrate for high-power AlGaIn/GaN devices. Of the alternatives, sapphire cannot handle very high powers due to its poor thermal conductivity, and although SiC and native GaN are better suited in that regard they

are both thought of as immature and expensive – particularly GaN.

“Thanks to improved material growth by Picogiga and TriQuint’s optimized field-plate gate process, we achieved high breakdown voltages and good isolation for these devices, which allowed us to operate them at a 40 V drain bias,” Dumka explained. “Consequently, we were able to achieve the best output power for GaN-on-Si HEMTs.”

The HEMT had a 0.3 μm gate length and produced a maximum current density of 850 mA at gate and drain voltages of 1 and 10 V, respectively. Its peak output power density was 7.03 W/mm with no external cooling, equating to an output power of 31.5 dBm.

TriQuint is now working on reliability and quality issues and will decide whether to move into commercial production of the devices after this evaluation process is completed.

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Ask the Expert



Rajiv K. Agarwal, Ph.D.

Lead
Research
Engineer

Q

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A

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Japan sets white LED target

Among the highlights of the Fourth International Conference on Solid-State Lighting were updates on government-sponsored programs in Japan and the US, and a report of white LEDs with a color-rendering index approaching the theoretical maximum of 100. **Tim Whitaker** reports from Denver.

The Fourth International Conference on Solid-State Lighting, held in the first week of August, opened with an update from Jim Brodrick of the US Department of Energy (DoE) on the Solid-State Lighting Program, which is seeking to improve the performance of both LED and OLED technologies for lighting applications.

The program has around 25 active projects and received some 100 proposals for work in 2003 and a similar number in 2004. Coinciding with the event, the DoE announced awards totaling around \$20 million for 11 new projects that will focus on core technology areas such as advanced phosphors, novel device concepts, and manufacturing technology for OLEDs (see *Compound Semiconductor* September p11). The DoE is also close to reaching an agreement with the Next-Generation Lighting Industry Alliance to act as its industrial partner and to assist with planning and agenda setting.

The purpose of the DoE program is to achieve energy savings that potentially could be made by replacing current lighting sources, such as incandescent and fluorescent lamps, with LED-based lighting. The table "Room for improvement" (p23) compares the cost and efficacy of current lighting technologies. One recent study suggests that solid-state lighting could reduce US energy consumption for lighting by around 30% by 2025, saving more than \$125 billion in consumer electric bills. These figures represent the predicted level of progress with an investment of \$100 million per year, which the DoE hopes to secure from Congress. At present around \$6–7 million is directed annually to the Solid-State Lighting Program.

Brodrick outlined some of the successes of the US program, including a project involving Lumileds and Sandia that has achieved quantum efficiencies of 76% using quantum dots for down-conversion in white LEDs. The DoE has also funded work at Cree Lighting to improve LED packaging efficiency and bright-

ness through the development of new structures and materials, resulting in a white LED demonstrator with an efficacy of 74 lm/W.

The Japanese government is just as keen on LED lighting as its US counterpart. Its initial five-year project, Light for the 21st Century, ended in March 2003, with partners demonstrating white LEDs with an efficacy of 60 lm/W, as well as practical RGB white LEDs with a high color-rendering index (CRI), an efficacy of 30 lm/W and a lifetime of 6000 hours. Like the US program, the Japanese project sought to benefit from the energy savings and the reduction of greenhouse gas emissions resulting from the development of high-performance white LEDs.

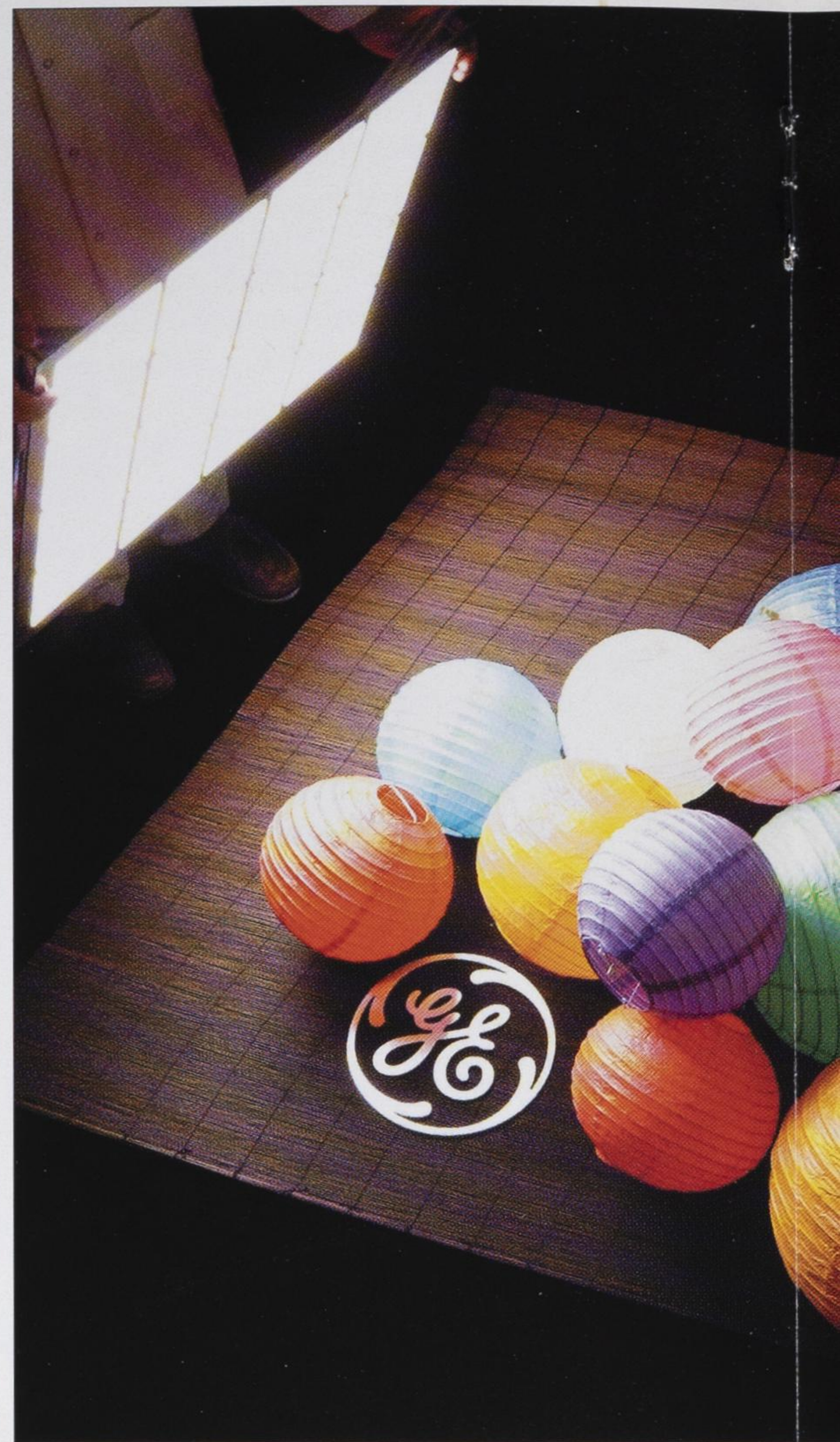
Entering a second phase

With funding from Japan's Ministry of Economy, Trade and Industry, phase two of the program is under way, according to Tsunemasa Taguchi of Yamaguchi University, Japan. Targets include white LEDs with efficacies of 80 and 120 lm/W by 2006 and 2010, respectively, and LED chips with external quantum efficiencies of 60 and 80% in the same time frames.

Taguchi also leads a national project in Japan entitled White LEDs for Medical Applications, which aims to develop products such as endoscopes for internal use, as well as surgical lighting and sterilization equipment. Taguchi says that among the requirements for medical applications are: avoiding strong blue emissions at around 450 nm, which, it is suggested, could cause retinal detachment; avoiding equipment heating to above 40 °C for internal use; and making a product easy to irrigate to avoid causing infection.

New phosphors improve CRI

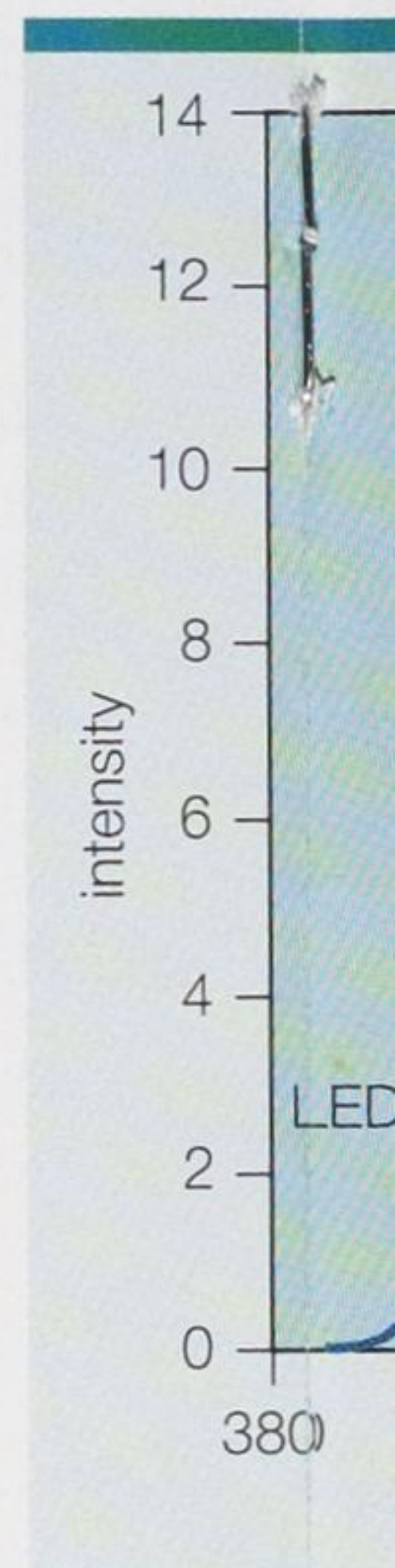
For white LED lamps that use phosphor down-conversion of blue or UV light, the development of new phosphors is a key requirement to enable improvements in color



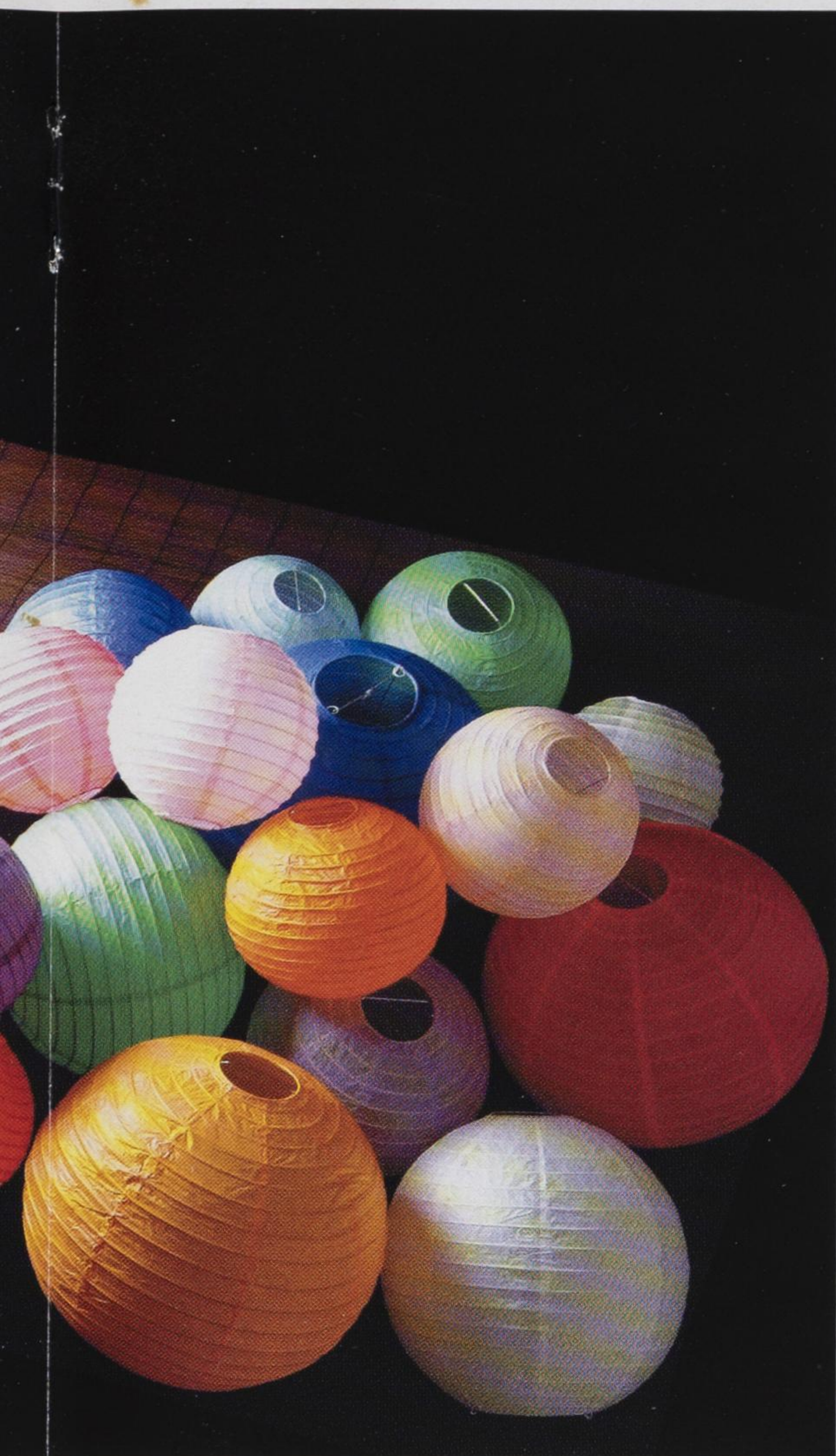
Large-area applications: GE Global Research has demonstrated a white LED chip that is capable of producing a total of 1200 lm at 15 lm/W – the

temperature and color rendering, and to open up new markets for LEDs. Several speakers from GE Global Research and GELcore described efforts to develop improved phosphors – notably GELcore's phosphor technology manager Emil Radkov, who unveiled a range of new phosphor blends that he described as having "unprecedented" performance. Radkov reported a specific white LED with an output of 25 lm at 23 lm/W, which had

Fig. 1. (Right.) The spectrum of a white LED that comprises a four-phosphor blend pumped by a near-UV chip. The GELcore LED has a color-rendering index of 97, which is close to the theoretical maximum.



ets as technology improves



Targets include white LEDs with efficacies of 80 and 120 lm/W by 2006 and 2010, respectively, and LED chips with external quantum efficiencies of 60 and 80%.

JAPAN'S LED PLANS

a CRI of 97 and color temperature of 3000 K. Figure 1 shows the emission spectrum of this LED. The color co-ordinates were $x = 0.441$ and $y = 0.410$, and the direct contribution of LED light to the down-converted spectrum was less than 2%.

Unlike deluxe linear fluorescent lamps, which have a broad spectrum, the blue LED/YAG phosphor combination has distinct deficiencies in the violet and blue-green regions. Both types of lamp are also deficient in the red region, which makes them poor at rendering deep-red colors. Compared to a traditional blue LED with a YAG phosphor, the combination of blue, cyan and orange phosphors pumped with a near-UV chip represents a major improvement in lumen output at color temperatures of below 4000 K, while further CRI enhancement is achieved by adding a fourth phosphor emitting in the deep-red region.

The highest CRI value for commercial white LEDs is about 90, which falls just short of the value of 100 defined for incandescent lamps. Radkov described a range of white LED blends with four-color phosphors, which had CRI values exceeding 95 over the entire range of color temperatures from 2500 to 8000 K. In some cases the CRI values (particularly the R9 component, which refers to the rendering of deep-red colors) can approach the theoretical maximum value of 100. Although there is a trade-off between luminous efficacy and color rendering, improvements continue to be made to both parameters through optimization of phosphor blends.

A number of novel and diverse applications were discussed during the meeting. LED manufacturers were encouraged to start producing LEDs for plant cultivation by a

research team from Vilnius University, Lithuania. Gintautas Tamulaitis from the team described how replacing conventional light sources with LEDs enhances photosynthetic productivity and leads to better plant morphology. Key wavelengths include 640 and 660 nm – where light is absorbed by chlorophyll – as well as 455 and 735 nm.

Jack Curran of US-based industrial safety specialist Wheelock Inc described the potential replacement of xenon gas flashtubes in visual fire-alarm signals, a market that has grown exponentially in the US due to the 1990 Americans with Disabilities Act. LEDs offer a comparable output for a smaller footprint, although at a higher cost. In an office environment, Curran found that the response times of test subjects were similar for both types of fire signal, although obstacles remain for the introduction of a new technology such as LEDs into such a safety-driven application.

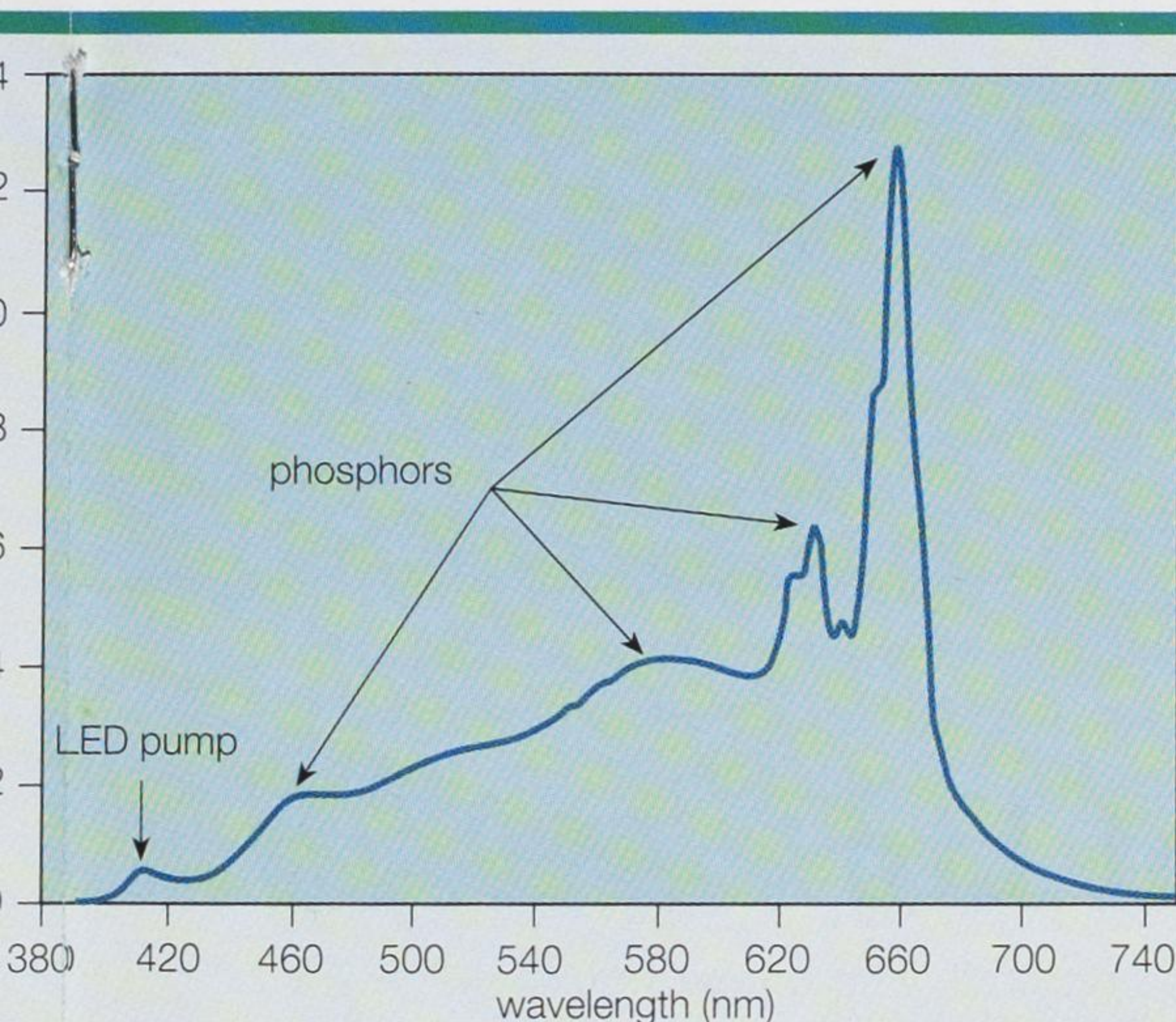
Andrew Siegel of MIT Lincoln Labs, near Boston, conducted a practical demonstration of covert communication using ultraviolet LEDs, transmitting data to a non-line-of-sight (NLOS) detector with a sharp cut-off solar-blind filter. LEDs with wavelengths of around 275 nm, developed as part of DARPA's SUVOS program (see *Compound Semiconductor* May p20), have been used to demonstrate NLOS links over distances of 2.1 km.

