

COMPOUND SEMICONDUCTOR

October 2006 Volume 12 Number 9

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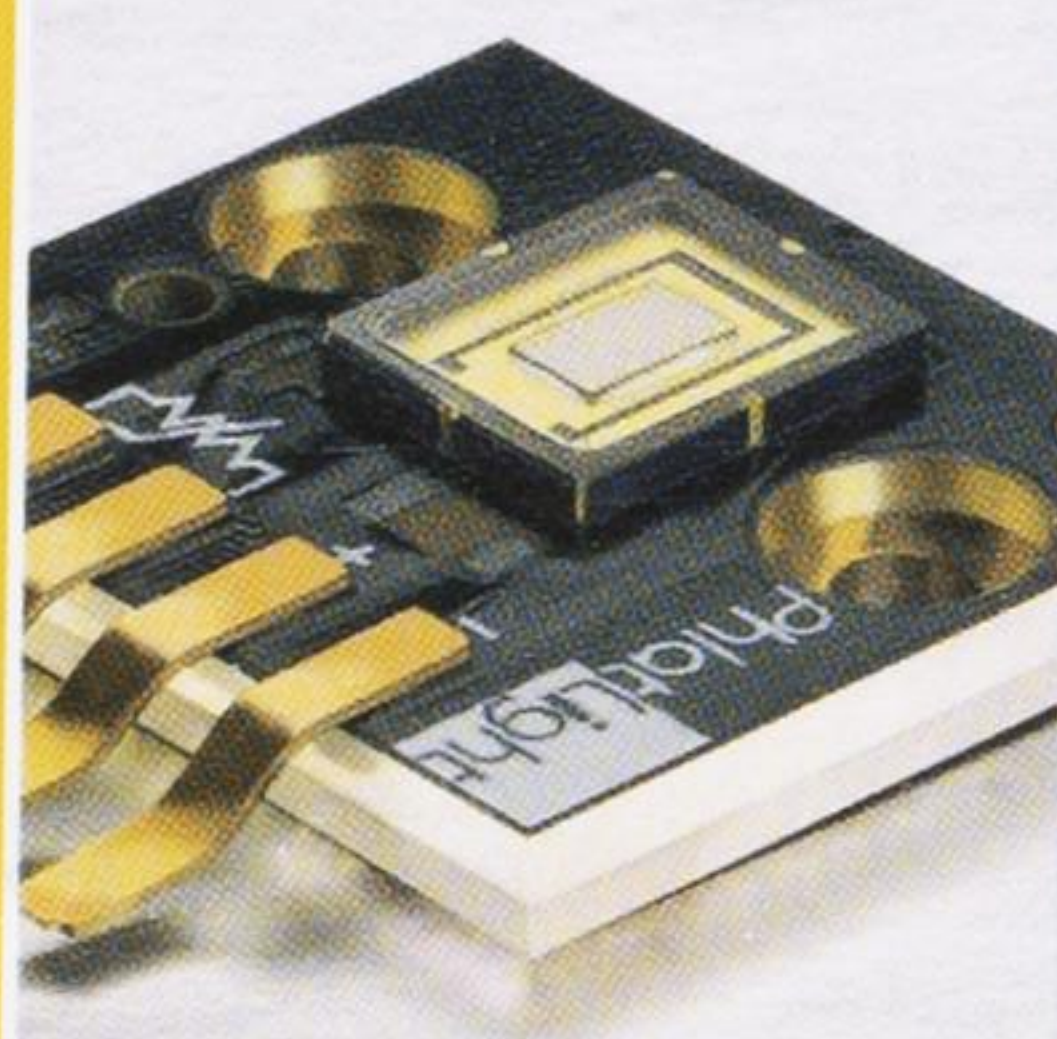
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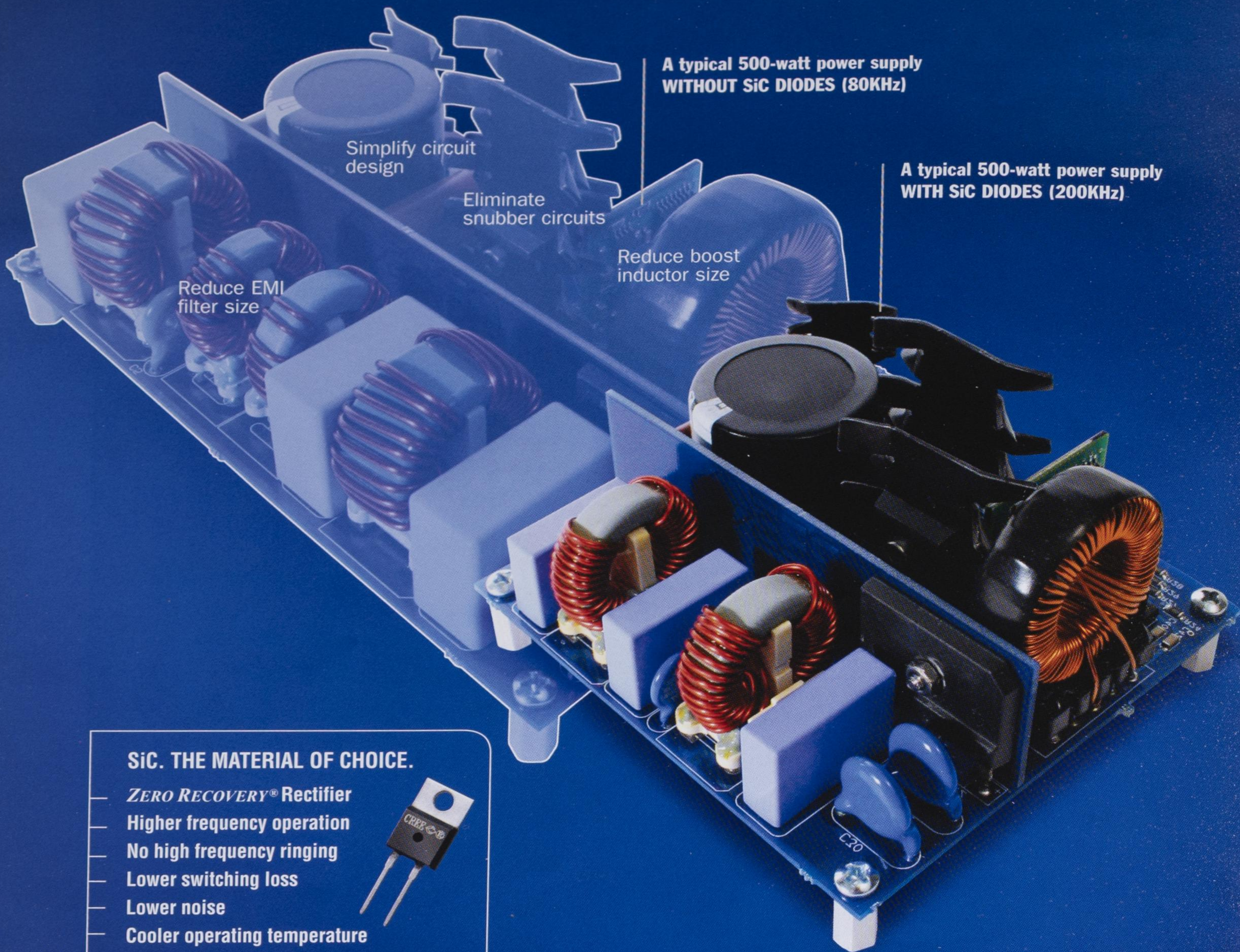
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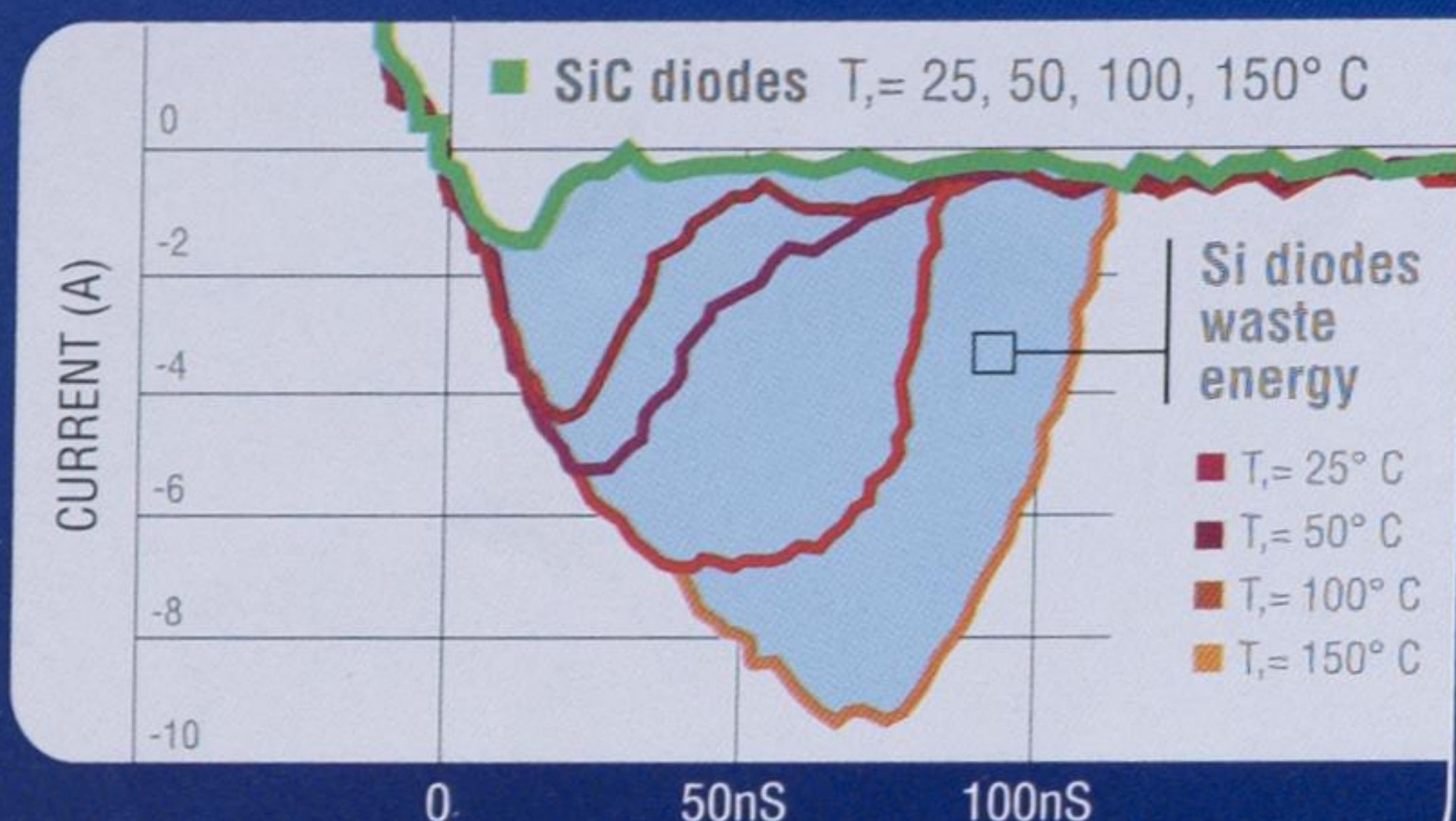
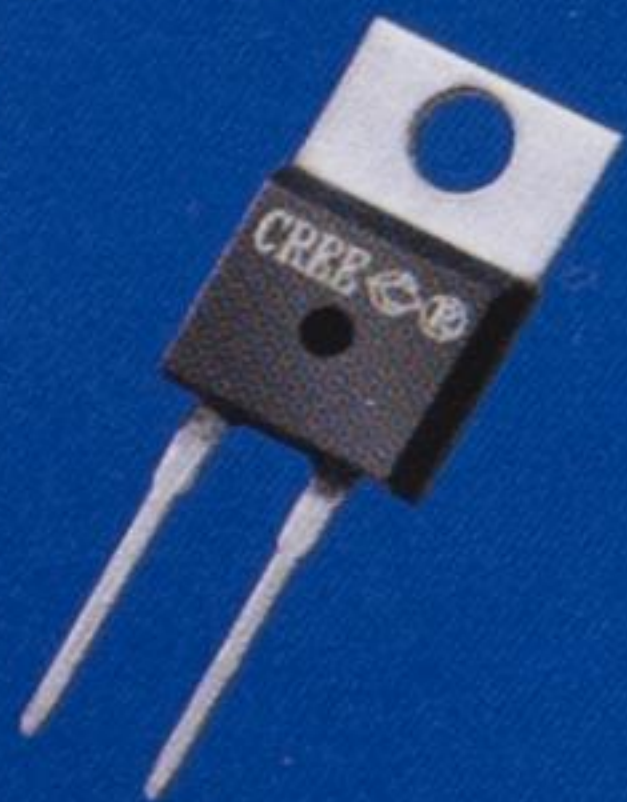
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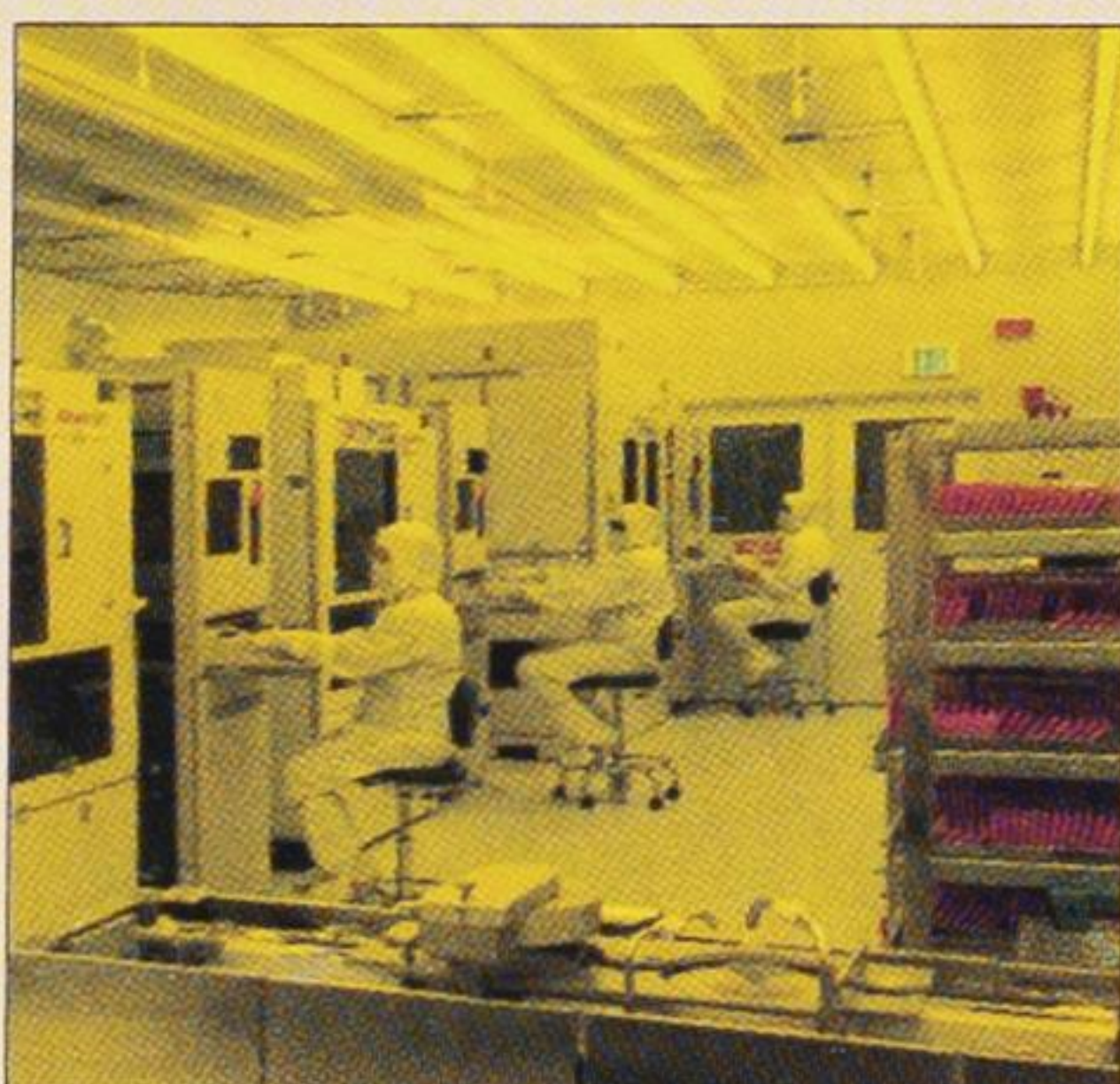
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Facing new challenges

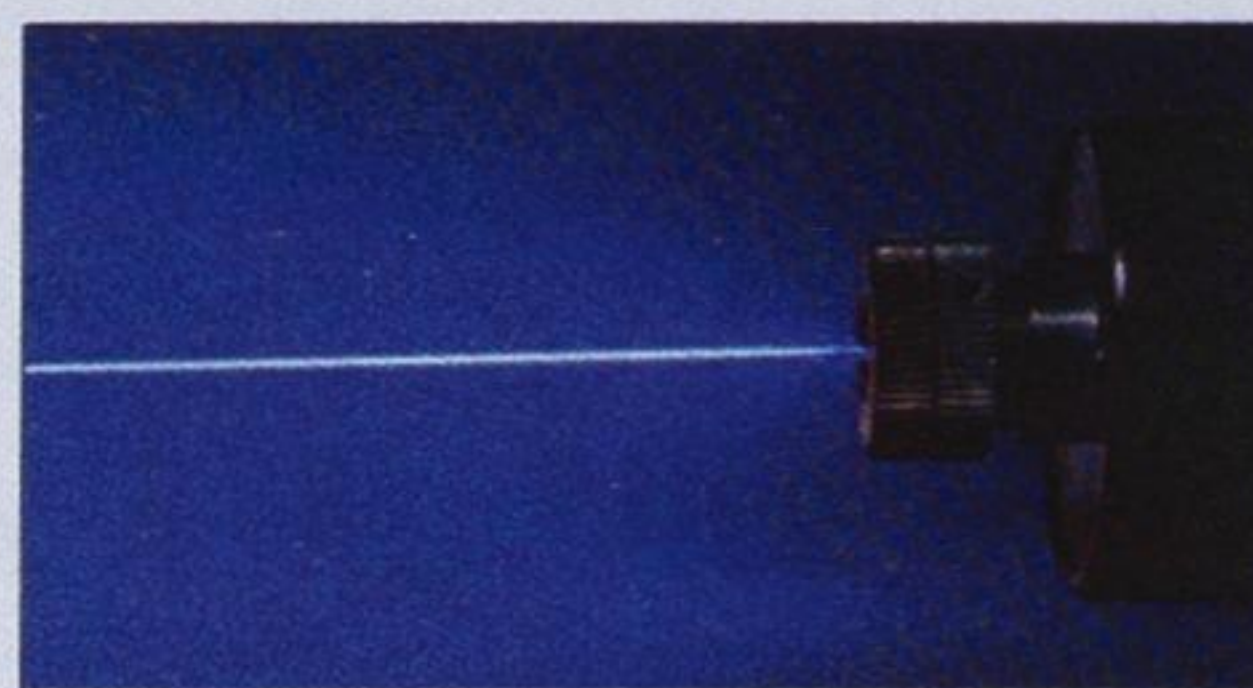
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Continuous-wave blue-violet lasers

GaN material with a low defect density has enabled TopGaN to produce MOCVD-grown blue-violet lasers with a continuous wave output of almost 200 mW. **p23**

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Solar cells are being developed to recharge the batteries that power a soldier's GPS navigation system and other electronic devices. **p27**

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Main cover image: Photonic crystal LEDs can be made using a novel, low-cost lithography technique developed by a firm in Texas. Credit: Molecular Imprints.

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Sony seeks virtue in adversity



There's an old Japanese proverb: "adversity is the foundation of virtue". If that's the case then Sony's senior management must be hoping to see plenty of virtue in the near future.

It's been a rotten few months for this superpower of the electronics and semiconductor industry. Following the alarming sight of a blazing laptop computer on the front pages of newspapers around the world back in August, faulty batteries made by Sony have been held to account and become a PR disaster for the firm.

Almost all of the major laptop manufacturers use Sony's batteries in their products, and a battery recall has affected millions of computers manufactured by Apple, Dell, Toshiba and others.

As if that wasn't enough, Sony has also been forced onto the back foot for the launch of its flagship and pioneering PlayStation 3 games console. The development of the high-speed "Cell" microprocessor and blue laser diodes based on GaN structures are just two of the innovations making possible the latest version of the world's best-known gaming machine.

"It's been a rotten few months for the superpower Sony."

Unfortunately, it seems that problems with the manufacture of these 405 nm lasers are largely to blame for a series of slips in the launch of the console, originally scheduled for spring 2006. Initially, low device yield caused by relatively

high defect levels in the epilayers was thought to be the reason. But referring to a more recent setback, which has delayed the launch of the console outside of the US and Japan until spring 2007, Sony Computer Entertainment's European division is now blaming the transfer of laser manufacturing from a small machine to high-volume equipment.

You can learn more about Sony's long-term laser-manufacturing strategy at next month's Key Conference in San Antonio, TX (see page 4 for details). Representing the business-development department within Sony's semiconductor-laser division, Michiro Chiba will outline future plans for both the consumer electronics and industrial laser markets at the event.

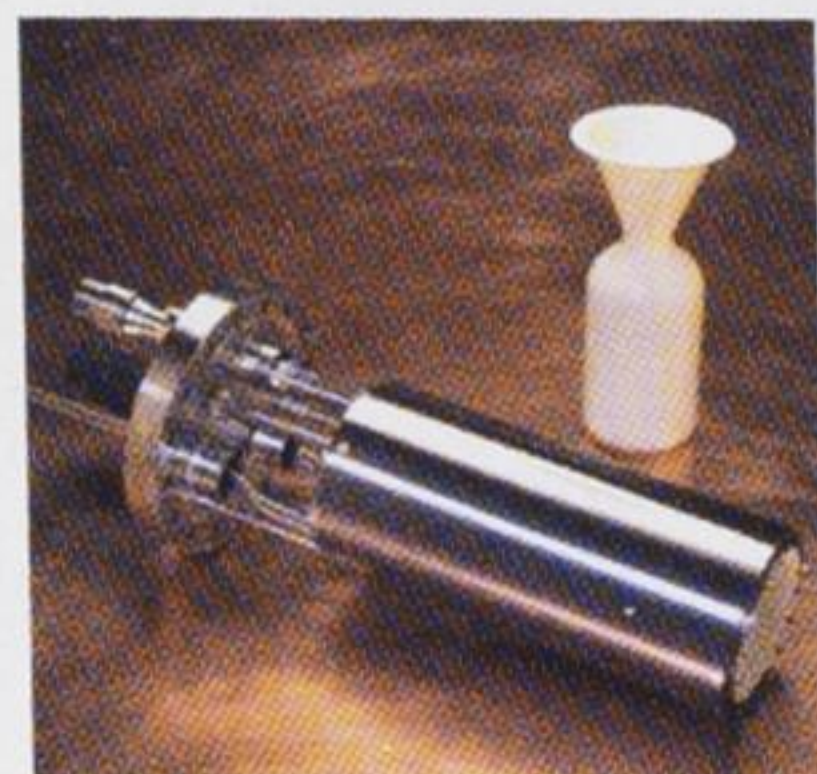
The Key Conference coincides with Sony's new launch date for the PlayStation 3 in Japan and the US. By then, hopefully, the virtuous response to this year's problems will have become apparent.

Michael Hatcher *Editor*

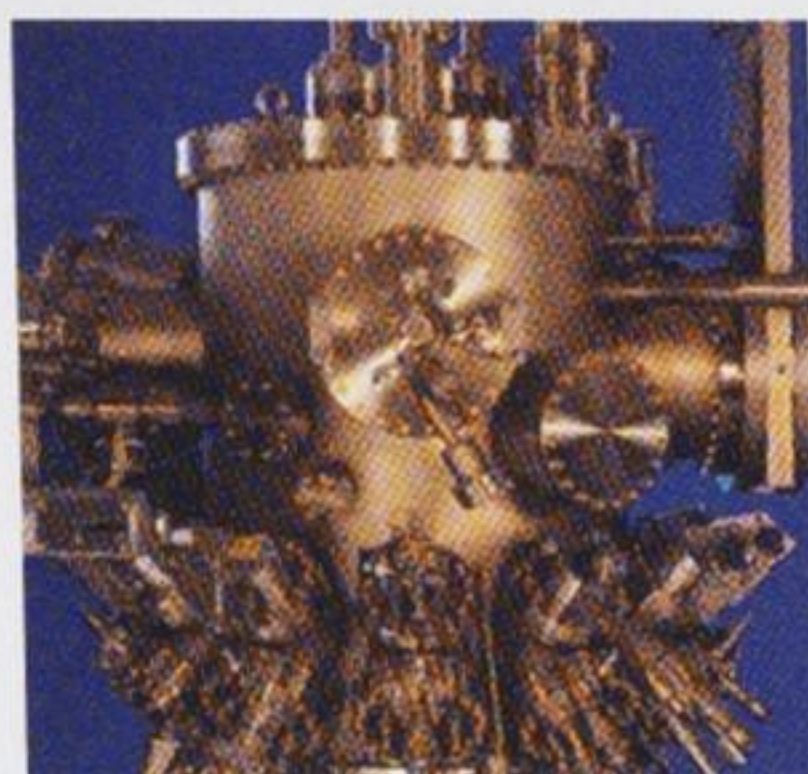
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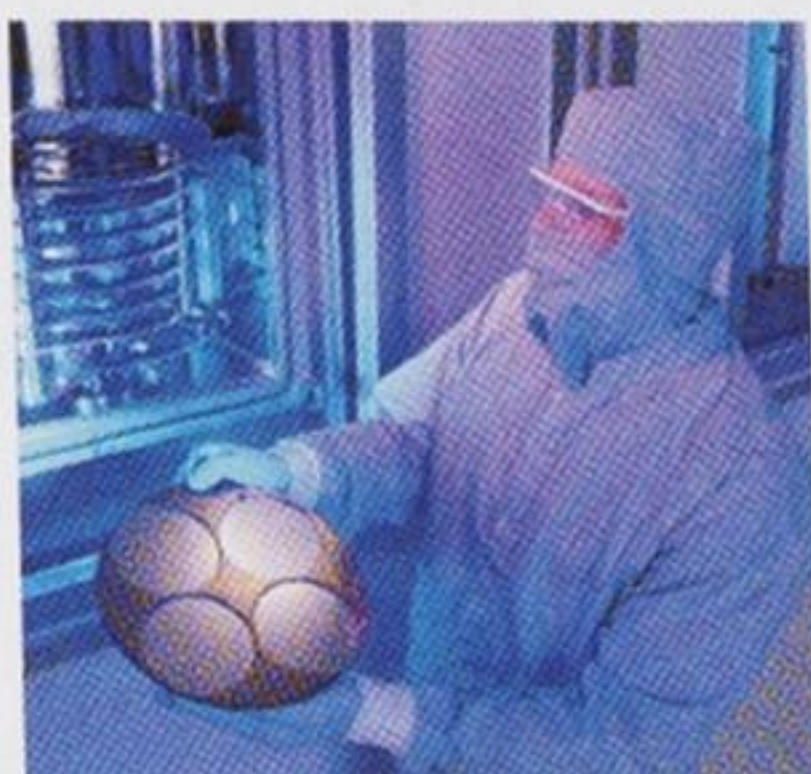
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OPTOELECTRONIC INTEGRATION

Intel heralds a new era of silicon lasers

A significant increase in speed for high-end computing applications could be on the cards after a team of US researchers announced that it had created the world's first electrically pumped "hybrid" silicon laser.

In making the device, Intel and University of California Santa Barbara (UCSB) researchers have combined the light-emitting properties of InP with the manufacturability of silicon for the first time.

"This could bring low-cost, terabit-level optical 'data pipes' inside computers and make a new era of high-performance computing applications possible," said Mario Paniccia, Intel's Photonics Technology Lab director.

The initial laser developed by Intel emits at $1.58 \mu\text{m}$ but this wavelength can be adjusted by modifying the silicon waveguides used. In the hybrid structure, III-V material is electrically pumped to inject electrons and holes into a series of quantum wells. That creates gain in the silicon waveguide, which subsequently results in laser action. The optical mode confinement is defined by CMOS lithography steps, rather than by the III-V layer.

According to Intel, the key to making the device is the use of a low-temperature oxygen plasma. This creates a thin oxide layer on the surface of both materials.

When they are heated and pressed together, this oxide layer acts like a glue and fuses the two materials into a single chip. Intel claims that unlike other methods, this eliminates any problems related to lattice and thermal mismatches between the two materials. UCSB's John Bowers says that because bare epitaxial wafers are bonded to the silicon wafer, alignment of the two materials is not a major issue.

Bowers adds that this bonding method can be used at the die, partial-wafer or full-wafer level and could become a solution for large-scale optical integration on a silicon platform. He explained that the bonding in the initial device was done at the partial-wafer level, with lasers made from $1 \times 1 \text{ cm}$ pieces. These partial wafers were diced into bars and then pol-



Eye on the prize: UCSB's John Bowers with the electrically pumped hybrid silicon laser, produced with Intel.

ished to form reflecting mirrors. The same method has been used to bond 2 inch wafers.

"This doesn't eliminate compound semiconductors," Bowers said. "Rather, it is a way to use them to integrate electrically pumped lasers with silicon photonic devices and silicon electronics on a single silicon platform."

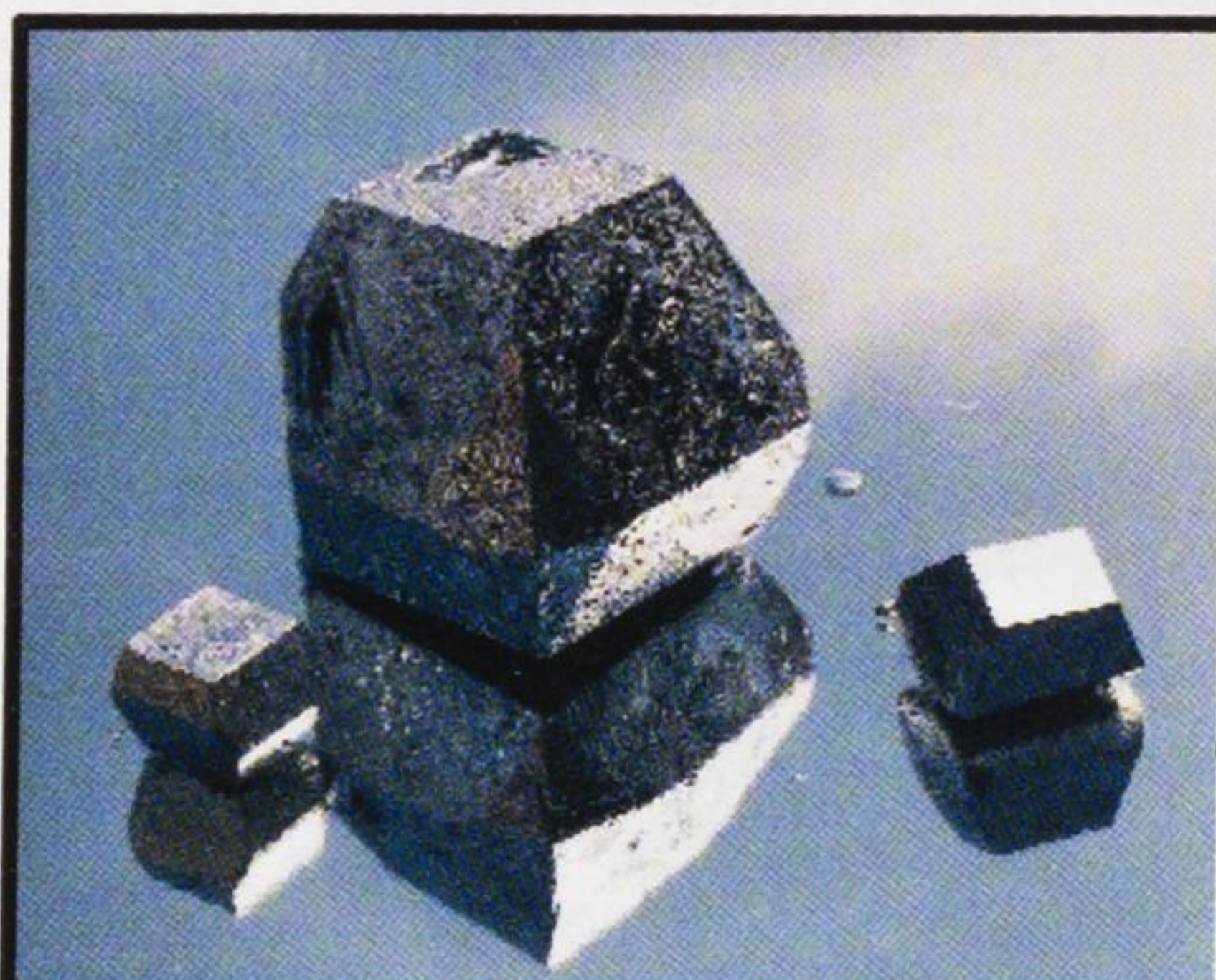
Bowers explained that all of the critical lithography steps are done in the silicon CMOS process prior to the wafer-bonding process. "It is not an external-cavity laser. Rather, there is a silicon singlemode waveguide," Bowers said. "The mode in that waveguide is evanescently coupled to quantum wells on the surface of the silicon-on-insulator wafer."

