

COMPOUND SEMICONDUCTOR

August 2006 Volume 12 Number 7

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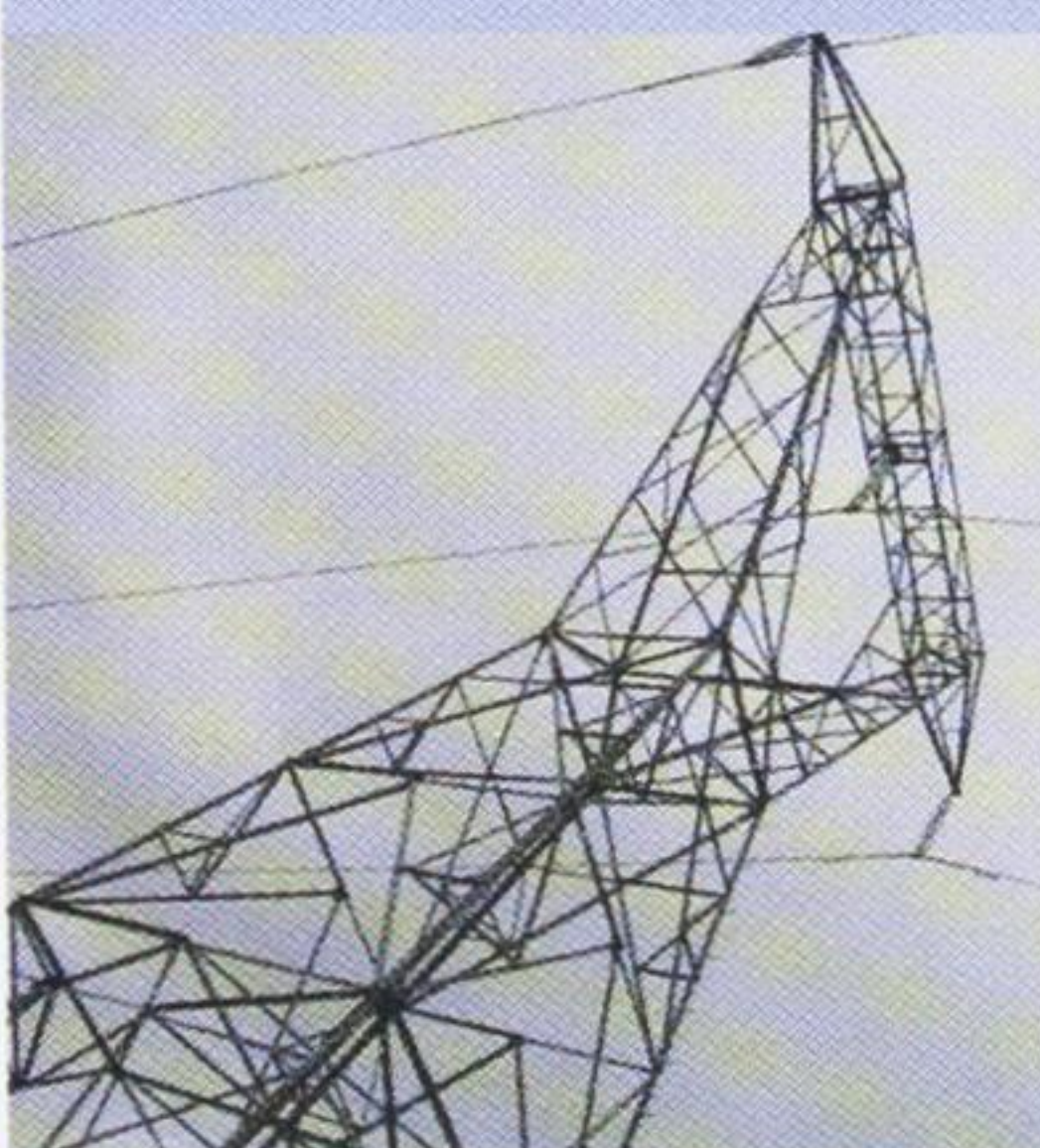
LEDs