Taking to the air

LEDs are also starting to penetrate the aviation lighting business, according to Jeff Singer of Honeywell, whose company's Astreon lights have been designed as replacements for position lights on business jets manufactured by Cessna, Gulfstream and Learjet.

Red and green position lights are used on the left and right wingtips, respectively, with white lights used at the rear of the aircraft. The color, light distribution and intensity levels of such lights are closely regulated through Federal Aviation Regulation documents. LEDs offer several advantages – most notably in that they are robust, do not require a colored lens and do not produce much heat. Problems include dealing with the different drive currents of red and green LEDs, the variations of properties within the same LED bins, and lifetime issues as the output of the LED degrades with time.

demonstrated a white OLED panel measuring 24 × 24 inches/W – this output is equivalent to an 80 W incandescent bulb.



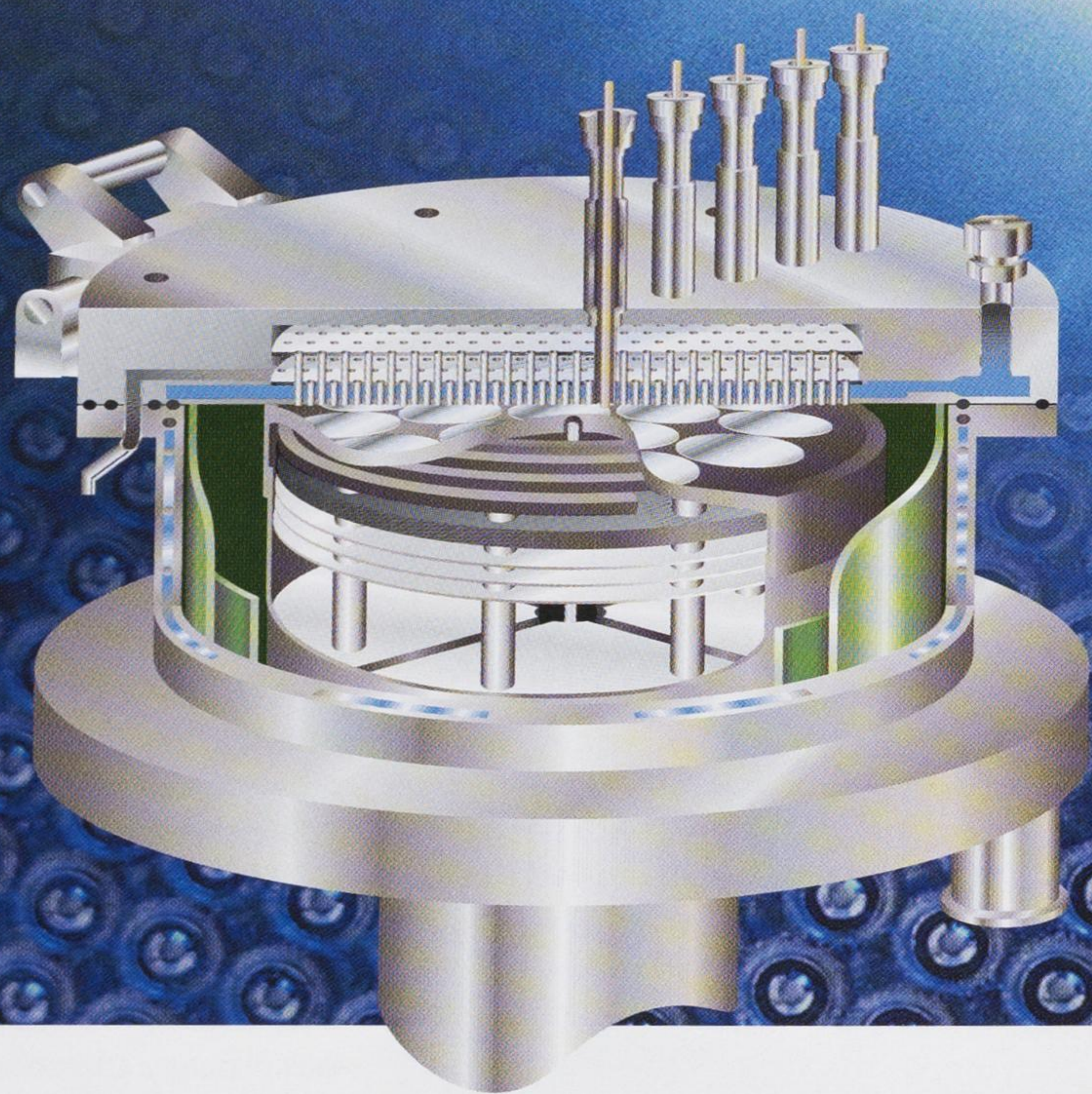
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(Right.) These LED-based position lights – designed for the wingtips of business jets – are intended to replace halogen sources.



Room for improvement

Source	Efficacy (lm/W)	Normalized lamp retail price (\$/klm)
incandescent (75 W)	13	0.60
fluorescent (T8)	83	0.73
high-intensity discharge (metal halide)	100	1.27
solid-state lighting (white LED)	20	250

(Left.) These typical values of efficacy and price per kilolumen (based on 2003 performance), indicate that white LEDs have a significant amount of room for improvement.

An emerging application for high-brightness LEDs is in projection displays. Won Yong Lee of Samsung Electronics in Korea – a firm that recently released a range of LCD monitors featuring LED backlights – described efforts to utilize RGB LEDs in a 40 inch projection TV. Four LEDs of each color were used to illuminate separate LCD panels, the output from which was projected onto the viewing screen. Crucial to Samsung's design was the use of parabolic reflectors, polarization converters and integration rods to collect and collimate the light for each LCD screen.

RGB LEDs offer a number of attractive features, notably a large color gamut (130% of the color space defined by the US National Television System Committee), a dynamic white point and a large dimming range. RGB LEDs also eliminate the need for color wheels, which are rotating filters used in color sequencing, and this makes the optical system much smaller and simpler. Also they can be turned on and off instantly, and have a relatively long lifetime.

Thermal management

Among the drawbacks of using LEDs are the need for very accurate thermal management and color compensation, and the problems caused by a relatively low light-output density produced by large high-power chips.

Despite a total LED flux of 745 lm, the system itself had a flux of only around 25 lm onto the screen; with an efficiency of 3.3%, this was deemed insufficient for the application. "For these systems, we need a large flux from a small chip with high light-extraction efficiency," said Lee.

In high-power LEDs, a key requirement is to increase the drive current without compromising reliability. Stanton Weaver of GELcore

described various ways to manage thermal issues, which include ensuring efficient current spreading at the chip level, and designing the chip and its package as an integral process. Weaver also used thermal modeling and high-resolution IR imaging to demonstrate that the placement and area of bump bonds has a strong influence on thermal gradients. Also, there is much less bump-to-bump variation using SiC compared with sapphire, due to the higher thermal conductivity of the former substrate material.

Yoshi Ohno of the National Institute of Standards and Technology in the US spoke about the issues involved with using CRI, the only internationally recognized metric for the way in which light sources bring out the appearance of colored objects. Unfortunately, there are many issues with using CRI – for example, the CRI value of a white LED source does not indicate how far the color co-ordinates are located from the blackbody locus.

Ohno also pointed out that there is a trade-off between color rendering and luminous efficacy, which are arguably the two most important parameters for light sources. Incandescent sources have (by definition) a CRI of 100, but the maximum luminous efficacy of radiation is 240 lm/W. For a green LED, efficacy can reach 640 lm/W, since the eye is most sensitive at 550 nm, but with a green source all objects appear green, and the CRI value can be as low as –28.

Ohno has developed a simulation program that allows metrics such as CRI to be calculated for different LED types – for example by altering the wavelengths of the individual LEDs in an RGB combination. He demonstrated that a well designed RGB LED can give good color rendering, while a 4-chip device has an excellent CRI value. However, the deficiencies

inherent in the CRI mean that a new metric needs to be devised for the LED industry.

Kevin Dowling of lighting-system designer Color Kinetics discussed how color is perceived by the human eye, and the issues that are peculiar to using LEDs. The human eye has a huge dynamic range but also has a non-linear response to luminance. Small changes are very noticeable at low brightness levels, but much larger changes can be tolerated at high brightness. One issue for LED lifetime, which is defined by lumen depreciation, is whether or not the change in lumen output can actually be observed by the user. Other light sources also depreciate, but for these there tend to be different ways of defining lifetime.

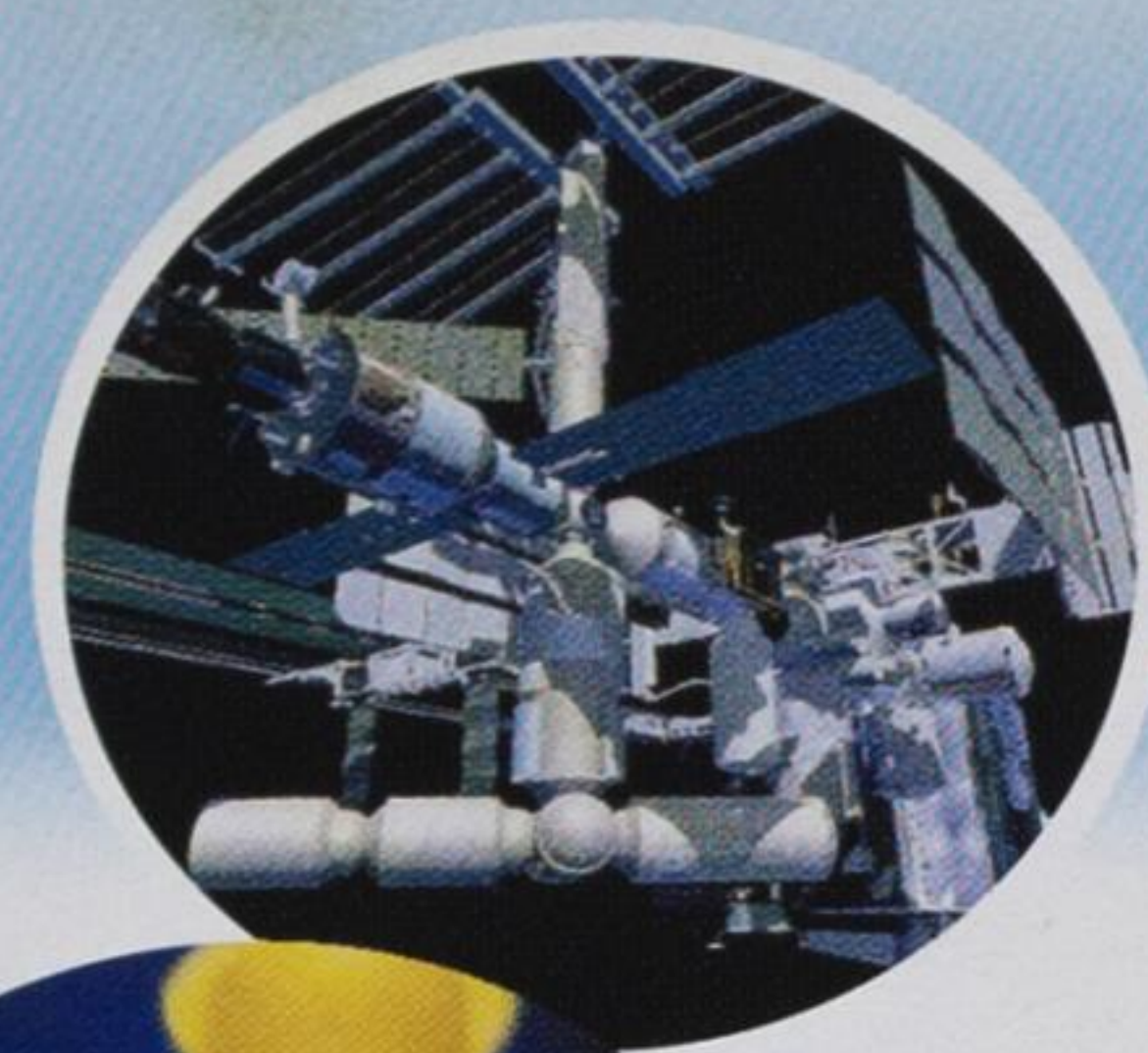
Another issue is color consistency between LEDs: "Customers can perceive differences and they care," said Dowling, whose company manufactures LED-based lighting systems. "It is sometimes possible to perceive differences between LEDs in the same bin, and color mixing can be dramatically affected by improper binning." Noting that the different LED manufacturers have different ways of binning their products, Dowling raised the question of the need for standardization in this area.

White OLEDs for lighting

Another DoE-funded project, this time to develop white OLEDs for lighting applications, was described in a talk by Anil Duggal of GE Global Research. Until now, the main focus of OLED development has been for the display market, but OLEDs can also be used as a diffuse light source suitable for large-area applications. The key advantages of OLEDs are high efficiency, the ability to construct the devices on thin and flexible substrates, and low potential cost – GE Global Research is involved in another project to develop a roll-to-roll production machine for OLED manufacturing.

Duggal explained that the company has already demonstrated an OLED panel measuring 2 x 2 ft, which produces a total of 1200 lm with an efficacy of 15 lm/W. This is equivalent to an 80 W incandescent bulb. A color temperature of 4000 K and a CRI of 88 – which exceeds the performance of most fluorescent tubes – were also reported. However, together with cost, the big drawback for OLEDs is lifetime: the 1200 lm panel had a lifetime of about 400 hours, which is significantly shorter than equivalent white LEDs experience.

Tim Whitaker is editor of LEDs Magazine, a new publication for the LED industry. E-mail: tim.whitaker@ledsmagazine.com.



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Cree seeks to stay ahead of the pack with five-year plan

Record profit, a five-year investment in manufacturing facilities of \$300 million and a sharp rise in its stock price mean that LED maker Cree is one of the brightest lights in the compound semiconductor industry right now. **Hamish Johnston** quizzes John Palmour, Cree's executive vice-president and director of advanced devices, on the company's manufacturing strategy.

Hamish Johnston: What will Cree spend the \$300 million investment on?

John Palmour: Most of the money will go toward expanding facilities for producing the chips. [It] covers the cost of the new building as well as the new equipment over the next five years. There is a significant amount of processing equipment included in that figure.

This investment is necessary because we have been operating at near maximum capacity in the production of LEDs. We expect unit volumes to increase and therefore we must increase our capacity to meet demand.

HJ: Will all of the \$300 million be directed at LED activity?

JP: The bulk of the investment is for LED production, but it will also support other areas that are growing. We need more capacity for growing the wafers and the epitaxy here, and some of the new space will be devoted to those applications. We are moving the 3 inch Schottky diode line to our Sunnyvale, CA, facility so we don't need extra capacity for this application.

HJ: How much impact will the switch to 3 inch wafers have on LED manufacturing capacity?

JP: Simply converting to 3 inch wafers would increase the capacity of our existing facilities, but we would still need more processing capability to meet the expected demand. In the next few years we are also looking to expand other facilities in the US and overseas. There are cost advantages to performing some of the more labor-intensive parts of the process overseas and we are constantly monitoring that.

HJ: Why are you packaging in the US rather than Asia?

JP: We package our XLamp product in Durham, NC. It is a very different product from our standard LED chips. Most of our business



Cree's John Palmour says that the firm plans to market GaN substrates openly, as well as use them in its own blue lasers.

"We are...starting to shift some development emphasis away from LDMOS and toward wide-bandgap devices."

involves selling standard LED chips to packagers, but we also make a much larger LED chip – called the Power Chip – and this is geared toward solid-state lighting applications. We have set up a manufacturing line in North Carolina to launch the high-power packaged LED, or XLamp, business. We expect the solid-state lighting business to take off, but it will be a while before it is as significant a portion of our business as the LED chip side.

We are now shipping commercial lamp products to customers. Although this is still a small part of our overall business activities, we expect it to grow rapidly.

The same manufacturing line that makes LED chips can also make the Power Chip, which feeds our packaging line. The extra space that we are building is not for packaging XLamps, because that facility is already there and we have the room to double its capacity.

Certainly the hope is that we will run out of packaging capacity very quickly, and we will then evaluate where the best location for additional lines would be.

HJ: How are you reacting to rapid expansion by Asian competitors?

JP: We have a dual strategy. The way that we have been keeping our blended average selling prices fairly even is by constantly improving our high-end LED-chip products in terms of brightness and performance. We compete in the high-end segment, where there isn't so much competition. The high-brightness products can command a higher price, but we are also competing directly on the lower-brightness products that are coming out of Taiwan. We have introduced a new chip called the UT230 [for white and blue cell-phone keypad illumination], which is geared to go head to head with these competitors on cost.

The XLamp is also a high-performance device, but it is a separate product line based on a much larger chip. Taiwan is not yet competing in the solid-state lighting business, and in this sector our competitors are Nichia, Lumileds and Osram Opto Semiconductors.

HJ: Is there the danger of a "bubble" scenario in LED manufacturing?

JP: We are constantly challenging our customers on whether they are over-ordering. Whenever there is a capacity problem it can lead to a bubble because people order more than they need to ensure their supply. We believe that the demand is very real and will continue to grow. The penetration of colour

INTERVIEW

screens into cell phones is still on the increase. The automotive lighting market (daytime running lights and headlamps) has not even begun. We think that a large part of the potential business remains essentially untapped.

There are so many products that are just starting to come out that the potential continues [to grow]. Of course, there are always risks.

HJ: What are the key markets for Cree's LED products?

JP: The cell-phone market is less than 40% of our overall revenue; however, it is probably the single biggest market, mostly in keypad applications. Many of the flashes in camera phones are also LED-based. The automotive market is also strong, and is being targeted by our XLamp product in future daytime running light applications.

Backlighting LCD television and computer screens with LEDs is a new, exciting market for us. There have already been products released using LED XLamp style backlighting.

HJ: Does Cree intend to continue manufacturing non-LED products?