A multiple quantum well region in the III-V structure features eight periods of 7 nm-thick AlGaInAs wells and barriers. At 15°C the laser has a 65 mA threshold current and produces 1.8 mW when driven at about 200 mA. Lasing carries on up to 40°C in continuous-wave mode and up to 80°C in pulsed mode.

Bowers says that by halving the SiO_2 layer thickness to $1 \mu\text{m}$ and reducing the distance between this layer and the n-contact, performance should be greatly improved. "Our calculation indicates that this should increase the output power and allow 70°C operation."

Intel CTO Justin Rattner explains that if the latest development can be scaled up for mass production, it ought to solve the cost issue with photonic chip manufacturing. Presently, the cost of a laser chip for communications can be up to 100 times that of a silicon chip.

Infinera, the Sunnyvale, CA, firm that has developed an integrated approach for current telecommunications applications, says that Intel's work is a "great endorsement" of the photonic integration concept. However, company CTO Dave Welch disagrees with Intel's conjecture that InP is an "exotic" material that is inherently expensive. Welch says that the cost of manufacturing devices is dictated more by the level of volume production required.



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EUROPEAN MICROWAVE WEEK

GaAs foundries expect further consolidation despite sales boom



European Microwave Week was held at Manchester's G-MEX/MMIC center from 10–15 September. The popular conference featured more than 300 exhibitors and attracted over 850 delegates during a week of highs and lows.

Richard Stevenson in Manchester, UK

Further consolidation will take place in the GaAs foundry business, according to a panel session at European Microwave Week (EMW) that included Filtronic, GCS, TriQuint, WIN Semiconductor and UMS.

"It's been an 'up' year in the market, but companies are not profitable," said Robert Donahue, vice-president of worldwide sales and marketing at WIN. And with sales in this sector expected to grow more slowly over the coming years, firms making a loss will struggle to get their bottom line out of the red.

However, it's not all doom and gloom. The recent upturn in the foundry market, which is now worth more than \$225 million a year, has seen a rapid growth in chip manufacturing.

TriQuint has quadrupled its production over the last year, and is seeing strong growth in its HBT and 0.5 μm E- and D-mode PHEMT processes. Fab use of its 150 mm line is now at 80%, explained Stephanie Duprey, marketing manager for the commercial foundry.

A hike in chip production has also occurred at WIN Semiconductor, which has seen sales increase by more than twenty times during the last four years. "WIN was profitable last month for the first time in its history," remarked Donahue. To cope with growing orders the Taiwanese foundry is planning to increase its capacity with a \$44 million investment.

Expansion is also taking place at Filtronic. The UK-based company, which specializes in PHEMT technology, typically produces 2000 wafers a month, but in the future will be capable of manufacturing 50,000 a year, according

to company CTO Wolfgang Bösch.

At UMS, which has foundries in France and Germany, there is also an upturn in activity. Foundry manager Eric Leclerc said that sales growth in 2006 was more than 50%. The number of foundry projects has also increased from 45 in 2004, to 64 in 2005 and 73 this year.

On top of all this growth is a change in the customer base of GaAs foundries, says Duprey, with more customers from other markets, such as CMOS. These clients have varying requirements for device testing, and want to work with stable high-volume manufacturers – ideally ones that own more than one fab.

Customers are also interested in processes that offer higher levels of integration, such as TriQuint's bi-HEMT process, claims Duprey, because this can reduce their bill of materials.

The panel also agreed that the GaAs foundry business now faces a greater threat from CMOS than from SiGe, and that the silicon process is more likely to impact power amplifiers than switches. "We were more afraid of SiGe three years ago," remarked Duprey.

All of the companies believe that GaAs foundries will still exist in ten years time. However, they could look more like silicon foundries and they might have to work together to overcome the threat from GaN and CMOS.

• TriQuint launched two high-performance GaAs amplifier products at EMW. Designed for point-to-point radio, K-band satellite communications and point-to-multipoint network infrastructure applications, the amplifiers operate in the 17–21 GHz band and are manufactured using TriQuint's 0.25 μm power PHEMT process.



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Skyworks bags Broadcom deal

In an agreement that could significantly boost its GaAs output, Skyworks Solutions is to supply Wi-Fi chipset giant Broadcom with GaAs-based front-end modules (FEMs) for new broadband wireless applications. Skyworks will supply SKY65225 FEMs for Broadcom's so-called Intensi-Fi chipset. The product is designed for the proposed 802.11n wireless communication protocol, which is expected to operate at up to 200 Mb/s – five times faster than the current Wi-Fi standard. The SKY65225 module features dual-band transmit/receive chains and includes four power amplifiers; two operating at 5 GHz and two at 2 GHz. Also included are low-loss, high-rejection duplexers based on GaAs to provide high linearity in all transmit paths.

Freescale going private

Freescale Semiconductor, the chip manufacturing spin-off of Motorola that runs a GaAs fab, is set to be acquired by a private equity team led by The Blackstone Group in a \$17.6 billion cash deal. If shareholders approve the deal, it is expected to be completed in early 2007. The equity group says that the company will retain its name and the switch will not affect any of its current manufacturing facilities, or its vendor supply agreements.

SiGe in the money

SiGe Semiconductor, the supplier of front-end RF components for wireless applications, has attracted \$19.5 million in new venture finance. The fabless company, with its headquarters in Ottawa, Canada, says that the cash will fund product development and growth in operations to support a rapidly expanding customer base. According to SiGe, company revenue has grown more than ten-fold over the past three years from \$3.6 million in 2003 to \$23 million in the first half of 2006 alone.

GigaBeam gets wireless build-out

GigaBeam, the Herndon, VA, manufacturer of gigabit-per-second wireless systems featuring compound semiconductor chips, has sold eleven "WiFiber" wireless fiber links to a company in the western US. The customer, which is a wireless local exchange carrier, is using the WiFiber links to build a city-wide communication network that will initially provide voice and data services at 10–100 Mb/s to local businesses. GigaBeam's WiFiber products operate in the 71–76 and 81–86 GHz spectral bands.

MERGERS & ACQUISITIONS

Teledyne acquires Rockwell Scientific for \$167.5 million

Teledyne Technologies has bought compound semiconductor IC manufacturer Rockwell Scientific in a cash deal worth \$167.5 million.

Based in Thousand Oaks, CA, Rockwell Scientific, which was previously owned by parent firms Rockwell Automation and Rockwell Collins, specializes in advanced semiconductor applications, including many based on a wide range of compound materials.

These include GaAs and SiGe for mixed signal ICs, and the company operates a GaAs foundry where it manufactures PHEMTs and MMICs for low-noise amplifier and power-amplifier applications.

Rockwell's technological expertise extends to GaN-based HEMTs, InAs HEMTs, InP HBTs, SiC-based Schottky diodes, and MEMS-based RF components. Its total sales in fiscal 2005 were \$114 million.

The firm has developed a SiC-based motor

drive that it claims operates at 99.4% efficiency, as well as 50 W output SiC MESFET power-amplifier modules for use in wireless communications systems.

The Teledyne group of companies, which is extremely diversified, makes everything from fighter aircraft ejector-seat electronics to LED backlights for flat-panel displays. It acquired Celeritek's defense electronics business in 2004 when the GaAs manufacturer was wound up amid financial difficulties.

The Rockwell acquisition was funded through Teledyne's \$400 million credit facility, and Rockwell Scientific's previous owners will retain certain liabilities under the terms that were agreed.

Following Teledyne's purchase, Rockwell Scientific will be split into two divisions, known as Teledyne Scientific Company and Teledyne Imaging Sensors.

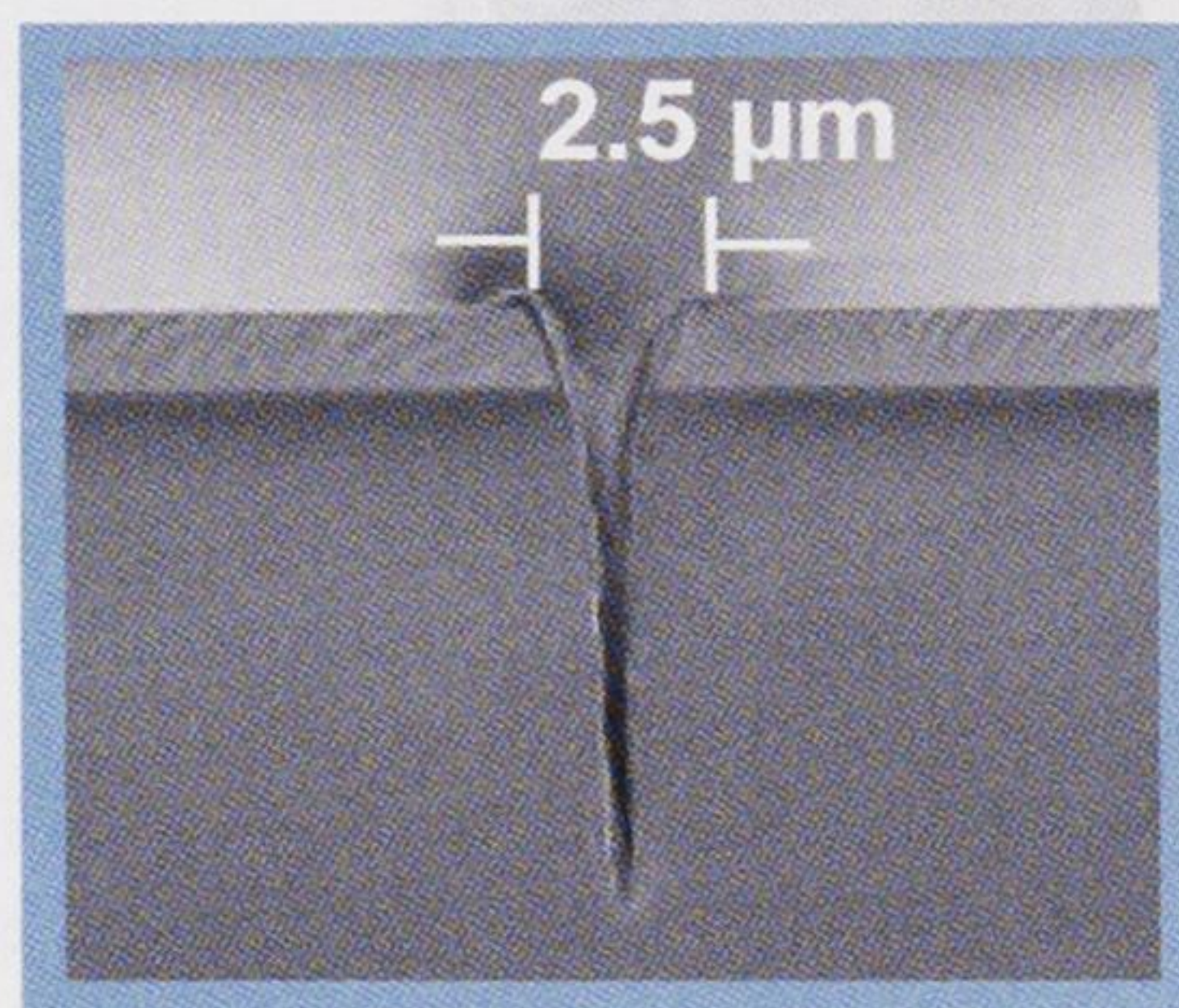
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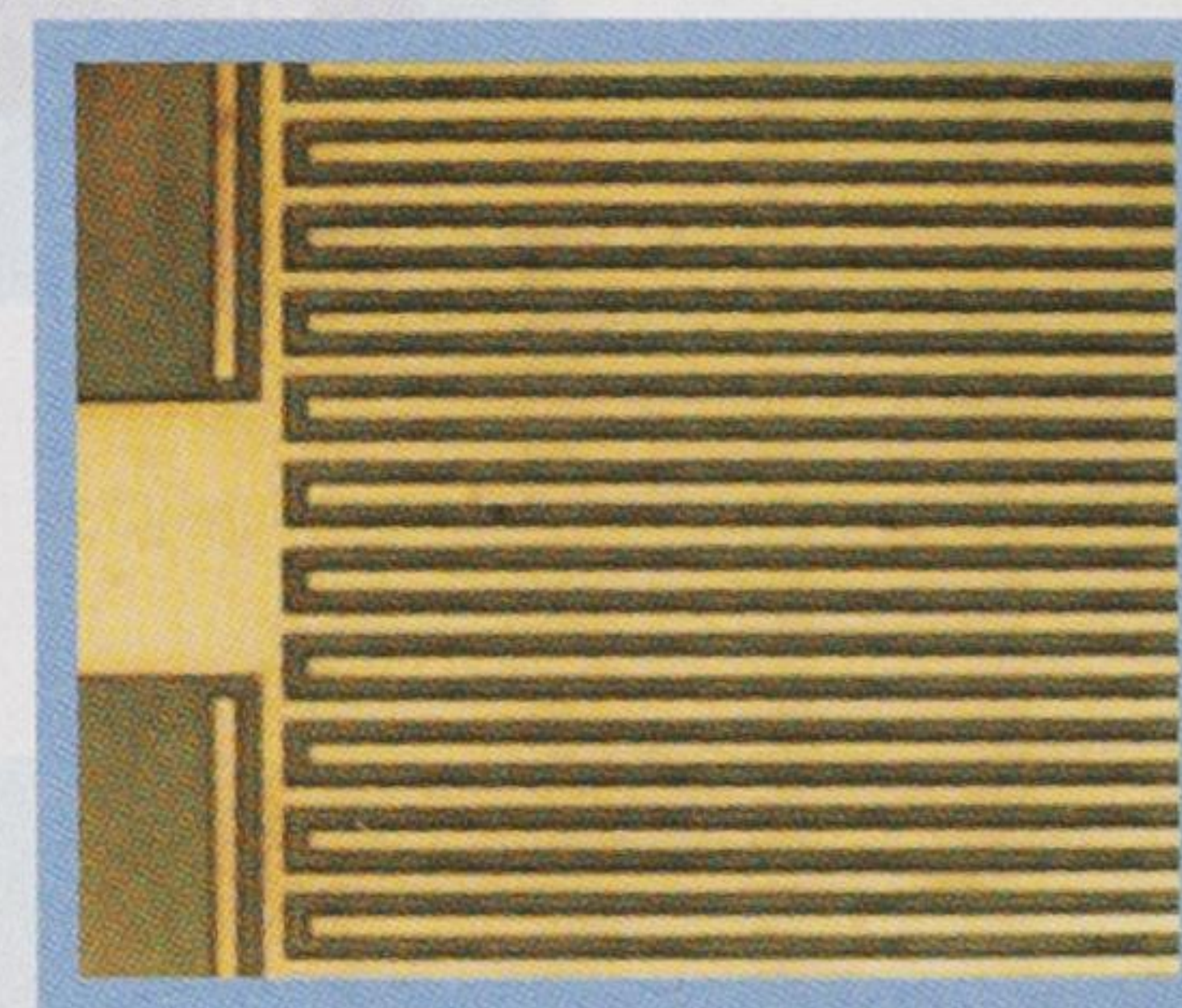
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Ask the Expert



Rajiv K. Agarwal, Ph.D.

Lead Research Engineer

Q

I am experiencing high n type background doping levels in my MOCVD process when I grow GaAs and AlGaAs devices. I think the problem is in the arsine I use. I'm buying the best grade available. What can I do?

A

Higher background levels of n type dopants in GaAs and AlGaAs structures are caused by trace levels of germanium, silicon and sulfur species present in the arsine. As customer applications evolve, the purity requirements for arsine must as well. Until recently, background doping levels of $10^{15}/\text{cm}^3$ were considered acceptable in most applications. In general, most currently available high-purity grades of arsine can satisfy these requirements. However, process changes and demand for more sophisticated devices have resulted in the need for lower background doping levels. To address these more stringent requirements, Air Products is introducing Megabit™ III arsine, our purest grade available. Our new Megabit III arsine has significantly reduced the amounts of germanium, silicon and sulfur species. Testing done at an independent laboratory proved the effectiveness of Megabit III on thick gallium arsenide films, with excellent results. In all cases, the background doping level was $<<10^{14}/\text{cm}^3$. Our research has shown that Air Products' Megabit III arsine will perform more consistently and produce fewer defects in our customers' finished products.

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EPITAXY

Arima expands AlGaInP capacity

Arima Optoelectronics, Taiwan, has ordered three more of Aixtron's 49×2 inch MOCVD systems, says the Aachen, Germany, firm.

The high-volume AIX 2600G3 reactors will manufacture AlGaInP-based LEDs at Arima's facilities in Dashi and Houko, while Arima also has plans to scale up laser-diode production.

The move comes amid some press reports that major LED producers such as Arima are waiting for demand for their chips to stabilize before committing to major capacity upgrades.

A recent story in *Electronic Engineering Times* reported that Arima would not expand capacity until early next year, for example, while Epistar was said to be waiting for

stronger demand for LEDs to be used in large-scale backlights before committing resources.

"We have already expanded our capacity for AlGaInP-based LEDs and related products at the Hsinchu plant we acquired through our merger with Kingmax," said Arima president PJ Wang. "The plan is to increase the volume to 40 million units per quarter by 2007. We also intend to begin shipping high-brightness blue LEDs this year and increase laser-diode production to 7 million per quarter."

Arima's most recent sales report (July 2006) showed revenue of NT\$288 million (\$8.8 million). That figure marked a decrease of 6.5% on June sales, but a 26% increase year-on-year.

INTELLECTUAL PROPERTY

Cree sues BridgeLux in dispute over patents

By Tim Whitaker

Cree has sued BridgeLux, a rival LED chipmaker. The suit alleges that BridgeLux (formerly eLite Optoelectronics) has infringed US patents 6,657,236 and 5,686,738.

Filed in the Middle District of North Carolina, the law-suit seeks monetary damages and injunctive relief to prohibit BridgeLux from infringing these patents.

Patent '236, which is assigned to Cree Lighting Company, relates to light-extraction structures used in LEDs, while '738 relates to semiconductor devices manufactured using a GaN-based buffer technology. The buffer specifically comprises a GaN layer and one or more doped GaN layers.

The '738 patent is owned by the trustees of Boston University and exclusively licensed to Cree. The university is a co-plaintiff.

The '738 patent was also the subject of two

prior suits by Cree and Boston University against Nichia Corporation and AXT. Cree and Nichia resolved their multi-faceted patent dispute in 2002 with a cross-licensing agreement, while Cree's dispute with AXT over the '738 patent was settled in March 2004.

eLite Optoelectronics was founded in December 2002 by former employees of AXT's LED operation, while AXT sold its own LED manufacturing business to China-based Lumei Optoelectronics in 2003.

Cree CEO Charles Swoboda said that the BridgeLux lawsuit demonstrated Cree's willingness to protect its R&D investments and patent rights. "This is especially at a time when some segments of the LED marketplace act as if there are no issues with intellectual property," he said. This may be a reference to the IP-Secure Lighting Alliance, founded by BridgeLux and Intematix, which brings together LED industry suppliers who are able to certify that their products do not infringe on other companies' intellectual property.

BridgeLux will defend its position.

● Tim Whitaker is editor of *LEDs Magazine*; see www.ledsmagazine.com.

ACQUISITIONS

Epistar swells with double merger plan

Less than a year after merging with United Epitaxy Company (UEC), Epistar Corporation is set to swallow up two more of Taiwan's leading InGaN LED makers.

Epitech and Highlink will become part of the fast-growing Epistar brand from March next year, assuming shareholder and regulatory approval.

Already the world's largest manufacturer of AlGaInP LEDs, the latest move will catapult Epistar into becoming one of the top five global suppliers of InGaN devices.

Since the UEC merger, Epistar has seen its revenue more than double, posting sales of nearly NT\$3 billion (\$91 million) in the first half of 2006 and seeing its profit almost quadruple to NT\$617 million.

If the latest deals get the go-ahead, Epistar will be by far the biggest InGaN LED player in Taiwan. Highlink chairman Semi Wang indicated that there would be little need for cut-backs following the consolidation: "The sales channels of Epistar, Epitech and Highlink do not overlap with one another," Wang said.

MANUFACTURING

Philips doubles power LED volumes

Philips, the lighting industry giant that owns LED chip maker Lumileds, is to set up a wafer facility in Singapore, where it will manufacture power LEDs for emerging lighting applications.

The fab, which should begin initial production in the first quarter of 2007, is expected to be fully ramped by the end of next year, at which point it will have doubled the company's total power LED production capacity.

Philips has already acquired an empty building in Singapore, which it is beginning to fill with the new chip manufacturing equipment required to make its flagship Luxeon emitters. The chips made in Singapore will be packaged at another Philips facility in Malaysia.

Philips says that the investment is necessary to keep pace with the demand for its high-power LEDs. It expects the devices to find use in camera-phone flash components, large LCD backlights and automotive lighting.

Lumileds currently makes the Luxeon power

LEDs at its headquarters in San Jose, CA, but it appears that this fab on its own would not have been able to meet the expected demand. A Philips spokesman said that LED production in San Jose would carry on as normal for the foreseeable future.

Although the precise floor area and the financial investment have not been made public, the Singapore fab is going to be a very large operation. At full capacity it is expected to employ some 900 people.

Philips Lighting CEO Theo van Deursen said, "This investment will not only double the production capacity of our power LEDs in the next year and strengthen our number-one position in this field, it will also significantly increase efficiency."

Just over a year ago, Philips became the sole owner of Lumileds when it bought out the half-share in the joint venture company previously owned by Agilent Technologies.

RESEARCH

Revealed: how InGaN LEDs emit blue light

By Darius Nikbin

Japanese researchers have worked out why the InGaN material that features in commercial blue LEDs can emit bright light despite its poor crystal quality and high defect levels.

"If the structural defect density is higher than 10^5 cm^{-2} for conventional LEDs, no light comes out from the material," reported lead author Shigefusa Chichibu from Tsukuba University in *Nature Materials*. "However, InGaN alloys can emit bright light even though the defect concentration is as high as 10^9 cm^{-2} , which is a million times higher than in conventional LED films."

The team concluded that the charge-carrying holes in In-containing alloys are preferentially

trapped or localized by atomic arrangements consisting of just three indium atoms alternating with nitrogen in a chain (In-N-In-N-In), or a tetrahedron. The trapped holes then form localized excitons (electron-hole pairs) to emit the light, which was found to be responsible for the material's brightness.

The researchers suggest the use of such atomic arrangements to develop highly efficient light emitters using defective crystals and even amorphous glass-like materials.

The team used time-resolved photoluminescence and slow positron annihilation measurements to determine the relationship between the lifetimes of light emission and the defect concentration in AlInGaN semiconductors. "We found that positron diffusion lengths in InGaN alloys are very short. This was strange, because usually this means that the material contains high-density point defects and may not emit the light," said Chichibu.

● Darius Nikbin is a science journalist.

DEVICE DEVELOPMENT

Cree's latest power chips are twice as bright

Cree has released the latest version of its EZBright range of high-power LED chips. The new InGaN-based products, which are available in commercial quantities, are said to deliver twice the brightness of the Durham, NC, company's existing offering.

"For the first time these chips should enable solid-state lamp makers to challenge the efficacy of not only incandescent, but also fluorescent lamps," said Cree CEO Chuck Swoboda.

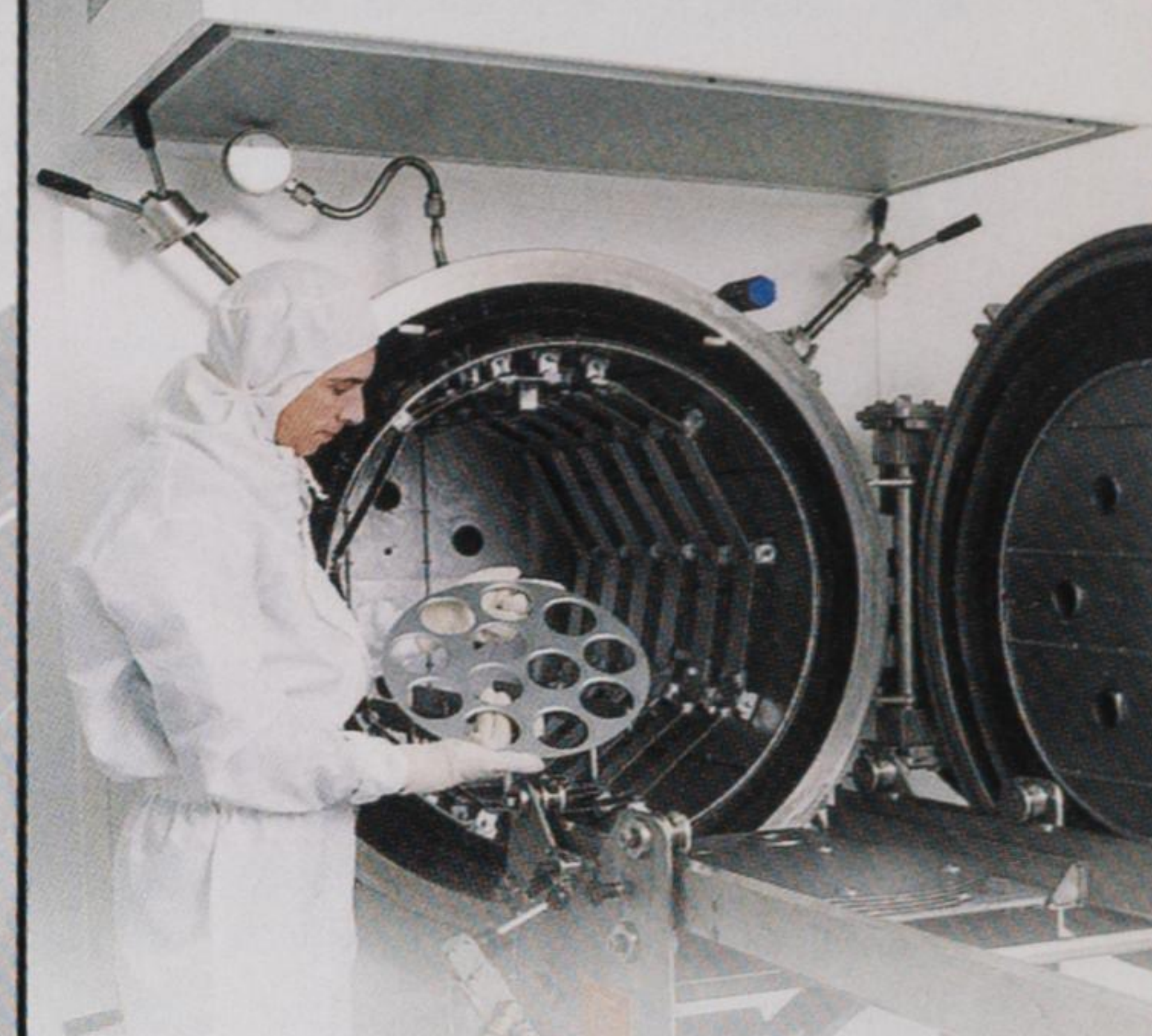
"The EZBright1000 LED power chip is one

of several advancements we are working on to help drive LEDs into more mainstream lighting applications," he continued. Applications include auto headlamps, streetlights, projector displays, and home and office lighting.

Measured as a bare die, the blue power chips deliver as much as 370 mW at 350 mA drive current, and up to 800 mW at 1 A. They were developed in part through the US Department of Energy's solid-state lighting program.