Zinc oxide emitters cover the spectrum

HEADLINE NEWS

Emcore to sell epitaxy unit to IQE for \$16 m p5

APPLICATION FOCUS



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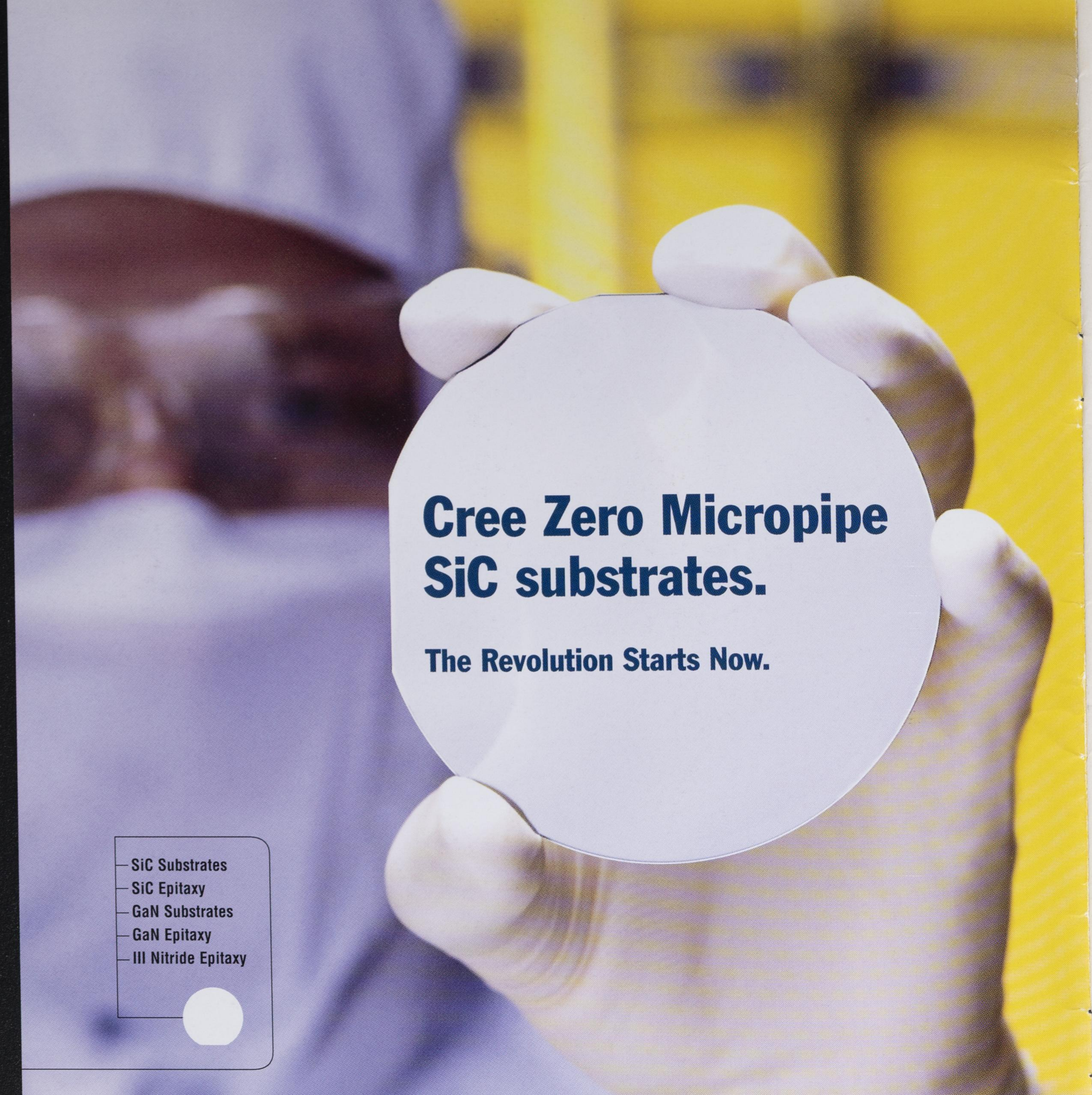
Why devices that look like pizzas could drive wafer volumes at JDSU. [p14](#)

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Crystal waters

Dirty drinking water prompts rapid development for ultraviolet LEDs. [p12](#)



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TECHNOLOGY

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- 29** **On-chip gratings add stability to high-power semiconductor lasers:** Quintessence Photonics has written gratings into its infrared laser diodes that narrow the emission spectra and reduce temperature sensitivity. This will lead to cheaper diode-pumped laser systems, and make the devices more attractive for medical imaging and Raman spectroscopy, says Paul Rudy.

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Main cover image: These zinc oxide LEDs from US start-up company MOXtronics use a variety of phosphors to operate at colors across the visible spectrum, but the company says that by using bandgap engineering it should soon be possible to make blue, green and red emitters on the same wafer, without the need for any phosphors. See p16.

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The old empire strikes back



The UK was once at the epicenter of the industrial revolution, leading the way in the development of the new technologies that helped to define much of the modern world. But that was all a long time ago, and in general the manufacturing industry on this side of the Atlantic has been on the wane for much of the past few decades.

While the strength of technological innovation at the academic and early research stage has always been, and remains, a significant feature of British culture, the fruits of those breakthroughs are now generally reaped elsewhere. So it is something of a pleasant surprise to witness what could turn out to be a renaissance being plotted by two of the remaining bastions of the country's compound semiconductor output.