JP: Yes, we will continue to make power devices and other products. The power-device sector is one of our fastest-growing areas. And although it is a relatively small part of our business now, the rate of growth and the total available market make it a key part of our strategy.

HJ: What does the future hold for Cree's LDMOS line?

JP: We are evaluating partnership arrangements for LDMOS and starting to shift some of our development emphasis away from LDMOS and toward wide-bandgap devices. For long-term growth in the RF area we are targeting wide bandgap materials such as SiC MESFETs and eventually GaN HEMTs.

HJ: What role do you see for the recently acquired ATMI GaN substrate business?

JP: The sale of substrates and epiwafers is another key part of our business, so this acquisition is a logical extension of our materials [activity]. We intend to market GaN substrates openly. We are already selling GaN HEMT epiwafers and we will augment this [venture] with the business acquired from ATMI.

At the same time we will be evaluating the use of GaN substrates for a variety of devices, but most notably for blue lasers and future RF devices. This is the long-term plan in regard to how we will use GaN internally.

HJ: Have IP arguments affected your expansion plans?

JP: It doesn't really matter where the product is made – what matters is where it is sold. There are two considerations where IP is concerned. There is the general worldwide market where IP is considered to be an important factor in purchasing decisions. And then there is the Taiwan/China market where IP is not such an important factor. I'd say that outside of Taiwan and China we have had a fair amount of success managing our IP.

Nichia has sued Sharper Image in the US for marketing products with lamps that violate Nichia IP rights. If products are sold outside of the Taiwan/China region then IP is going to be a concern.

Hamish Johnston is the editor of Wireless Europe magazine.

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III-NITRIDE SUBSTRATES

Native substrates spar with the established technology

As blue lasers and wide-bandgap RF devices begin to arrive on the commercial landscape, one of the key questions for manufacturers is the choice of substrates: foreign, quasibulk or native.

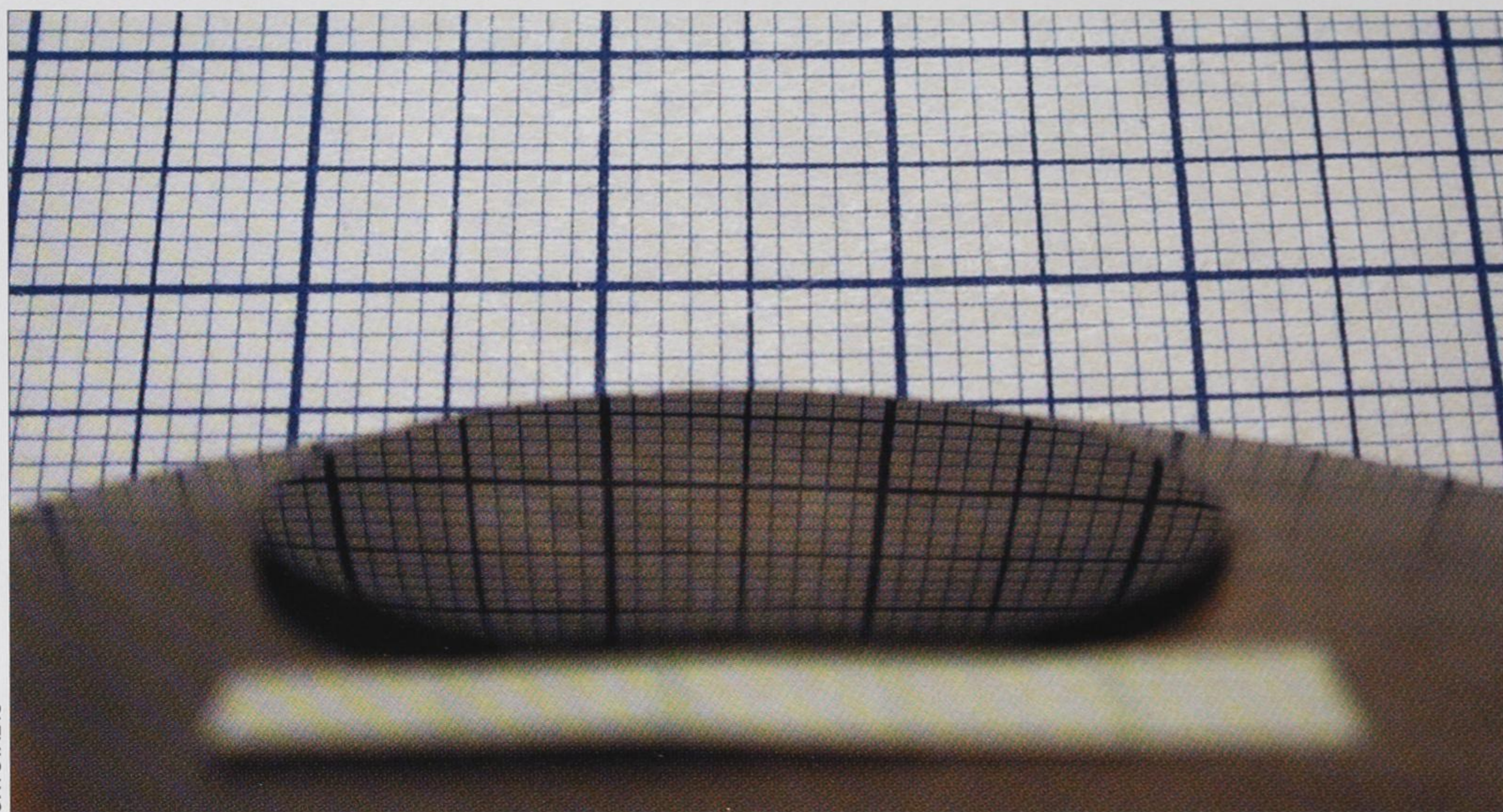
Keith Evans takes a closer look at what the three different technologies have to offer.

The great commercialization potential of III-nitride semiconductor devices has begun to be realized: witness the commercial success of visible LEDs and the recent introduction of blue lasers for optical storage. Many other III-nitride devices, including UV LEDs and laser diodes, high-power RF transistors, acoustic-wave devices, and MEMS devices, may also have a great commercial impact in solid-state white lighting, wireless communications, chemical and biological molecules sensing, and UV germicidal irradiation. According to some, the associated combined device market opportunity may surpass \$25 billion over the next decade.

Capturing these opportunities requires further improvement in device operating performance, reliability and cost – all of which are limited by the currently available substrate technology. Simple materials arguments suggest that all III-nitride devices could benefit from a native substrate (e.g. AlN or GaN), as history has demonstrated for silicon, GaAs, InP and, more recently, SiC (homoepitaxial) devices. However, there is no current supply of large-diameter, uniform, low-cost native III-nitride substrates.

Until recently, device developers and fabricators had been forced to rely primarily on foreign substrates like sapphire and SiC. These materials have supported blue- and green-LED commercialization and have enabled the demonstration of new devices such as UV LEDs and RF FETs with record-breaking physical characteristics.

Progress in blue-laser development has been limited by dislocations in the active region, and was slow until quasibulk GaN became available [S Tomiya 2001]. To meet future market requirements, the performance, reliability and cost of blue lasers and GaN-based RF FETs must improve. The most structurally perfect blue laser, giving rise to record pulsed output, appears to have been fabricated



According to Crystal IS, native AlN substrates can be made at larger diameters than their GaN counterparts. This image shows a 1 inch AlN substrate. The firm says that a limited supply of 2 inch materials will become available next year as the technology matures.

on ultralow defect density, native GaN substrates. Conversely, the performance of UV devices built on sapphire and SiC degrades rapidly at shorter wavelengths, where native AlN substrates may provide a solution. And in spite of the progress made in the performance of RF FETs on SiC, competing efforts on quasibulk and native substrates are beginning to show promise.

Substrate properties

The utility of a given substrate in building most devices is shown by several substrate-related properties as well as the quality of the buffer layers grown on it. Table 1 summarizes how the three basic substrate types compare in terms of the materials properties of both the substrate and the buffer layer. The buffer layer is assumed to be GaN for foreign substrates and a lattice-matched (Al,Ga)N composition for the others. Foreign substrates have low defect densities, but, owing to large lattice-

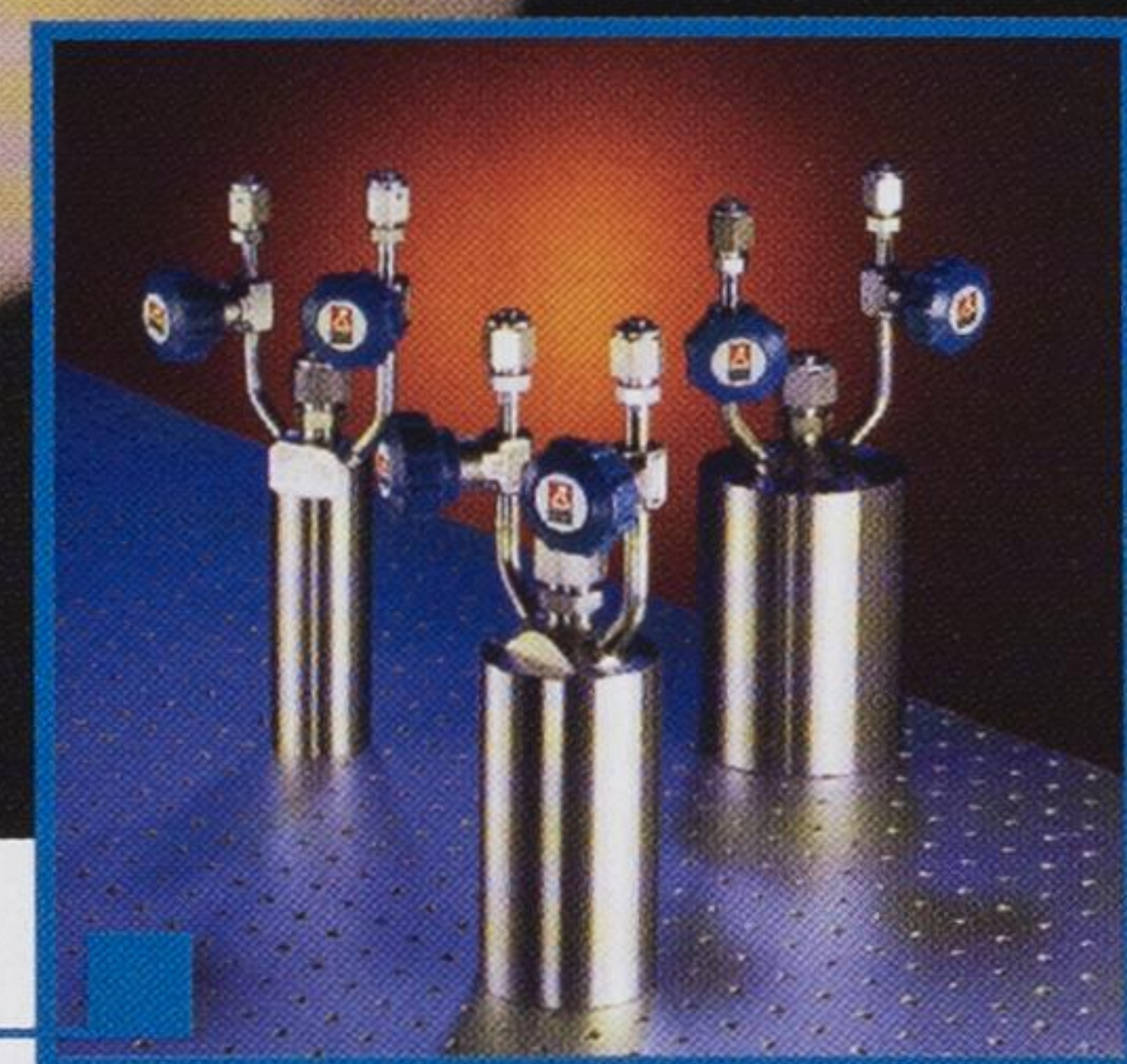
and thermal-expansion mismatches, they produce buffer layers with high defect densities.

Quasibulk approaches begin with large, foreign substrates and therefore have a good (large) size and shape. Through cost-additive intermediate processing steps (usually hydride vapor-phase epitaxy (HVPE) or epitaxial lateral overgrowth (ELOG)), their dislocation densities and those of the buffer layers grown on top drop to around 10^5 to 10^7 cm⁻².

Native III-nitride substrates show excellent structural quality, but suffer in terms of size, shape and uniformity. While native AlN substrate technology can currently achieve 1 inch diameter material and appears highly scalable, truly native GaN substrate technology (i.e. not grown by HVPE or ELOG methods) has not produced significant increases in substrate size over the past few years and only small-diameter material is currently available.

Foreign substrates are, by definition, materials that have already undergone the test of

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Table 1

Substrate property	Native		Quasibulk			Foreign	
	GaN	AlN	GaN	AlGaN	AlN	Al ₂ O ₃	SiC
lattice constant	●	●	●	●	●	●	●
thermal conductivity	●	●	●	●	●	●	●
electrical conductivity	●	●	●	●	●	●	●
electrical semi-insulation	●	●	●	-	●	●	●
UV optical transparency	●	●	●	-	-	●	●
thermal expansion match	●	●	●	●	●	●	●
dislocation density	●	●	●	●	●	●	●
current size and shape	●	●	●	●	●	●	●
long-term size and shape	●	●	●	●	●	●	●
current substrate cost	●	●	●	●	●	●	●
long-term substrate cost	●	●	●	●	●	●	●
Buffer layer property							
thermal conductivity	●	●	●	●	●	●	●
electrical conductivity	●	●	●	●	●	●	●
electrical semi-insulation	●	●	●	●	●	●	●
dislocation density	●	●	●	●	●	●	●
thickness	●	●	●	●	●	●	●

● poor ● average ● good

Observed/expected characteristics of three competing substrate types (native, quasibulk, and foreign) and (Al,Ga)N buffers grown on them.

diameter expansion. Quasibulk substrates begin as foreign structures and thus have the potential to be made with a large diameter. Native GaN and AlN substrates lag behind these other materials in terms of size.

The relative thermodynamic instability of GaN demands solution or liquid and high-pressure growth processes that, until now, have been difficult to scale past 1 cm. Native AlN substrates are produced by sublimation recondensation: a slow, yet deliberate mechanism for diameter increase similar to that of SiC. One key difference between AlN and SiC is the relative simplicity of the AlN phase diagram. This means that multiple crystalline phases are not competing during boule growth. As a result, the diameter of native AlN substrates can increase. Limited availability of 2 inch diameter substrates is expected in 2005.

Active-region quality

The relative concentration of dislocations in the active region of a typical device structure is expected to vary widely with the substrate used (see figure 1). In practice, growth on native GaN and AlN substrates has often shown defect levels of up to 10^5 cm^{-2} , primarily due to surface preparation and/or epitaxy initiation issues. The best device results have been obtained almost exclusively by the most experienced research groups.

For device manufacturers, it is device performance, reliability and cost that matter. For a given device performance and reliability,

the total manufacturing cost depends on the combined costs of materials, epitaxy and device processing. A low-cost substrate that produces a device that fails basic performance or reliability requirements because of a highly dislocated active region is not a low-cost solution. On the other hand, an expensive yet high-quality substrate (from an isolated single device perspective) that cannot be scaled or reduced in cost is not a long-term solution. The important question is which substrate can provide the lowest cost of manufacturing for devices that meet target performance and reliability specifications.

It is still useful to understand the cost factors that will limit the pricing structure of a given substrate technology. The cost of substrate manufacturing depends strongly on the effective substrate growth rate (EGR), which accounts for three elements of the process speed: actual growth rate during the boule production process; boule growth-process overhead time (i.e. growth initiation and termination); and process equipment downtime.

The EGR depends on many variables, including the length of the boule that is grown (since long boules lead to greater reactor utilization efficiency). The EGR for quasibulk substrates is less than 0.1 mm/h and is limited by the relative slowness of the HVPE process or, in the case of ELOG, by additional (epitaxy and lithography) processing steps. In marked contrast, EGRs for native AlN substrates and foreign substrates like SiC are believed to be

closer to 1 mm/h. So foreign substrates offer a cost advantage that will be shared by native substrates as the latter mature. Quasibulk substrates may have an inherent cost disadvantage due to process-throughput limitations.

Lattice constant issues

The a-direction lattice constant of AlN and GaN differ at room temperature by 2.4%, which results in a critical thickness of about 12 nm. Hypothetical structurally and otherwise perfect AlN and GaN substrates therefore differ in their ability to lattice-match to any given epitaxial-layer structure. The simplest wisdom, albeit unproven experimentally, is that gallium-rich epitaxial-layer structures are best produced on GaN substrates, while aluminum-rich epitaxial-layer structures are best produced on AlN substrates. Intermediate average-composition epitaxial-layer structures might best be grown on (Al,Ga)N substrates, which are now in development, albeit at dislocation densities characteristic of HVPE.

Gallium-rich epitaxial-layer structures are currently used in visible LEDs and lasers, and for most RF FETs. Gallium-rich designs have led to difficulties in obtaining semi-insulating buffer layers, yet it is difficult to change buffer-layer composition when using foreign substrates since the buffer-layer growth must be re-optimized to minimize cracking and defect generation.