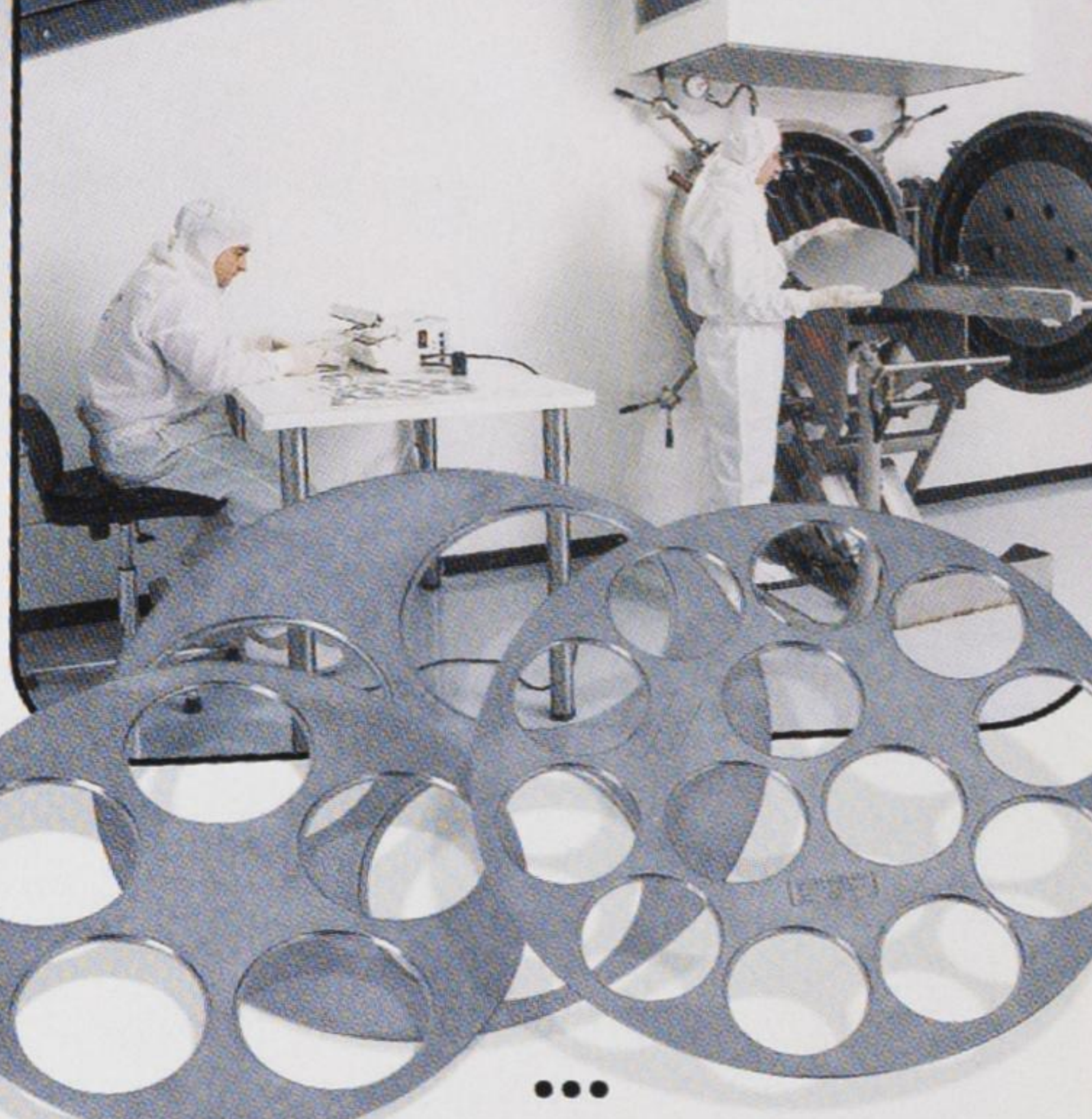
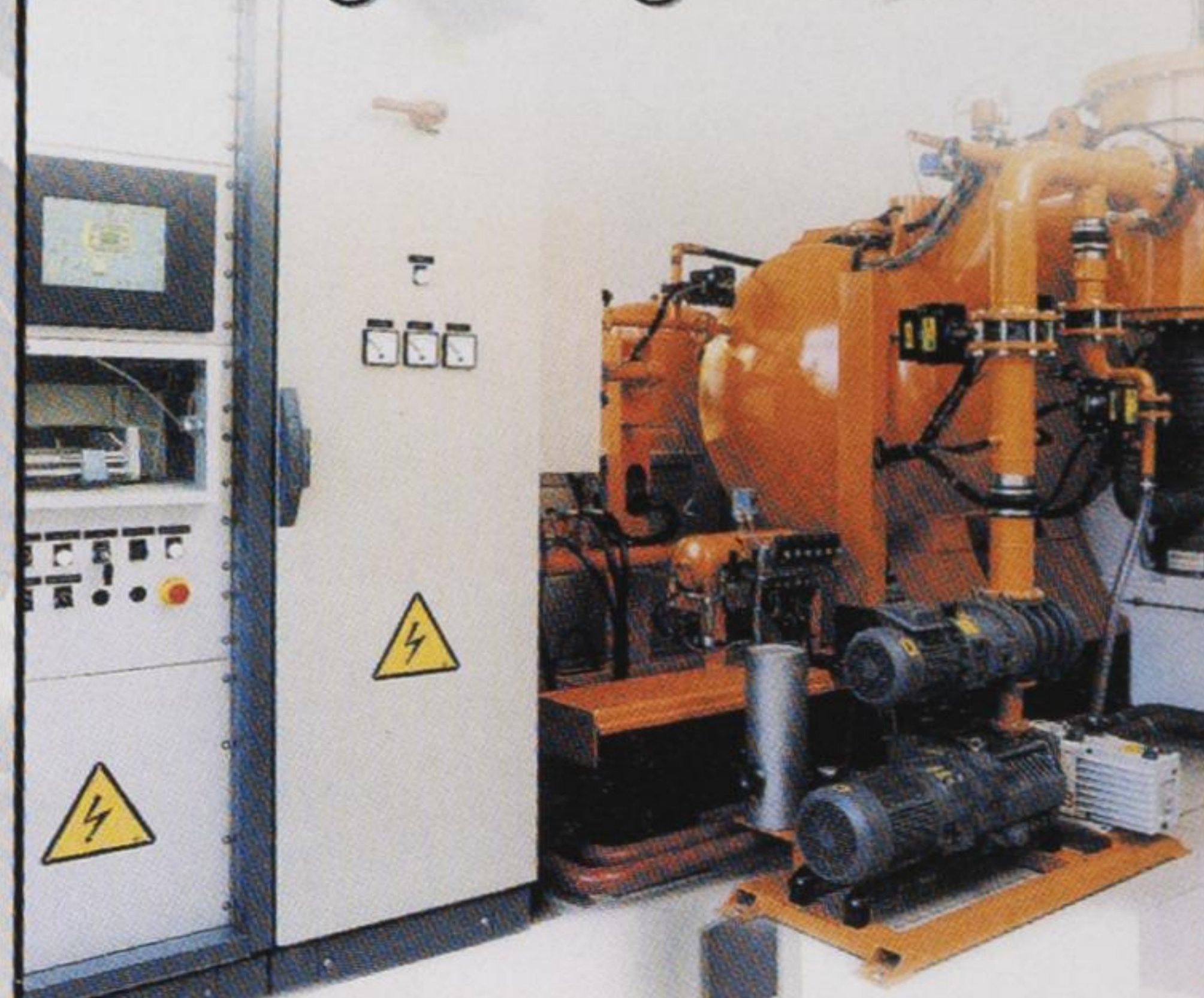
● Read our interview with Cree on page 13.

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COMPANY FINANCE

IPG Photonics files initial public offering to aid fab expansion

Oxford, MA, fiber laser and amplifier specialist IPG Photonics has filed a registration statement with the US government's Securities and Exchange Commission (SEC) for a proposed initial public offering (IPO) of its common stock.

Although the firm is yet to reveal details of the anticipated timing or value of the IPO, its S-1 registration statement with the SEC contains plenty of information.

IPG uses MBE to make high-power, multi-mode diodes based on the AlInGaAs material system at its 123,000 sq ft wafer fab in Oxford.

These diodes are the key components in the firm's fiber laser systems, which are used in materials processing applications and provide a much smaller, more convenient alternative to carbon dioxide and solid-state lasers.

Part of the expected proceeds from the IPO will be used to fund an 82,000 sq ft expansion of the diode laser facility. With 900 employ-

ees and 300 customers, IPG posted sales of \$64.9 million and a net profit of \$6.1 million in the first six months of 2006.

Valentin Gapontsev, company founder and CEO, is the majority shareholder in IPG, owning 62.6% of shares prior to the IPO. His son Denis is VP of R&D. Following a bout of litigation resolved in August 2003, rival diode laser maker JDSU now owns 5.5% of IPG stock.

On its balance sheet, IPG lists total assets worth \$132 million, with cash and cash equivalents totaling \$11.3 million and long-term debt of \$22.7 million. It is anticipated that certain existing stockholders of IPG Photonics will be permitted to sell a portion of their holdings in the IPO. Merrill Lynch & Co and Lehman Brothers are acting as joint book-running managers of the offering. Needham & Co, LLC, Jefferies & Co and Thomas Weisel Partners LLC are acting as co-managers.

VCSELS

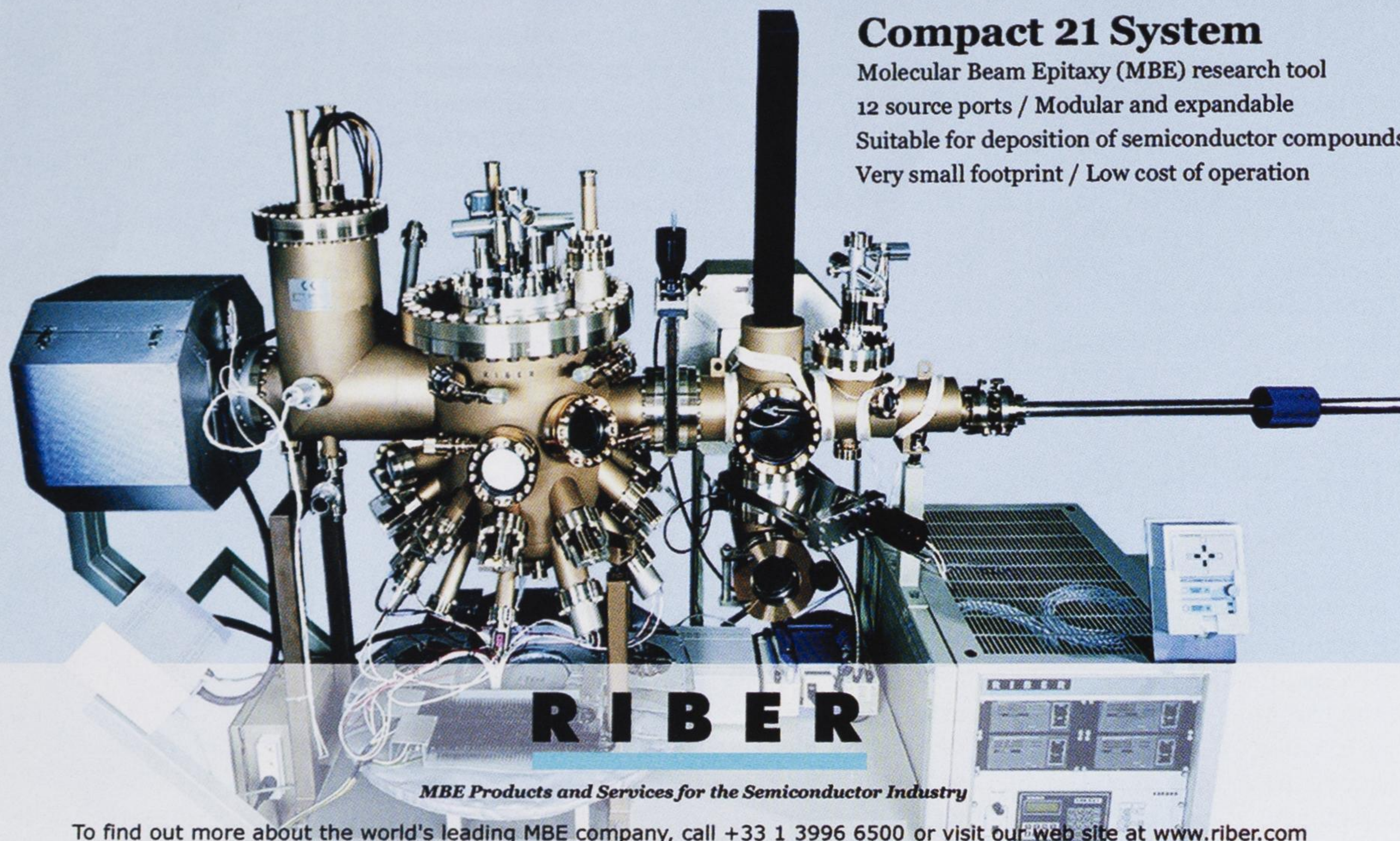
Ulm extends optical mouse arrangement with Microsoft

Microsoft has teamed up with German VCSEL specialist Ulm Photonics on its latest optical mouse product. As the preferred supplier for the existing Wireless Laser Mouse 6000 and its notebook PC equivalent, Ulm Photonics has already delivered a significant number of singlemode 850 nm VCSELs, which have been used in the 2.5 million or so optical mice that Microsoft has sold in the past few months.

With Ulm also selected for the follow-up product family, that lucrative relationship is set to continue. Ulm, which has enough capacity to make approximately 10 million laser chips a year, carries out all of the device processing steps in-house, while device assembly is outsourced.

Ulm's Martin Grabherr added that the company also produces around 1 million chips for other sensor and datacom applications.

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MANUFACTURING

Laser problems hit PlayStation 3

Problems with the manufacturing ramp of blue laser diode chips have been blamed for Sony delaying its introduction of the PlayStation 3 games console in Europe.

The PlayStation 3 launch dates in Japan and the US remain set at November 11 and 17 respectively, but in Europe, Russia, the Middle East, Africa and Australasia the games console will now be launched in March 2007.

Sony said that a delay in the mass production schedule of the blue laser diode, which is at the heart of each PlayStation 3, was to blame.

Blue laser diode producers have experienced yield problems with the technology

before, due to the lattice mismatch between the substrate and active layers of the devices.

The relatively high number of defects that result have generally been blamed for these yield problems. Although Sony has indicated that difficulties with the switch from low-volume to mass production equipment is behind the delay, it is possible that a device yield problem is to blame for the split launch schedule.

Despite the European setback, Sony is still expecting its PlayStation 3 launch to result in the shipment of 6 million units – each featuring a GaN laser – within fiscal 2007.

COMPANY FINANCE

Bookham sells UK test facility

InP-based fiber-optic component and module supplier Bookham has agreed to sell its test and assembly site in Paignton, UK, to an undisclosed buyer for £5 million (\$9.5 million).

The deal, which includes an option to lease back a portion of the site from the new owner, is expected to be completed in mid-November. Bookham will be able to lease back part of the site for a two-year term that it will be able to

terminate at three months notice.

The sale generates more much-needed cash for the San Jose, CA, chip manufacturer, which has also been bolstered through a recent share issue that generated \$31.4 million.

The operations carried out at the Paignton site focused on test and assembly, and the firm had been trying to shift this part of the business to its site in Shenzhen, China, to reduce costs.



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...Infinera trio bag award

Three engineers from photonic integrated circuit pioneer Infinera have won the Aron Kressel Award in recognition of their contribution to the field of optoelectronics. Charles Joyner, Radha Nagarajan and Richard Schneider from the Sunnyvale, CA, company will be presented with their gongs at the annual meeting of the Lasers and Electro-Optics Society being held in Montreal, Canada, on October 30.

...Submarine diodes resurface

Fremont-based Avanex has introduced two products based on its PowerIntense 980 nm laser chips. One of these, a new submarine pump laser emitting 400 mW, is said to be the highest-power source available for such applications. Hopeful of renewed opportunities in this sector after a protracted downturn, Avanex CTO Giovanni Barbarossa said: "These lasers exceed the reliability and performance demands of the submarine market, giving us the chance to have substantial participation in the coming market for undersea optical repeaters."

...Diode laser firm gets \$10 million funding

Oxxius, a French manufacturer of laser modules pumped by III-V diodes, has secured \$10 million in its second round of venture funding. The new round was led by Sofinnova Partners, which also funded the company's initial financing round with €2.4 million (\$3.1 million) back in 2004. Oxxius will use the new funds to extend its range of products. It currently makes and sells a variety of modules that emit in the green, blue and ultraviolet range of the spectrum. Those modules can be based around crystals that are powered by diodes emitting at 808 nm or which use GaN-based laser chips.

...Finisar posts record sales

Californian fiber-optic component vendor Finisar posted \$96 million in record-breaking sales of optical subsystems in the quarter that ended on July 31. The figure equates to a 30% increase from the same period one year ago, illustrating the strong market demand for datacoms products. Finisar has upped capacity by 30–40% with a new reactor at its VCSEL fab in Allen, TX.

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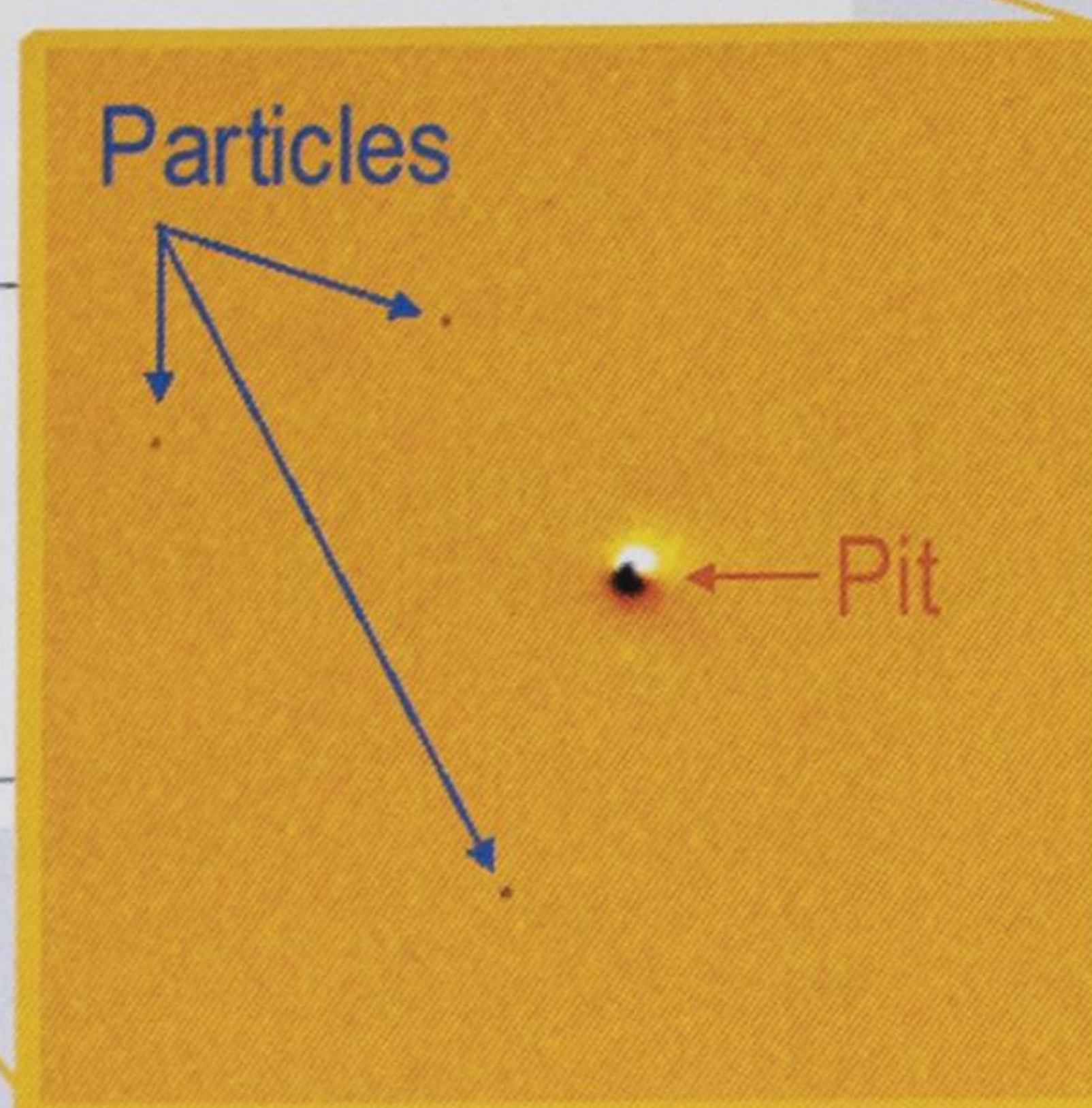
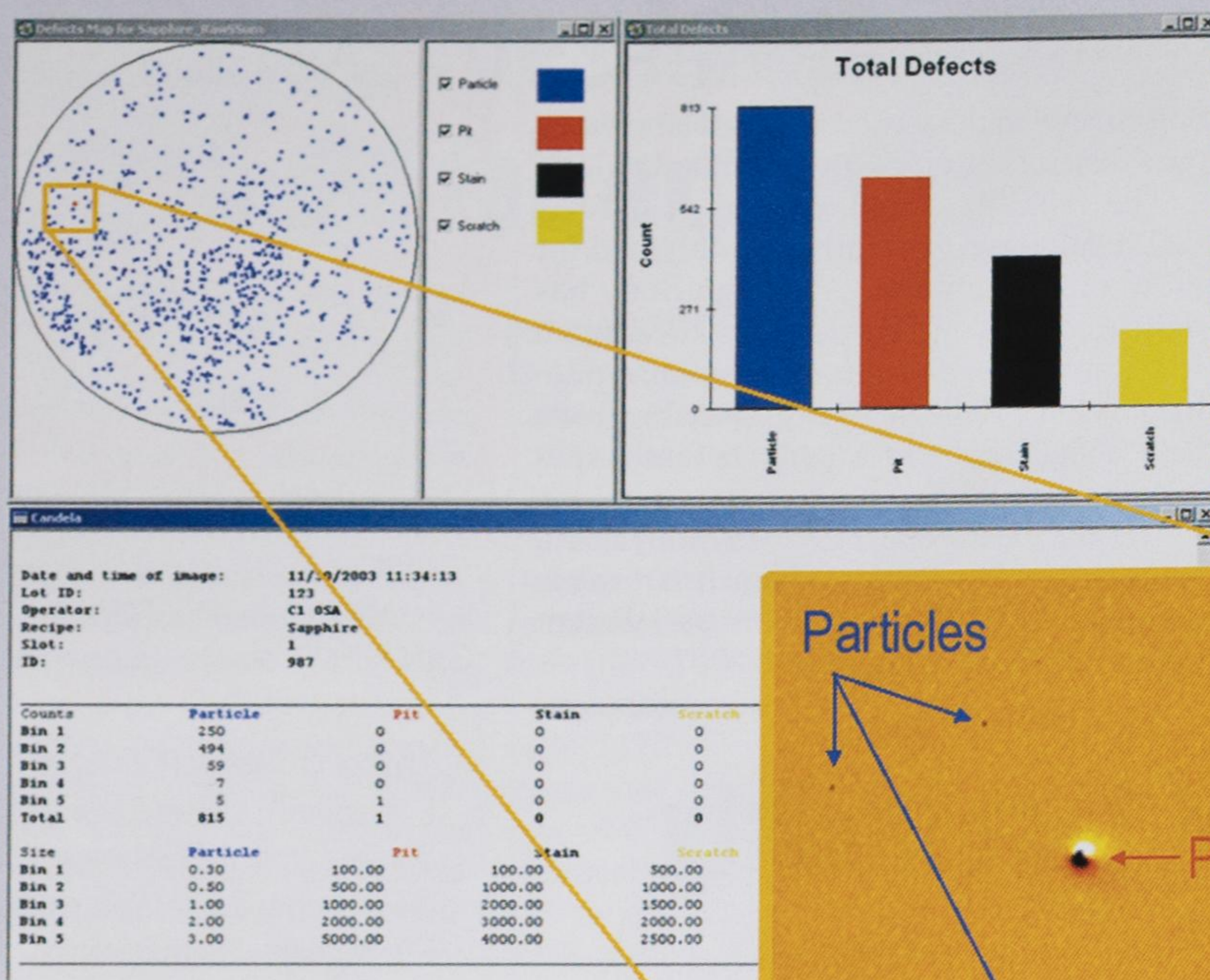
\$650 for NPT35015 Kit
(Kit includes 1 device and an application board)



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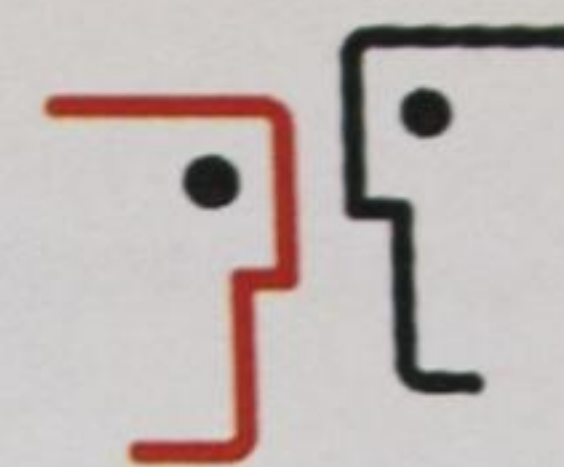
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CREE

Evolving Cree hits a crossroads



CREE

Cree co-founder John Palmour believes that by employing SiC Schottky diodes in switched-mode power supplies, total energy losses can be cut by one-third.

The global move towards greater energy-efficiency is one that Cree can tap into from many angles as it looks beyond its traditional territory of blue LEDs. **Bob Metzger** visited the company's new North Carolina fab to learn more about its latest strategy for growth.

Cree is a quintessential start-up success story. Founded by a handful of researchers from the State University of North Carolina at Raleigh less than 20 years ago, the company has grown to more than 1000 employees, made annual sales of \$400 million and become the world leader in SiC technology as well as one of the primary manufacturers of GaN-based LEDs.

Now, Cree faces a new challenge. Its one-time paradigm-breaking technology – blue-green emission from GaN – is being implemented by dozens of rival manufacturers and penetration of LED die has reached saturation point in its most important market: that of lighting up cell phone keypads and displays.

As John Palmour, one of Cree's original founders and now its vice-president of advanced devices, explains: "If cell phone growth slowed [in the past], we were able to power through it because we had not fully penetrated the market. So even if cell phone growth was flat, we were able to increase revenues. We have now penetrated the cell phone market and are riding with [its own] fluctuations." With continued falls in average selling prices, sales increases are required just to maintain flat revenues. Cree has faced this problem for the last four quarters.

Entering a transition period, Cree needs to penetrate new markets in order to grow. When it comes to LEDs and new applications, Mark McClear, solid state lighting director, is quick to recite a three-pronged mantra when determining whether Cree's GaN-based LEDs are positioned to enter a new market. "Brightness, efficacy (the optical output for a given electrical input) and the economic value proposition must all be met," he said.

When GaN can compete with existing technologies on each of those fronts, McClear considers it a market ready for Cree to tackle. In his sights is what he characterizes as "a trillion dollar market" – white light.

If the name Cree has become synonymous with blue LEDs, then to navigate this crossroads successfully, it needs to become synonymous with white light. The markets that Cree is eyeing within this arena are the back-lighting of large LCD screens (primarily in notebook PCs) and general white-light illumination.

Before Cree could even consider attempting to sell LEDs for the large panel LCD market, it needed to at least match the performance of today's dominant back-lighting technology – cold cathode fluorescent lamps (CCFLs), which run at an efficacy of 50–60 lm/W. "There is a real expertise in designing these systems and you have to know the chips to make the design. A customer who has been using CCFL is not suddenly going to be a world expert in LEDs, so it is very natural for us to take that next integration step," McClear said.

This is exactly what Cree has done and its display now delivers 11% more lumens per watt than the CCFLs. By the end of 2006 McClear predicts that Colorwave systems will be shipping and generating revenue.

Low-hanging fruit

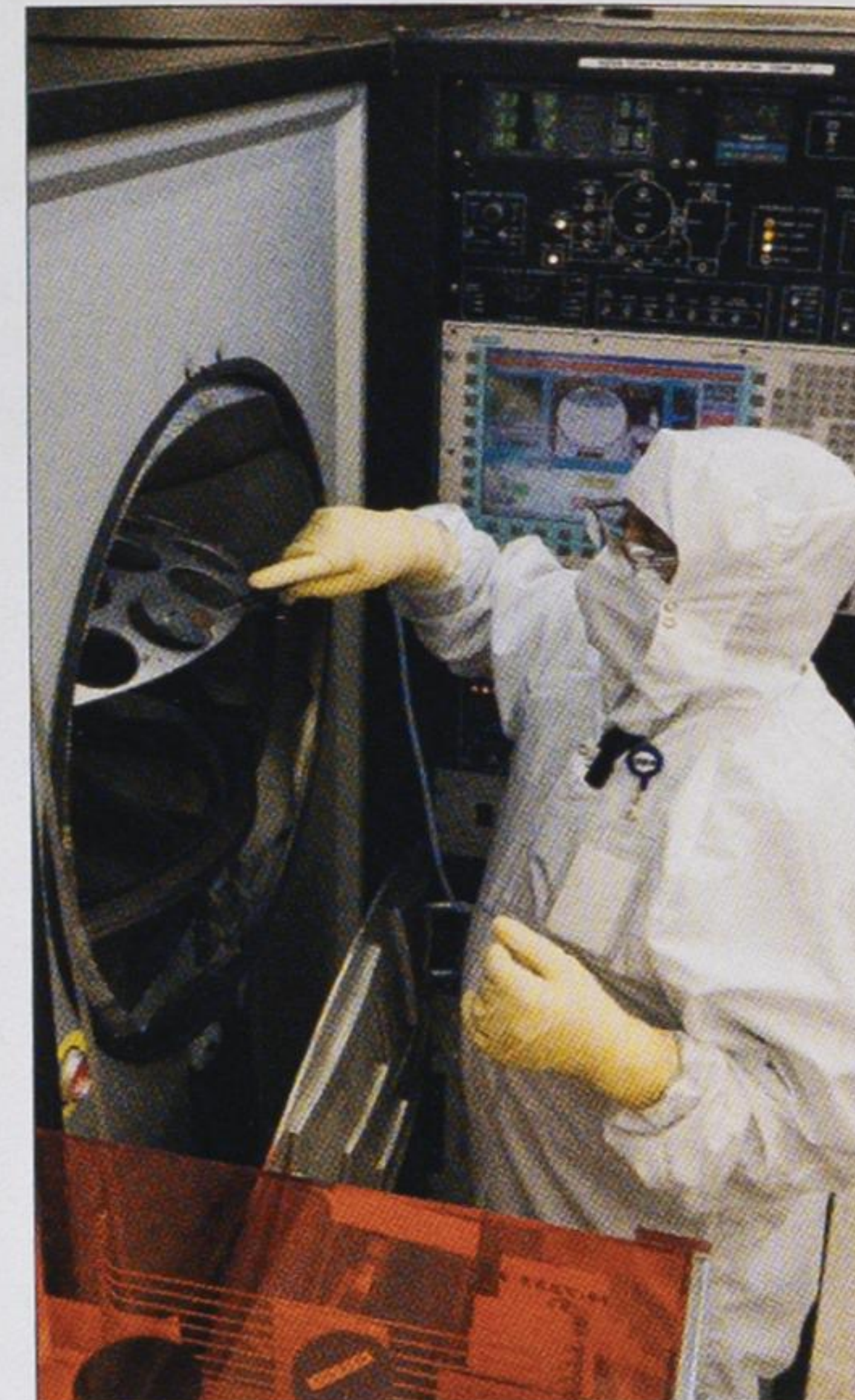
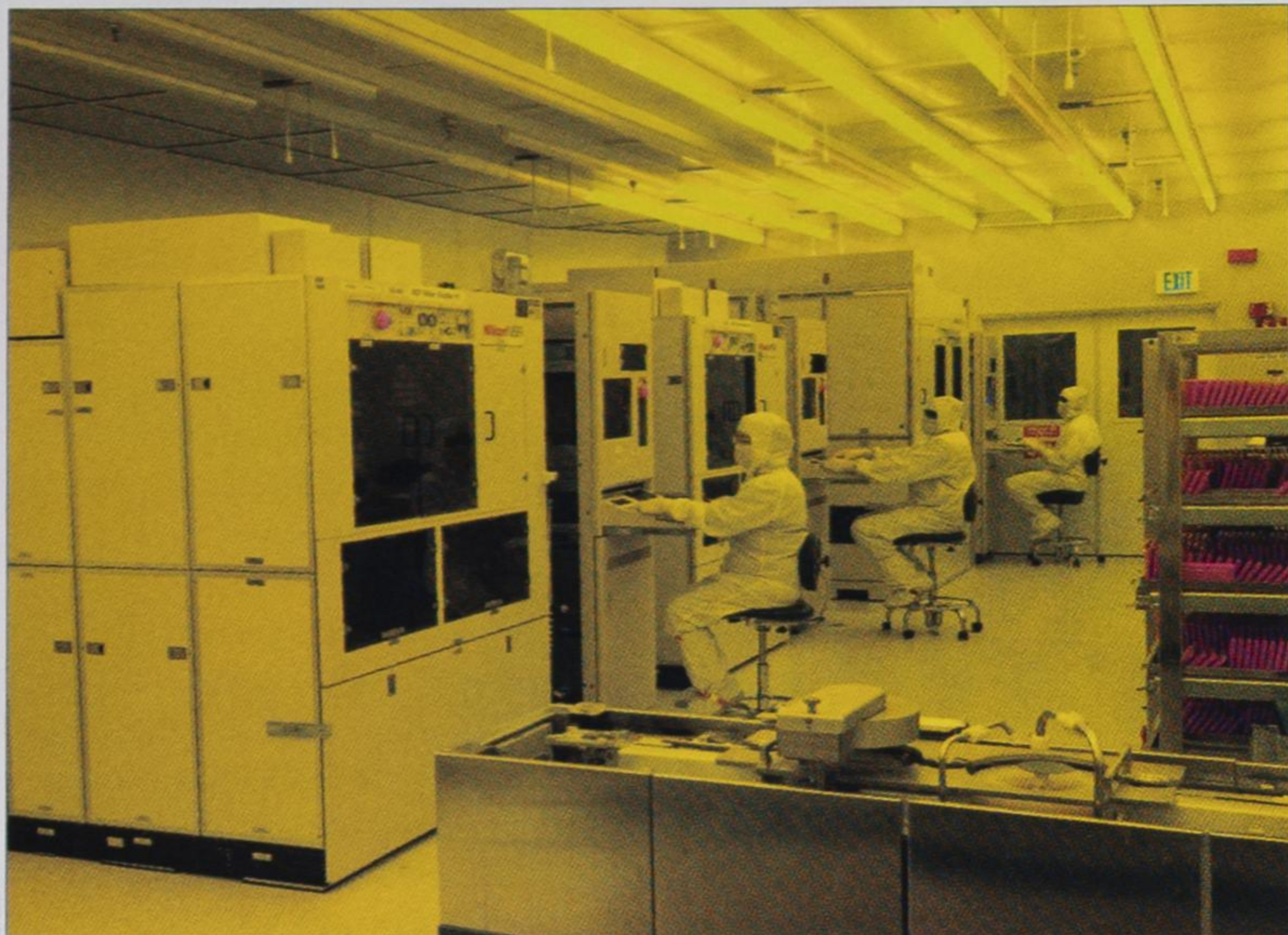
General illumination has long been dominated by two standard sources: the Edison socket filament bulb and the fluorescent bulb. Edison bulbs deliver 10–15 lm/W, while fluorescents have an efficacy in the 70–100 lm/W range. Cree's latest commercial XLamp packaged die produces 70 lm/W.