First up – Filtronic. Based in England's industrial north-east, the huge building that the wireless chipmaker bought in 1999 and turned into a 6 inch GaAs fabrication facility looks to be the key element in Filtronic's new corporate strategy.

Having already disposed of its wireless antenna business last year, the company more recently agreed to sell its wireless infrastructure unit to Powerwave Technologies for a whopping \$345 million. Its shareholders, along with the regulatory authorities, will be taking a close look at the proposed deal at the time of writing. But should it go through, the impact on its GaAs fab could be enormous, with Filtronic's board of directors said to be fully committed to a massive investment in the facility.

Then there's IQE, the independent epiwafer foundry based in South Wales – another region of the country that is steeped in its industrial past, thanks to the local fields of coal and other minerals. Assuming shareholder approval, IQE will shortly take over the epiwafer business that belongs to that most pioneering of III-V companies, Emcore.

That two of the regions left most scarred – both physically and socially – by the rise and fall of the UK's industrial past should be at the forefront of this most cutting-edge of industries is particularly satisfying.

Michael Hatcher *Editor*

“It is a pleasant surprise to witness what could be a renaissance by two of the remaining bastions of the UK's compound semiconductor output.”

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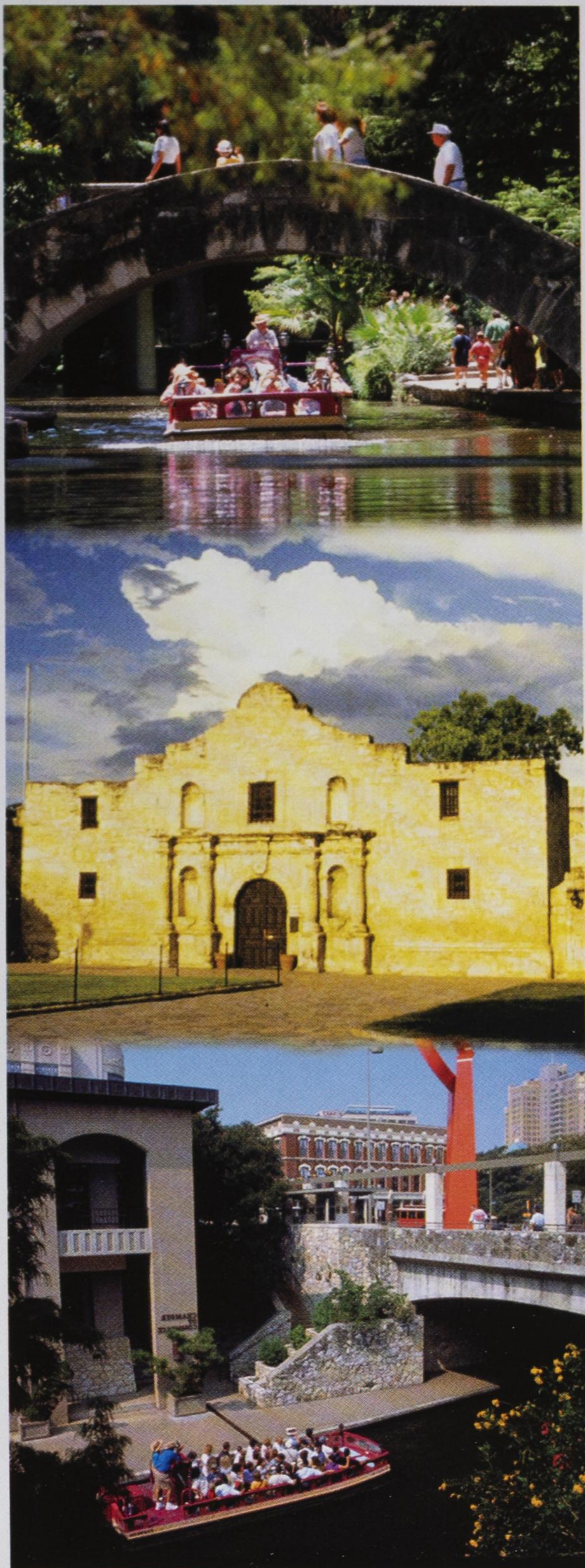
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EPIWAFER FOUNDRIES

IQE sets up 'one-stop shop' with Emcore

IQE, the epiwafer foundry based in Cardiff, UK, will acquire Emcore's electronic materials division (EMD) – provided that a £12 million (\$22.2 million) share offering all goes according to plan.