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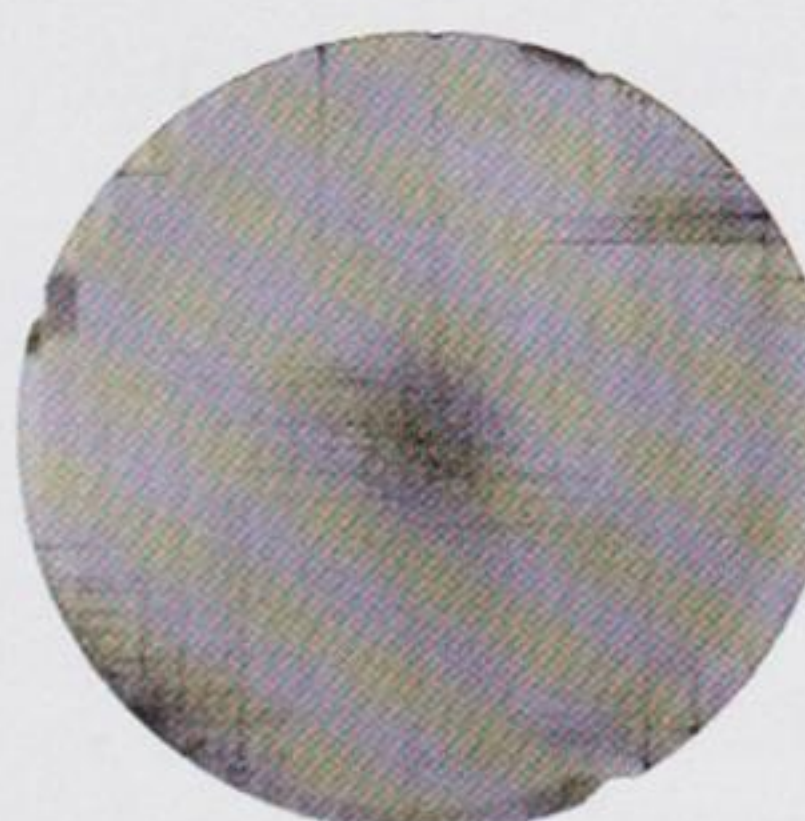
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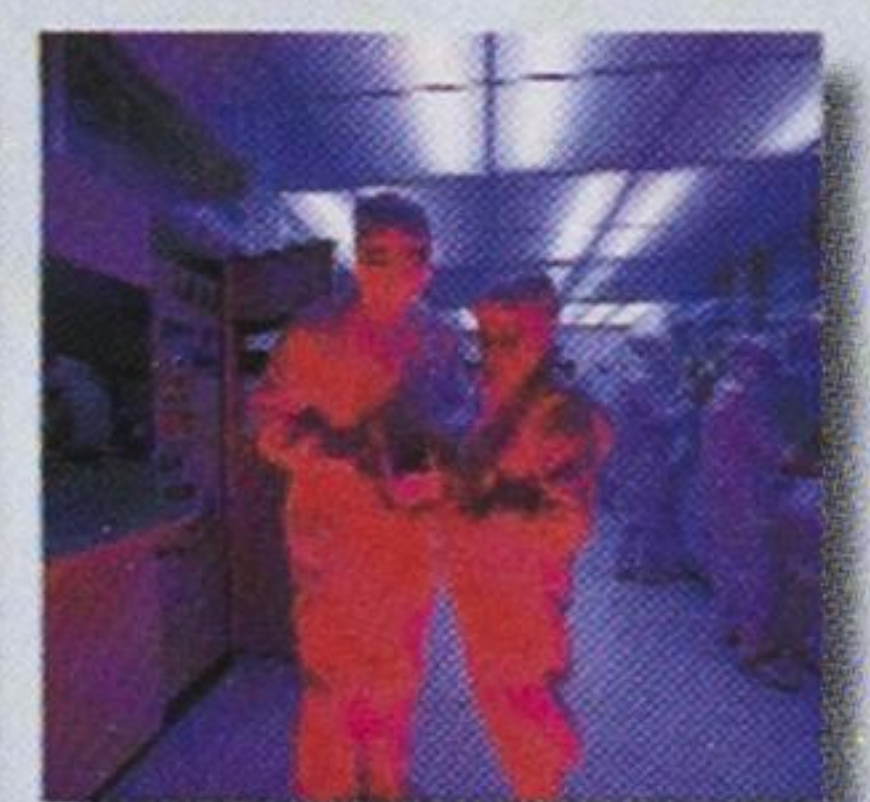
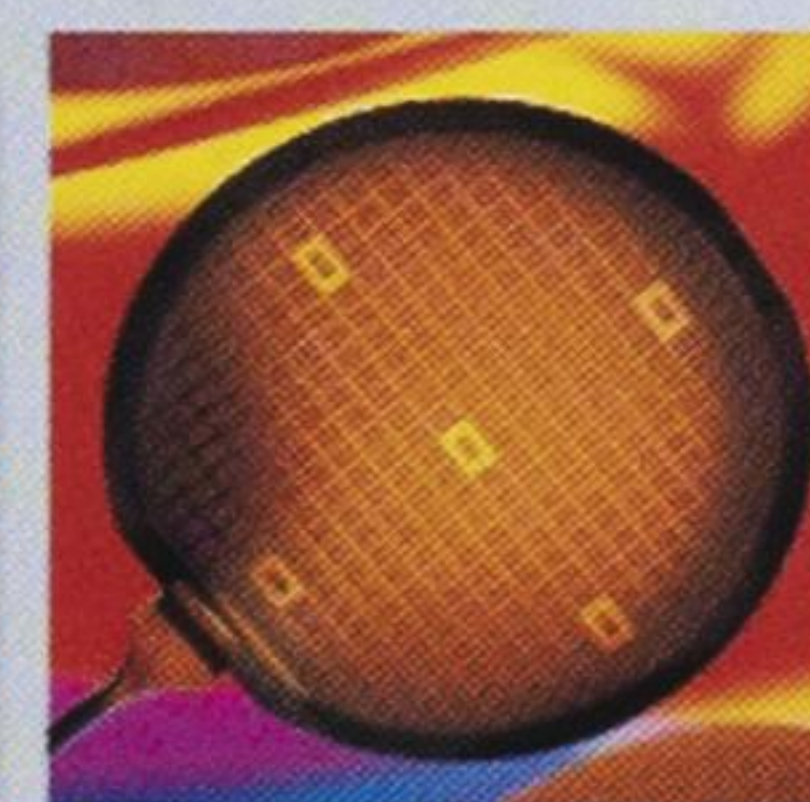
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nificantly higher voltages should benefit from highly insulating AlN buffer layers. The drive to develop UV LEDs and lasers also requires aluminum-rich structures.

Thermal expansion

Strain build-up and film-cracking result from differences in thermal expansion coefficients (TECs) between epitaxial films and the underlying substrate as they cool after epitaxial growth, which is typically carried out near 1100 °C. The degree of potential strain build-up is calculated by integrating the change in the TEC between the film and substrate from the film-growth temperature to room temperature.

Figure 2 shows the integrated change in TEC in the a-b plane of GaN grown on AlN, SiC and sapphire. C-plane GaN films grown on a-b plane substrates at 1100 °C that are cooled to room temperature can suffer integrated TEC-mismatch-associated biaxial strains of up to 1200 ppm (tensile) on SiC and 2600 ppm (compressive) on sapphire. Because the TECs of GaN and AlN are fairly close and cross at 475 °C, the potential strain build-up is only 100 ppm (compressive).

In practice these strains may be at least partially relaxed through extended defect generation during cool-down and can be compensated for by building opposing strain elsewhere in the epitaxial structure.

The impact on heat flow

Thermal issues play an important role in the performance and reliability of most III-nitride devices. When pushed hard, the device generates heat due to suboptimal operating efficiencies linked to the quality (traps and scattering centers) of the device's active region and to higher than desired contact and device-layer resistances. The choice of substrate affects not only the quality of the device's active region but also its ability to dissipate heat.

Of the four materials, SiC has the highest thermal conductivity (see table 2; the upper range reflecting the highest-purity variations is quoted). However, the imperfect lattice match and TEC match between SiC and typical III-nitride epitaxial-layer designs results in poor structural quality buffer layers, which are thought to represent major thermal bottlenecks. The thermal conductivity of GaN is known to depend on dislocation density [D Kotchetkov *et al.* 2001], which is important for understanding thermal bottleneck issues in buffer layers on foreign substrates and quasibulk substrates in general.

The thermal boundary resistance associated

Table 2

Material	Thermal conductivity ($\text{W cm}^{-1} \text{K}^{-1}$)
AlN	3.0
GaN	2.2
sapphire	0.3
SiC	3.0–5.0

Thermal conductivities reported for HVPE-grown GaN, native AlN, and foreign substrates SiC and sapphire.

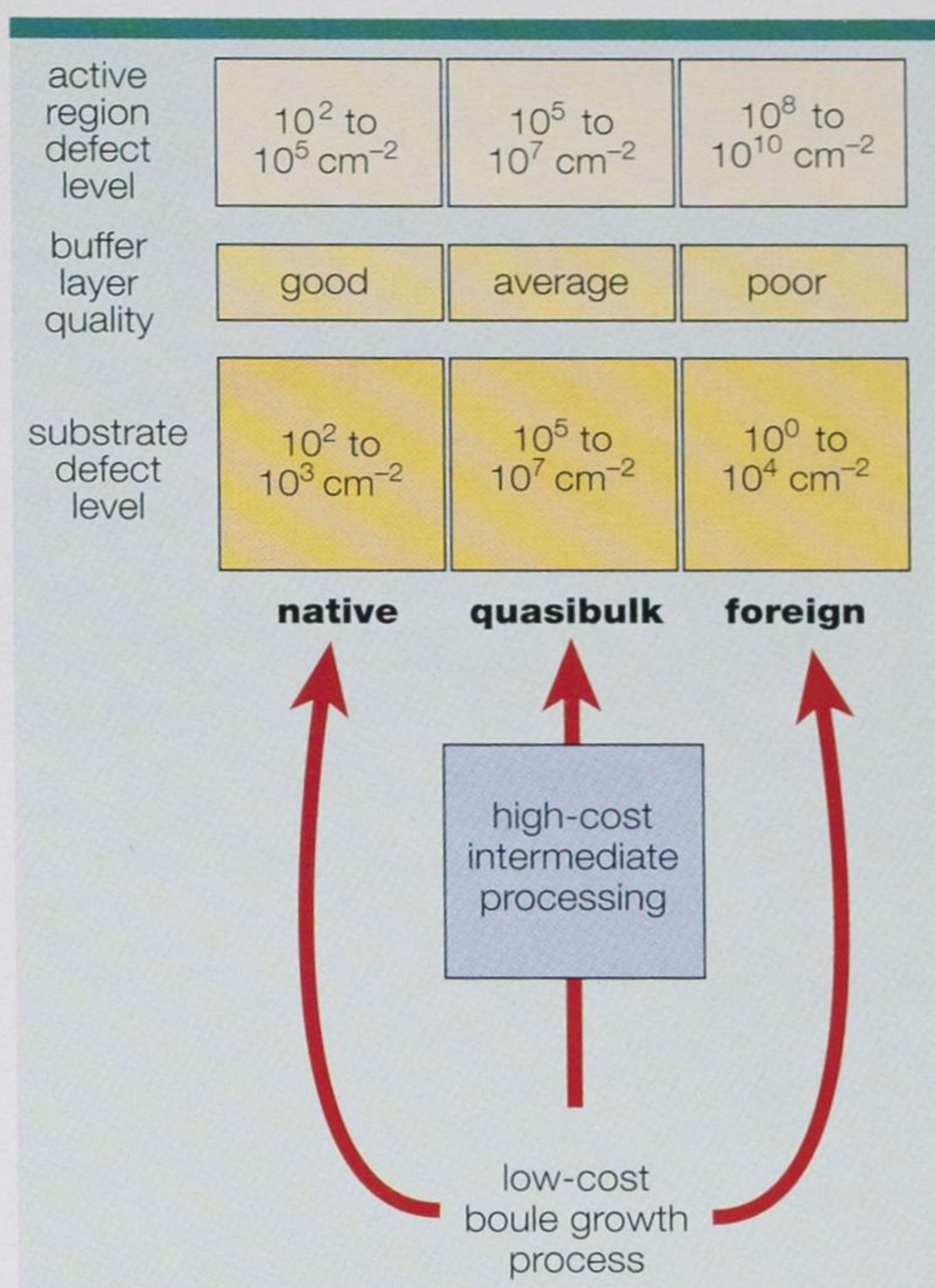


Fig. 1. The three primary substrate approaches and their expected defect concentrations in the device active region. Foreign substrates have size and maturity advantages, yet suffer the most in terms of active-region quality. Quasibulk approaches offer reduced defect density but with added cost due to a more complex manufacturing process. Native substrates produce the best active regions, yet currently suffer from limited quality, size and availability.

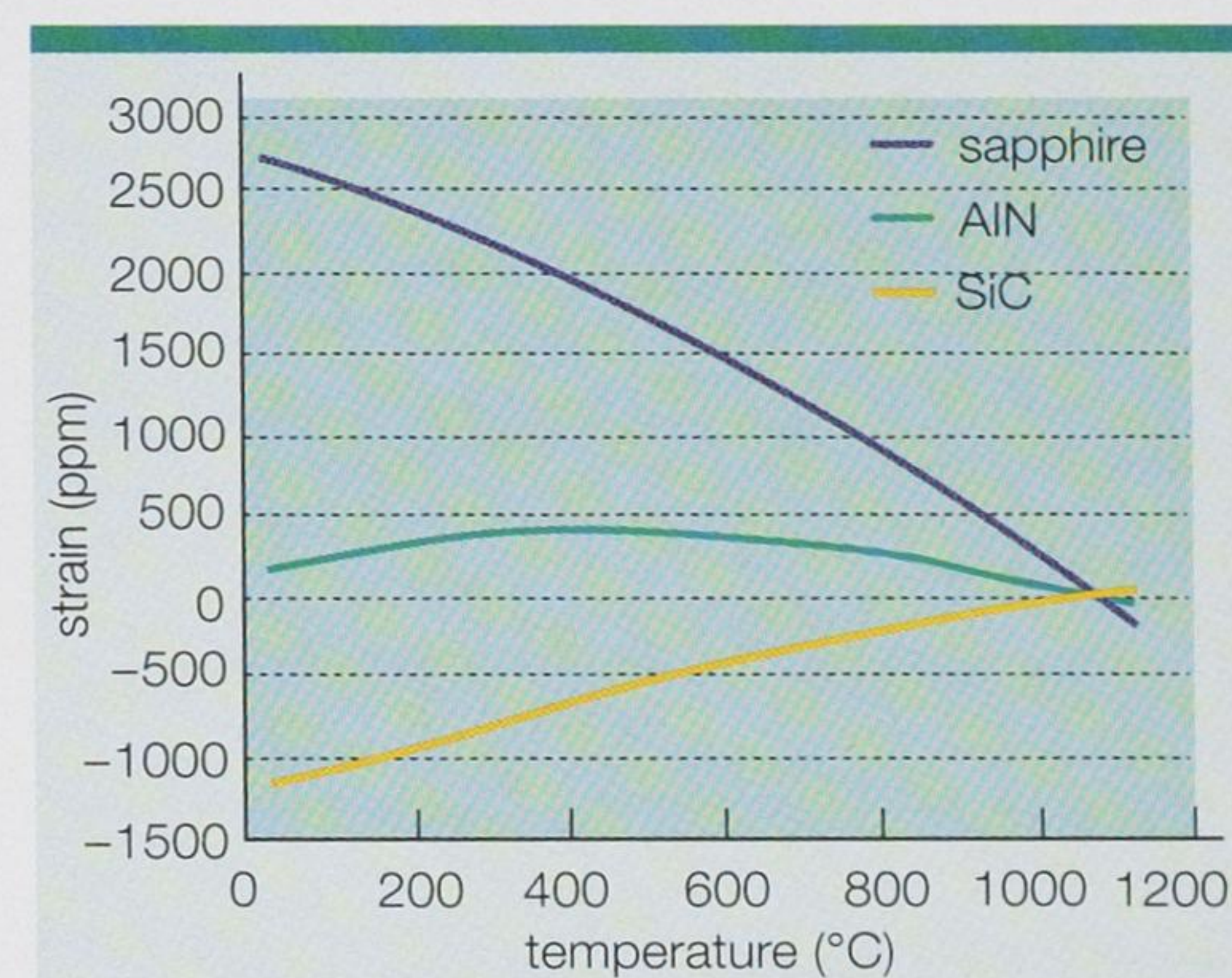


Fig. 2. Strain build-up and film-cracking result from differences in TECs between III-nitride films and the underlying substrate.

with the heterointerface between the buffer layer and a foreign substrate has also been implicated in modeling studies as a general device heat-dissipation bottleneck [K A Filippov *et al.* 2003]. Native AlN may therefore be the best substrate choice from a thermal-dissipation perspective, thanks to its high thermal conductivity ($3 \text{ W cm}^{-1} \text{K}^{-1}$) and amenability to producing high-quality AlN buffer layers and active regions.

Proof in device results?

Since foreign substrates have so far dominated III-nitride device development, and because so few devices have been produced on native and quasibulk substrates, a comparison of device results is of limited usefulness. However, native AlN substrate use has led to increased optical device efficiency at short emission wavelengths, as well as improved RF FET gate characteristics, apparently due to more structurally perfect active regions.

Quasibulk “free-standing” GaN substrates were recently used to build RF FET devices with good power performance [K K Chu *et al.* 2004], while native GaN substrate based efforts have demonstrated the highest output power (3.9 W for a 30 ns pulse) blue lasers. Piotr Perlin and colleagues at Poland’s High Pressure Research Center made these lasers using GaN substrates manufactured by TopGaN in what is likely the lowest defect-density blue-laser structure produced to date.

Cree has made similarly good progress with wide-bandgap electronics on quasibulk substrates. In very recent unpublished work, the US-based company fabricated high-quality HEMT devices grown on its own semi-insulating GaN wafers. Operating at 4 GHz and 68 V, these devices had an output power of 9.2 W/mm a power-added efficiency of 55% and a gain of 16 dB.

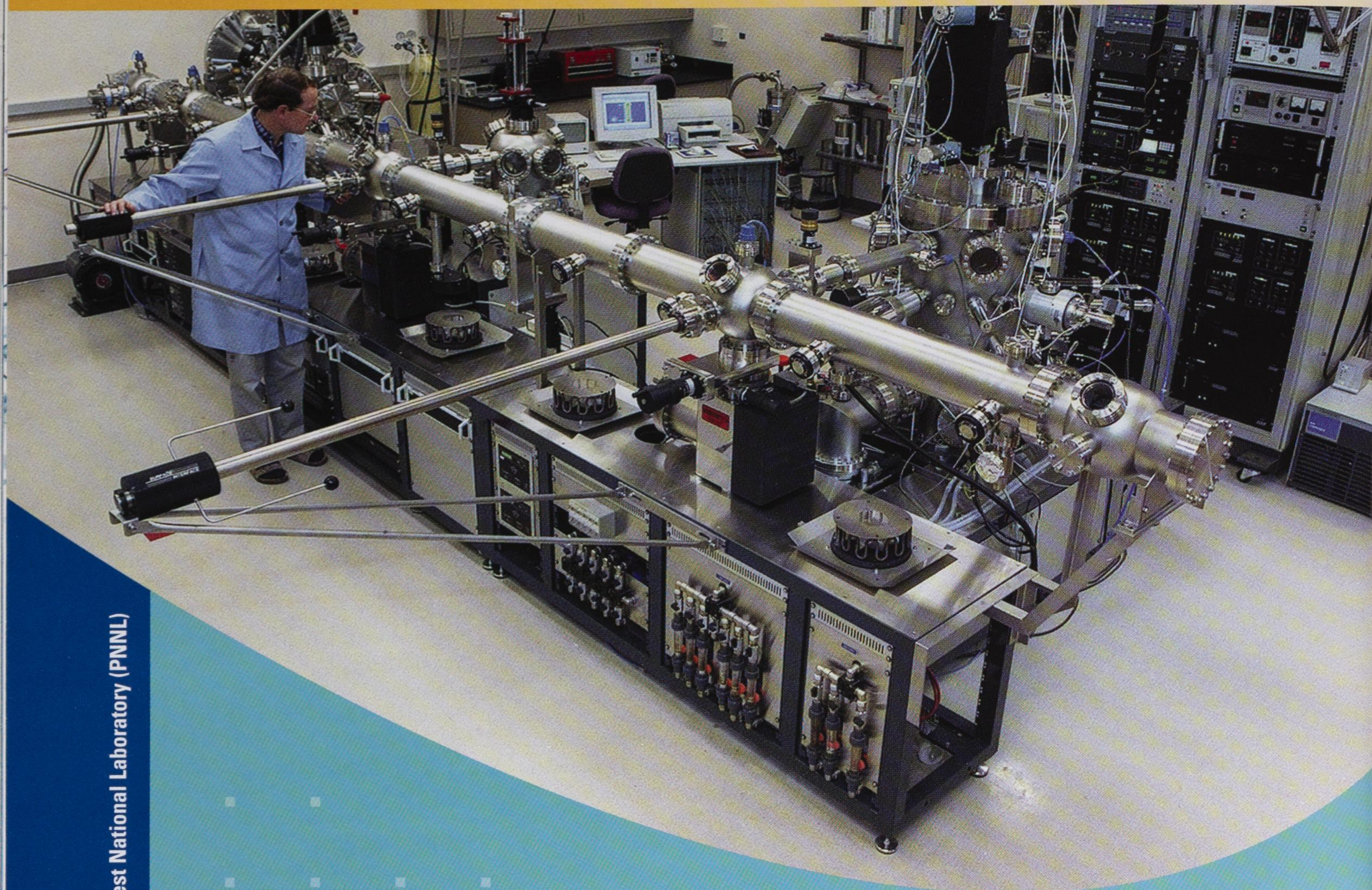
Further reading

- K A Filippov *et al.* 2003 *MRS Internet J. Nitride Semicond. Res.* **8** 4.
- P Perlin *et al.* 2004 *MRS Internet J. Nitride Semicond. Res.* **9** 3.
- K K Chu *et al.* 2004 *Electron Device Letters* **25** 9.
- D Kotchetkov *et al.* 2001 *Appl. Phys. Lett.* **79** 4316.
- S Tomiya 2001 *Phys. Stat. Sol. (a)* **188** (1), 69–72.