From this perspective it would appear that the Edison socket market has the potential to be penetrated by XLamps. However, because of the relatively high cost of LEDs and the amount of time it would take for customers to feel the benefit, McClear is less than enthusiastic: "I am not a big fan of the Edison socket for LED applications – there is lower-hanging fruit to be picked."

The lower-hanging fruit includes streetlights, torches and large high-intensity discharge (HID) warehouse lighting. "Torchtlights are dominated by LED bulbs and this has only happened in the last year," said McClear.

The reason that these applications can now succeed is that there can be more to the economic value of a bulb than just its upfront cost and the cost of powering it. "It costs about \$150 to buy a new streetlight and another \$150 to replace it when you send a crew out with a \$200,000 truck," McClear explained. "So if a bulb lasts only 1–2 years, you end up paying for it five times [in 10 years]. An LED lamp can have equivalent light output and costs about twice the amount from an original purchase point of view, but it lasts at least 10 years."

For municipal authorities with thousands of streetlights, this represents a significant saving and the LED advantage is much easier for a large-scale consumer to appreciate than an individual. When the additional costs



Despite the advanced material being processed there, Cree's new SiC power and RF device facility is much like any GaAs or silicon fab. It features a bay of I-line lithography steppers (left), an inspection station with scanning electron microscopes (center) and an electron beam metal-evaporation system (right).

associated with replacement of bulbs are included, streetlights, HID lights and torchlights based on LEDs start to make economic sense.

Historically, there is roughly a one-year time lag between developments in Cree's research labs and turning that breakthrough into a commercial product. Recently, the company produced laboratory LEDs with an efficacy of 131 lm/W. "If historical trends continue, next year should see a commercial XLamp device with efficacy above the 100 lm/W range," said McClear.

At that point, a potentially massive market becomes accessible – the replacement of fluorescent bulbs by white LEDs – a key element in McClear's vision of the "trillion dollar" white light market.

While many other GaN LED manufacturers will tread the path to LCD backlights and general illumination, Cree's experience in SiC technology gives it more options. Besides the obvious advantages of an internal source of substrates, SiC and GaN-on-SiC offer a wide range of electronic applications and moving these devices into the commercial market is another key aspect of Cree's current transition.

Nowhere is this more apparent than in the recent opening of its new facility in Raleigh's Research Triangle Park. The 275,000 sq ft fab and its 150 employees are solely devoted to the design, manufacture and test of SiC and GaN-based electronics, while the site also houses Cree's SiC MMIC foundry line. Currently running 3 inch SiC substrates, it is already configured to make the anticipated jump to 4 inch material, a critical yield consideration when fabricating large MMIC die.

Despite the rather unique materials it processes, this fab looks like, and is run as, a fairly conventional GaAs or silicon facility, with bays of I-line steppers for photolithography, dielectric and metal deposition, dry etching and inspection equipment. The only portion of the process remaining in the older Cree facilities is that of SiC boule growth, and SiC and GaN epitaxy using equipment that serves double-duty for LED production.

The other important link between Cree's LED and electronic offerings is the increased energy-efficiency that both types of device deliver. SiC Schottky power

diodes are a prime example of improvement in device performance reaching a critical threshold that has enabled commercial penetration.

Cree Schottky diodes operating at reverse voltages of 300, 600 and 1200 V, and a variety of currents, are now available. What has made these diodes a commercial reality is not so much the fact that the wide bandgap of SiC can withstand such large reverse biases, but the reduction in micropipe densities that are fatal to SiC Schottky diodes. Under reverse bias, breakdown will take place along the length of these voids, which run through the wafer. Micropipes have now been sufficiently reduced that the large-area Schottky diodes can be manufactured with a high yield.

These devices can be inserted into many systems that currently use silicon PIN diodes. Unlike a PIN, a unipolar Schottky diode does not require charge to be stored or dissipated before it can switch on or off. This property makes it a faster switching device, in turn improving system efficiency. "When you take a switched mode power supply that is [already] 85% efficient and improve that 3–4% by switching out the silicon PINs with SiC Schottkys then your total losses actually go down by 33%," explained Palmour.

This improvement also means that a system using SiC Schottkys dissipates less heat, which allows for a more compact system footprint. The higher efficiency and faster switching of SiC Schottkys is already driving their penetration of the silicon PIN market for motor-control and electrical inverter applications.

Add to that the potential for both SiC and GaN in high-power, high-efficiency base station amplifiers for wireless communications and Cree appears to be well on its way to making its transition from a "simple" blue LED die manufacturer. The end result of that change should be a much broader solution-oriented company that is focused on producing a range of energy-efficient components. "We are moving into LED backlighting, general illumination, and SiC and GaN devices for power and wireless applications," summarized McClear. "Any one of those market segments would make a great business, but we have all four."

About the author

Bob Metzger is a freelance science journalist based in Chapel Hill, NC. E-mail ram@rametzger.com.

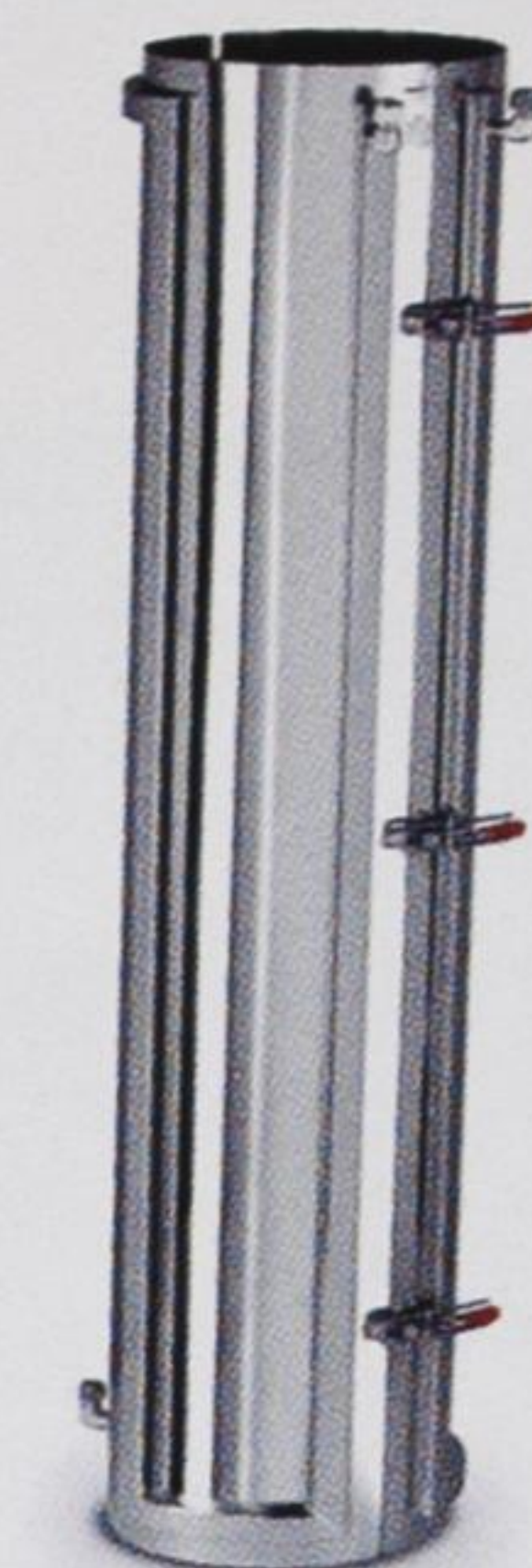
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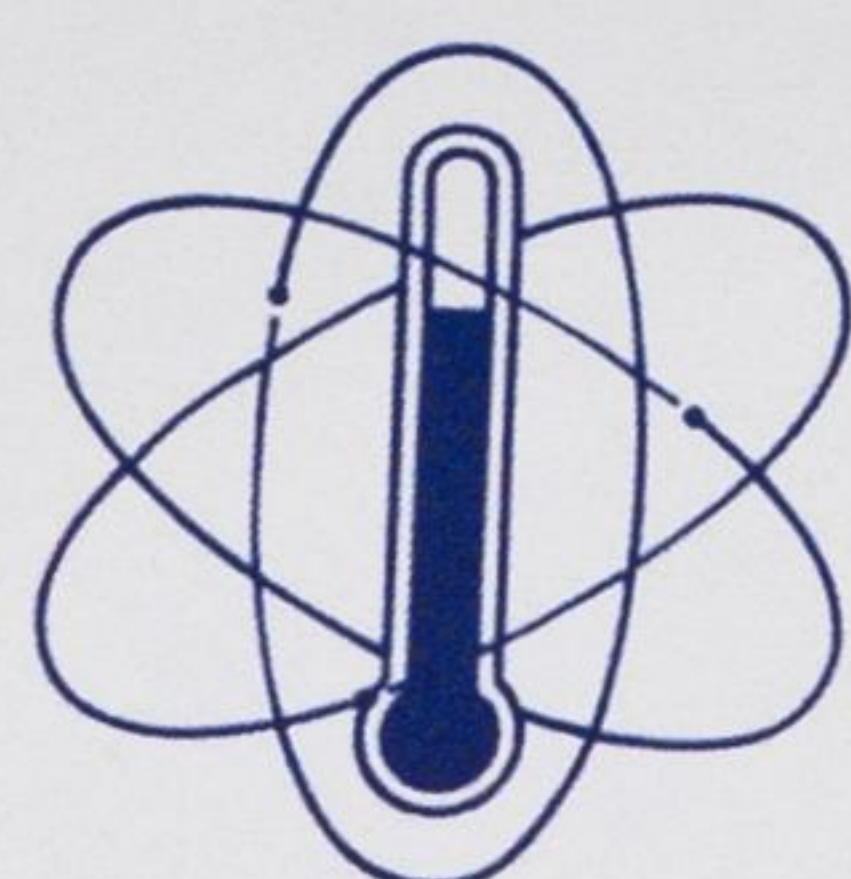


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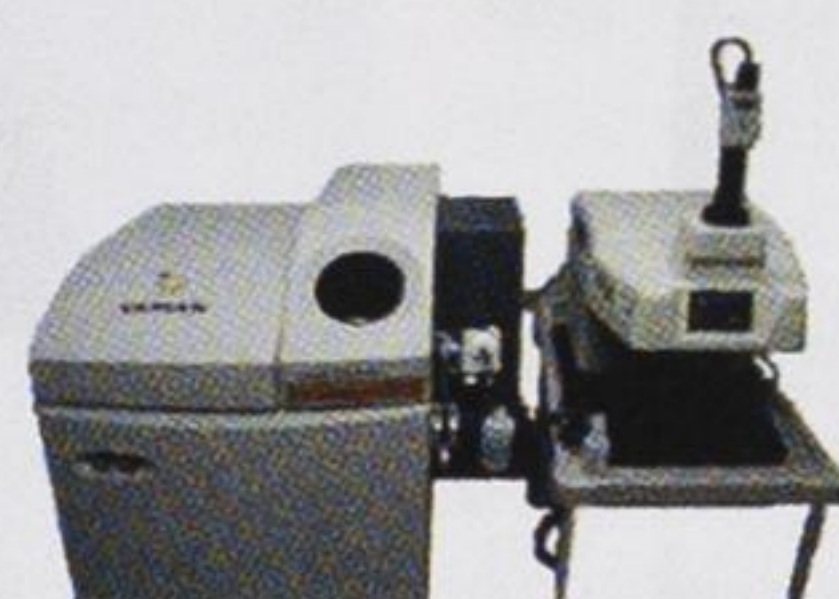
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Imprinting technique offers low

Rob Hershey from the Texan company Molecular Imprints explains how a simple and low-cost whole-wafer imprinting technique can increase the extraction efficiency of LED chips.

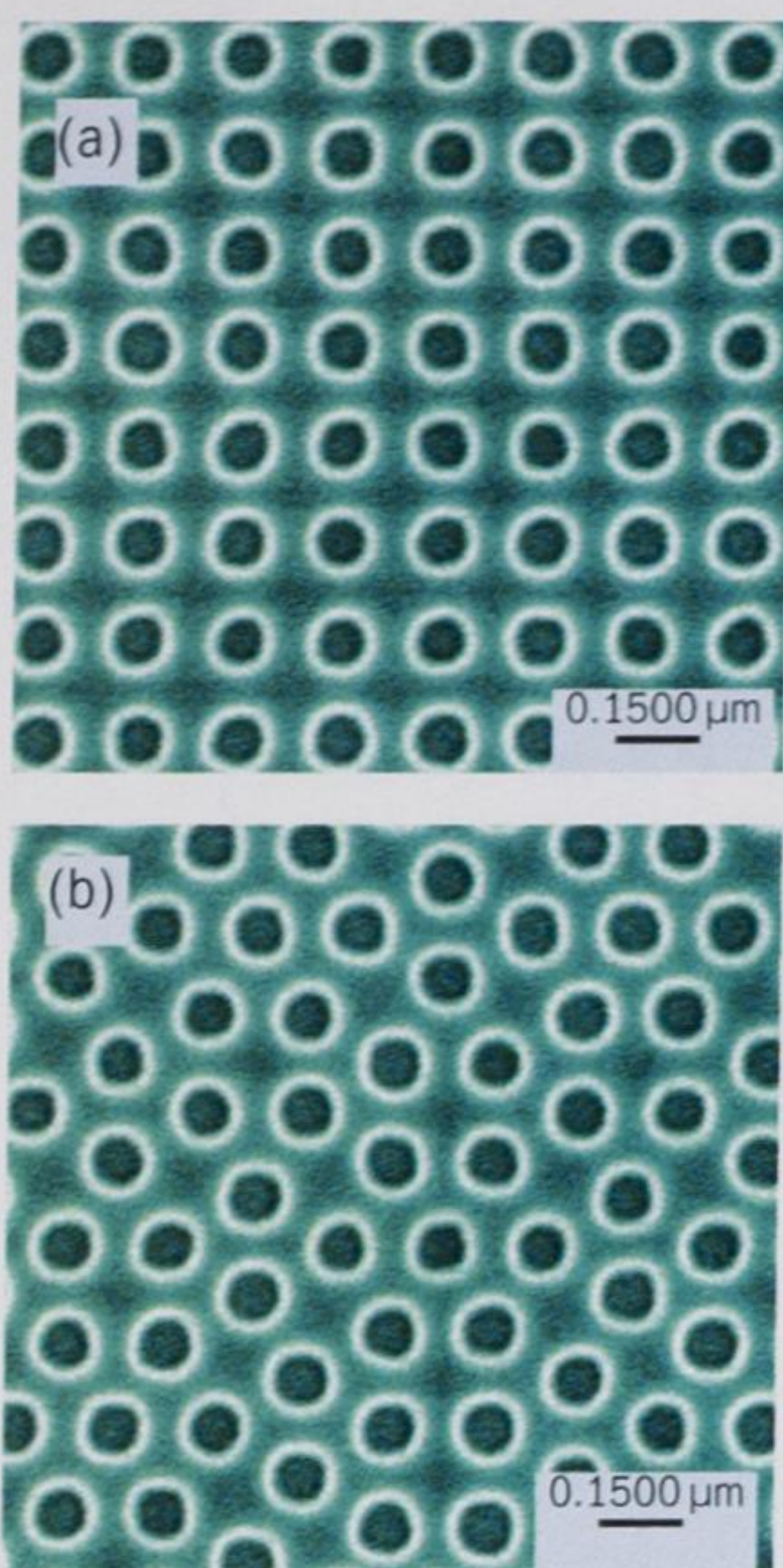


Fig. 1. Electron-beam lithography can produce photonic crystals (a) and photonic quasi-crystals (b) that are able to boost LED extraction efficiency, but the technique is slow and expensive.

LED makers are always striving to cut the cost-per-lumen of their devices so that these chips can penetrate new markets like solid-state lighting. It's a goal that has led manufacturers to employ rougher surfaces, or to incorporate mirrors within the device, to boost extraction efficiency. However, greater gains can be made by using photonic crystals that can block light propagation in unwanted directions and redirect it to where it is needed.

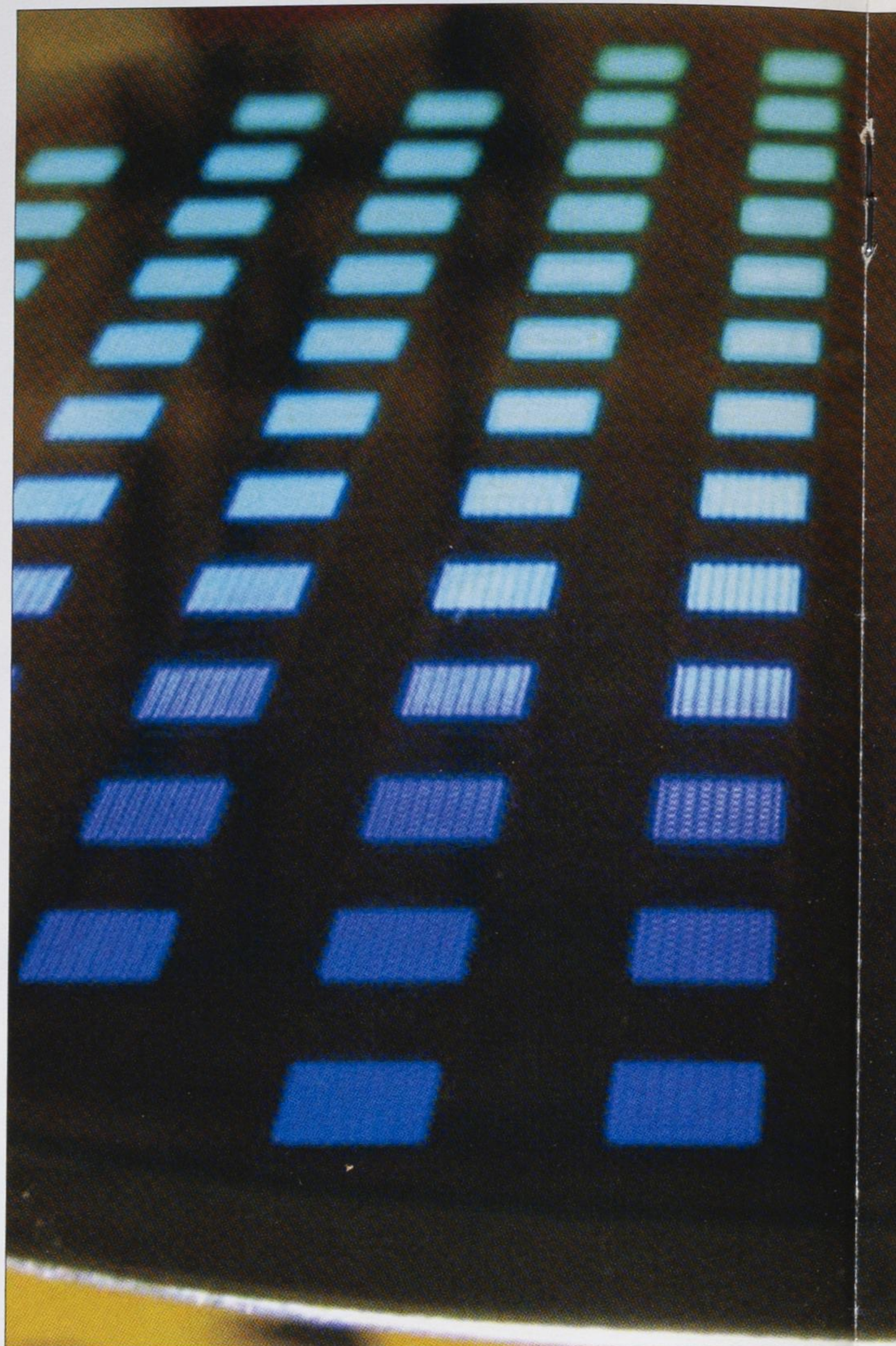
The effectiveness of these photonic structures increases with the depth of these features, their density and their proximity to the active region of the device that generates the emission (see box "LED designs for high extraction efficiencies"). The performance can be modeled using supercomputers by companies like Mesophotonics, a spin-off of Southampton University, UK, which can even design quasi-crystal structures that are able to emit beams, cones and rectangles with specific angular directions. Yet today's LED makers use expensive package-level components such as index-matching sol-gels and beam-directing optics to construct their devices because the manufacturing methods associated with patterning and etching periodic structures are too slow and expensive.

Patterning options

Patterned photonic crystals and other 2D periodic light extraction features have been produced by several university groups using "deep ultraviolet" interference lithography. However, this low-cost technique is ill-suited to manufacturing because it requires a controlled environment to produce stable nanometer-scale fringe patterns. The range of patterns that can be produced with interference methods is also limited to simple periodic multibeam interference patterns and precludes the fabrication of photonic quasi-crystals.

Consequently, many commercial researchers and universities prefer to use electron-beam (E-beam) lithography to create photonic crystal structures. This approach is used by semiconductor manufacturers to generate the fine features on leading-edge photomasks and semiconductor wafers. However, even commercial grade E-beam pattern generators can only process up to three 2 inch wafers per day and with a price tag of more than \$5 million they have been restricted to proof-of-concept demonstrations.

Fortunately, these E-beam resources are not wasted because they can be used to produce a pattern on a master template that can be replicated on several wafers



Molecular Imprints has developed a high-throughput imprint process for producing p

using nano-imprint lithography (NIL). The NIL technique is already proven in commercial niche applications such as specialized optical element production, which has higher margins and lower costs than commercial LED manufacturing. In the commodity-driven LED market, high-resolution NIL needs to deliver incremental costs of less than \$20 per wafer ($\sim \$0.01/\text{mm}^2$), inclusive of incremental support equipment costs that may be required to implement the process.

At Molecular Imprints, a nano-imprint company based in Austin, TX, we have developed a new high-throughput imprint approach that meets the cost requirements for LED processing. A typical process will involve coating the epiwafer with an imprint material and then pressing a template or stamp with the

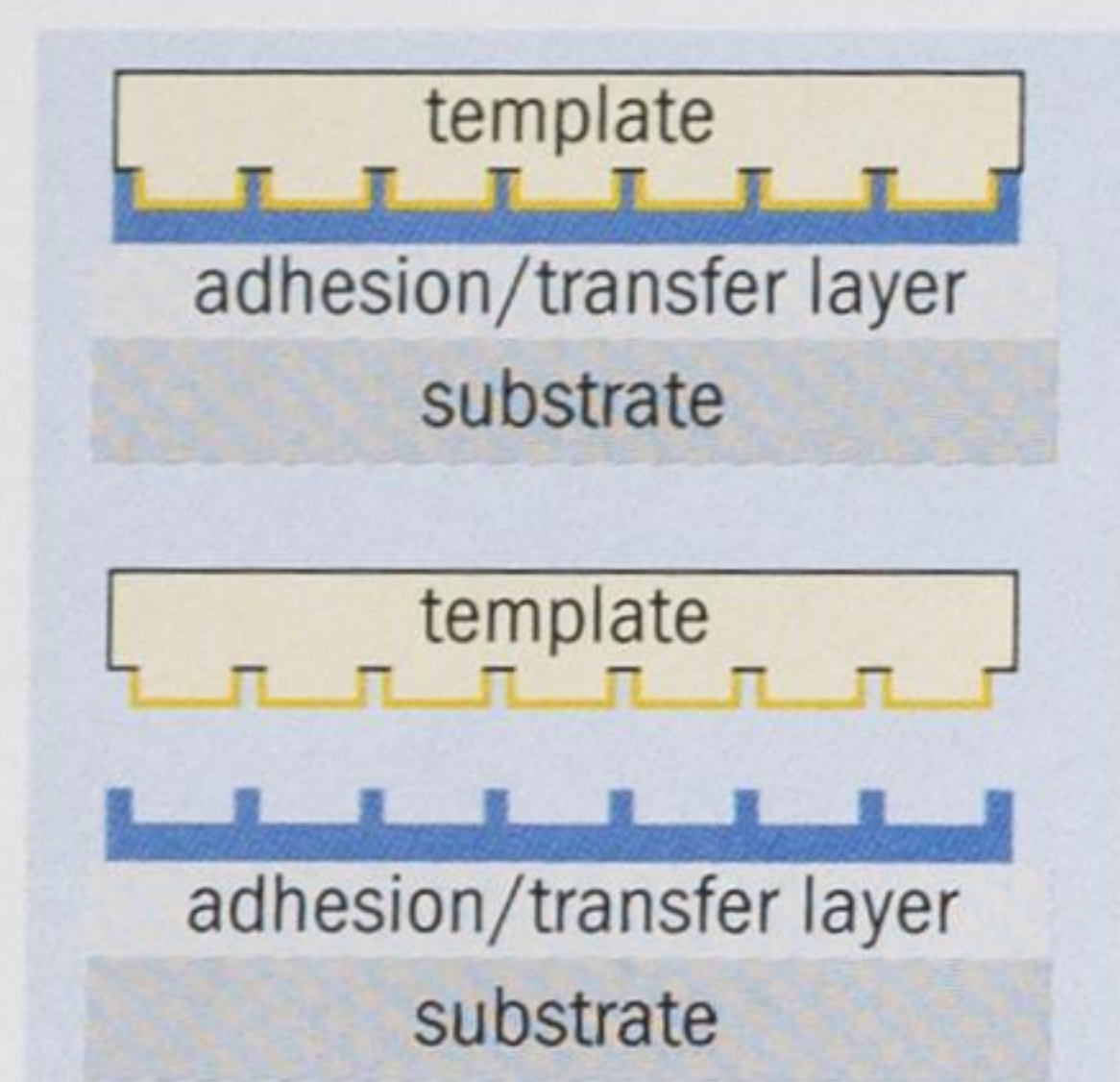
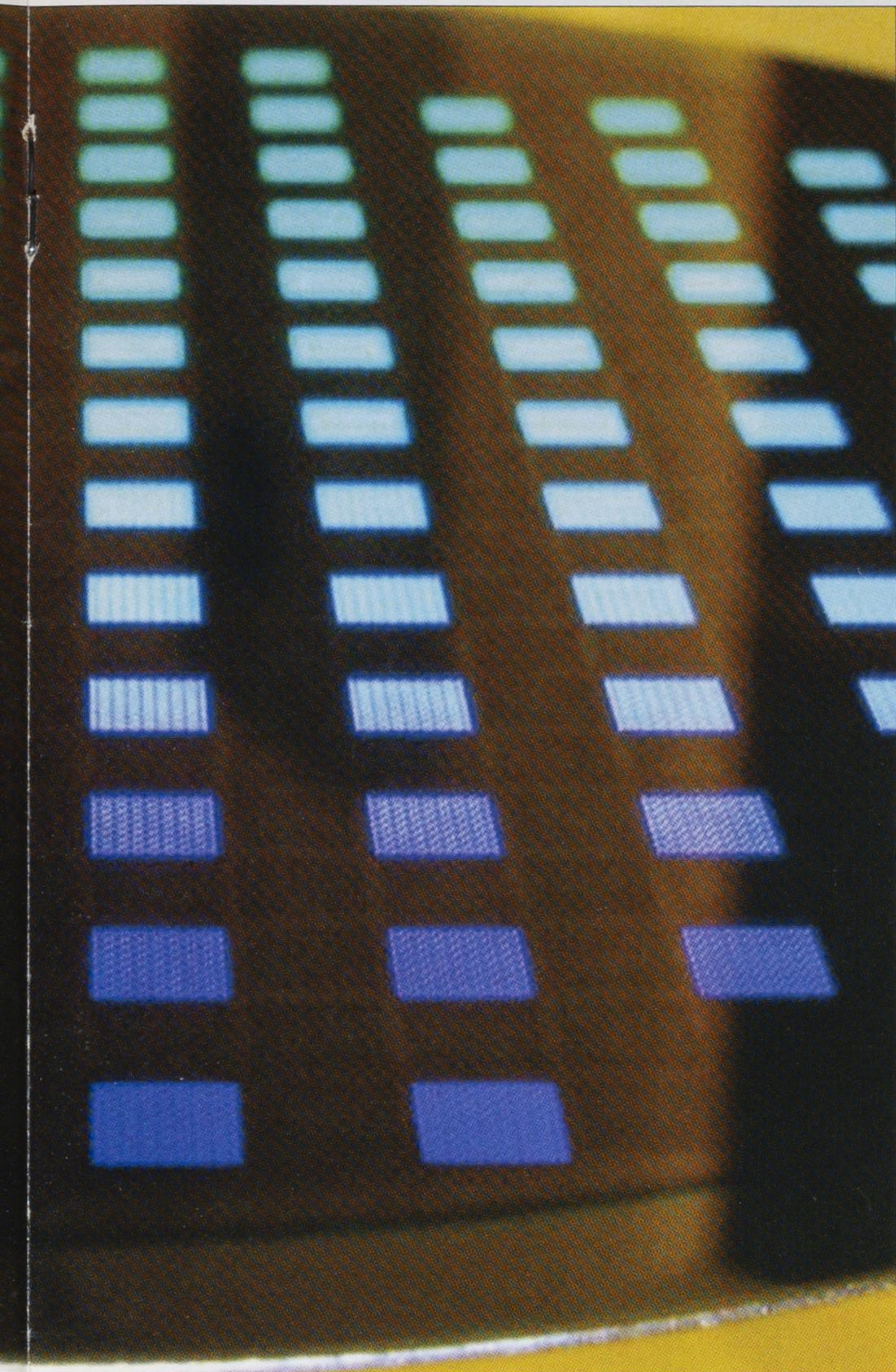


Fig. 2. The nano-imprint lithography process transfers the relief image on a stamp or template onto an epiwafer. The imprinted material is cured while in contact with the template.