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Etched facets set to cut the cost of diode arrays

Californian start-up QPC says that its 2D surface-emitting diode arrays will be a good deal cheaper than conventional high-power diode stacks.

Oliver Graydon reports.

Compact laser-diode arrays that emit more than 1 kW and are far easier and cheaper to package than conventional diode stacks could result from a new technology being pioneered by a US start-up. Quintessence Photonics Corporation (QPC) in California claims to have developed 2D surface-emitting diode arrays that are made from a single piece of etched semiconductor.

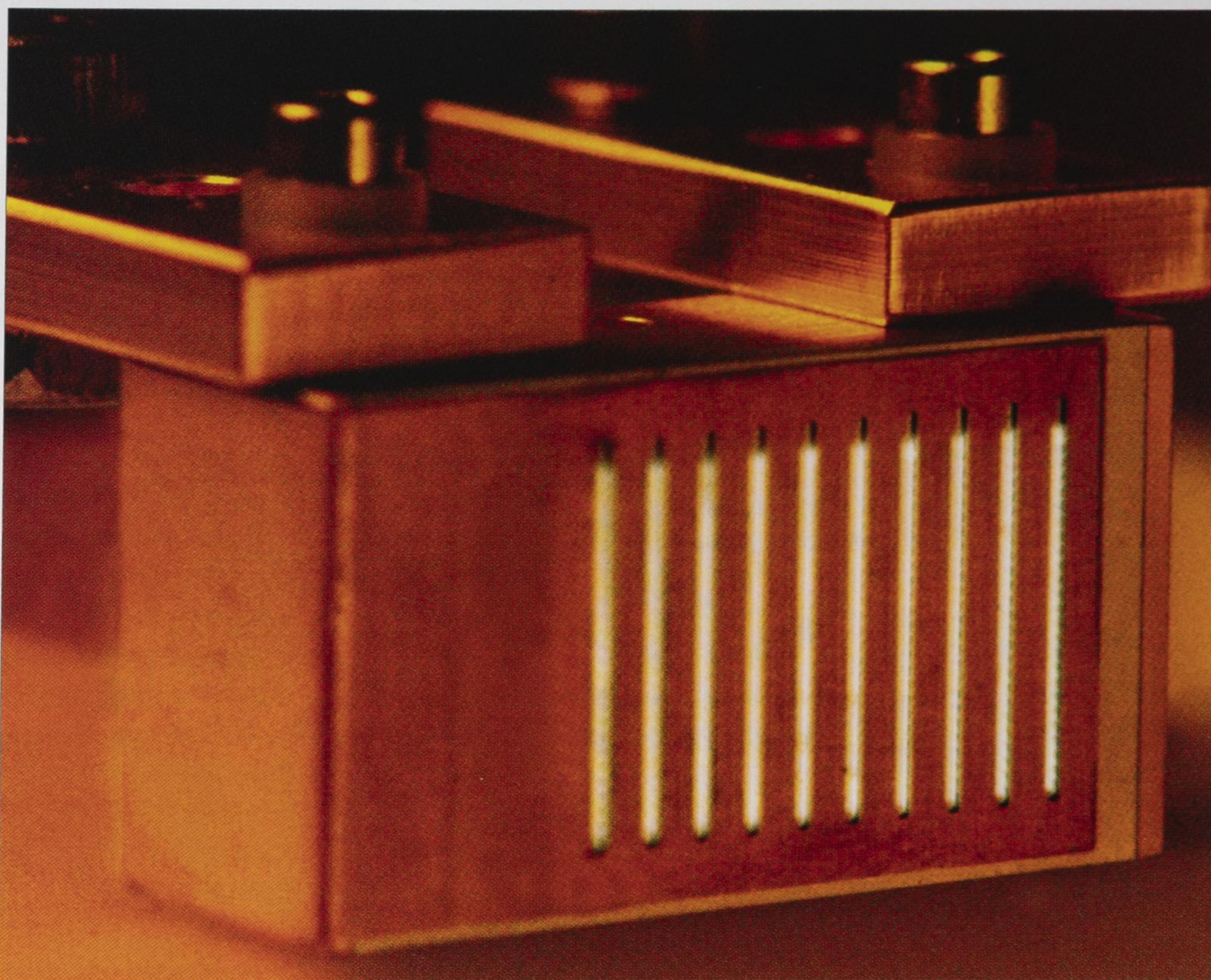
The Los Angeles-based firm, which was founded in November 2000, has demonstrated prototype semiconductor chips that emit up to 100 W in continuous-wave mode from monolithic arrays containing 66 surface-emitting elements. However, the firm believes that the technology is scalable and could ultimately produce chips containing hundreds of elements that emit a total power of 1 kW or more.

Prototypes nearly ready

QPC hopes to have something on the market soon, according to its chief executive officer Jeffrey Ungar. "We plan to have products at a prototype level by the end of the year, with commercial products following soon after," said Ungar. "Initial products will be replacements for diode stacks – say a few hundred watts for pumping thin-disc lasers or conventional YAG lasers, for example. However, prices will be somewhat less than what people are paying right now for stacks."

The development could be an important step forward in the creation of cost-effective and practical kilowatt solid-state lasers, which are sought by the military and commercial sectors. The US military, in particular, is keen to develop solid-state lasers in the 100 kW to megawatt range and with today's diode technology that is simply not feasible due to their high cost and poor reliability.

ALL IMAGES: QPC



Fluorescence from a 10 × 22 surface-emitting diode array made by the Quintessence Photonics Corporation. The device has 220 discrete emitters, but the light emission appears as stripes due to the broad beam divergence in the vertical direction. The Los Angeles-based company hopes to have commercial prototypes ready by the end of the year.

"The economics of today's diode pumps in the rack and stack configurations are such that they make it totally impractical to have a field weapon at these sorts of power levels," explained Ungar.

"If you want a 100 kW solid-state laser then you need about 250–300 kW of diode power to pump it. With today's style of diode arrays you're looking at several millions of dollars for just one of these weapons."

Currently, high-power diode arrays are usually made from a stack of edge-emitting discrete bars – a strip of semiconductor wafer containing several individual laser diodes – which each emit a few tens of watts.

Although stacks can achieve total output powers ranging from a few hundred watts to a few kilowatts by combining the output from

many bars, they are tricky to package and cool. Each bar has to be cleaved, individually cooled and electrically connected to its neighbors. As a result, the stacks tend to be expensive to scale to higher powers.

High-power stacks are also vulnerable to reliability problems, especially a cooling failure. Each bar, or layer of the stack, has to be connected to a microchannel cooler that pumps water through a series of miniature channels, each just tens of microns wide. The problem is that these channels can clog up or corrode.

"If you imagine a stack with 50–100 W per layer then you're looking at having hundreds of layers [bars] to create a multikilowatt pump and then the likelihood of a failure is very high," commented Ungar. "To a large extent the reliability issues are not specifically semi-

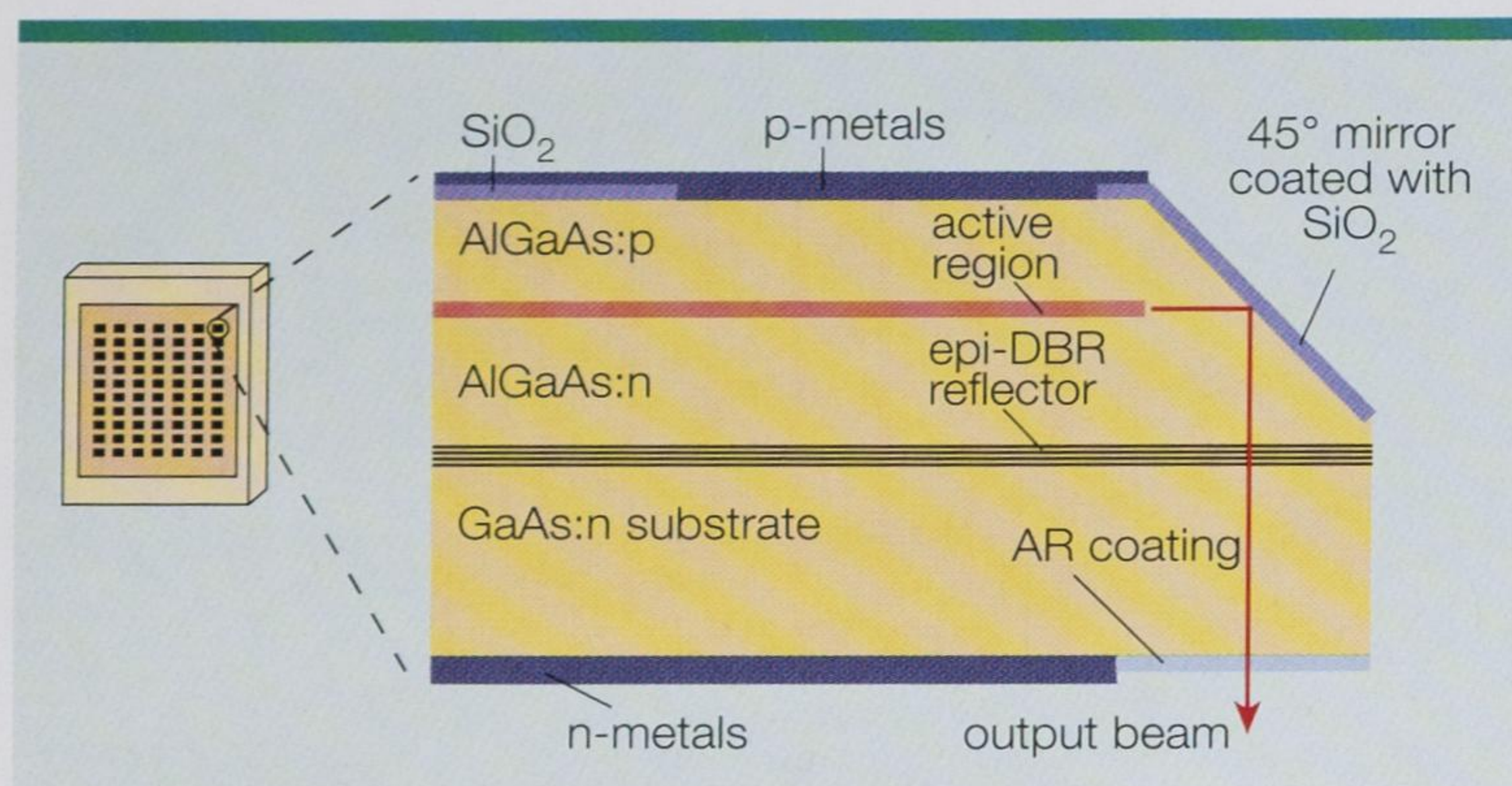
Quintessence Photonics Corporation

- Based in Sylmar, CA, QPC was founded by Jeffrey Ungar and George Lintz in November 2000.
- The company boasts an 18,000 sq. ft fabrication facility and manufactures devices using its in-house MOCVD laboratory.
- In June this year, QPC raised \$3.25 million in an oversubscribed sale of securities notes.
- As well as developing high-power diode arrays, the company is involved in a variety of projects with

the US Army, US Navy, and US Missile Defense Agency. This includes the development of mid-IR (3–10 μm) lasers and a source for high-energy pulsed-laser radar.

- On the intellectual property front, QPC has been awarded two key US patents within the past year. US patent 6,668,003 describes the way in which laser emission from adjacent laser stripes is phase-shifted to maximize the coherence and output

power of the array, while 6,711,199 explains the distributed feedback and amplifier section of the diode laser structure. The reflectors used effectively “fold” the optical path of the laser beam, thus extending it and increasing the laser’s amplification. The result is that higher-power devices can be fabricated using the same die size. The patent covers devices fabricated on either n-doped InP or GaAs substrates.



A schematic of one of the surface-emitting elements in the array. Light created in the active region is internally reflected by the 45° angled mirror and directed out through the wafer's surface. The laser's DBR cavity mirrors are also shown.

conductor issues, but are in many cases due to the cooling and mounting technologies.”

QPC seems to have come up with an ingenious solution to the problem. When making its wafer of edge-emitting laser diodes, it etches a series of 45° mirrors next to the diodes to reflect their light out of the surface of the wafer. As a result, 2D surface-emitting arrays of laser diodes can be made without the need for cleaving the wafer into a series of discrete bars.

The beauty of QPC’s monolithic design is that devices are potentially much easier to package and cool. This should in turn mean that the technology is very cost competitive when it hits the market. Instead of having to mount a cooler to each cleaved diode bar, with QPC’s design a single more powerful cooler can be attached to a substrate of the entire chip. This cooler removes heat from all of the emitters simultaneously.

“The cost benefits come through the simplicity of the cooling and the packaging. Instead of, say, a 20-layer [bar] stack with 20 microchannel coolers, you have a single semi-

conductor chip with a single cooler,” explained Ungar. “We’re striving to make large arrays where the price target for a packaged array is \$1–2 per watt.”

Power output

The firm’s latest test results were unveiled at the recent meeting on diode lasers in Albuquerque, New Mexico, US (2004 solid-state and diode-laser technology review).

To date, QPC’s demonstration chips are based on several rows of 22 surface-emitting elements and emit light at around 980 nm. At the event, QPC announced a 1 × 22 array that produced 50 W at a drive current of about 110 A and a 3 × 22 array that generated 100 W at a drive current of about 220 A.

Typically each emitting element is square, 100 μm long and emits between 1 and 2 W, although higher powers may be possible

“We have also made a 10-row device [10 × 22] containing 220 emitters, but that has not yet operated in lasing mode,” said Ungar. “At the moment it’s mounted on a piece of

copper and we’re waiting for a custom-made water cooler to support the high power densities that it will generate.”

However, with appropriate cooling it is likely that the device could generate 300–400 W of optical power, a figure comparable to many stacks.

In all of QPC’s devices, light from edge-emitting laser elements is flipped by 90° so that it comes out from the top of the wafer. Light leaves the AlGaAs active region parallel to the wafer surface and is then bent upwards by 90° using an etched 45° mirror that acts as a total internal reflector (see figure).

Stabilizing emission

The laser’s cavity mirrors are formed by two distributed Bragg reflectors (DBRs) made from thin layers of varying refractive index. One of these is placed after the 45° mirror and also serves as an output coupler letting light out of the wafer.

The use of DBR mirrors also helps to stabilize the emission spectrum from the laser, and experiments indicate that the beam from a 980 nm array can have a full-width half maximum (FWHM) value of just 0.6 nm.

As with conventional edge-emitting lasers, the beam leaving each element of the array is highly non-symmetric with a typical divergence of 35° (FWHM) in one dimension and 5° (FWHM) in the other. This causes the beams from neighboring emitters along a row to overlap and gives the emission an appearance of stripes.

“The critical component in all of this is being able to make a perfect 45° mirror,” explained Ungar. “The idea of using such a reflector has occurred to others but was never a practical proposition. The mirror surface must be absolutely perfect, if it’s rough or out by a degree then you’re sunk.”

Although QPC’s etching process is proprietary and Ungar was reluctant to go into detail, the firm appears to have refined a wet-etch process so that it can reproducibly fabricate a 45° total internal reflector that has a beautifully smooth optical surface. It claims that the orientation of its etched reflector is accurate to within 0.5°.

In effect, the new type of laser combines the power of edge-emitting laser technology with the easy processing of vertical-cavity surface-emitting lasers (VCSELs).

According to Ungar, the advantage of the new design is that the output power of each surface emitter can be scaled to several watts per emitter instead of just a few milliwatts,

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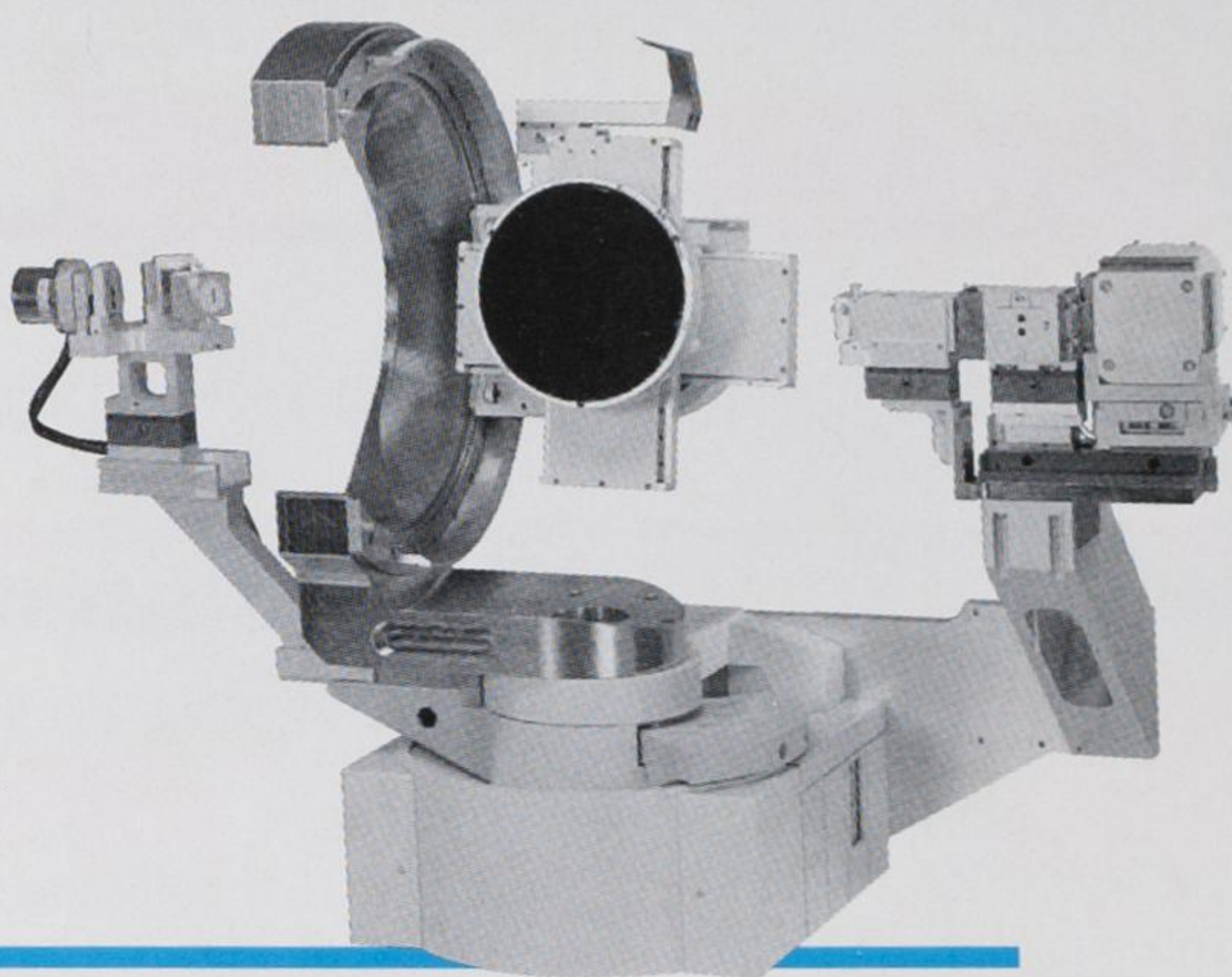
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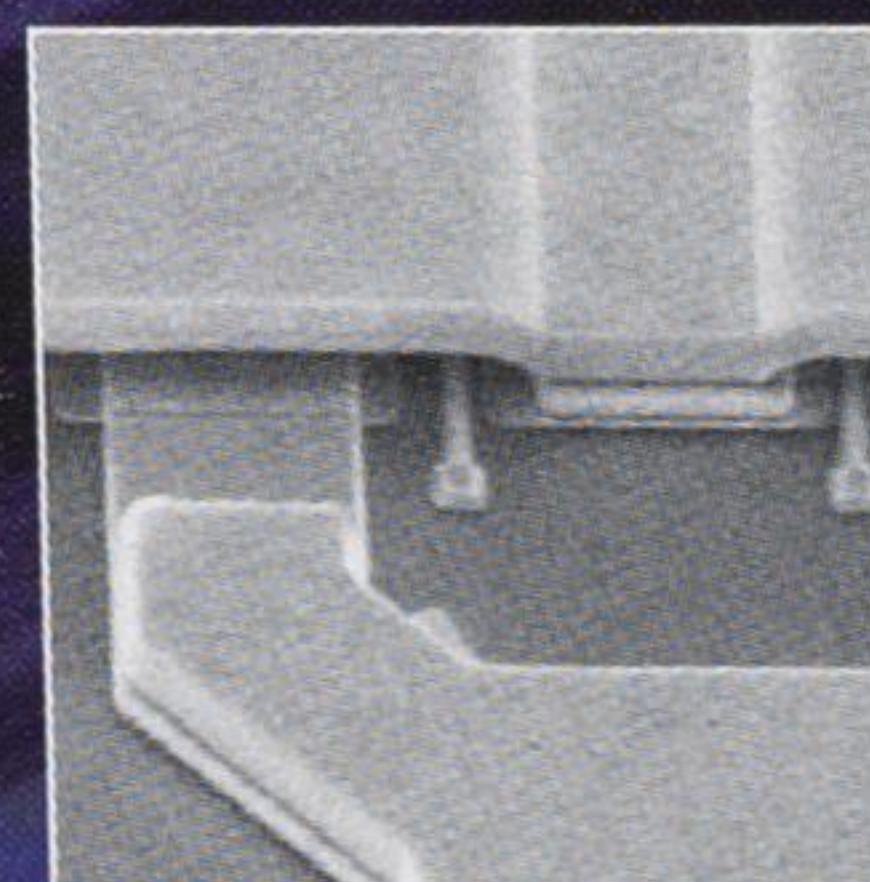
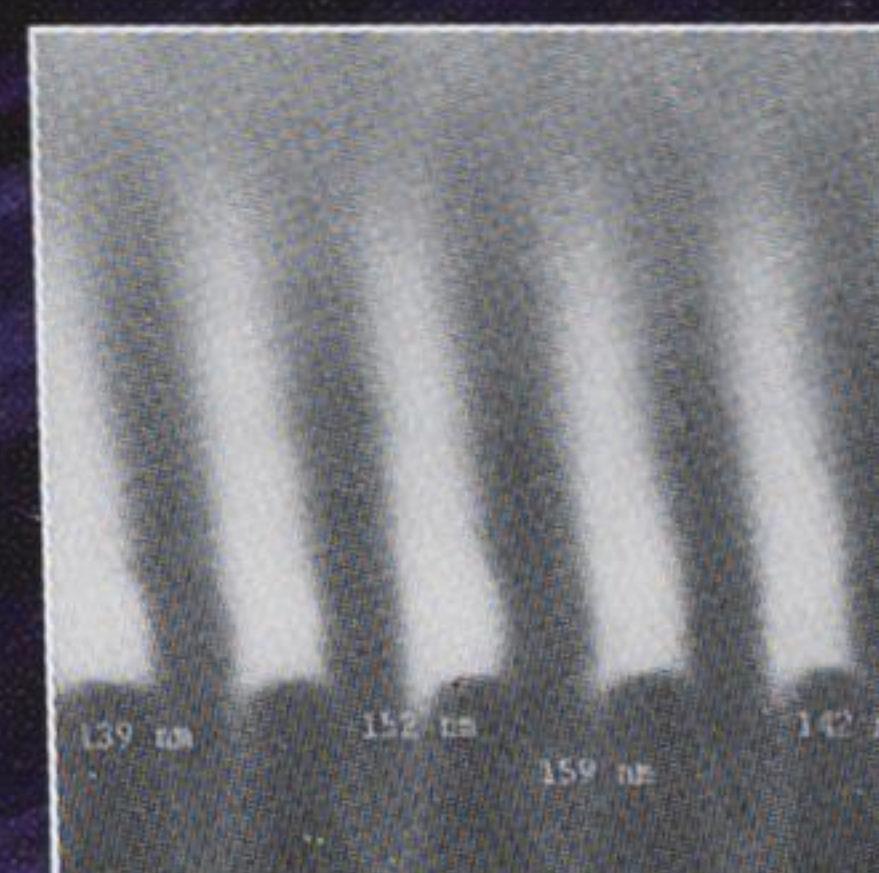
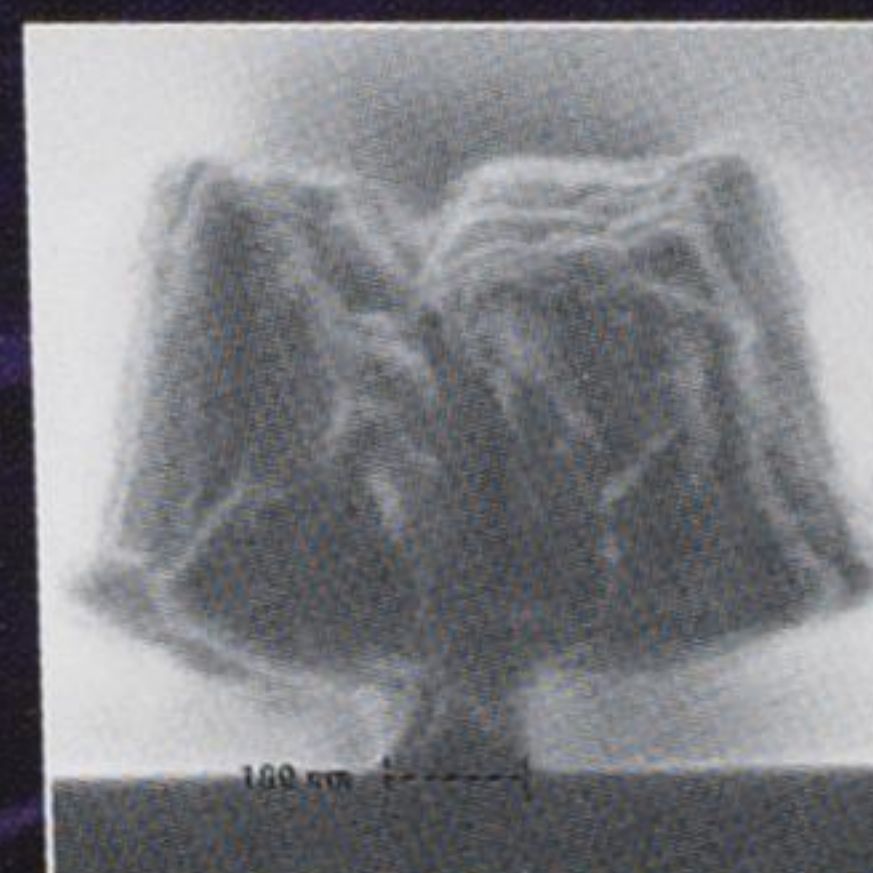
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which is the typical limit for a VCSEL.

"The VCSEL design is completely inappropriate for high powers because its geometry has high thermal and electrical impedance," said Ungar. "It's a fine structure for producing a milliwatt or so at 800 nm, but it's a difficult proposition to get higher powers."

At the same time, QPC's design maintains the cost-effective on-wafer testing that is often touted as a benefit of surface emitters such as VCSELs. In effect, the emitting elements can be tested on the wafer with no need for any cleaving of individual devices.

In fact it was searching for an alternative to

long-wavelength VCSELs that first inspired QPC's research in the area.

"Our initial thought was that this would be a great way to make 1300–1550 nm vertical emitters where one could get much higher powers than with a VCSEL," explained Ungar. "However, we soon realized that this design was probably even more appropriate for high-power pumping."

Before founding QPC, Ungar and several members of his technical team were working at Ortel, a firm specializing in lasers for telecom applications. Ortel was purchased by Lucent for \$3 billion at the height of the tele-

com boom in 2000 and Ungar left to form QPC in November of the same year.

However, another start-up in the US is now pursuing QPC's initial ideas for a long-wavelength VCSEL alternative. Binoptics of Ithaca, US, has developed an InP 1310 nm laser based on a ridge waveguide with an etched 45° mirror at one end. The surface-emitting device produces 20 mW of optical power and is aimed at telecom applications. ●

A version of this article previously appeared in the September issue of Opto & Laser Europe magazine, edited by Oliver Graydon.

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Fabry-Pérot lasers promise low-cost 10 Gb/s Ethernet

The two hot topics driving today's short-reach 10 Gb/s optical networks are cost and standardization. Expansion of this sector has been inhibited through high-price modules containing expensive components such as distributed feedback (DFB) lasers and electro-absorption modulated lasers (EMLs). One solution is to use relatively low-priced Fabry-Pérot (FP) lasers that are manufactured by a higher yield process not requiring equipment-intensive gratings and overgrowth steps.

Further savings arise through the omission of ancillary components. For example, expensive optical isolators – which are required to eliminate the influence of back reflections in reflection-sensitive DFB lasers – are not necessary for reflection-tolerant FP lasers.

Although DFB lasers offer better spectral purity and single longitudinal-mode operation, they do so at an unbearably high price for enterprise applications. With the vast majority of transmission distances being less than 300 m, high-quality transmission can be obtained using multiple longitudinal-mode FP lasers, provided that a narrow spectral width is maintained during their manufacture.

Arrested development

A lack of suitable standards has hampered the development of FP lasers for short-range networks. In 1999, serial 10 Gb/s Ethernet interfaces using uncooled, unisolated FP lasers were promoted by many manufacturers. However, the physical media-dependent (PMD) sublayer was omitted from the IEEE 802.3ae standard, partly because the number of PMD options was simply getting too large.

In the intervening years, a greater up-take of 10 Gb/s Ethernet has increased pressure to set an IEEE standard for low-cost sources. Today the recently formed IEEE 802.3aq study group is considering the multimode fiber solution 10GBASE-LRM, which utilizes Electronic Dispersion Compensation. In this application, FP lasers can deliver significant component cost reduction. Investigating this benchmark, engineers from Infineon Technologies noted that connector offset introduced loss and, consequently, a relatively large power

With 10 Gb/s Ethernet port shipments rising fast following two quiet years, the opportunity now exists for increasingly reliable, affordable Fabry-Pérot lasers to replace more complex designs. Modulight's **Pekko Sipilä** reports.

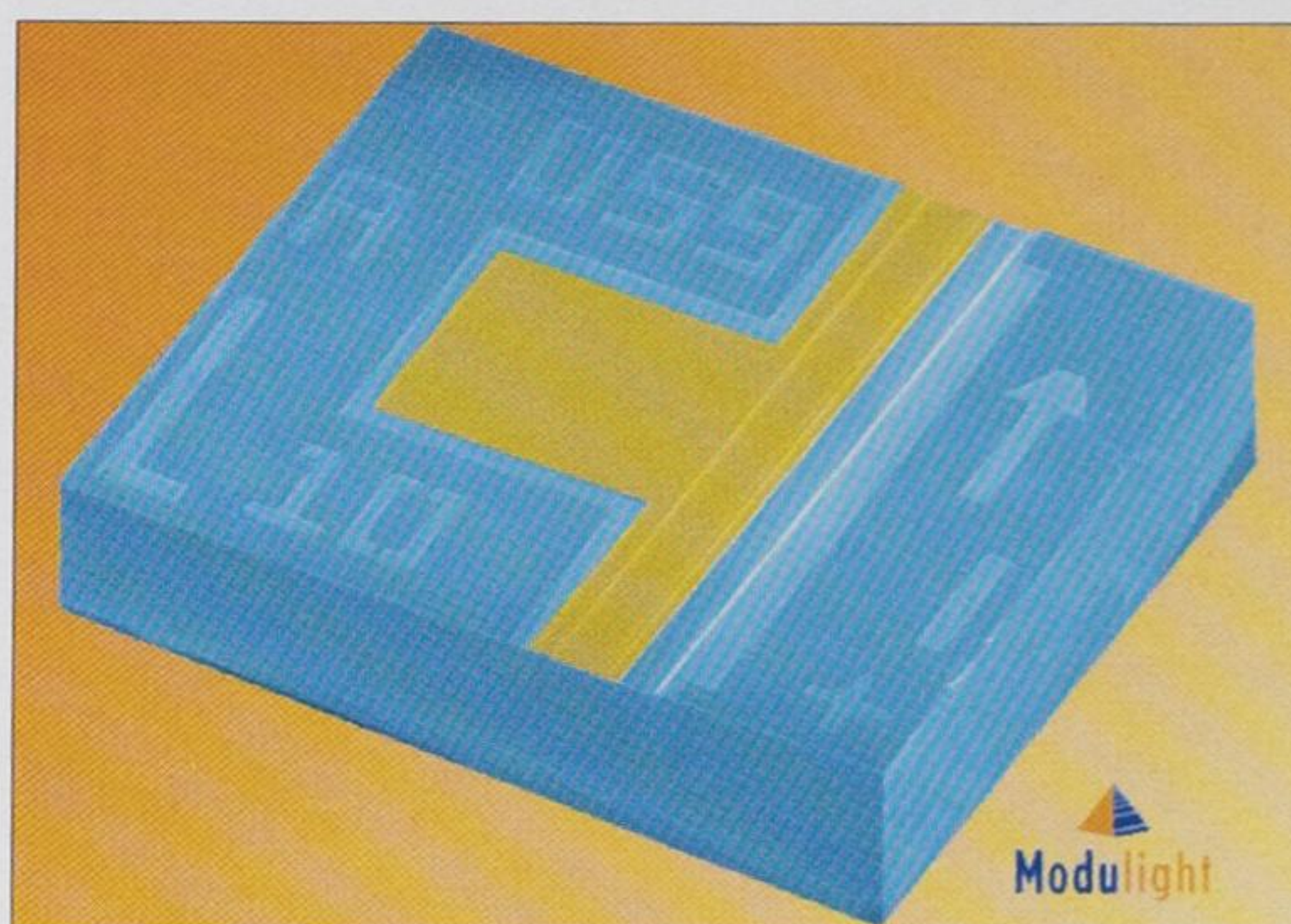


Fig.1. This micrograph shows Modulight's 1310 nm 10 Gb/s Fabry-Pérot laser die.

penalty, but FP laser performance was superior to that of both DFB lasers and EMLs.

Modulight's 1310 nm 10 Gb/s FP laser chips were released in January 2003, and have been shipped to a number of customers. The lasers are based on the AlGaInAs material system, which, historically, has been associated with poor reliability due to the presence of aluminum (which readily oxidizes). However, AlGaInAs-based laser reliability has improved substantially over the years and this system is used today in many 10 Gb/s lasers. Indeed, reliability tests of Modulight's lasers suggest lifetimes of hundreds of years.

Modulight's FP lasers are fabricated in-house using an all-solid-source MBE reactor, which provides good control of the growth of the quantum wells and barriers that form the active region. The laser structure – grown on exactly cut, n-type InP substrates – contains an active region with multiple compressively strained (~1.4%) AlGaInAs quantum wells, which are tuned for laser emission at around 1310 nm. The quantum well layers have a thickness of 5 nm and are separated by lattice-matched, 10 nm thick AlGaInAs barriers. This optically active region is surrounded by AlGaInAs (with a bandgap of 1.35 eV) and AlInAs/InP layers to form a typical wave-

Table 1

Parameter	Median at 25 °C	Median at 85 °C
I _{th} (mA)	12.69	24.38
Slope (mW/mA)	0.32	0.25
R _s (Ω)	4.67	3.99
λ (nm)	1297.53	-
Δλ (nm)	0.85	-
Vertical FWHM (°)	34.20	-
Horizontal FWHM (°)	23.70	-

Median values of static parameters for Fabry-Pérot lasers in accelerated life tests.

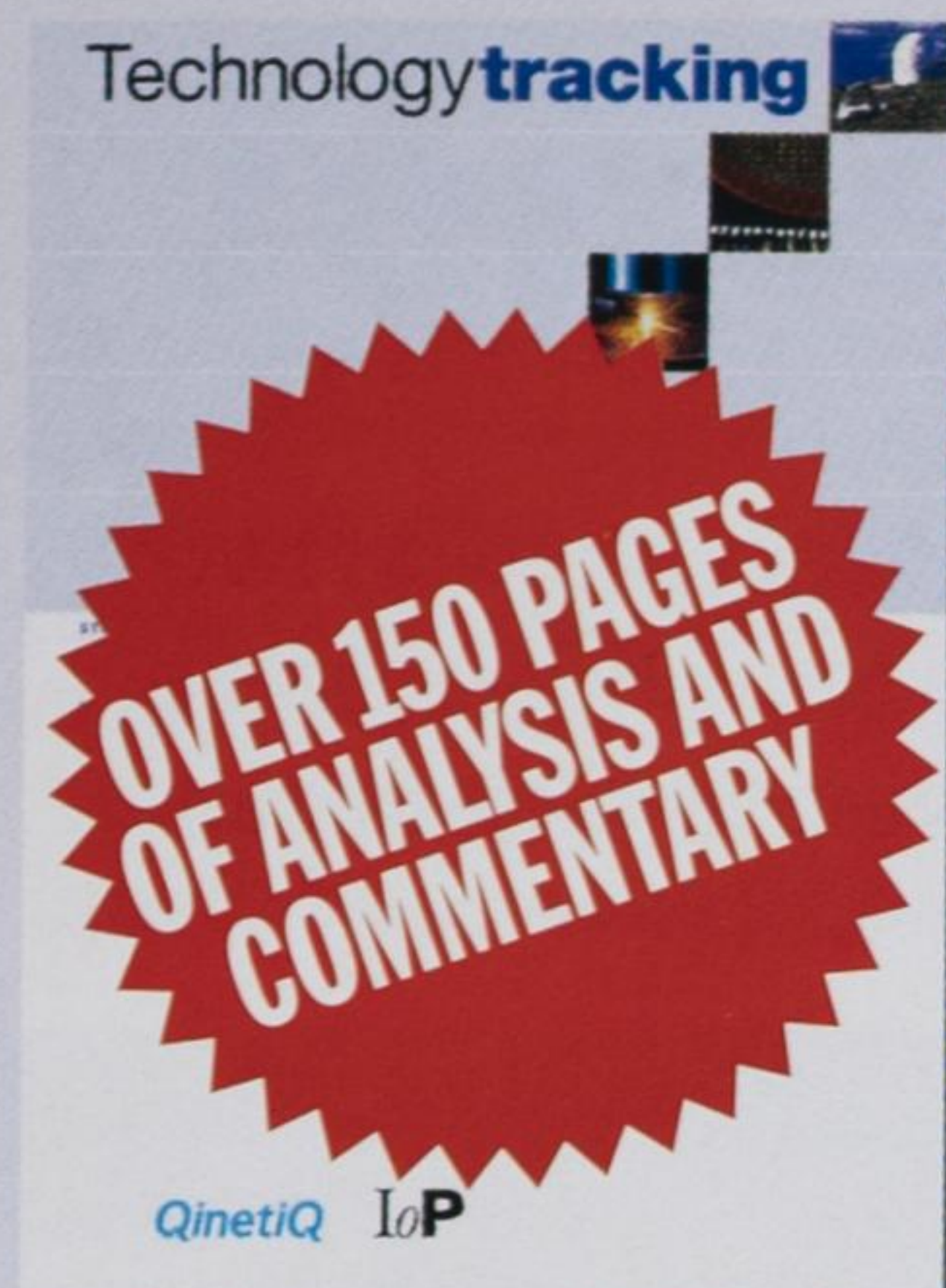
guiding structure for a semiconductor laser.