Low-cost photonic crystal LEDs



ducing photonic crystal LEDs that is compatible with high-volume manufacturing.

master pattern into this coating (figure 2). Heating and high pressures are applied to high-viscosity imprint layers, but capillary forces are sufficient for low-viscosity films. Cooling or exposure to ultraviolet radiation solidifies the imprinted film before the template is removed to form an imprinted epiwafer.

Our approach uses a two-step template manufacturing process to deliver high throughput at a low cost. The master stamp is created using commercial semiconductor mask processing technology and is imprint-replicated to form a thin whole-wafer template that can imprint an entire LED wafer in a single step. With this approach the E-beam written master can be kept to a typical minimum size of 5×5 mm and replicated 100, 200 or 350 times to fully populate a thin whole wafer

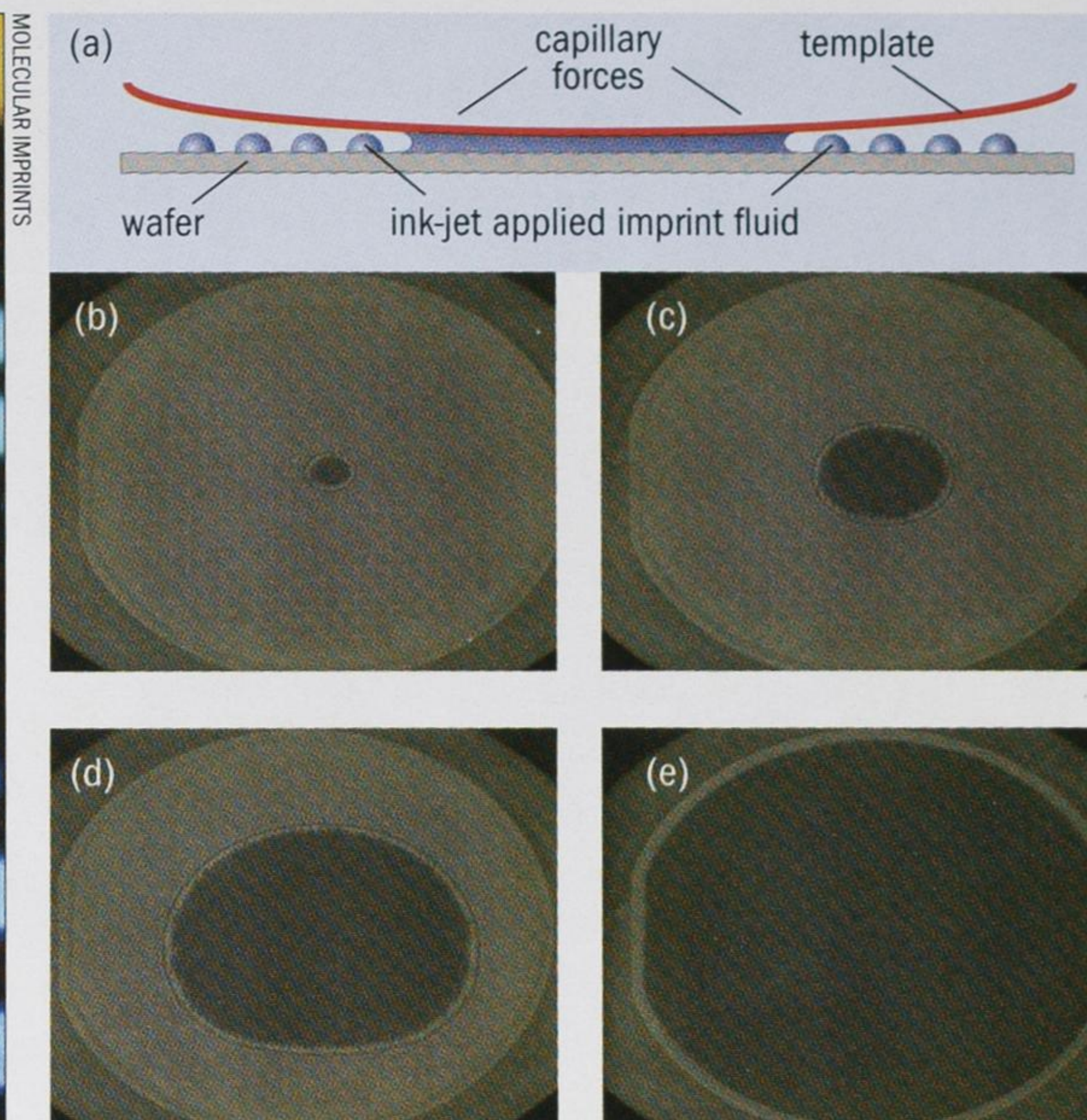


Fig. 3. Molecular Imprints' whole-wafer imprint lithography process uses a thin, flexible template, a low-viscosity imprint fluid and capillary forces to establish conformal contact (a). Commercial inkjet technology dispenses an array of tiny droplets on the surface of the wafer that are separated by $200 \mu\text{m}$. When the template is relaxed the imprint fluid spreads over the wafer, as shown in the series of images taken after 3 s (b), 5 s (c), 9 s (d) and 15 s (e).

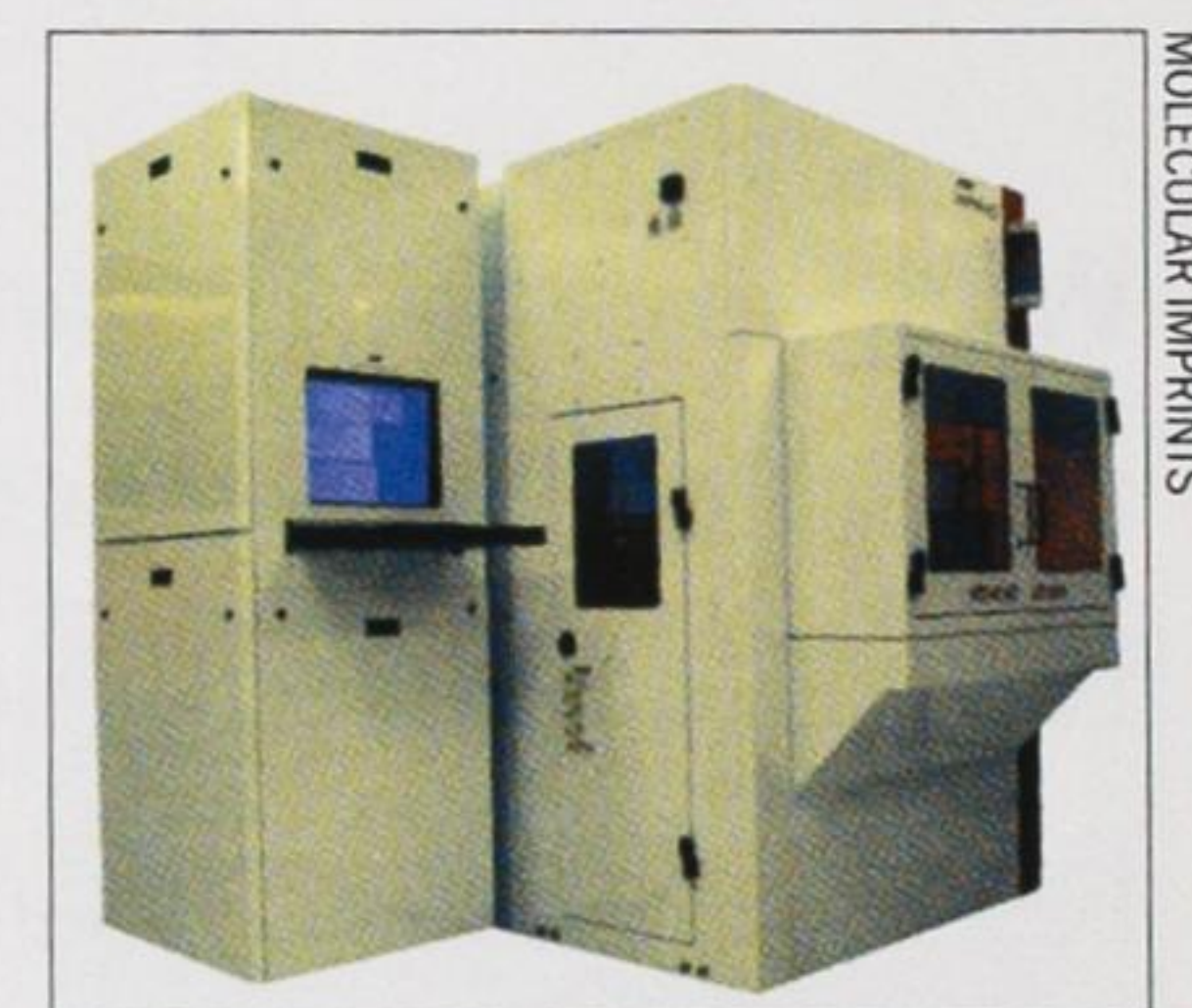
replicate template for 2, 3 or 4 inch material, respectively. The master template can produce hundreds of thin quartz replicas that can each imprint thousands of wafers before they require recycling, making it possible to imprint millions of wafers from a single master.

We have developed a tool that has the capacity to fill the features of the template while simultaneously producing a uniform thin residual layer and can process 2, 3 and 4 inch LED wafers with an undulating topography of more than $10 \mu\text{m}$ in under 3 min. The thin template is bowed and brought into contact with a low-viscosity imprint fluid, which is dispensed in seconds directly onto the wafer using a commercial inkjet technology (figure 3). The template is then relaxed, which allows capillary forces to pull the template into conformal contact with the surface and expel all of the air from the wafer.

Manufacturing considerations

The key to any lithographic process is the robustness of the pattern transfer process to the underlying material. To produce effective photonic crystals, this pattern needs to be etched to a depth of several hundred nanometers into the LED's upper region of GaN or GaP. Today's LED manufacturers commonly use a SiO_2 hard mask and a reactive ion inductively coupled plasma etch, which can produce etch depths of 250 nm from SiO_2 hard masks just 50 nm thick. We have used this process in conjunction with our imprinting technique to etch photonic structures into GaN epiwafers with a 150 nm thick SiO_2 mask (figure 4).

Processes that are successful in high-volume manu-



Molecular Imprints' Imprio 1100 "step and flash" imprint lithography system will deliver a throughput of more than twenty 2 inch or 3 inch wafers per hour and is able to reproduce features with dimensions of less than 50 nm on clean substrates. Production shipments will begin in early 2007.

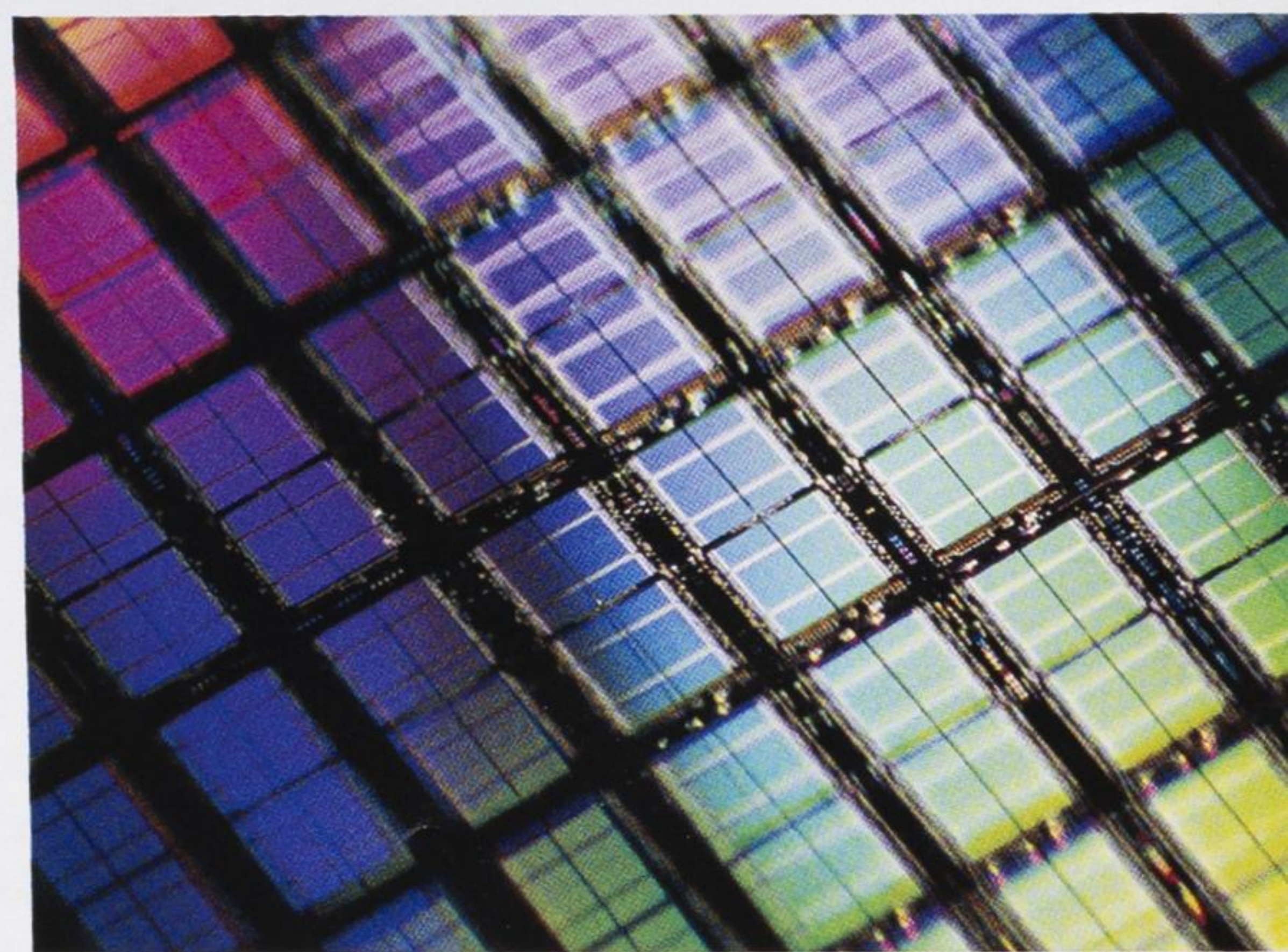


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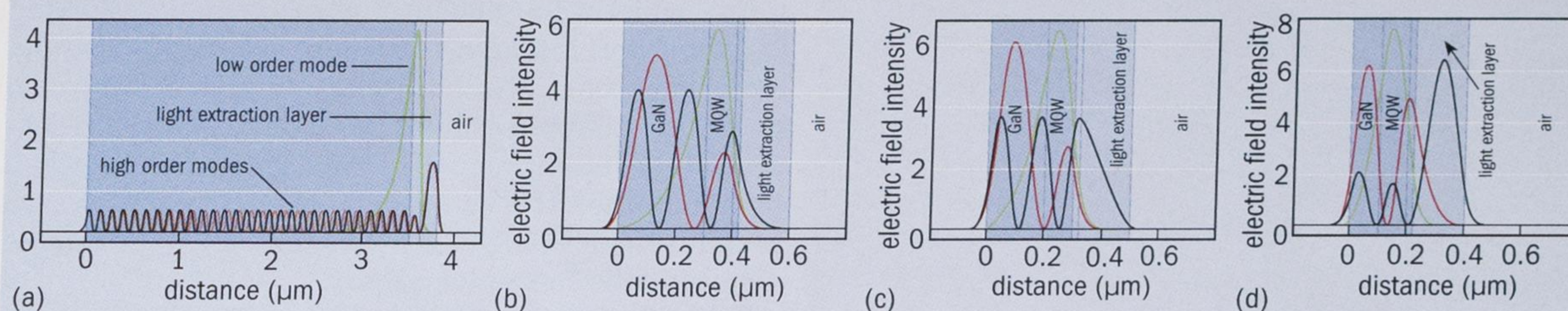
LED designs for high extraction efficiencies

Geometrical optics is often used to model the light trapped within an LED. This method, which treats photons as rays of light bouncing around inside a device, accurately predicts the optical characteristics of thick LEDs but cannot model the behavior of their thinner cousins, which are nanometer-sized and strongly affected by the wave nature of light.

Recently, researchers have been using more complex modeling methods for calculating the behavior of light within an LED. Such methods can be used to accurately calculate the light intensity distribution in a 4 μm thick GaN heterostructure emitting at 400 nm (a). The higher order modes in the device, which correspond to light travelling out of the plane of the epilayers, have intensity peaks near the LED's surface that is next to the light extraction layer. The low order modes that correspond to light propagating parallel to the film's plane have little

light intensity in the extraction layer and will be unaffected by any light extraction feature, even if it is very efficient.

Properly manufactured photonic crystals are excellent light extraction features and can intercept all of the optical energy that attempts to propagate within the crystal and redirect it into higher-order radiating modes. However, if these devices are to be effective the LED's structure must confine the light that is propagating in the lower order modes close to the light extraction feature. Such heterostructures have been proposed in the patent literature by Luminus Devices (US006831302b2). These designs contain 2D periodic surface texturing and thin heterostructures, which combine to force the light in the device to interact with the extraction layer. The benefits of thinner LEDs are shown in figures (b), (c) and (d), which shows the increase in light extraction produced by thinning the device from 600 to 400 nm.



The low-order modes in the 4 μm thick GaN heterostructure are trapped within the device and only high-order modes can be easily extracted (a). As the heterostructure is thinned – (b), (c) and (d) – three lowest order modes are forced into the light extraction layer, which boosts the structure's output. (Plots are courtesy of University of Twente online mode calculator, which can be accessed at wwwhome.math.utwente.nl/~hammerm/oms.html.)

facturing are reliable, repeatable and cost effective. If there is an Achilles' heel to imprint technology, it is the need for a clean, flat surface on which to imprint. Unfortunately, many LED manufacturing facilities fall short of this requirement as they have class 10,000 or class 1000 cleanrooms that provide ample opportunity for particles to fall onto the wafers prior to imprinting. At relatively low imprint pressures sharper particles can damage the template and shorten its lifetime. Large particles can also cause problems, as they can prevent the template from conforming to the substrate surface, which leads to unpatterned areas on the epiwafer.

The surface protrusions on the imprint layer are often caused by particles falling on the wafers before or during the epitaxy or hard mask deposition (or during the GaN etchback process if laser lift-off is used). However, the density of these defects can be reduced to acceptable levels for most types of imprint lithography, which use reusable templates such as SiO_2 , by using class 100 clean room conditions. This level of cleanliness is achievable by using low-cost "mini-environments" in selected areas of existing cleanrooms and must be implemented in conjunction with regular preventive maintenance and cleaning of process chambers, which has been shown by the silicon industry to efficiently eliminate particles in deposition tools. Improving the cleanliness of these processes also benefits the overall yield.

Our imprint tool development shows that nano-scale

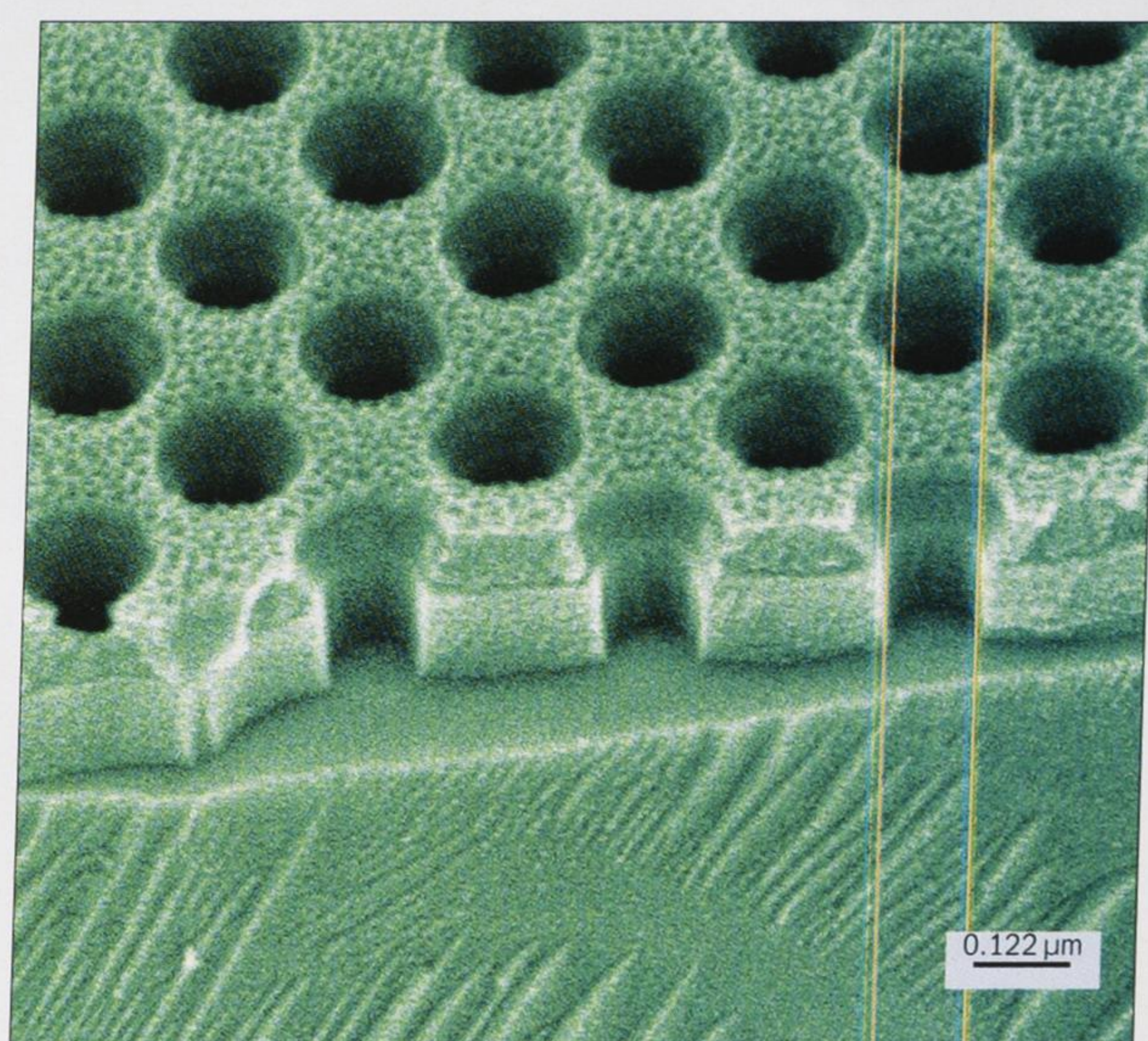
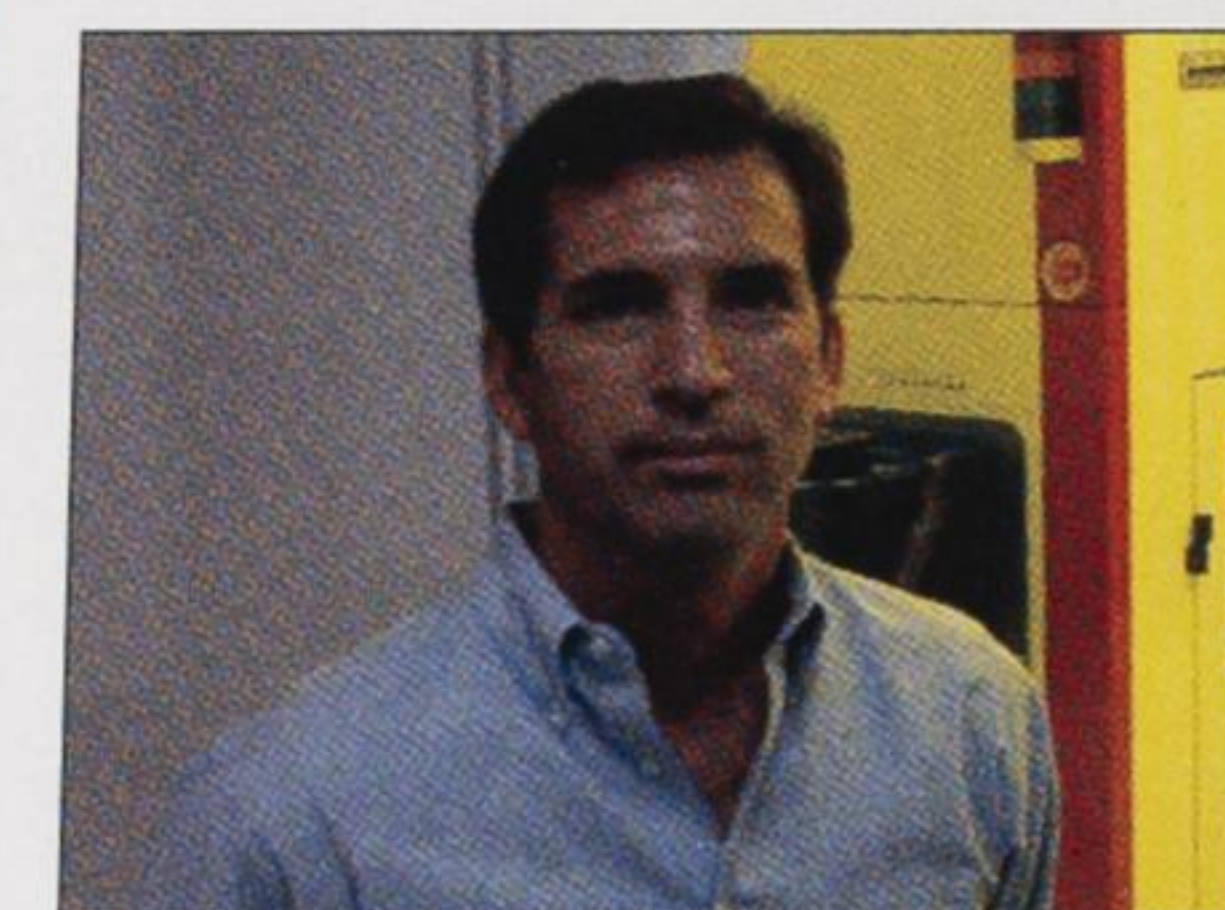


Fig. 4. This GaN epiwafer has been prepared for etching to form a photonic crystal LED. The scanning electron microscopy image clearly shows the 120 nm of remaining imprint resist (top layer), the 150 nm layer of etched SiO_2 and the GaN active layer (bottom).

light extraction features can be manufactured on LED wafers at a low cost. These machines are able to process at least 20 wafers per hour at an incremental cost of less than \$20 per wafer and will empower chip makers to produce LEDs with photonic crystals or other nano-extraction features within the next 12–18 months. ●

“It is possible to imprint millions of wafers from a single master.”



About the author

Rob Hershey is a product manager at Molecular Imprints Inc. He is responsible for the LED and photonic applications of the company's lithography technology.

OPTOELECTRONICS

Surge in demand for super-size TVs

Jon Cartwright talks to three US chip makers who are battling it out to provide the best light source for large screen rear-projection televisions.



With its photonic lattice LED technology already appearing in rear-projection TVs such as this 56 inch monster from Samsung, Luminus Devices has stolen a march on its laser-touting rivals.

Gone are the days of the humble 14 inch portable television. Lounges all over the globe are being pervaded by high-definition, super-sized displays. According to a recent report by market researcher DisplaySearch, the average display area for one technology prevalent in the large screen rear-projection television (RPTV) market – LCDs – has grown by more than a third in the past year, with 32 inch displays rated as the current top-grosser.

This surge in demand for larger screens is not going to stop any time soon. Already we are seeing 50 inch displays as the most coveted product behind electrical retailers' windows and by the end of this decade those could well be replaced by 60 inch displays or larger. But there is an obstacle in the path of ever-increasing RPTV screen size: the light source. RPTVs have to work on a different principle to smaller, flat-panel displays typified by computer monitors and the like. Instead of using an LCD the same size as the screen to constitute the display, RPTVs project light through a miniature version of the image – a microdisplay – and then optically magnify it to a screen many times the microdisplay's size. In the past the light has been provided by ultrahigh-pressure (UHP) lamps, but these will be too dim to illuminate the next generation of TVs.

Thankfully, consumer electronics companies have a few new solid-state technologies to choose from. One of these is LEDs, whose small size has enabled them to

be used extensively in mobile phone backlighting. While they have enjoyed some success in mid-sized displays, a step-up into the world of large RPTVs has become possible by an innovation that uses photonic lattices to enhance the light output. The other option is lasers. These are less of a direct replacement for UHP lamps, and until recently have suffered from cost and power issues, but in spite of these hindrances two companies are foretelling them as the future of light sourcing.

PhlatLight LEDs

In 2002, a young Alexei Erchak collected his doctorate from the Massachusetts Institute of Technology having had the clever idea of using photonic lattices to extract more light from LEDs. Four years on and his established company, Luminus Devices in Woburn, MA, has successfully demonstrated the PhlatLight technology as a light source for RPTVs. Models featuring the chips, such as Samsung's 56 inch RPTV, are already beginning to appear on the consumer market.

The effectiveness of PhlatLight LEDs all hinges on the bandgap of the photonic crystal that is fabricated into the top cladding layer of the standard epitaxy material (AlInGaP for red LEDs, and GaN for green and blue). This photonic bandgap is analogous to the electronic bandgap in a semiconductor, but rather than restricting the conduction of electrons based on their energy, it is the propagation of photons that is restricted. The bandgap is tuned to include the emission wavelength of the semiconductor, without coupling to the guided modes – a major source of loss. In this way, the LEDs are free to radiate more light.

"In a PhlatLight LED the light is emitted from the surface of the chip, [whereas] in standard LEDs the light is emitted from the edge," explained John Langevin, the VP of marketing and business development at Luminus. "Surface emission allows Luminus to scale the chips without losing light and efficiency."

Available light is just one of the benefits of PhlatLight LEDs and other solid-state devices. Environmentally, they are preferable to mercury containing discharge lamps, they can be turned on and off rapidly, and they have a large color gamut (in other words, they have a wide color spectrum). But one of the biggest advantages is lifetime: UHP lamps fail roughly every 8000 h and at \$300 (€240) for a new lamp, in addition to the inconvenience of calling out a qualified technician, replacement several times in a TV's 30,000 h life expectancy is an undesirable prospect. LEDs, on the other hand, can be expected to last 20,000 h, so may only need to be replaced once, if at all.

However, refining the PhlatLight technology has not been easy. "The most challenging obstacle for Luminus has been the ability to mass produce devices efficiently," said Langevin. With 10 different manufacturers having demonstrated PhlatLight in RPTVs at the Consumer Electronics Show in Las Vegas in January this year, we



Novalux hopes to have its extended-cavity lasers in consumer displays by the end of 2007, but will face competition from Principia Lightworks, which has developed a novel take on VCSEL technology in collaboration with Bandwidth Semiconductor.

can expect to see a lot more from Luminus.

LEDs may be the first solid-state technology to be used in RPTVs, but Don Klein, VP of business development at Principia Lightworks in Woodland Hills, CA, considers lasers to be the light source of the future. "The reason LEDs have got any traction is because of the industry's need to replace UHP lamps, and the cost and power efficiency obstacles to a broad adoption of laser light sourcing. Principia's eVCSEL [electron-beam-pumped-vertical-cavity surface-emitting lasers] overcomes those obstacles."

eVCSELs

VCSELs are preferable over their edge-emitting counterparts because they can be grown and tested on a single wafer, reducing manufacturing costs. Principia's eVCSELs further exploit the same benefit by using a cathode ray tube (CRT) to stimulate lasing, instead of applying a direct current. Wafers are provided by Bandwidth Semiconductor, a subsidiary of Spire, with InGaP/AlGaInP used for red lasers, ZnCdSe/ZnSSe for green and ZnSe/ZnSSe for blue.