Industry-standard device-processing steps enabled the fabrication of ridge waveguide FP lasers with ridge widths of 2.5 μm, 250 μm cavity lengths, and high-reflection and anti-reflection facet coatings of 70 and 30%, respectively. A higher back-facet reflectivity would suppress the threshold current, but also reduce the signal from the standard monitor photodiode that is used to maintain constant laser output during operation.

Low-cost 10 Gb/s transceivers in XENPAK, X2 and XFP packages do not use active cooling for the laser, and so stable behavior as a function of case temperature is essential for the laser dies. Lasers emitting at 1310 and 1550 nm are traditionally made from the InGaAsP-InP material system. However, InGaAsP-based lasers offer poor performance at high temperature. AlGaInAs-InP lasers [1] have been developed to overcome these high-temperature-related problems and they replace InGaAsP-based lasers in applications where uncooled operation is required over wide temperature ranges, including up to 85 °C.

The light-current behavior was studied for a set of Modulight 10 Gb/s FP lasers operated with 25 and 85 °C case temperatures in continuous-wave mode. Linearity of the power

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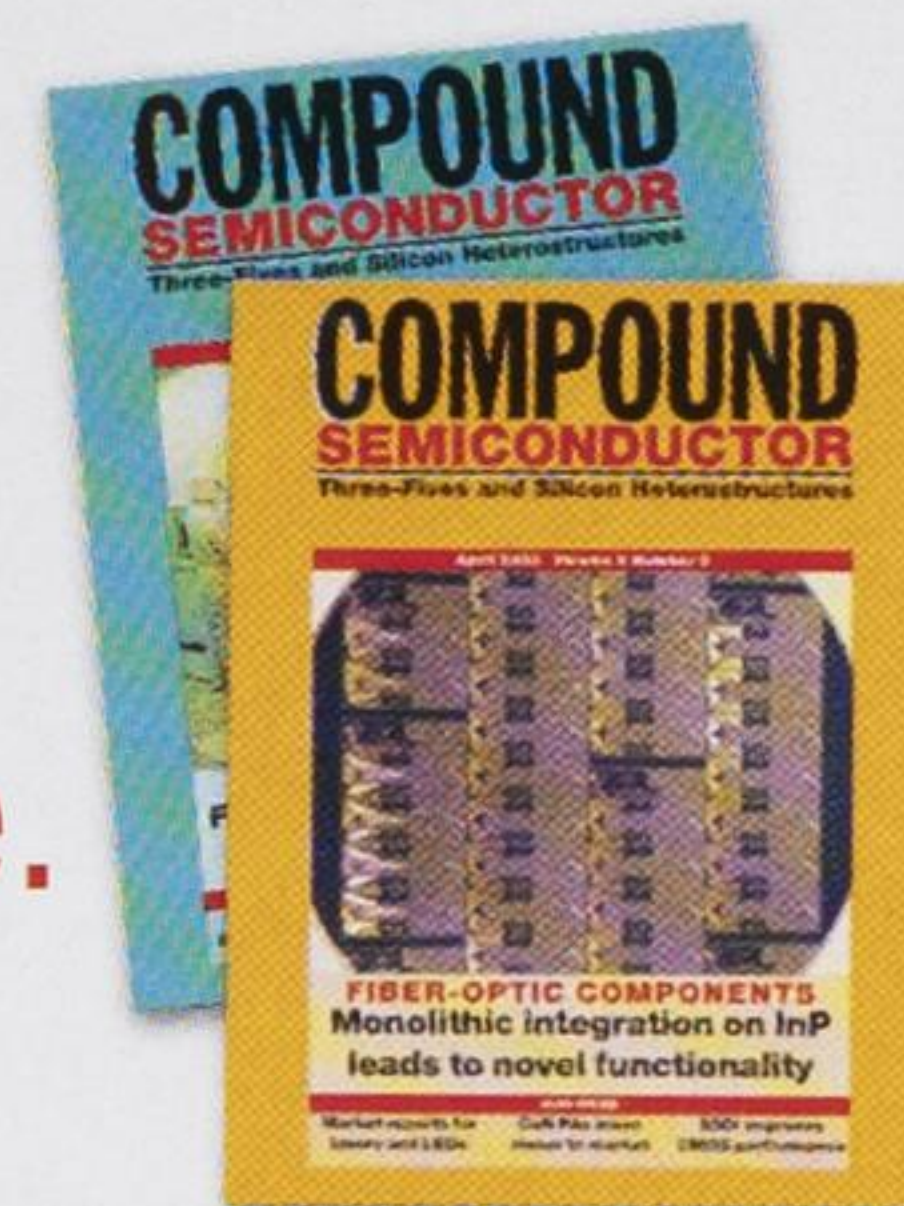
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output is very good even at 85 °C – at this temperature InGaAsP-based lasers already show a significant power drop due to saturation of the slope efficiency. For our lasers, slope efficiency as a function of temperature is fairly constant. The median threshold current for the device is 12.97 and 25.41 mA at case temperatures of 25 and 85 °C, respectively.

Control is key

An important factor that limits transmission distance is chromatic dispersion. Early suggestions for FP laser-based 10 Gb/s PMDs for 2 km transmission assumed a maximum root-mean-square (RMS) spectral width of 2–2.5 nm. This requires a high degree of control throughout the entire manufacturing process, from wafer growth to test and measurement. The spectral properties of Modulight's lasers are measured with an optical spectrum analyzer, and spectral RMS values are calculated assuming a noise level of –20 dB. Figure 2 shows the distribution of the RMS spectral width for a population of Modulight's 10 Gb/s FP lasers operating at 5 mW at two case temperatures. A typical value for the spectral width is 0.9 nm for a 25 °C case temperature; the spectral width remains well below 2 nm even at a 85 °C case temperature.

The frequency response of the laser chips was measured using a microwave probe and a network analyzer. The resonance frequency, which determines the maximum modulation speed of the device, was 13 GHz at 25 °C and 11.6 GHz at 85 °C with a bias level of $I_{th} + 66$ mA. The change in resonance frequency over 60 °C is only 11%, which is small compared with traditional InGaAsP lasers and AlGaInAs lasers [2].

The long-term reliability of Modulight's 10 Gb/s, 1310 nm FP lasers has been studied by extended accelerated ageing tests in accordance with Telcordia guidelines. The study involves characterizing bare die laser chips at 25 and 85 °C prior to bonding on submounts. Before starting the time-consuming ageing test, devices were screened from standard production lots using a 24 hour burn-in test, conducted at 80 mA constant current and 100 °C.

A burn-in induced change of more than –5 or 1% in threshold current, or –2 or 5% change in slope efficiency in output power versus current measurements at 25 °C led to rejection.

Eleven devices meeting these criteria underwent an accelerated lifetime test, with conditions of 10 mW constant output power at 85 °C. Chip-level static parameters for these lasers are summarized in table 1. These

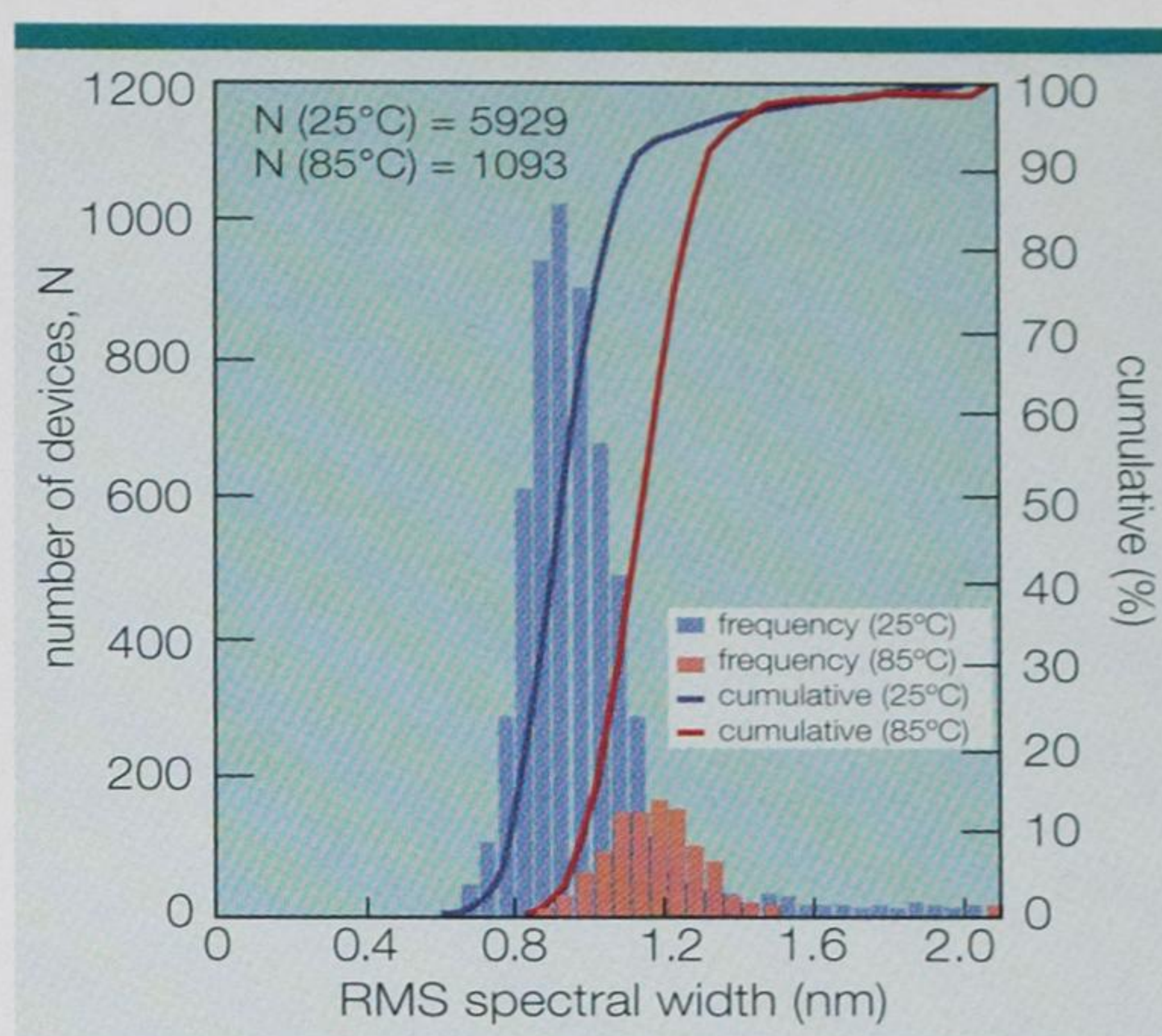


Fig. 2. More than 90% of Modulight's lasers have an RMS spectral width of less than 1.3 nm at 85 °C, which is well inside the 2–2.5 nm required for 2 km transmission.

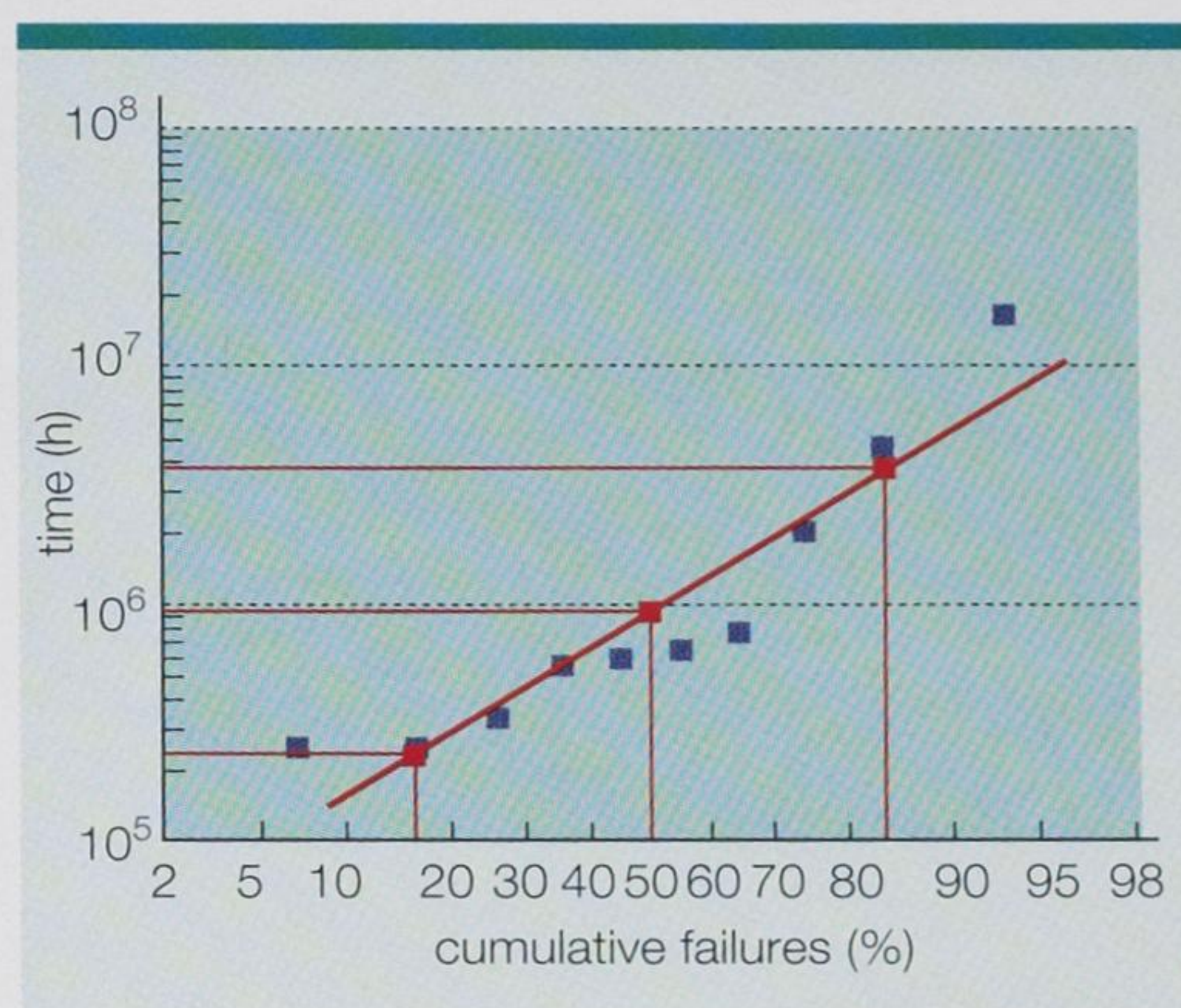


Fig. 3. The median lifetime of a Modulight laser is calculated to be 9×10^5 hours.

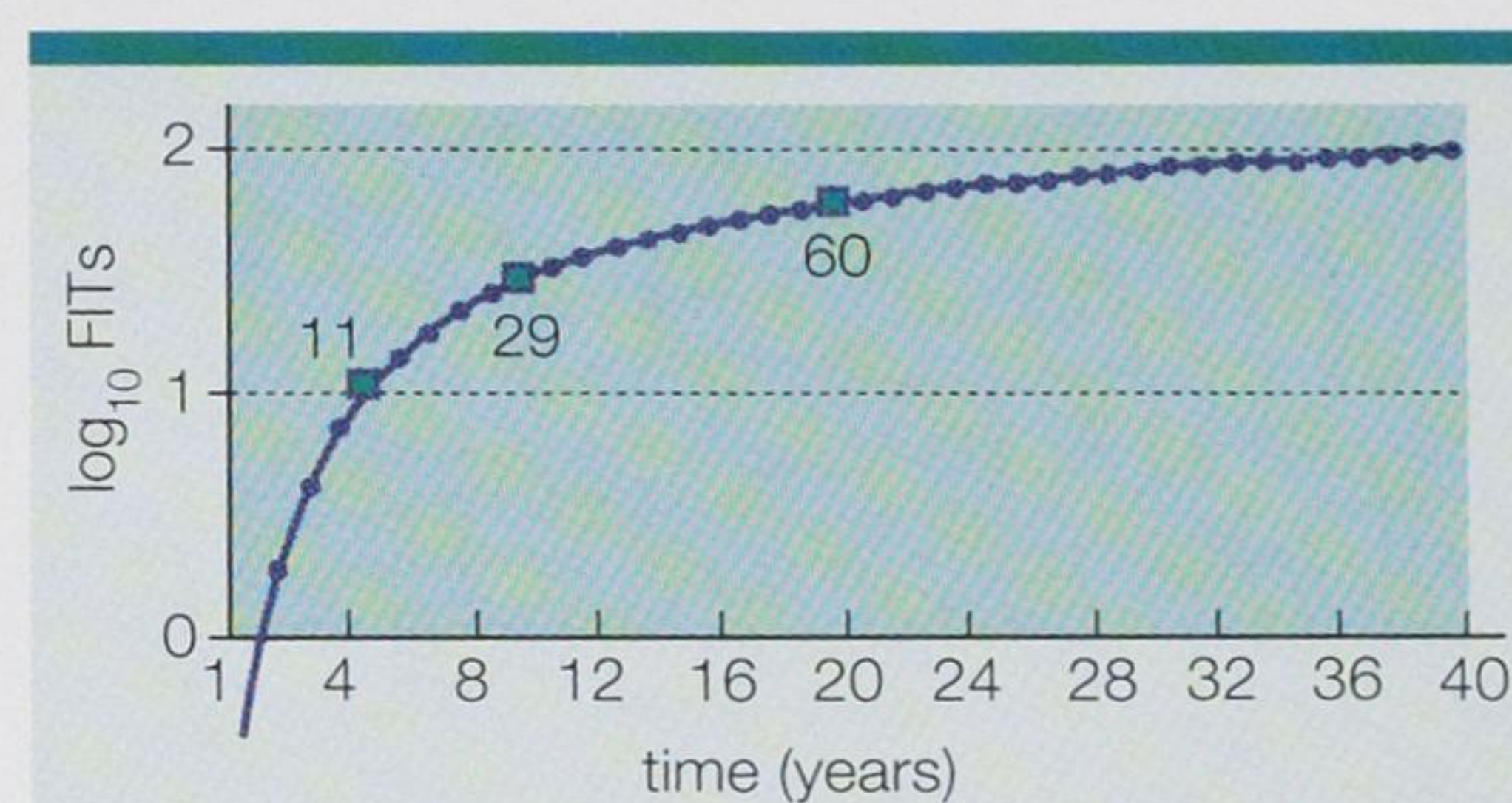


Fig. 4. These FIT values show that the lasers are reliable enough for telecom applications.

figures are typical of the several thousands of lasers fabricated by Modulight using the same process. More than 130,000 device hours have been collected and analyzed to evaluate laser reliability.