"CRTs and their related electronics are a mature, readily available and inexpensive technology," said Klein. "There is no functional difference between an eVCSEL and a traditional VCSEL. However, eVCSELs are simpler in construction because p-n junctions are not required, as electrons are injected into the laser cavity by the CRT's scanning electron beam."

For many, the CRT will conjure unwelcome recollections of cumbersome, dusty boxes that should be consigned to the scrapheap. Unlike those of yesteryear, however, Principia's CRTs can fit into a similar width of housing as the thinner RPTVs currently on the market. They also bring a large degree of flexibility in coupling to the microdisplay and produce a better picture quality, as the ability to let the screen go completely black through modulation of the beam gives a contrast ratio of more than 10,000 to 1.

"Lasers have been the 'holy grail' of light sources for projection displays for many years," said Klein. "In general they offer the widest colour gamut – substantially

greater than phosphors or LEDs."

The earliest that customers can expect to see laser-based RPTVs is late 2007. But the head start that LEDs have does not worry Klein: "Cost is our trump card. The eVCSEL offers these performance enhancements with minimal increases in costs to consumers."

Necsel

Principia is not the only manufacturer vying for the laser RPTV limelight. Just down the road in Sunnyvale, Novalux has got big ideas for its Necsel, or extended-cavity surface-emitting laser, which can achieve high power output without the need for a CRT.

This, said Novalux's VP of marketing Greg Niven, is why Necsel will prosper: "Principia is very specifically targeting RPTV – Necsel is a platform technology. It could potentially be used in many other applications that currently use lasers, such as in medical equipment."

Necsel are singlemode external-cavity lasers, which use GaInAs quantum wells in the gain region. Novalux produces the colors required by efficient frequency doubling. In principle this is a restrictive technique, but one that proves perfectly satisfactory for the red, green and blue light that a microdisplay necessitates. Nevertheless, they do maintain the characteristics that make lasers a tempting alternative to UHP lamps and LEDs: a 30,000 h lifetime (as long as the TV itself) and a color gamut that is more than double the requirements of the US standardizing body, the NTSC.

The trick up Novalux's sleeve, however, is the variety of devices aside from RPTVs that its Necsel projectors could be built into. The compactness through lack of a CRT, and the ability to scale to any required power, means that the projectors could find their way into, for instance, mobile phones in the form of "pico-projectors".

"In the short term the company is 100% focused on projection, which includes both RPTVs and mobile projection," explained Niven. "The latter could be either a 200 lm projector the size of a mobile phone, or a 20 lm projector actually embedded inside a phone."

Head to head

With three not-too-dissimilar technologies all competing for the largest share of the high-end RPTV market, it is hard to see who will eventually come out on top. Novalux's Necsel is set to be inside RPTVs by the 2007 holiday season to coincide with Principia's eVCSELs. Although Principia will have an initial price advantage by cashing in on the ubiquitous grounding of CRT technology, the mobile projection applications that Novalux are offering could prove to be a crucial venture. On the other hand, Luminus's PhlatLight LEDs will already have a year's worth of production before laser RPTVs hit the shelves. Only time will tell.

"Lasers offer the widest color gamut – substantially greater than phosphors or LEDs."

Don Klein

Principia Lightworks

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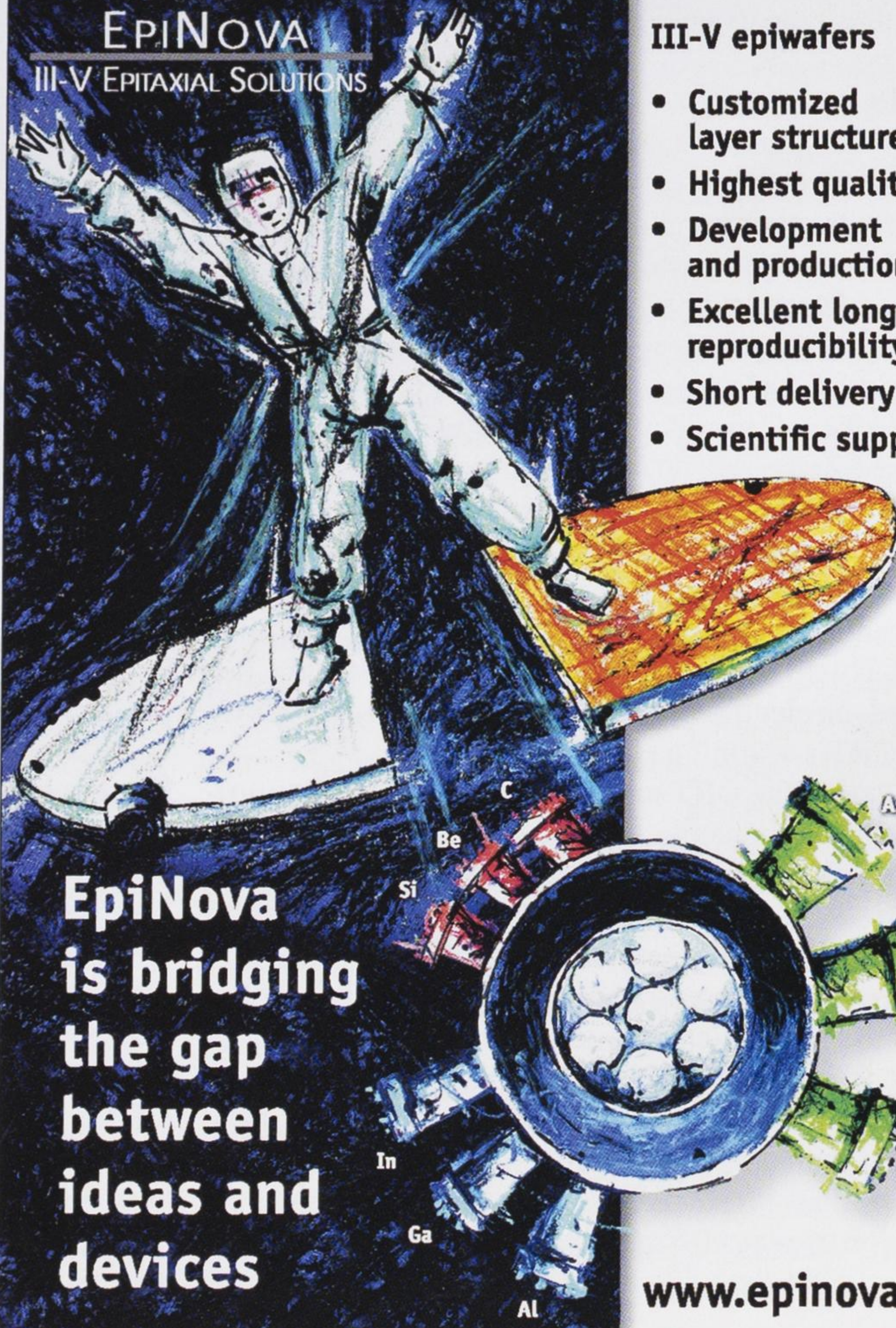
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HVPE magnifies perfect crystals

TopGaN's pressure-grown GaN platelet and needle crystals have record-breaking low defect densities, but are limited in size. However, they can be extended by a high growth rate hydride vapor phase epitaxy process that does not compromise on quality, says the company's vice-president **Izabella Grzegory**.

Ideally, GaN devices would be grown on native substrates. However, the large, high-quality crystals that are needed to form them cannot be synthesized by the stoichiometric methods used to produce GaP and GaAs crystal growth because to melt GaN requires extreme conditions of 2225 °C and 6 GPa. So instead devices are usually fabricated on foreign substrates, such as sapphire, which have different lattice constants and thermal conductivities. The differences ultimately limit device performance because they lead to high defect densities in the epilayers – even when advanced techniques such as epitaxial layer overgrowth or low temperature buffer growth are employed.

The desire for low defect density material has prompted the recent launch of free-standing 2 inch GaN wafers by several companies, including Technologies and Devices International, Lumilog and Kyma Technologies. Hydride Vapor Phase Epitaxy (HVPE) is used to deposit GaN on a foreign substrate, which is subsequently removed to leave a free-standing GaN layer with a typical dislocation density of 10^6 cm^{-2} . This platform is suitable for LEDs and lower-power lasers diodes, but restricts the performance of high-power lasers that would benefit from dislocation densities of less than 10^5 cm^{-2} .

Much lower defect densities can be produced by forming crystals from a gallium-based solution in a high-pressure nitrogen environment, which is an approach that we have developed at TopGaN and the Institute of High Pressure Physics in Warsaw, Poland. This method can deliver dislocation densities below 100 cm^{-2} , but it is restricted to a maximum temperature of 2333 °C. This corresponds to nitrogen gas pressure of 2 GPa and a nitrogen concentration of less than 1 atomic percent, and leads to very low growth rates that limit crystal dimensions to 1–2 cm.

Most of the crystals produced with our high-pressure technique are thin, hexagonal platelets with major

“We have used thin platelets to grow high-power laser diodes and GaN-based structures that have record-carrier mobilities.”

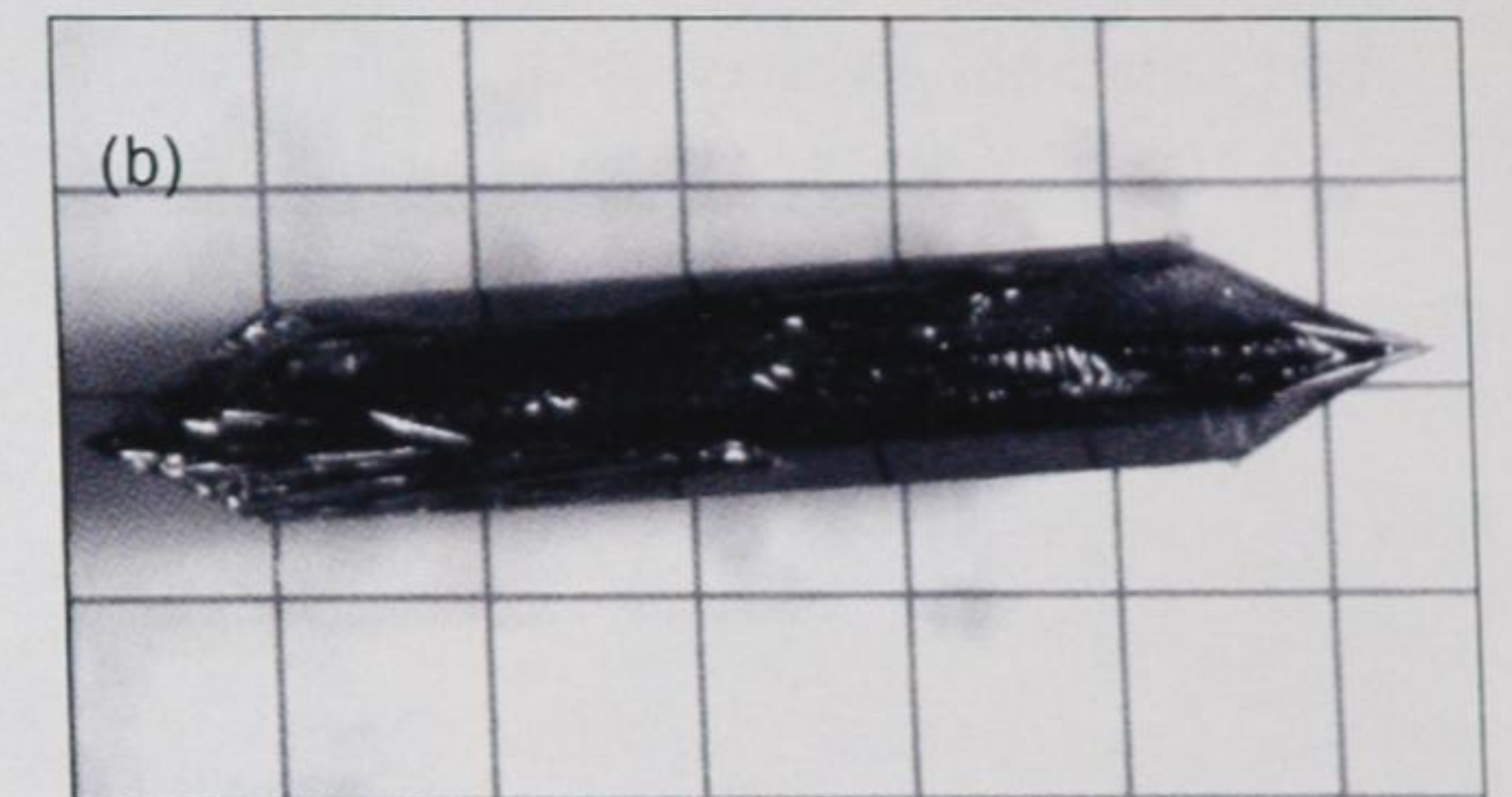
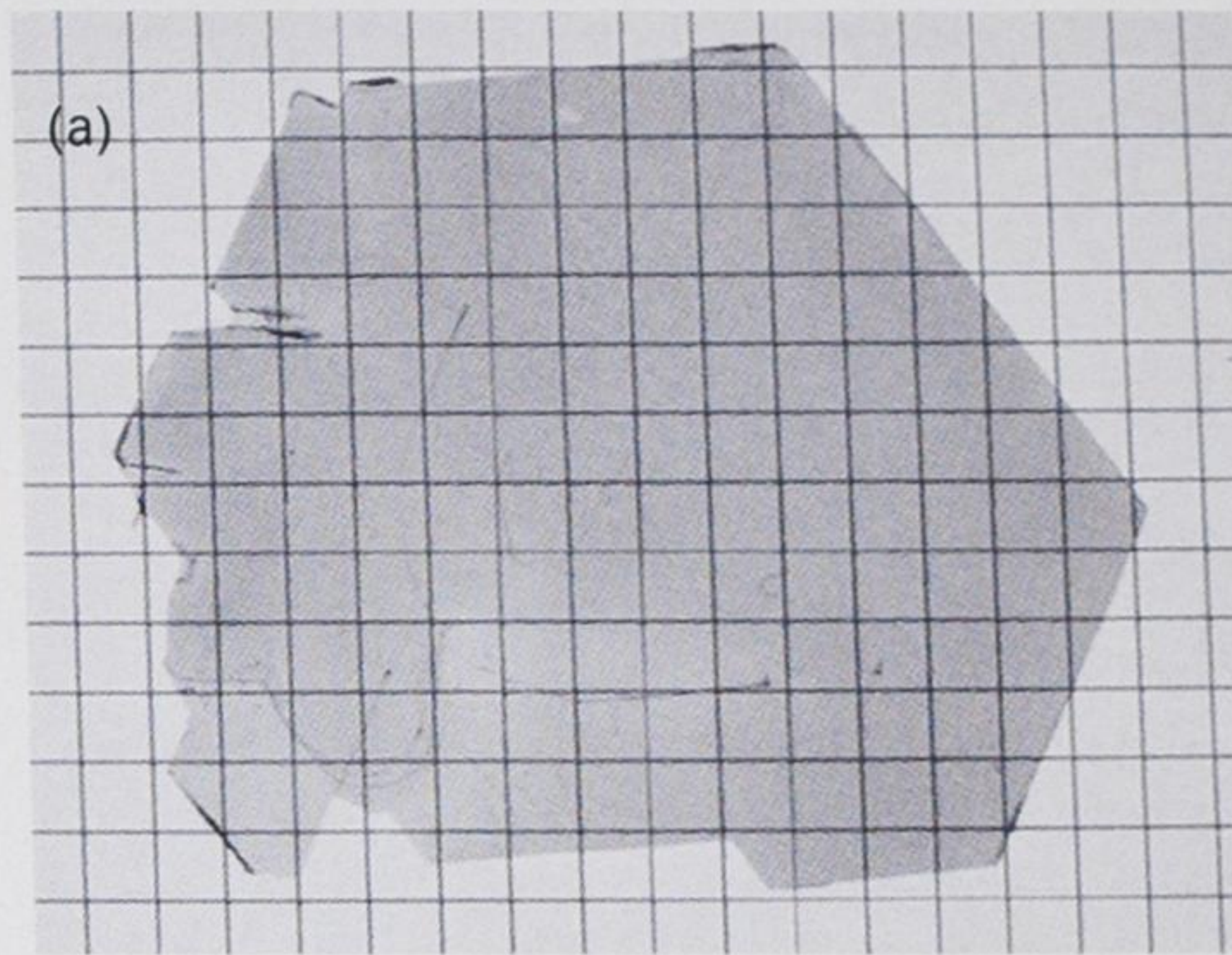


Fig. 1. TopGaN's high-pressure GaN growth method forms hexagonal platelets (a) and hexagonal needles (b). These photographs were taken against a 1 mm-grid background.

surfaces along $\{0001\}$ polar crystallographic planes of the wurzite structure (see figure 1a). These platelets take between 100 and 150 h to grow and are 10–20 mm long and 80–120 μm thick. At very high super-saturation conditions partially hollow needles with elongated c -directions are also formed, which have well developed $\{10\bar{1}0\}$ faces (see figure 1b).

We have used these platelets to grow high-power laser diodes and GaN-based structures with record carrier mobilities (see box “Lasers grown on GaN crystals”). However, their limited size is a major drawback, which has led us to develop a HVPE process for extending the size of our platelet and needle-shaped crystals (see figure 2). HVPE offers growth rates of 100–200 $\mu\text{m}/\text{h}$ in both polar and non-polar directions, but can suffer from a parasitic deposition that involves the formation of GaN particles that can then fall onto the crystal. This unwanted process significantly alters the local growth conditions and makes it difficult to grow large bulk GaN single crystals by HVPE.

Building on our platelets

We have used HVPE to grow flat and uniform layers on the pressure-grown platelets at a rate of 100 $\mu\text{m}/\text{h}$ (see figure 3). Non-polar cross-sections of these extended crystals reveal that the material is macroscopically continuous and that growth proceeds in both the polar (0001) direction and other directions perpendicular to the crystal's c -axis. The electrical and optical properties of these crystals are direction-dependent, according to Jan Weyher, a member of our research group who also holds a position at Radboud University Nijmegen, the Netherlands.

Complementary photo-etching, micro-Raman spectroscopy and photoluminescence measurements show that the free electron concentration is often less than 10^{17} cm^{-3} for the growth in (0001) direction, but is about

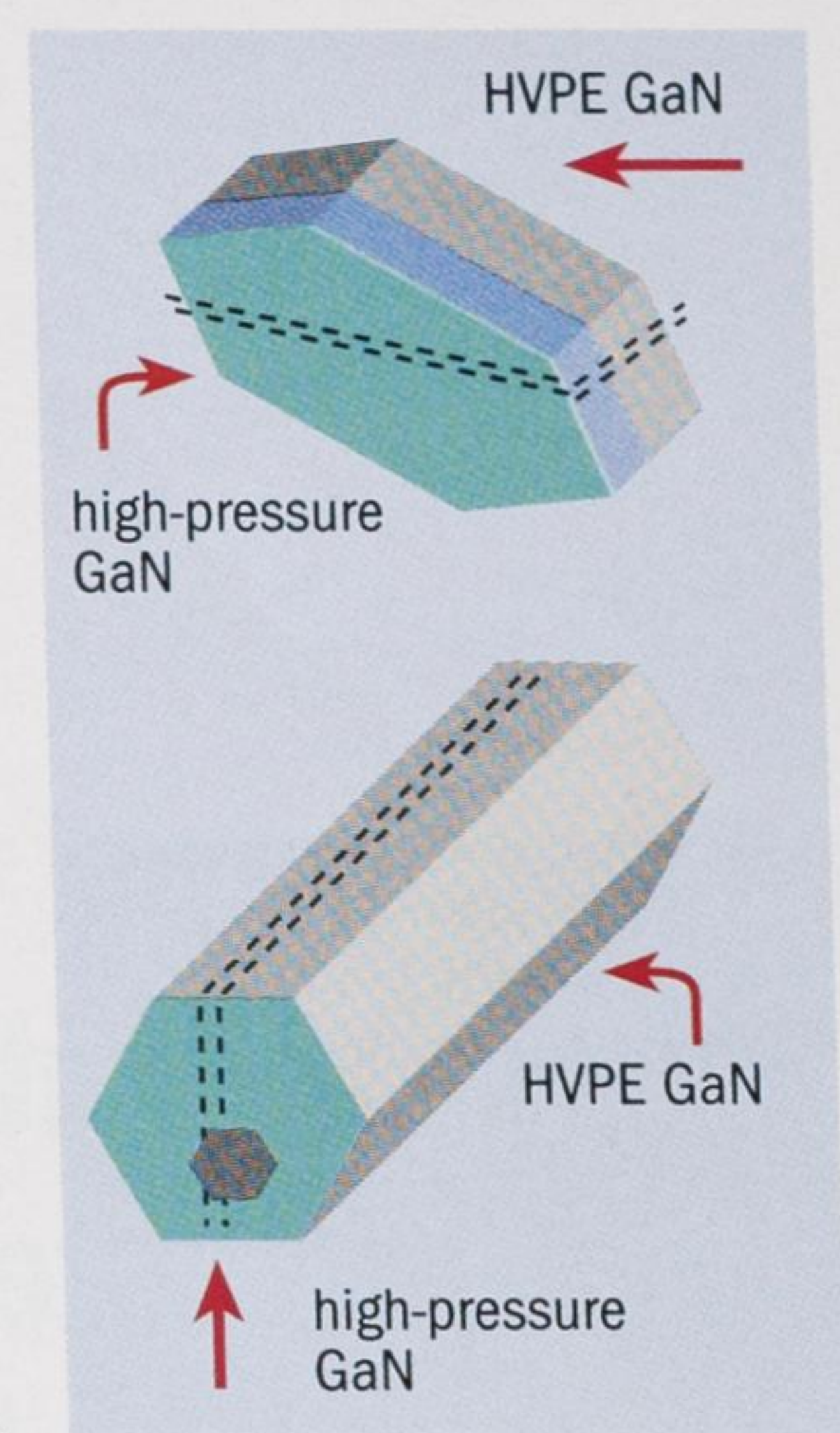
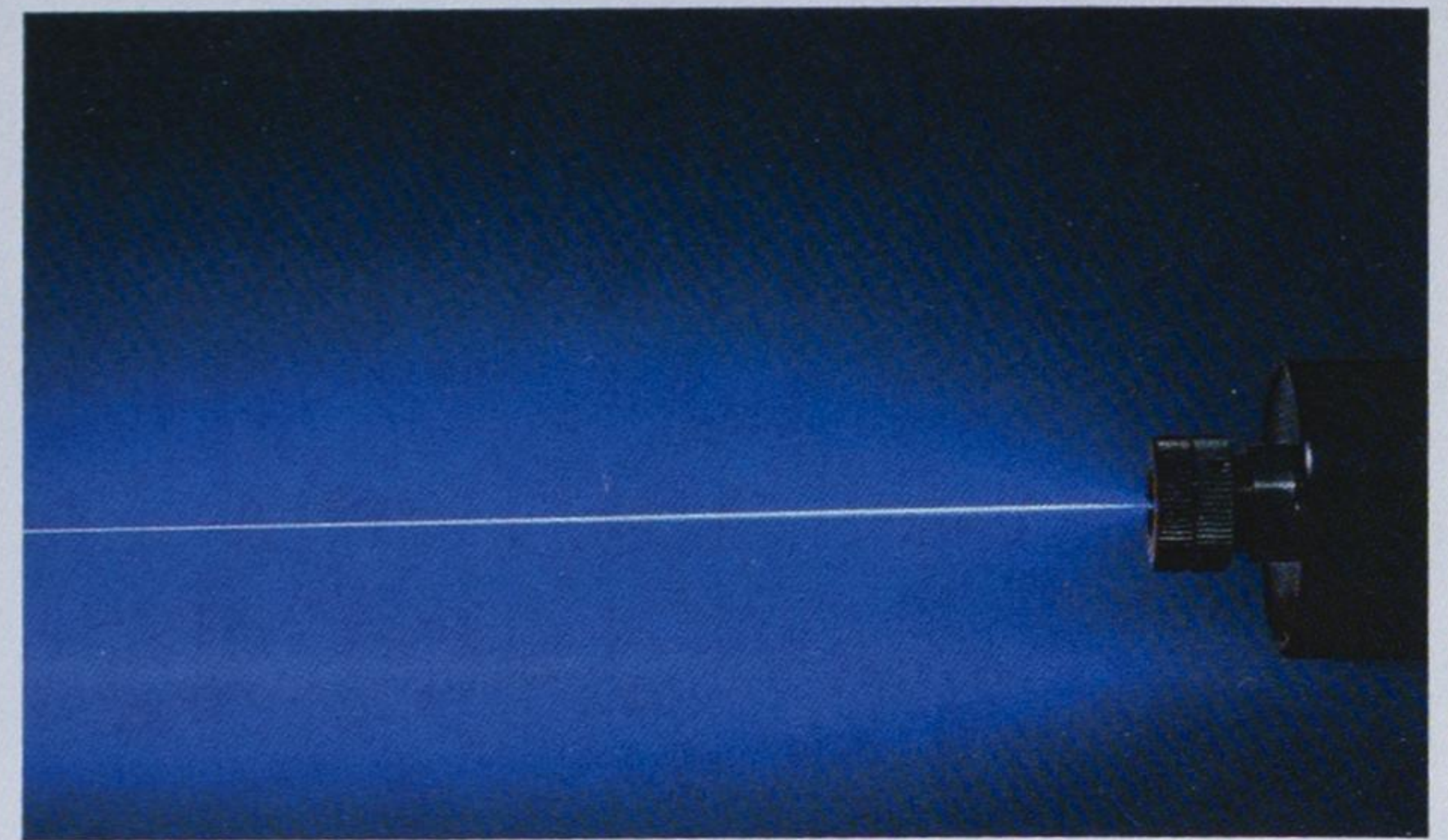


Fig. 2. The size of TopGaN's GaN pressure-grown platelets (a) and needles (b) can be extended by using HVPE to deposit additional material. The dashed lines demonstrate possible ways of slicing along $\{11\bar{2}0\}$ planes.

Lasers grown on GaN crystals

The separate confinement heterostructure lasers contained AlGaIn cladding layers and magnesium and silicon-doped GaN waveguides, and were grown by MOCVD and MBE. No special steps were needed to match the AlGaIn layer to the substrate and structures were produced with dislocation with typical dislocation densities of 10^5 cm^{-2} . The MOCVD-grown blue-violet laser produced a continuous wave (cw) output of almost 200 mW.

The low-defect density substrates also have the growth of GaN and InGaIn layers by plasma-assisted MBE (which uses far lower growth temperatures than MOCVD or MBE methods using an ammonia source of nitrogen). With this approach 410 nm lasers have been fabricated with a lifetime of several hours and a 60 mW cw output power.



GaN material with a very low defect density has enabled TopGaN to produce high-output continuous-wave blue-violet lasers.

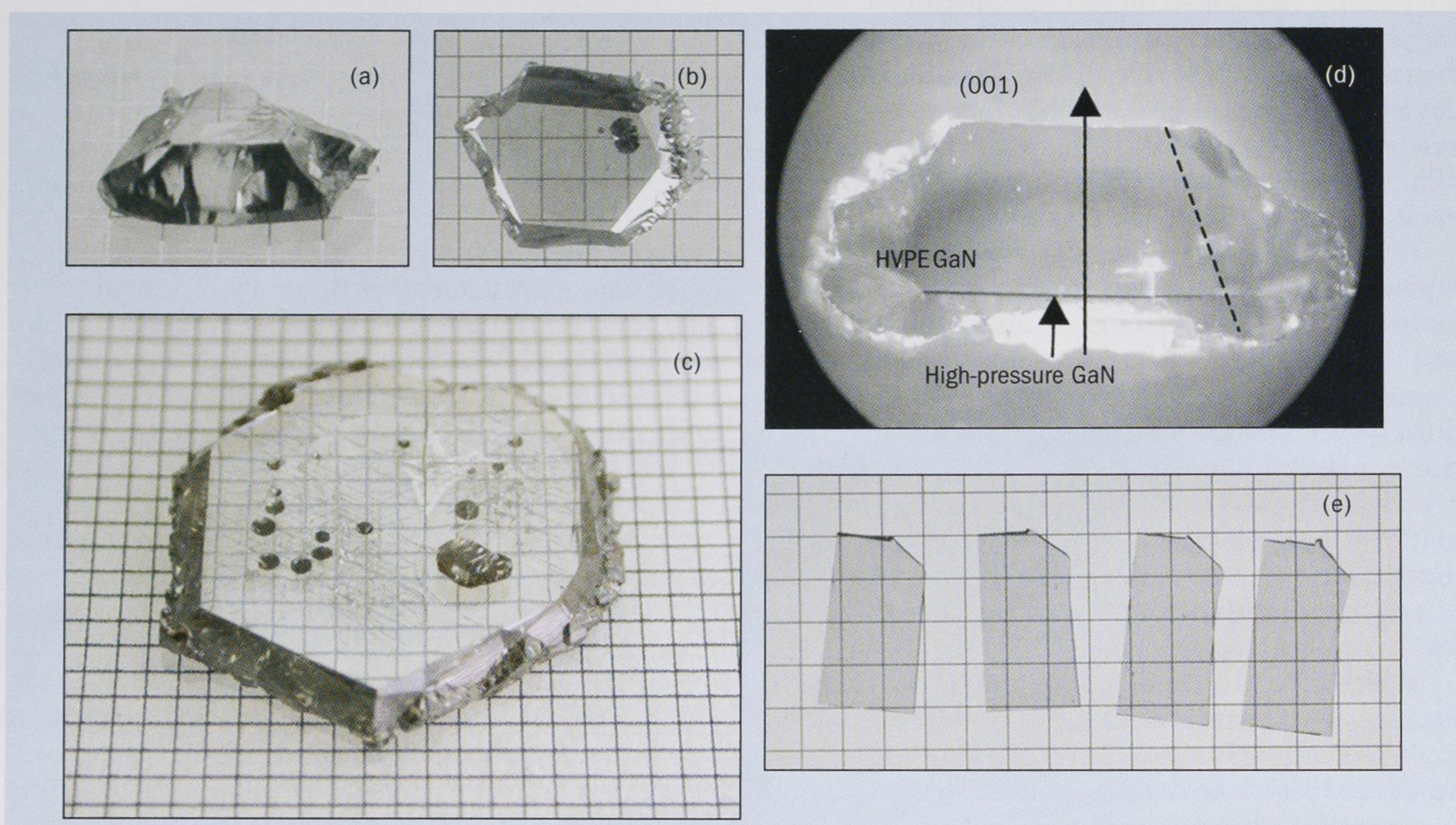


Fig. 3. The typical shape of extended crystals formed from high-pressure platelets are shown in (a), (b) and (c). The interface between the original crystal and the hydride-grown material can be seen in a $\{11\bar{2}0\}$ cross-section (b). The original crystal can be removed to leave rectangular pieces that have upper edges corresponding to the side faces of the bulk material (e). The profile of the lower edges is formed during a cutting process. All of these photographs were taken against a 1 mm-grid background.

“Our investigation reveals no deterioration in material quality with subsequent hydride vapor phase epitaxy growth runs.”

10^{19} cm^{-3} for lateral directions such as $\langle 10\bar{1}1 \rangle$ and the $(000\bar{1})$ N-polar direction. This dependence of the material properties on the growth direction impacts crystal enlargement by HVPE. At high growth rates, local changes in growth direction can take place at the edges of 3D islands or columns, macrosteps and pinholes, and lead to inhomogeneities in physical properties that ultimately produce strain and defect generation.

We have found that our bulk GaN crystals, which are grown

directly on almost dislocation-free platelets have dislocation densities of up to 10^6 cm^{-2} and low-angle grain boundaries. The defects were generated in n-type and highly resistive magnesium-doped substrate material after exceeding critical thicknesses of 30–50 mm and typically 100 mm, respectively.

However, these defects can be overcome by reducing the growth rate to $20 \mu\text{m/hr}$ and with this approach we have grown almost dislocation-free 100 mm thick films on n-type substrates. The improvement results from the suppression of growth mechanisms that can generate strain, and further studies of this approach may enable routine production of these very high-quality hybrid crystals.

The high-pressure technique can also form highly

crystalline GaN needles. These needles suffer from an unstable morphology, but HVPE growth on these seeds stabilizes the shape and produces a transparent and colorless or slightly yellow top layer (see figure 4). The free electron concentration in these crystals, which are grown entirely in $\langle 10\bar{1}0 \rangle$ directions, is $5\text{--}8 \times 10^{18} \text{ cm}^{-3}$.

Using the same growth conditions and rates used for platelet growth leads to larger needles with a crystallization front that shows no deterioration with additional growth. This allows their size to be bolstered with subsequent HVPE growth runs (see figure 5a). With this approach we have increased the size of our needle-shaped crystals through a series of four separate HVPE runs, but it is obviously preferable to enlarge crystals by the same amount in a single, longer run. However, this requires a new HVPE reactor that is capable of continuous operation for more than 100 h.

We have analyzed the defects in these crystals by etching the material in a molten potassium hydroxide and sodium hydroxide eutectic, and then examining polar and non-polar cross-sections. Our investigation reveals no deterioration in material quality with subsequent HVPE growth runs. More than half of the crystal usually has a defect density below 10^4 cm^{-2} and the seed crystal is usually free of dislocations. On areas of the (0001) surfaces there are areas with non-uniformly distributed hexagonal etch pits that spread from the morphological imperfections in the seed. Etching of non-polar $[11\bar{2}0]$ surfaces reveals lines that are perpendicular to the crystal's c -axis, which have been identified with transmission electron microscopy (TEM) basal stacking faults.

Boosting quantum well emission

We have grown heterostructures on 300 μm -thick substrates with lengths of 5–9 mm and widths of 2–3 mm, which we formed by slicing our HVPE-grown platelet crystals in the $(11\bar{2}0)$ direction. These substrates are non-polar and provide a platform for making light-emitting devices that emit polarized light and are free from piezoelectric fields, which can reduce emission intensity.

We have deposited a tenfold GaN/AlGaIn sequence of 2, 3, and 4 nm-thick GaN quantum wells separated by 7 nm $\text{Al}_{0.11}\text{Ga}_{0.89}\text{N}$ barriers onto these non-polar substrates with plasma-assisted MBE. The quality of this heterostructure, according to TEM images and X-ray diffraction plots, is equivalent to that of our control structure, which was grown on a polar GaN substrate for comparison.

The quantum well structure grown on the non-polar substrate produces an emission intensity that is typically 100 times brighter than the equivalent structure on polar GaN. Photoluminescence measurements from these samples at low temperatures reveal a series of well-resolved excitonic lines. The position of these spectral features reveals that there is no built-in polarization field in the multi-quantum-well samples.

Non-polar substrates can also be fabricated from HVPE-extended high-pressure needles. This material has a high electrical conductivity, making it particu-

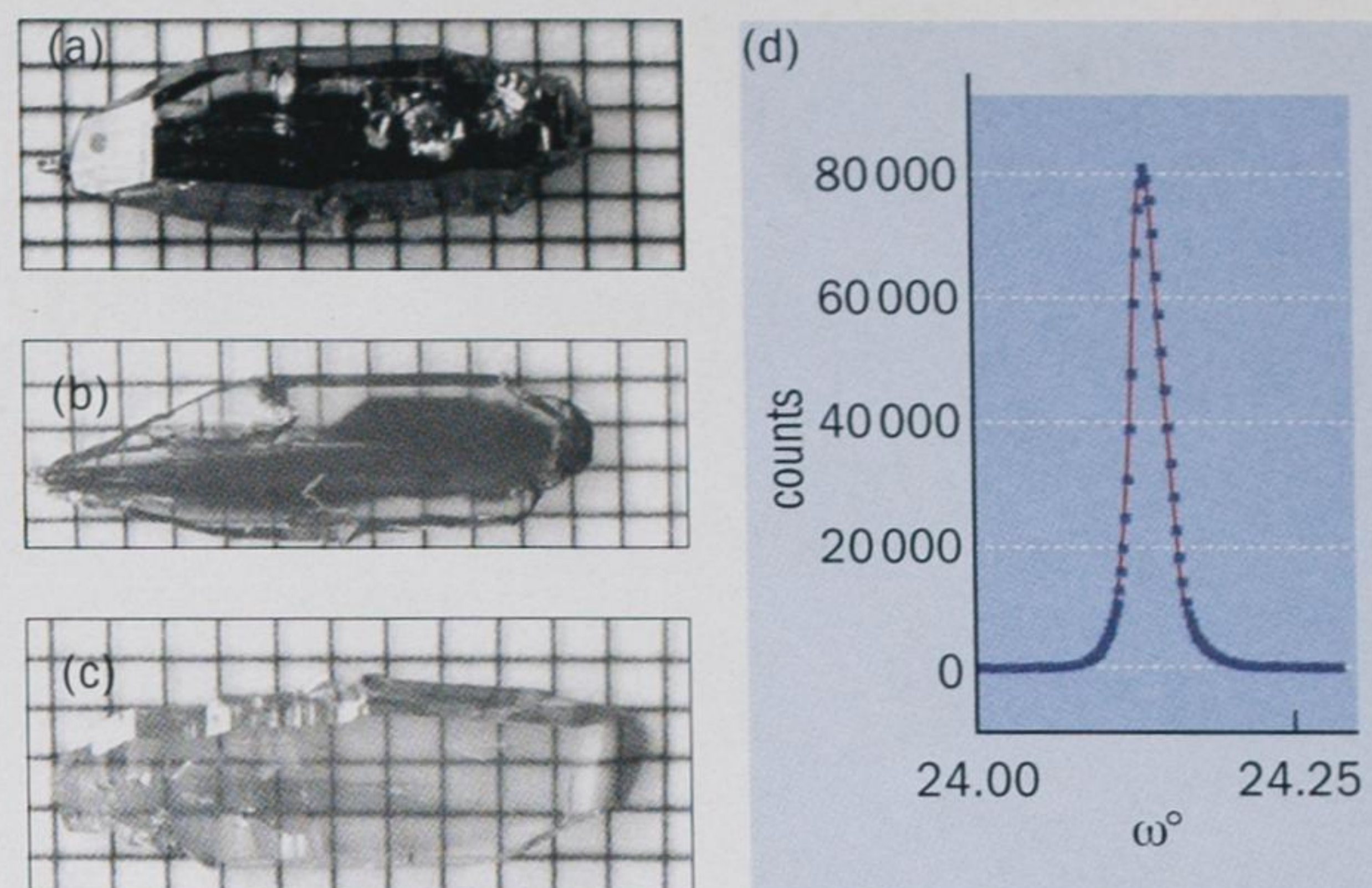


Fig. 4. Needle-like seeds can also be used as the starting point for HVPE growth. After 10 h of HVPE growth the GaN crystals typically look like (a). Two cross-sectional images of this crystal, which were taken against a 1 mm-grid background, are shown in (b) and (c). X-ray diffraction measurements of these crystals (d) produce very narrow curves, indicating high-quality crystals.

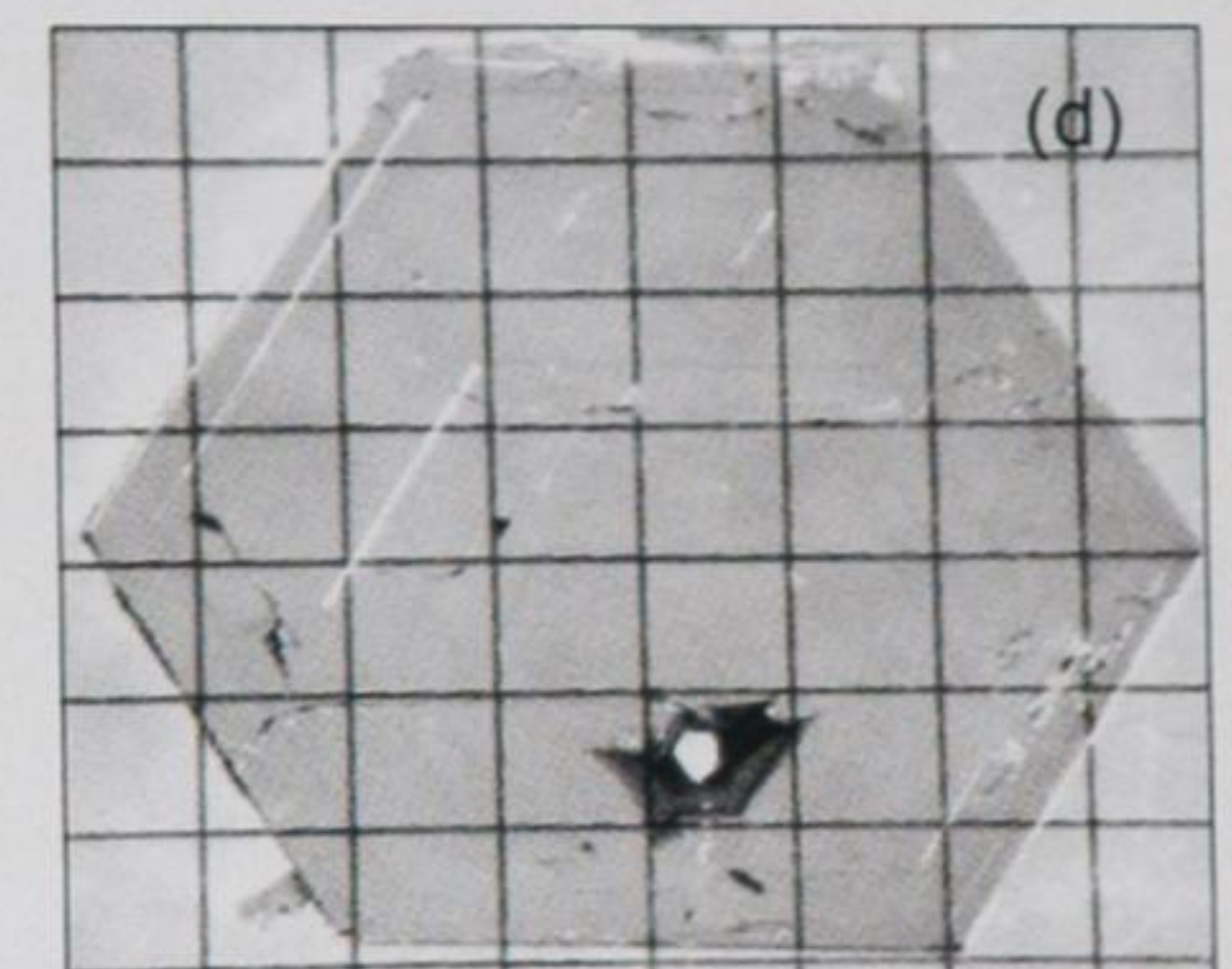
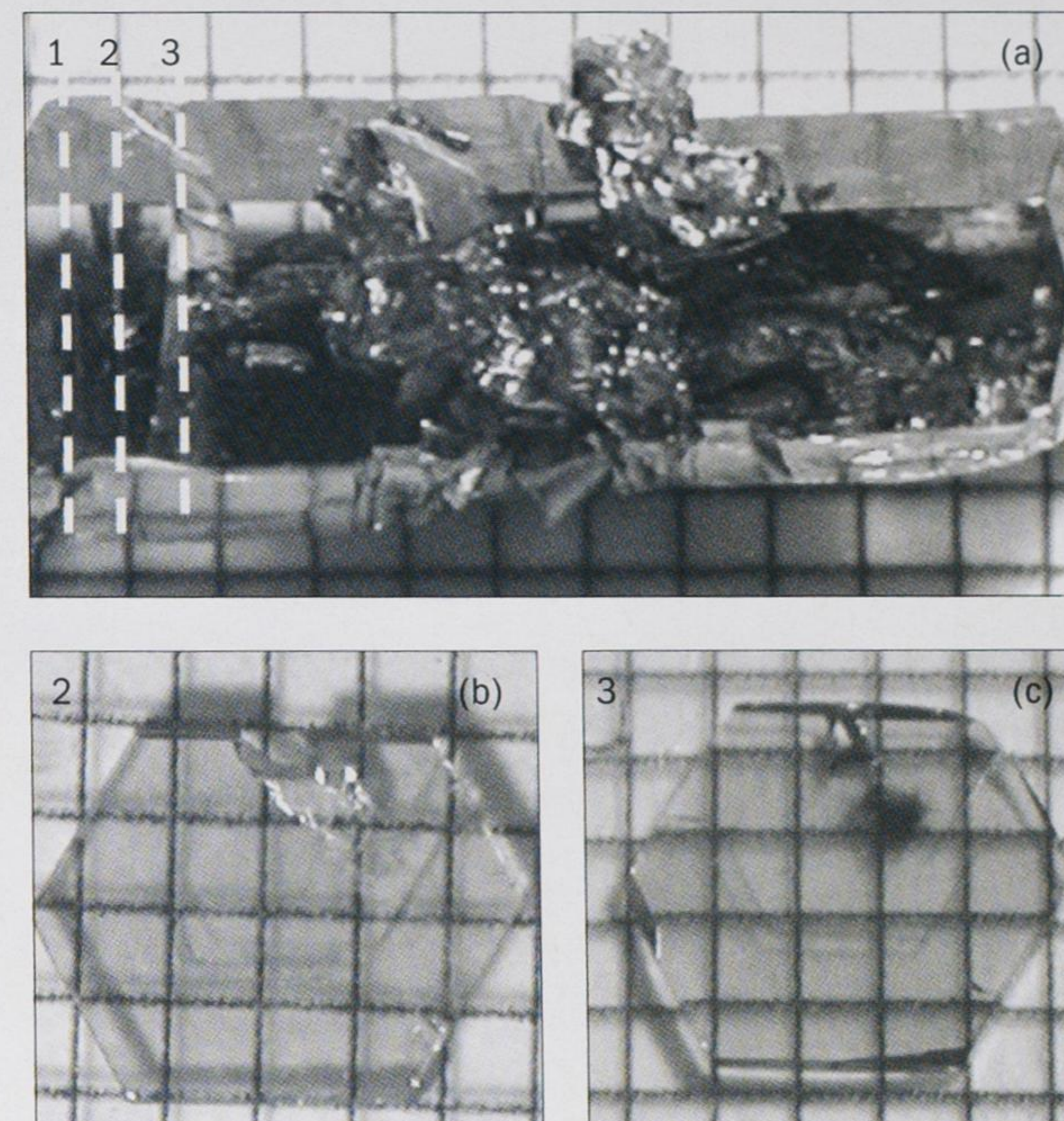


Fig. 5. Multiple growth by HVPE can boost the crystal's dimensions. A double HVPE process on a needle-shaped crystal (a) creates two interfaces that can be seen as a dark hexagonal line in the images of [0001] cross sections (b) and (c), taken from cuts along lines 2 and 3 respectively. The [0001] cross-section image (d) reveals the four HVPE growths used to enlarge this crystal.

larly attractive for laser fabrication.

The HVPE method is well suited to enlarging high-quality pressure-grown crystals, but we need to carry out further studies regarding the influence of growth mechanisms on defect generation to improve the yield of our extended platelet crystals. Fabrication of extended needle-shaped crystals by HVPE is a much more stable process and more extended growth times are the only barrier to the production of a larger form of crystal production. Improvements to our extended crystal production process can also be made through more careful and thorough selection and preparation of seeds, which would eliminate parasitic 3D nucleation that takes place on seed imperfections.

Further reading

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About the author

Izabella Grzegory has been the leader of the High Pressure Crystallization Laboratory since 1995. She is also the vice-president of TopGaN Ltd, an institute spin-off created for commercialization of GaN-related technologies.



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Photovoltaics take a load off soldiers

A US consortium is aiming to smash the solar-cell efficiency record with a radical design that uses a lateral architecture and a dispersive concentrator. If they are successful, soldiers will be freed from a 20 lb load of spare batteries.

Richard Stevenson reports.

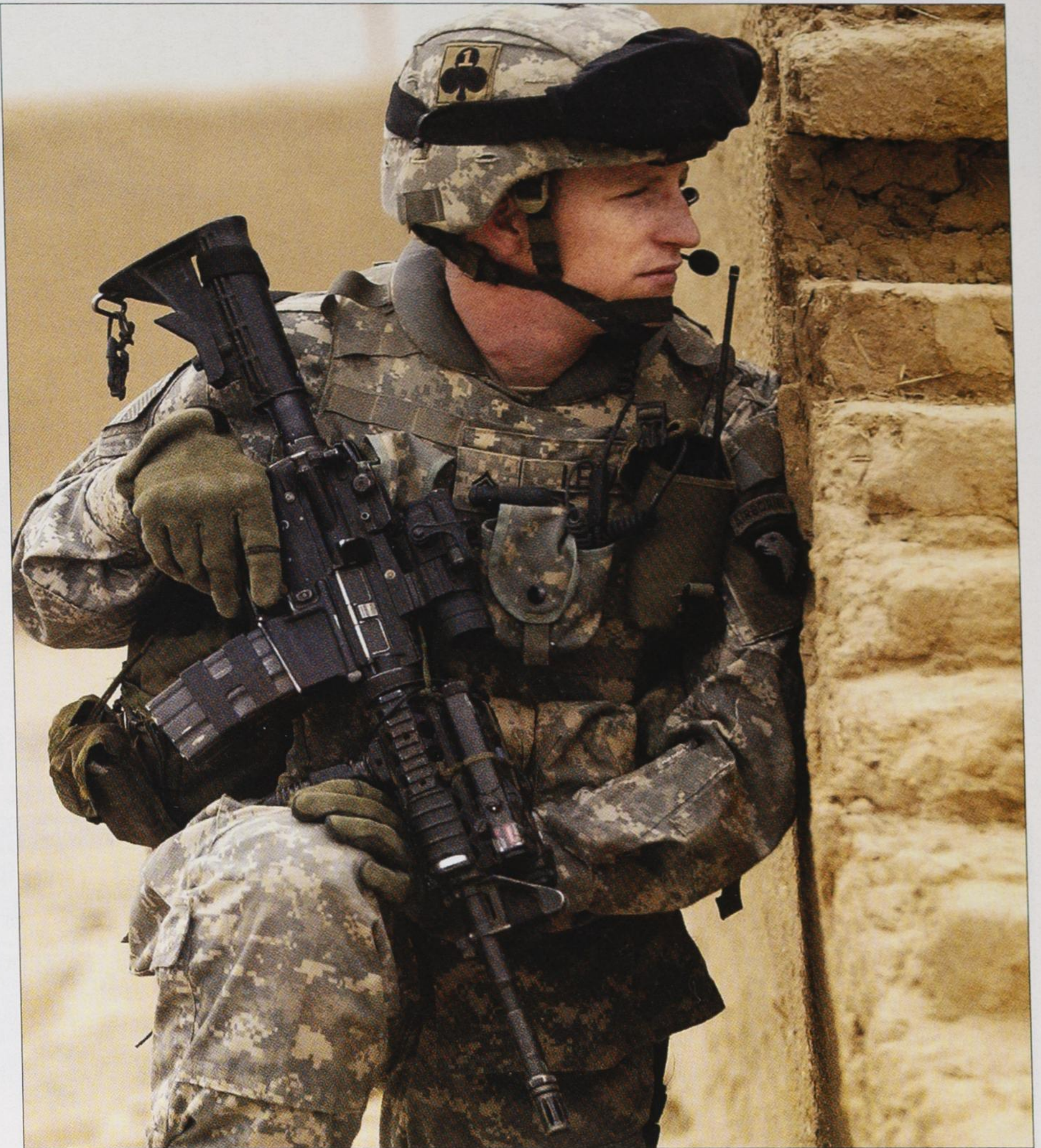
Think of solar cells and you probably think of high-tech devices powering satellites or arrays of devices in sunny climes generating electricity for the national grid. But the US Defense Advanced Research Projects Agency (DARPA) has another application in mind. It believes that solar cells can be used to recharge the batteries that power a soldier's radio, night vision goggles, GPS navigation system and other electronic gadgets, and it is supporting a program that will receive up to \$53 million to develop photovoltaics with the required efficiency.

The main disadvantage of batteries is their weight. Despite advances in technology, spare batteries still account for one-fifth of a soldier's 100 lb battlefield load, which includes a pack, weapon, protective gear and a suite of electronic gadgets. Although these batteries are used to operate devices that can save lives, the weight encumbers movement and increases vulnerability.

Batteries also have to be replaced regularly because a 20 lb stock will only last three to seven days. This is a significant logistical task, requiring military aircraft to transport batteries to airfields and then helicopters or ground transport to ferry them on to where they are needed. The cost in people, material and transport assets to keep this supply chain filled is staggering, says DARPA program manager Douglas Kirkpatrick.

Although the battery's weight and lifetime are major drawbacks, solar-cell technologies are not efficient enough to offer viable alternatives. The space available on the soldier's gadgets for a solar cell varies, but it is too risky to fix cells on equipment with more space and use them to power other gadgets because damage to an individual piece can have knock-on effects. So instead each gadget must have its own cell, which places an upper limit on the size of the solar panel of 10 cm^2 .

Silicon falls well short of this 10 cm^2 criteria. If a silicon solar cell were used to recharge tactical battlefield flashlights over eight-hour periods (and other devices used by soldiers, which have similar requirements), it would need an active area of 33 cm^2 and an efficiency of 15%. Today's best triple-junction cells can get closer to the efficiency target with cells approaching 40% – although they require $500\times$ concentrations that are not suitable for portable applications – but a hike in effi-



A consortium of 22 institutions is aiming to develop 50% efficient solar cells that could provide a replacement for spare batteries, which account for one-fifth of a soldier's carrying load. The team is led by the University of Delaware and includes Emcore, BP Solar, DuPont, Corning, Blue Square Energy, SAIC, Fiberstars, ORA, Lightspin, Purdue, Harvard, Massachusetts Institute of Technology, Georgia Tech, the University of California Santa Barbara, California Institute of Technology, the University of California Berkeley, the University of Rochester, the University of New South Wales, Carnegie Mellon University, Yale and the National Renewable Energy Laboratory.

ciency to 50% is needed to meet the 10 cm^2 target.

To reach this goal, DARPA launched its Very High Efficiency Solar Cell (VHSEC) program, which began in November 2005. Led by Allen Barnett from the University of Delaware, this project is using multiple-junction solar cells and involves contributions from 21 additional institutions including Emcore, BP Solar, Corning, the National Renewable Energy Laboratory and various high-profile US universities.

The team, which Barnett describes as the "broadest high-capability group established in the field", aims to deliver 1000 prototype 10 cm^2 modules with a minimum efficiency of 50% and an output power of 0.5 W

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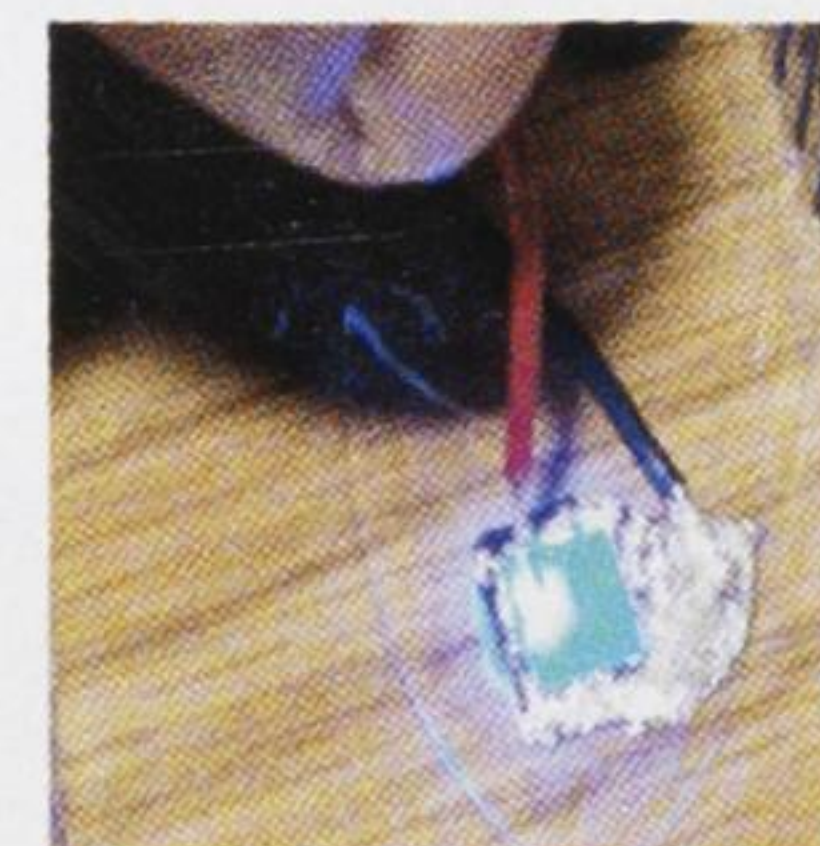
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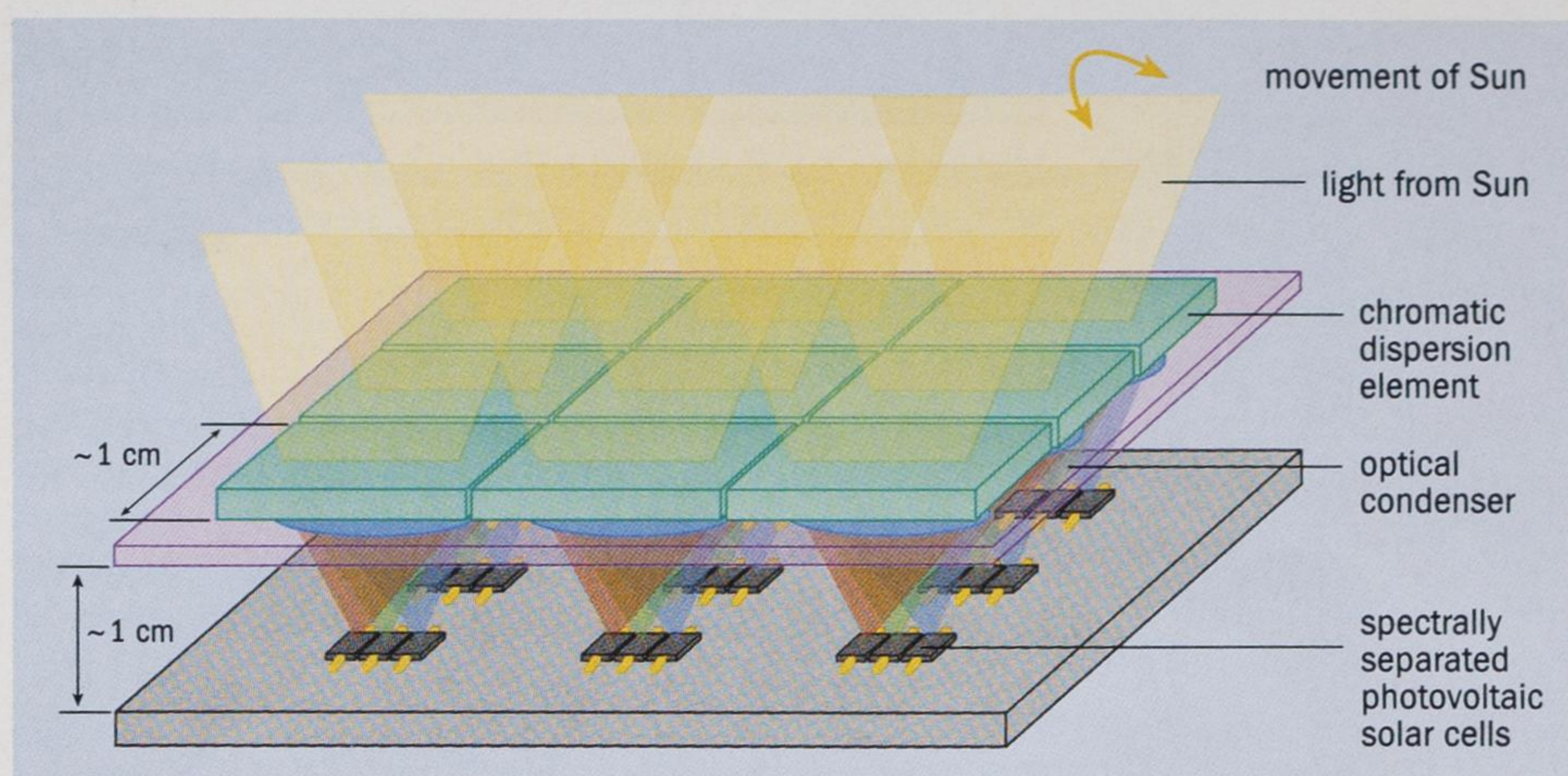


Fig. 1. The use of a specially designed concentrator and a lateral solar-cell architecture holds the key to producing efficiencies in excess of 50%. Incident solar light is split by the concentrator and directed onto three separate solar cells – for high-energy, medium-energy and low-energy photons. The concentrator design uses tiled elements because these enable compact and robust packaging.

“I think we will turn the solar world on its ear in the next 18 months. This architecture gives everybody the freedom to succeed, and I think that’s going to make a big difference.”

Douglas Kirkpatrick, DARPA

by 2009. The weight of these cells is not an issue: “Even if it was made out of solid metal it would weigh less than one set of spare batteries,” says Kirkpatrick. Cost is not a big issue either because even if the price for solar material was \$10 000 m⁻², a 10 cm² cell would cost \$10, which is a fraction of the total cost of a soldier’s equipment.

Barnett believes that the 50% target cannot be met by just making refinements to the most efficient photovoltaics ever built. Instead, a radically different approach is needed that combines a lateral architecture, which was first proposed many years ago, with non-imaging concentrators that disperse and focus various portions of the incident spectrum onto different cells (see figure 1). “The real advantage of the lateral design is that it brings plug-and-play to solar photovoltaic technology,” explains Kirkpatrick. “You can swap improvements in and out without starting from scratch.”

The concentrator’s design is based on work that Kirkpatrick carried out for DARPA’s high efficiency distributed lighting program and uses dichroic coatings to manipulate and direct the incident radiation. According to Barnett, Kirkpatrick’s idea was confronted with skepticism: “The optics-based researchers gave him all the reasons why it wouldn’t work.” For the concentrator to be effective, 90% of the photons have to land on the correct solar cell. “We have exceeded 90%”, enthuses Barnett, “and there’s a chance we could go over 95%, which would be very exciting.”

The concentrator is fixed and a wide-acceptance-angle optical element captures a high proportion of diffused light, which typically makes up one-tenth of the incident power in the solar spectrum. Tracking concen-

trator designs were also considered but DARPA thinks that they are too risky to use in the desert, where many of the US Army’s soldiers operate.