For the laser analysis we defined end-of-life (EOL) as the time taken for the threshold current to increase by 50% from its initial value. The time to failure for each device can then be calculated by assuming that the EOL can be extrapolated linearly as a function of time. Calculations were performed on 10

lasers – the remaining laser showed no clear degradation trend during the lifetime test, indicating an infinite lifetime.

The analysis also assumed that only one wear-out failure mode exists and that laser lifetime follows a lognormal distribution. The lifetime data of the lasers at 85 °C, alongside the line of best fit, is presented in figure 3. The median lifetime – the point where the fitted line intercepts the 50% point – is equal to 9.38×10^5 hours (107 years). The median lifetime at other temperatures can be calculated if the activation energy – the energy associated with a particular failure mode – is known.

Using Telcordia default activation energies of 0.4 eV for wear-out failure and 0.35 eV for random failures, at 25 and 40 °C median lifetimes are 1.27×10^7 hours (1450 years) and 6.04×10^6 hours (689 years), respectively.

Lasers with longevity

To the best of our knowledge, only a few reports exist regarding the reliability of AlGaInAs-based transmitter lasers operating at 1310 nm [1, 3]. In reference 1, mean-time-to-failure, or median life, is estimated at 82000 hours (9.4 years) at 85 °C, which is significantly less than that predicted for our lasers. Work carried out by Takaguchi *et al.* [3] only indicates that no failures have been observed after 3400 hours of operation.

Wear-out failure rates at 40 °C after 5, 10 and 20 years of service can be calculated using the same lognormal model. A FIT value of 11 – that is 11 failures per billion device hours – is calculated for lasers with 5 years of service (see figure 4). Corresponding FIT values after 10 and 20 years are 29 and 60, respectively. These FIT numbers show that the lasers have sufficient long-term reliability for use in telecom equipment, where the industry-standard requirement is a FIT value of less than 200 for 20 years' design life. The reliability, allied with the attractive price of FP lasers, makes these devices competitive in short-haul 10 Gb/s communications, particularly if standardization work proceeds successfully.

Further reading

- [1] C-E Zah *et al.* 1994 *IEEE J. Quantum Electron.* **30** 511–523.
- [2] T Ishikawa *et al.* 1998 *IEEE Photonics Technology Letters* **10** 1703–1705.
- [3] T Takaguchi *et al.* 2000 *ECOC Proceedings* **26** 1.

Pekko Sipilä is product line manager for transmitter laser products at Modulight.

Quinary alloy forges 1.5 μm emitters

By Michael Hatcher in Edinburgh

The 2004 International Conference on MBE was held in Edinburgh, UK, in late August. This year's event touched on many of the same topics as its MOVPE counterpart, which was held in Hawaii a couple of months previously – namely quantum dots and nitride structures.

Dilute nitrides provided a strong theme in the Scottish capital as the subject of one plenary talk and two technical sessions. James Harris of California's Stanford University delivered the opening plenary talk, which concentrated on the development of devices based on dilute nitrides for future optoelectronic applications.

The attraction of dilute nitrides is simple – the material provides the opportunity to connect the desktop to the fiber-optic backbone optically, using devices fabricated on GaAs substrates. This technology has been actively researched in recent years, in particular with a view toward components emitting in the 1.2–1.6 μm fiber window. According to Harris, the quinary alloy GaInNAsSb provides a near-perfect lattice match with GaAs, as well as the relevant bandgap energy, prospective optical characteristics and a low threshold current density.

Harris contends that, as yet, no single materials technology has proved suitable to address all of the next-generation optoelectronic components required for direct fiber access at a reasonable cost. Expected requirements, he says, include long-wavelength VCSELs, high-power pump lasers for Raman amplifiers, and semiconductor optical amplifiers.

A winning solution?

Dilute nitrides could one day provide a winning solution and deliver the base material for all three of these technologies. Harris and his colleagues at Stanford have made new structures featuring GaInNAsSb quantum wells and strain-compensating GaNAs barriers. This materials combination yields 1.5 μm lasers in both edge-emitting and vertically emitting formats. By adding small quantities of antimony in the quantum well growth stage, higher concentrations of indium and nitride can be incorporated, along with thicker active layers. This helps to avoid problems with nucleation and phase segregation, while also extending the material's wavelength coverage to the 1.6 μm range.

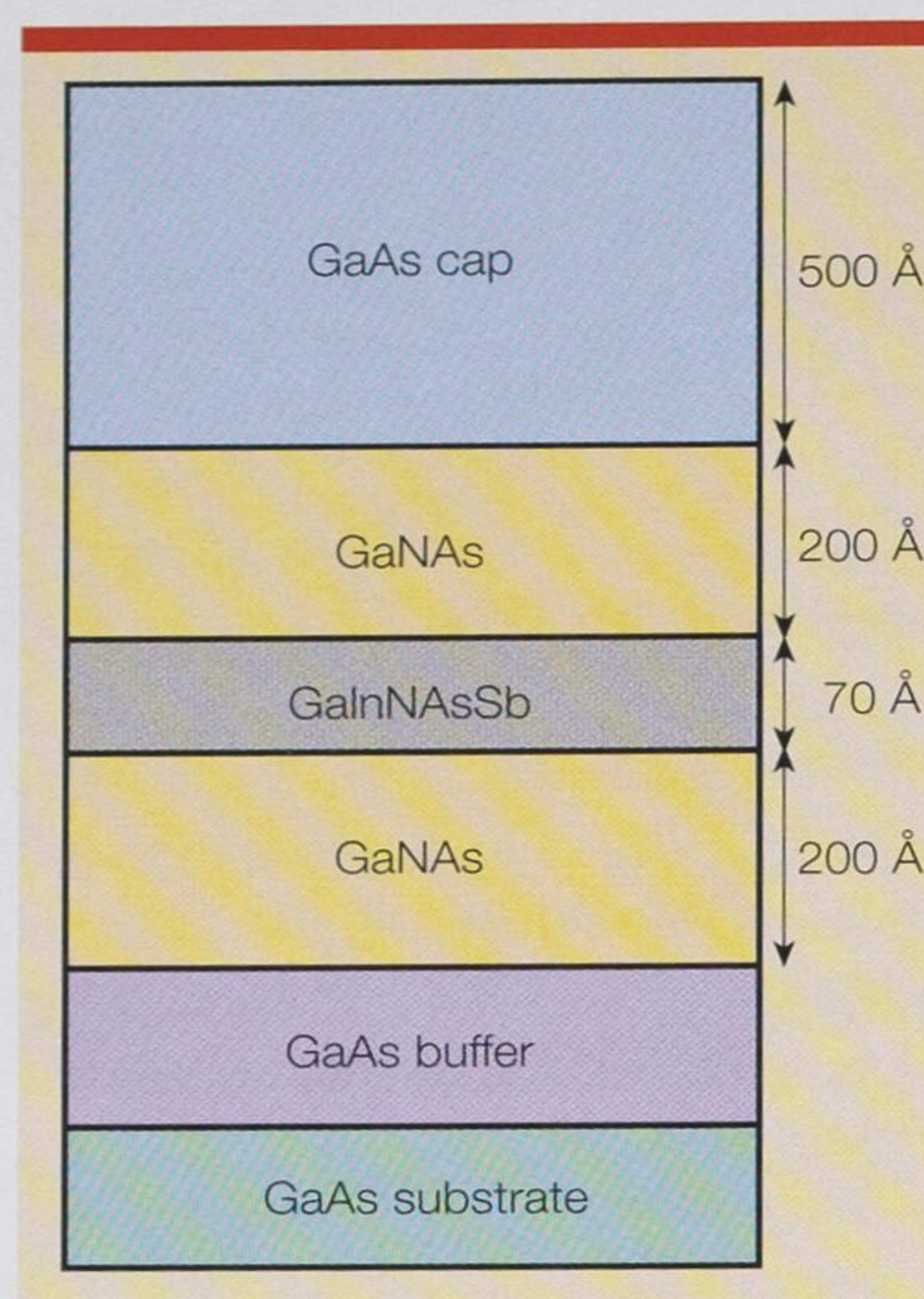
One question that Harris is seeking to answer is this: is the quinary alloy system the ultimate solution for low-cost optoelectronics, or simply an over-complex "recipe for disaster" as far as controlled growth and reproducibility are concerned?

"We finally understand this materials system, and the [device] results keep getting better and better," Harris told *Compound Semiconductor*. "The laser thresholds are now down to the level of InGaAsP/InP-based lasers, with a higher output power and better thermal performance."

"We are still a long way from optimizing both the material and device structures, but I think that the system also offers great promise for integrating photonic crystals and nonlinear optical structures with active components such as lasers, detectors and modulators. This is because of the high-index contrast one can get by oxidizing AlAs to form AlO_x ."

According to Harris, growth temperature is the single most important parameter to control. In optimizing the device structure to gener-

The Stanford team made what Harris called the "first monolithic 1.5 μm VCSEL on GaAs".



The Stanford team working on dilute nitrides found that GaNAs barrier layers reduced the emission linewidth better than either GaNAsSb or GaAs.

ate the narrowest linewidth for 1450 nm lasers, a GaNAs barrier layer was found to be superior to GaNAsSb and GaAs.

In photoluminescence experiments, the (GaIn)(NAs)/GaAs structures showed a peak emission at 1.3 μm , while the (GaIn)(NAsSb)/GaAs maximum was at 1.5 μm .

The GaInNAsSb devices made by the Stanford team showed a record low threshold current of around 0.6 kA/cm² for a 1.5 μm edge-emitting laser. Turning their attention to VCSELs, the Stanford team made what Harris called the "first monolithic 1.5 μm VCSEL on GaAs". Cooled to -10 °C, the VCSEL emission peaked at around 1460 nm.

In the dilute-nitrides technical sessions, a team from Infineon Technologies in Germany revealed details of the progress that the company has made with the quaternary GaInNAs material system at slightly shorter wavelengths. Robert Averbeck and colleagues have made lasers emitting beyond 1.4 μm . By carefully optimizing growth and annealing conditions, Averbeck says that Infineon's GaInNAs lasers "clearly outperform all current antimony-free devices".

Integration is key

Harris says that integration holds the key to the future of optoelectronics, and that the AlAs/ AlO_x system is the closest thing that the industry has to the critical silicon/ SiO_2 relationship that has been so successfully exploited in the silicon industry. This could be critical for the development of photonic crystals, and Harris believes that oxide growth on a GaAs substrate could lead to the photonic equivalent of the MMIC.

Quantum cascade lasers were another topic to feature strongly in Edinburgh. A team from Humboldt University in Berlin developing AlAs/(In, Ga)As lasers on InP substrates said that it had produced 3.82 μm -emitting heterostructures with a maximum output power of 6 W per facet (12 W in total) at 8 K, and 240 mW per facet at room temperature. With a wallplug efficiency of 23% at ultralow temperatures, these devices may be the most efficient to ever operate at this wavelength. Humboldt's Ted Masselink says that he believes the structures may emit at wavelengths as low as 3.2 μm .

● Jim Neave and Jeff Harris won this year's MBE Innovator award, with recognition of the pair's work in observing the oscillating RHEED (reflection high-energy electron diffraction) effect – which is now a routinely used method by which MBE growth rates are measured.

Also in the winners' enclosure was this year's conference chair Tom Foxon from the University of Nottingham. Foxon won the Riber-sponsored Al Cho award for contributions to MBE.

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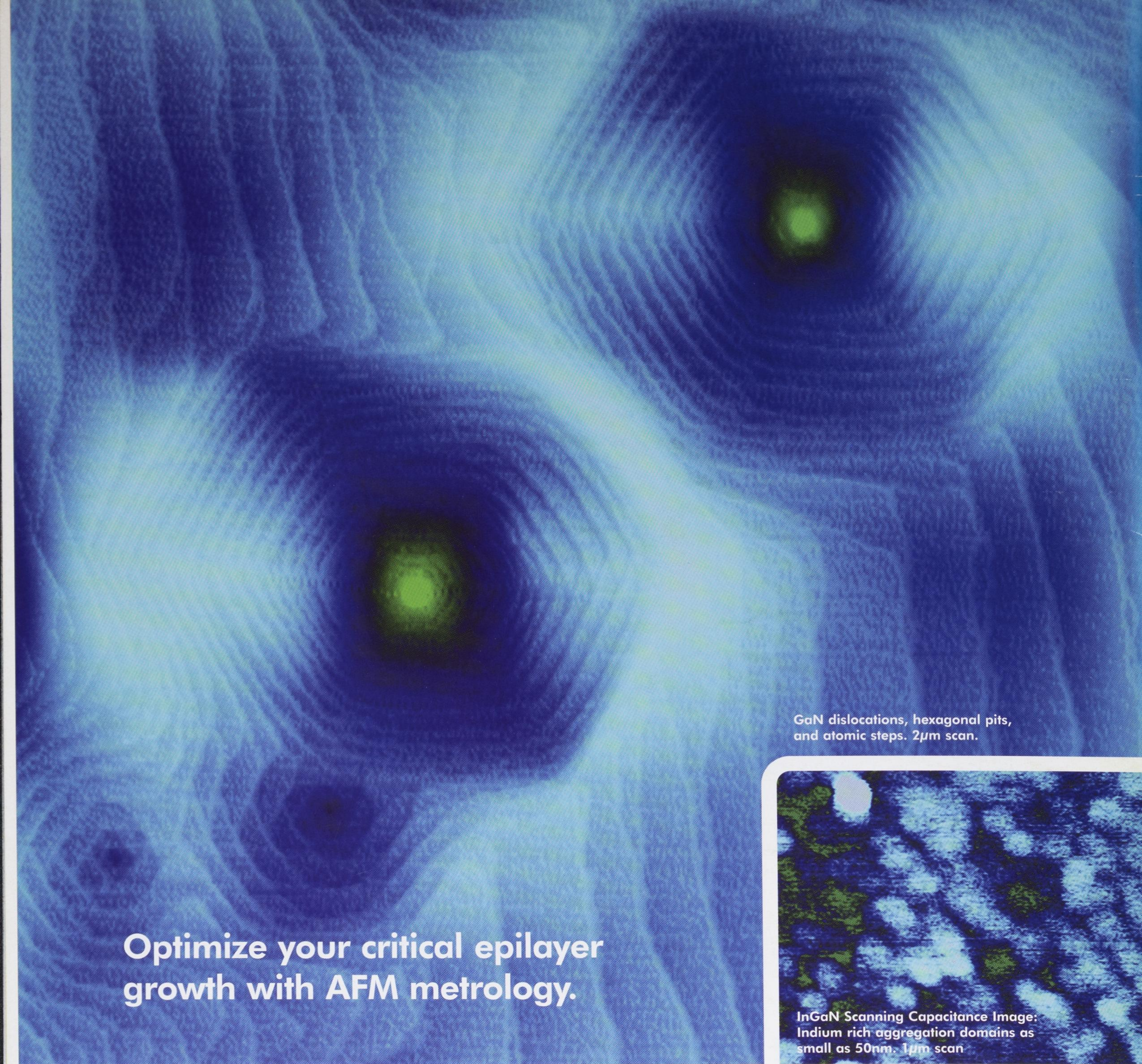
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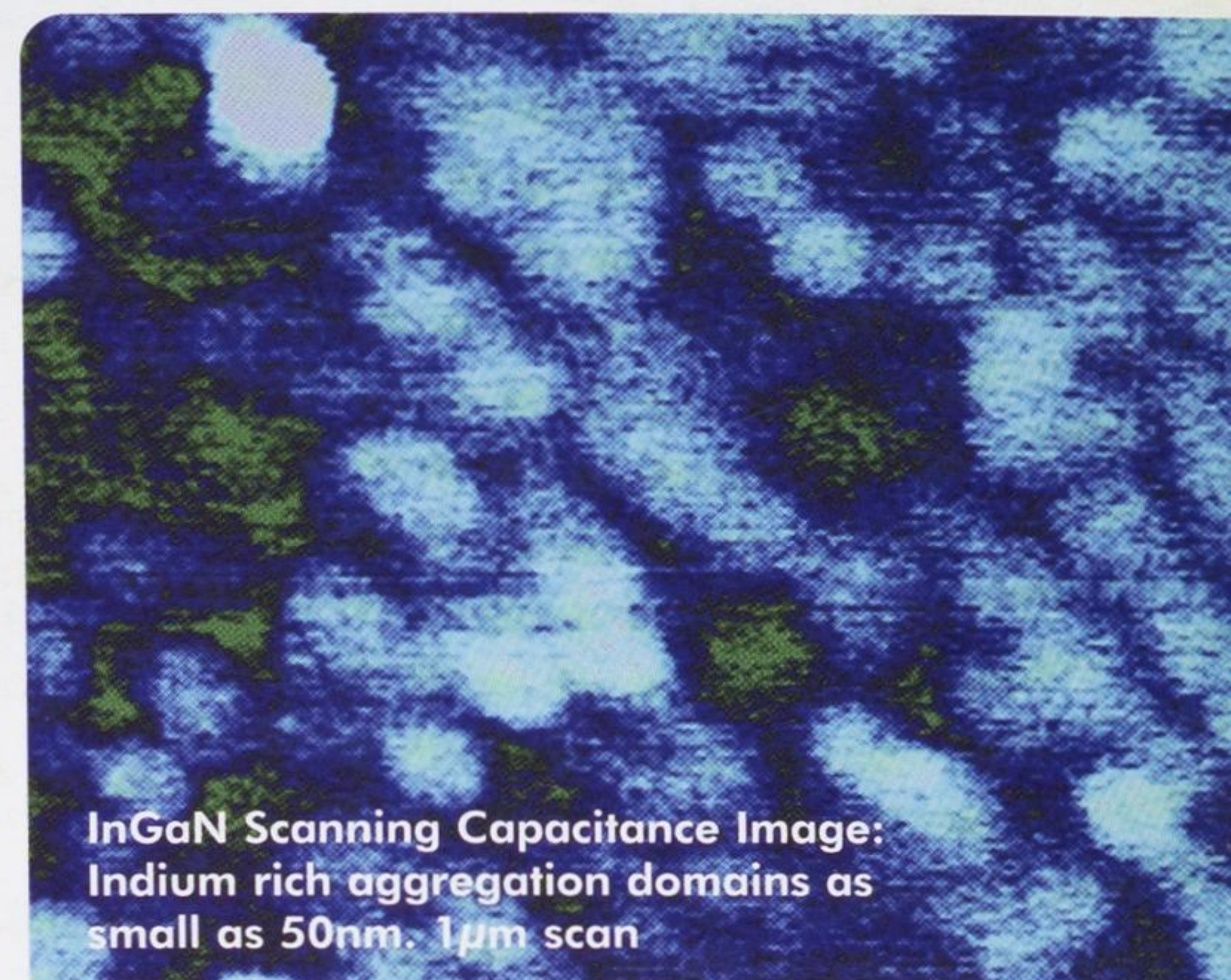
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