The concentrator used by Barnett and his team delivers a lot of freedom in terms of the number of cells that can be used in the design. However, theoretical calculations have determined a constraint that at least six junctions are required to make a practical device operating at over 50% efficiency (see figure 2). These six junctions could be fabricated as six separate cells. However, this is not the most efficient way to do it because a higher proportion of the light is steered onto the “wrong” cell as the number of spectral bins increases. So Barnett’s team is using a design that divides the radiation into just three bins – a high-, mid- and low-energy bin – and focuses them onto different solar cells that have up to three junctions (see figures 1 and 3). These solar cells can be independently contacted, which avoids the current-matching issues that complicate conventional multi-junction cells. Lattice-matching constraints are also relaxed, which allows more freedom in the choice of bandgap for the device. The architecture is also very flexible because improvements made to one type of cell can be implemented without any detriment to the other cells.

Working with the new design rules

Part of the project involves establishing the best material combination for each of the three cells. Nitrides are being investigated for the high-energy cell and a GaInP/GaAs tandem design for the mid-energy cell. Silicon is being used as part of the low-energy triple-junction cell, alongside materials with bandgaps of

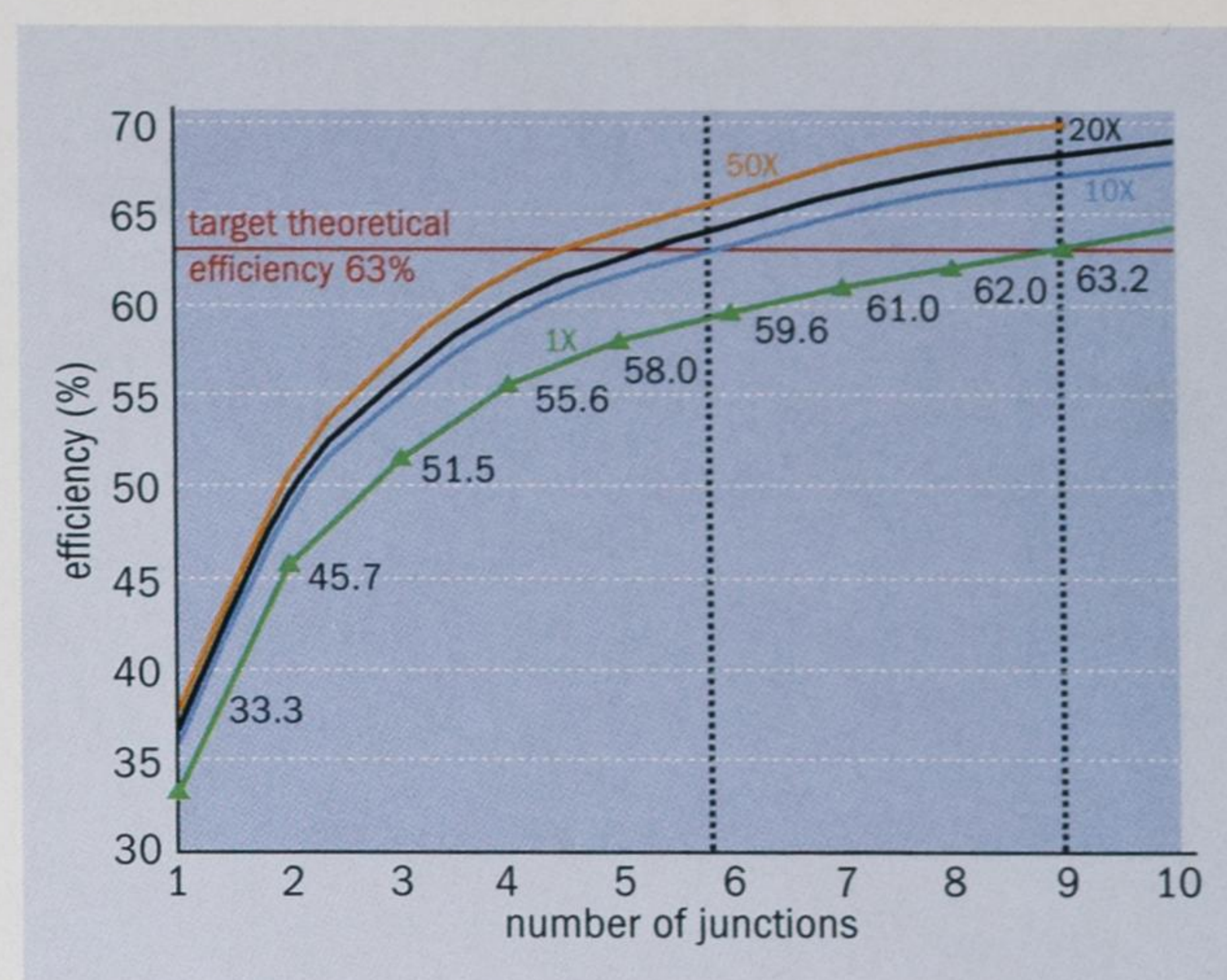


Fig. 2. Improvements to solar-cell efficiencies can be produced by increasing the power of the concentrator and the number of junctions in the cell. Practical solar cells can probably only deliver four-fifths of their theoretical limit, so a theoretical efficiency of more than 63% is needed to produce a working efficiency of 50%. For this efficiency at least six junctions are required, alongside a 10× or greater concentrator. The focusing power of the concentrator also boosts the solar-cell efficiency, by increasing the current in the device, which in turn drives the voltage up. “You don’t get more current – in fact you lose some optically – but you pick it up in the voltage,” explains Allen Barnett from the University of Delaware.

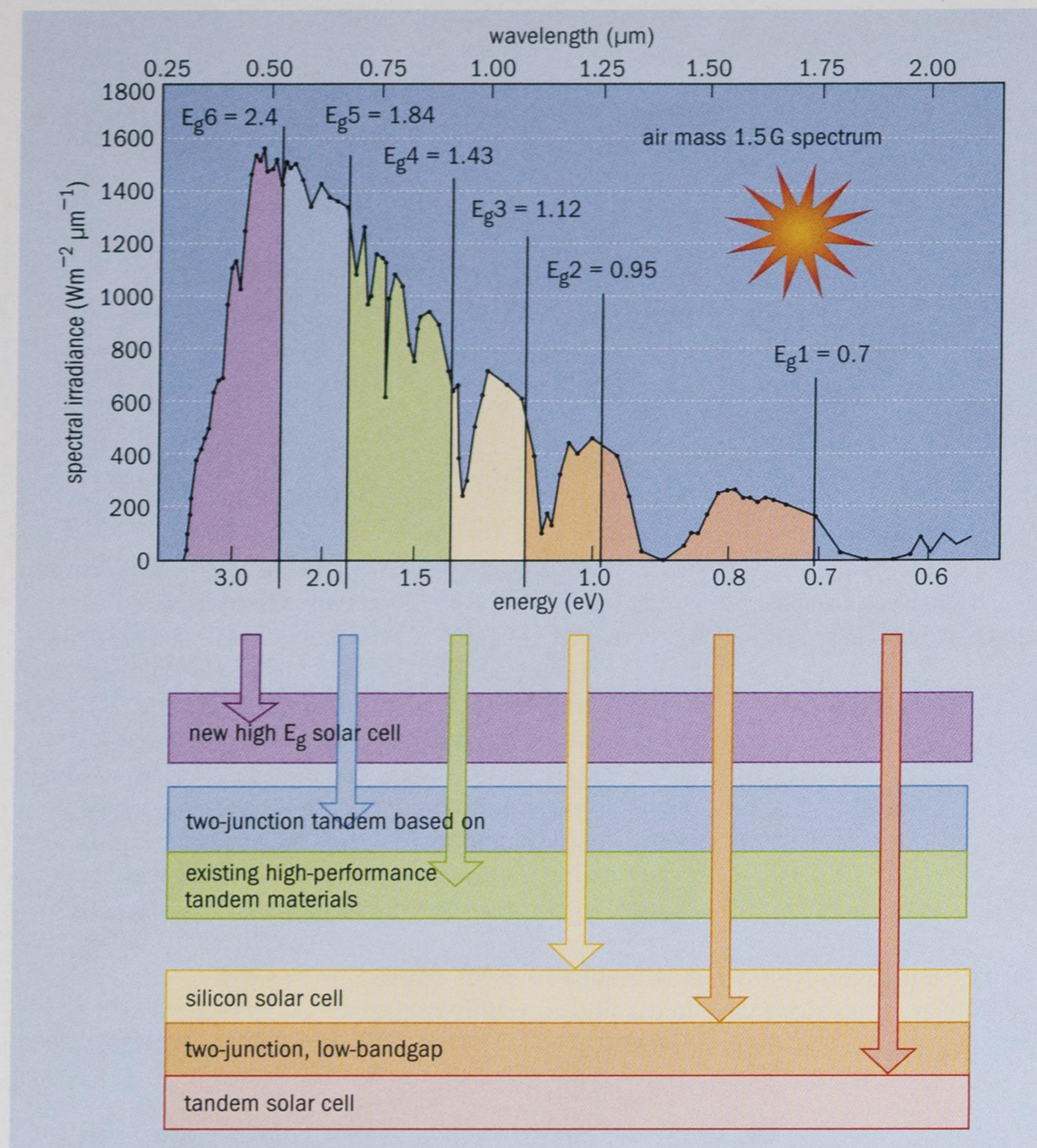


Fig. 3. The consortium plans to build a high-bandgap solar cell, a two-junction tandem cell and a cell made from silicon and low bandgap materials to cater for the high-, medium- and low-energy photons.

six-junction solar-cell bandgaps	six-junction solar cell at 20X		100X
	thermodynamic efficiency	practical efficiency limit	practical efficiency limit
high E_g 2.4 eV	14.9%	13.8%	13.8%
GaInP 1.84 eV	16.6%	14.3%	14.3%
GaAs 1.43 eV	13.9%	11.7%	12.0%
Si 1.12 eV	9.7%	7.8%	8.5%
0.95 eV	5.0%	3.8%	4.0%
0.70 eV	4.1%	2.9%	3.0%
	total $\eta = 64.2\%$	total $\eta = 54.3\%$	total $\eta = 55.6\%$

Fig. 4. A 50% efficiency goal for a six-junction cell can be broken down into targets for each device.

0.95 eV and 0.7 eV that could be made from either III-Vs or germanium-based compounds. The specific bandgaps for these cells, their thermodynamic efficiencies and their practical efficiencies at 20 $\times$ and 100 $\times$ concentrations are listed in figure 4. “We’ve built our

whole approach on a silicon platform because it is well known, well established and you’re standing on the shoulders of something that’s known to be good,” explained Barnett.

Research has already been carried out for each type of cell. GaInP/GaAs tandem cells for the mid-energy bin have been built with efficiencies of 28.4% and 29% at solar-cell concentrations of 20 and 40 suns, respectively. This is a very encouraging value, says Barnett, because the theoretical maximum for a two-junction cell is only 41.6%. If all three bins had devices offering this performance level, then the DARPA’s target of 50% would be comprehensively broken.

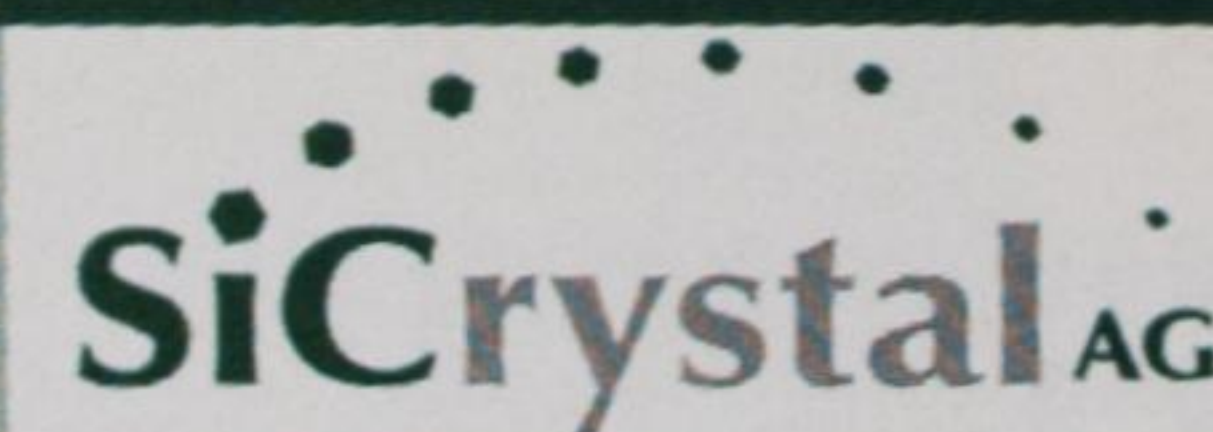
GaInAsP/GaInAs tandem cells are being investigated for the low-energy bin. These MOCVD-grown devices feature 0.95 eV and 0.74 eV subcells on an infrared-transparent iron-doped InP substrate interconnected with an essentially transparent tunnel junction. The back contact is attached to the device mesa and the front contact is made through a highly conductive window layer on the front-side of the device. This solar cell produced an efficiency of 3.5% at a concentration of 5.7 suns and improvements are expected when a two-layer antireflection coating is added and changes are made to allow higher concentration ratios.

Efforts are also being directed at developing InGaN-based cells for the high-energy bin that draw upon advances made in GaN LED and photodetector technologies. PIN structures have been grown by MOCVD on 2 inch sapphire substrates that feature a low-temperature GaN nucleation layer, a 2 μ m-thick GaN template and InGaN layers with an indium-concentration ranging from 0 to 40%, which correspond to bandgaps of 3.4 eV to 2.4 eV. Devices ranging from 1 $\times$ 1 mm to 5 $\times$ 5 mm were fabricated from these wafers. Internal quantum efficiency measurements on these cells, which have an In_{0.05}Ga_{0.95}N absorption layer, show quantum efficiencies of up to 60% at 3.26 eV. Improvements to the cell efficiency can be made by decreasing the light absorption in the current-spreading metal layer and reducing recombination at heterojunction interfaces.

The consortium is also investigating alternative lower-cost growth techniques, such as bio-fabrication processes that can make electronically active material at room temperature and standard pressure. The processes are capable of yields greater than 50% of the starting feedstock, which is at least five times more than typical MOCVD processes. At the University of California, Santa Barbara, Daniel Morse, Birgit Schwenzer and co-workers have used this approach to form GaN and other optoelectronic materials at very low temperatures using ammonolysis – a bio-chemically inspired process route.

The progress made on low-temperature processing techniques, devices for each of the three energy bins, and the dispersive concentrator have been described by Kirkpatrick as phenomenal. “I think we will turn the solar world on its ear over the next 18 months. This architecture gives everybody the freedom to succeed, and I think that’s going to make a big difference.”

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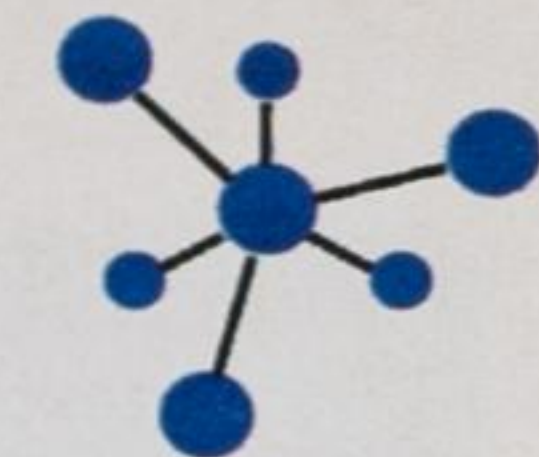
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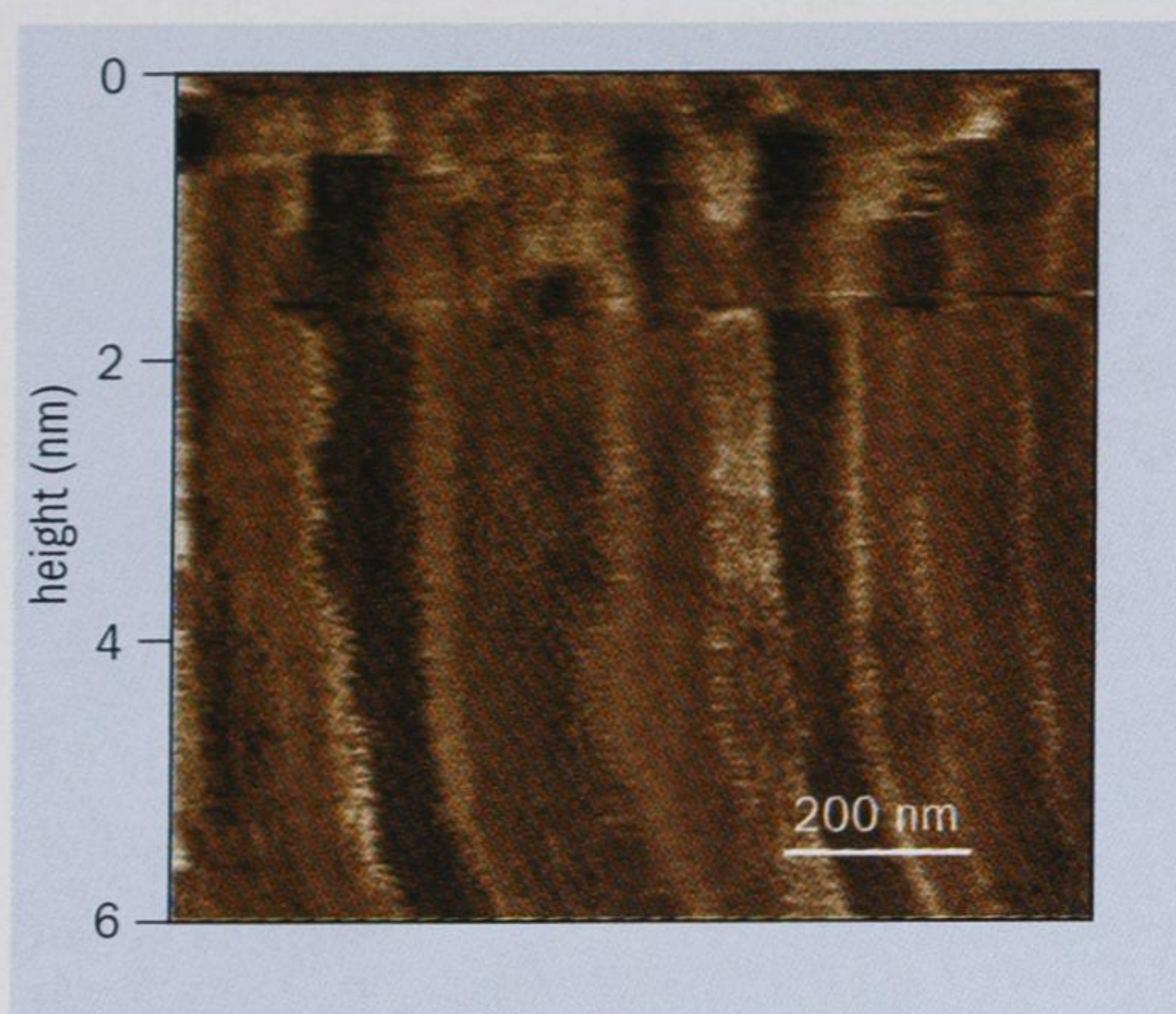
First in situ STM images in MOCVD kit

Researchers from the Technical University of Berlin, Germany and Tor Vergata University, Italy, have made the first ever in situ scanning tunneling microscopy (STM) images inside an MOCVD reactor.

These images offer direct monitoring of growth at an atomic level, which is not possible with today's commonly used techniques for process control, like reflectance anisotropy spectroscopy or ellipsometry.

STM has not been applied to *in situ* studies of an MOVCD growth up until now because the high-temperature, vibration-ridden environment is incompatible with the STM instrument's requirements.

The researchers have prevented the growth temperatures from damaging the microscope by adding an active cooling shield, which is cooled by a stream of gaseous nitrogen. With this method the instrument's coarse approach motor can be maintained below 80 °C for growth temperatures of up to 650 °C. The



The first ever in situ STM images in an MOCVD reactor were taken on an offcut GaAs substrate. The fuzziness around the edges of the atomic steps is either caused by noise or rapid atomic movements at elevated temperatures. Towards the end of the scan the heater was turned off, which caused the temperature to fall by 50 °C and the scan area to drift.

vibrations caused by the MOCVD reactor's rotary pump were reduced by attaching two coupled springs to the top of the instrument.

With these modifications the team obtained in situ images of the steps of GaAs (001) substrate offcut at 2 ° along the [110] direction at a reactor temperature of 500 °C (see figure). This type of structure forms an ideal test sample because the topography – step bunches 2–3 nm high and separated by 50–100 nm – is known down to the nanoscale.

Research team member Markus Pristovsek explained to *Compound Semiconductor* that they are now investigating the evolution of In(Ga)As quantum dots at different growth temperatures. "With a large scan area the current density was small enough to not affect the surface," said Pristovsek.



Journal reference

B Rähmer et al. 2006 *Appl. Phys. Lett.* **89** 063108.

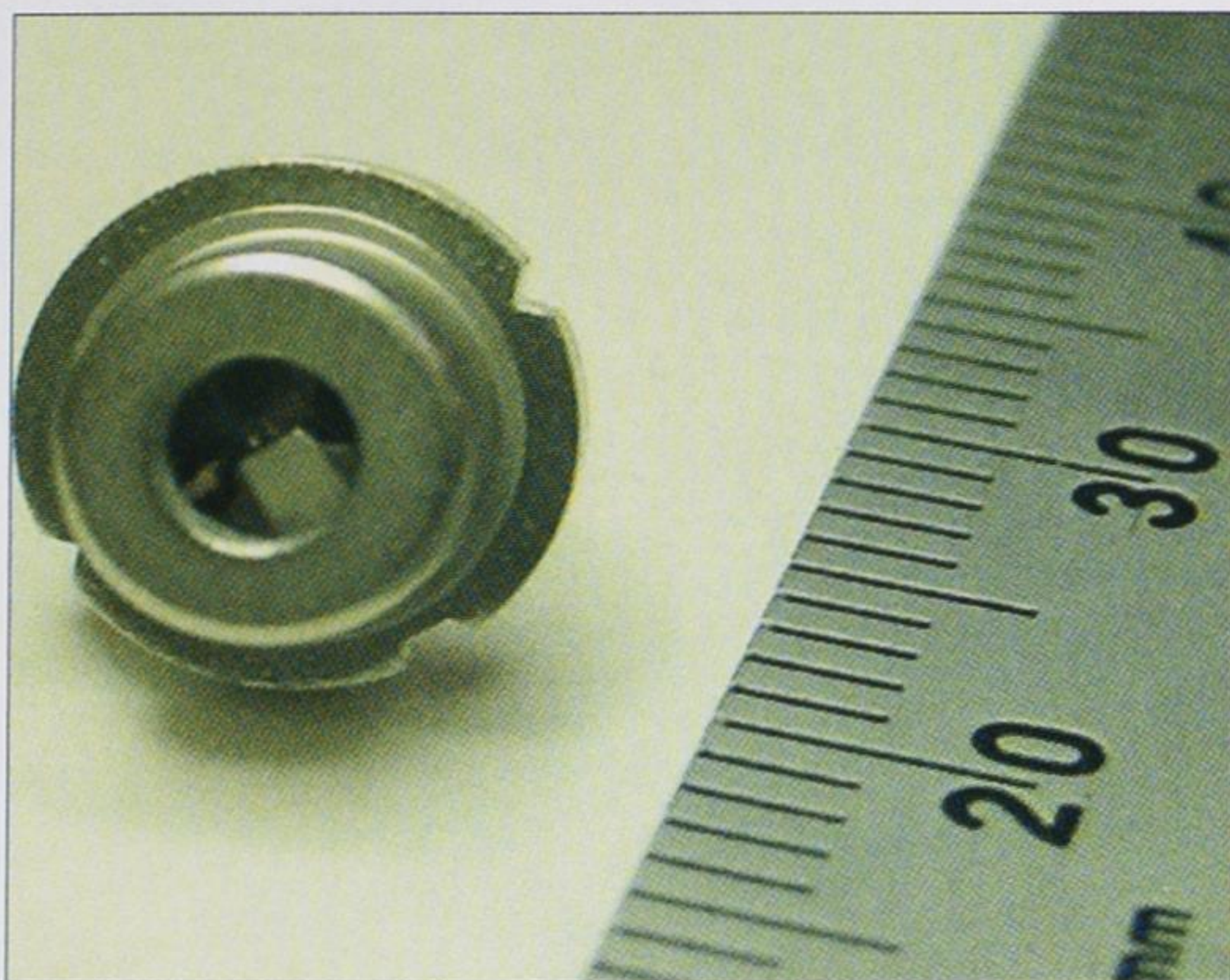
LASER DIODES

Fuji develops longer lifetime for red lasers

Japan's Fuji Photo Film Company has developed 660 nm red-emitting lasers that have a sufficiently long lifetime to be used in plastic optical fiber (POF) communication networks in offices, hospitals and data centers.

The team's 5 mW lasers, which have an estimated lifetime of 1×10^6 h at 60 °C, exceed the minimum lifetime requirement for deployment in networks operating at this temperature by a factor of 10.

In comparison, commercial red lasers used in DVD players – which also emit at a wavelength close to the plastic fiber's attenuation minimum at 650 nm – have an estimated



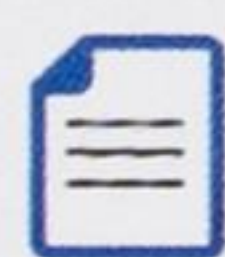
Fuji Film's 5 mW lasers have an estimated lifetime of over a million hours at 60 °C, making them ideal for POF networks in offices, hospitals and data centers.

median lifetime of only 5000 hours at 70 °C. The improvements to the lasers were made

by optimizing the MOCVD growth conditions of the AlGaInP cladding layers, the device's cavity length and doping concentration.

Fuji's laser was mounted in a junction-up configuration on a copper heatsink, produced modulation speeds of up to 1.25 Gbit/s and a threshold current of 65 mA at 25 °C. At a 5 mW continuous wave output the diodes have estimated lifetimes of 3×10^5 h and 1×10^6 h at 70 °C and 60 °C, respectively.

Tsoyoshi Ohgoh and co-workers have recently made further improvements to laser reliability that were announced at the Japan Society of Applied Physics Autumn Meeting. The latest diodes show no degradation after 3500 h at 90 °C, the operating temperature of sources used in POF-based car networks.



Journal reference

T Ohgoh et al. 2006 *Elec. Lett.* **42** 1033.

LED DESIGN

Lumileds doubles brightness of devices

LED chip manufacturer Lumileds has more than doubled the brightness of its GaN-based flip-chip devices by separating the sapphire substrate from the epilayers.

Using this technique – which also involved roughening of the exposed GaN – Lumileds researchers fabricated 1×1 mm blue-emitting thin-film flip-chips (TFFCs), which produced

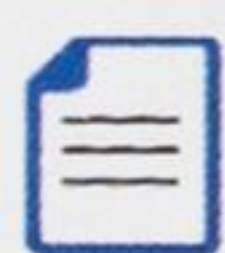
a radiance of 168 mW/mm² sr and an output power of 750 mW when operated at a 1 A drive current in pulsed mode. The radiance is 130% higher than that of conventional flip-chip LEDs produced from the same epiwafer and 20% greater than that of vertical thin-film chips with a high-reflectivity silver contact.

Lumileds' Oleg Shchekin and colleagues say that their TFFC emitters produce a higher radiance and output power than vertical thin-film chips because they eliminate the occlusion by top-contact and wire bond pads.

According to the researchers, even though the patterning of a top metal contact in a verti-

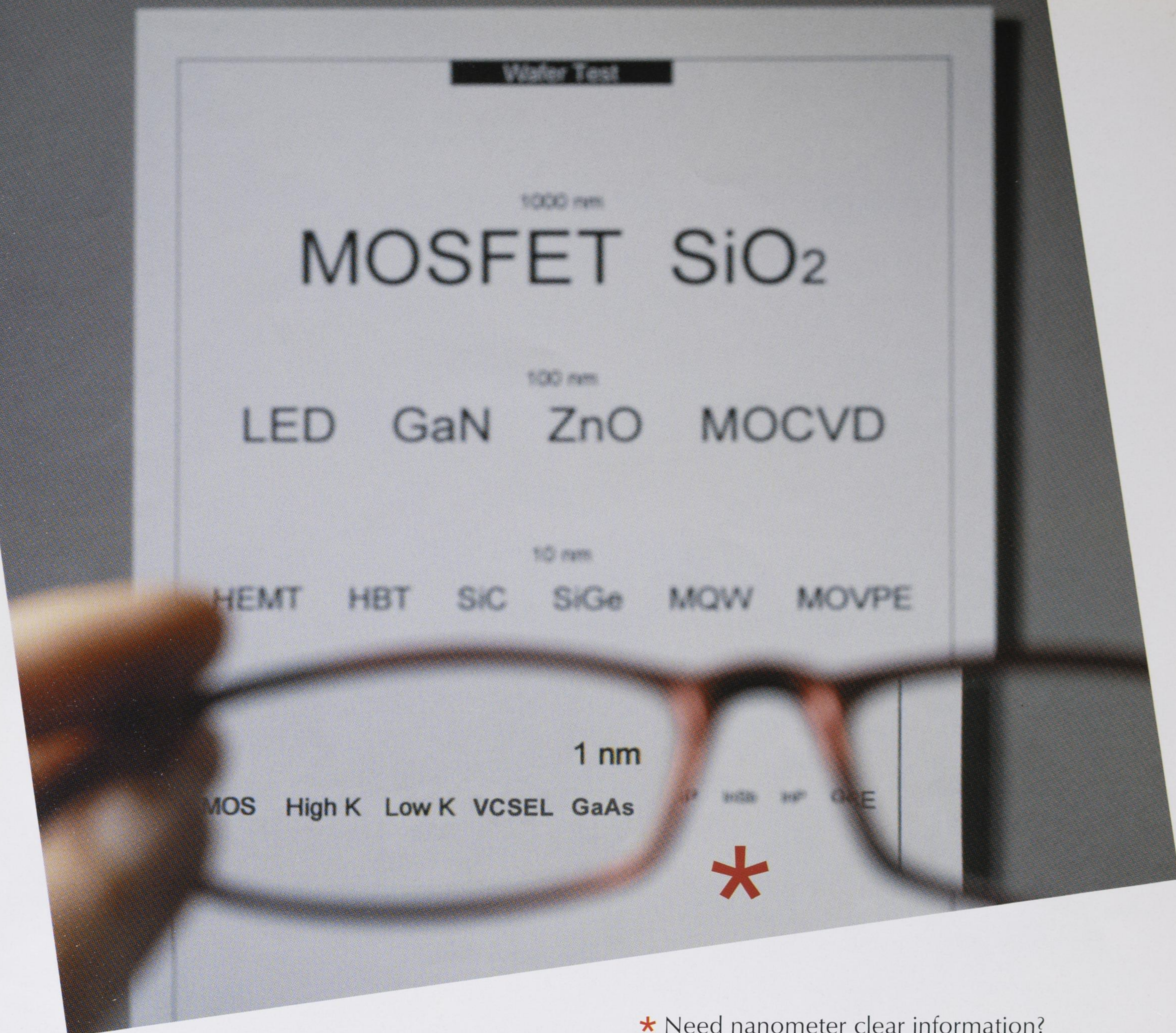
cal thin-film device can be further optimized, there is a trade-off between extraction efficiency and high current operation. The top contact has to be minimized to boost extraction, but brighter devices need a larger contact area to reduce current crowding effects.

The team coated blue-emitting TFFC LEDs with a phosphor to produce white lamps with peak luminous efficiencies of 96 lm/W at 20 mA, 60 lm/W at 350 mA and 41 lm/W at 1 mA.



Journal reference

O B Shchekin et al. 2006 *Appl. Phys. Lett.* **89** 1109.



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