If that offering gets the go-ahead from IQE shareholders at an extraordinary general meeting on August 15, the UK firm will acquire the Somerset, NJ, operation, including 10 Turbodisc MOCVD tools and 50 employees. To finance the acquisition, 87.5 million ordinary shares in IQE will be offered for sale.

Buying EMD would position IQE as a "one-stop shop" for a wide variety of epiwafers, with a very strong offering in both the RF and optoelectronic sectors. Analysts from market research company Strategy Analytics and Edison Investment Research – of which IQE is a client – have both welcomed the deal as a positive one that IQE shareholders should endorse.

"We estimate that the deal could enhance [IQE's] earnings by about 80% in fiscal 2007," said Edison, while Strategy Analytics predicted: "[This] will increase IQE's share of the commercial epiwafer market by 77% in 2006. Overall demand for epitaxial substrates will grow 40% year-on-year in 2006 and 30% in 2007. IQE will have the necessary tools to generate net profits by the end of 2007."

Assuming shareholder approval, IQE will pay \$13 million in cash to Emcore initially, with the \$3 million balance to be paid off quarterly in four installments. Drew Nelson, the CEO at IQE, said that the deal represented a big opportunity for the company to add some complementary technologies and clients to its existing portfolio: "Emcore's customer base will increase IQE's customer reach to a broad spectrum of world-class RF manufacturers," he said.

Despite recommending the deal to IQE



IQE shareholders were set to vote on the share offering and EMD acquisition at an extraordinary general meeting near its Cardiff, UK, headquarters on August 15 – after this issue of *Compound Semiconductor* went to press.

shareholders, Strategy Analytics did sound one note of caution. "IQE will still need to overcome some significant obstacles before this acquisition makes it the largest commercial supplier of semi-insulating GaAs epiwafers," said Asif Anwar from the company.

Staff at both EMD and IQE are believed to be in favor of the deal, which appears highly complementary. IQE's Bethlehem, PA, facility has expertise in GaAs PHEMT production using MBE equipment, while EMD is focused on HBT processing using MOCVD. "We certainly believe that this is a major coup for IQE," said Chris Meadows, head of investor relations at the UK firm. "As far as we know, it makes IQE by far the largest independent epi foundry."

Emcore's development of integrated PHEMT and HBT structures, known as BiFETs, as well as wide-bandgap materials based on GaN, will certainly add diversity to IQE's existing products. While RF products make up the bulk of EMD's current production, the division's GaN capability, to which three MOCVD reactors are

dedicated, also suggests that cutting-edge optoelectronics could be a target application.

After selling its Turbodisc MOCVD equipment division to Veeco Instruments in 2003 and now its materials expertise, Emcore's strategy to move up the semiconductor value chain is increasingly evident. Despite the impending sale of EMD, Emcore remains a vertically-integrated company and will continue to manufacture epitaxial material for use in its fiber-optic and photovoltaic products.

Emcore COO Scott Massie said that the move would improve the firm's overall financial performance: "It will lower our cost base, improve gross margins and allow us to consolidate operations in New Mexico and California."

● IQE says that its revenue for the first half of 2006 should be in the region of £14.5 million, up 50% on the equivalent period in 2005. Drew Nelson said that sales would continue to grow in the second half of 2006, while the planned acquisition of Emcore's materials business should add significantly to that figure.

RFICS

RF Micro Devices eyes its billion-dollar target

RF Micro Devices (RFMD) says that it is "well on track" to meet its long-stated goal of annual revenue in excess of \$1 billion. Already the world's largest GaAs chip manufacturer, its current wafer fab expansion program will enable the firm to dominate the RFIC market as chip capacity becomes an increasingly useful weapon against competitors.

Surging demand from top-tier makers of cell phones drove a 50% year-on-year sales increase in the quarter ended June 30, as revenue reached

\$238.3 million. Under standard accounting methods, which included \$6 million in charges, RFMD posted a net profit of \$14 million.

An increase of up to 5% in revenue is being predicted for the current quarter, while the traditionally strong end to the calendar year should push total RFMD sales close to the billion-dollar mark in fiscal 2007 overall.

With the total market for mobile-phone handsets expected to grow by at least 15% this year, the top four manufacturers – Nokia, Motorola, Samsung and Sony Ericsson – are increasing their collective market share. RFMD has strong supply deals with all the top-tier phone manufacturers, and is clearly reaping the benefit of those relationships.

Currently adding the capacity to manufac-

ture GaAs PHEMT switches and GaN-based transistors, as well as its traditional volume GaAs HBT products, RFMD has taken out an additional \$25 million in financing to support the wafer fab expansion.

CEO Bob Bruggeworth said that this investment in capacity is allowing RFMD to capture the strong demand from customers, and added that the company is set to continue increasing its market share in handsets.

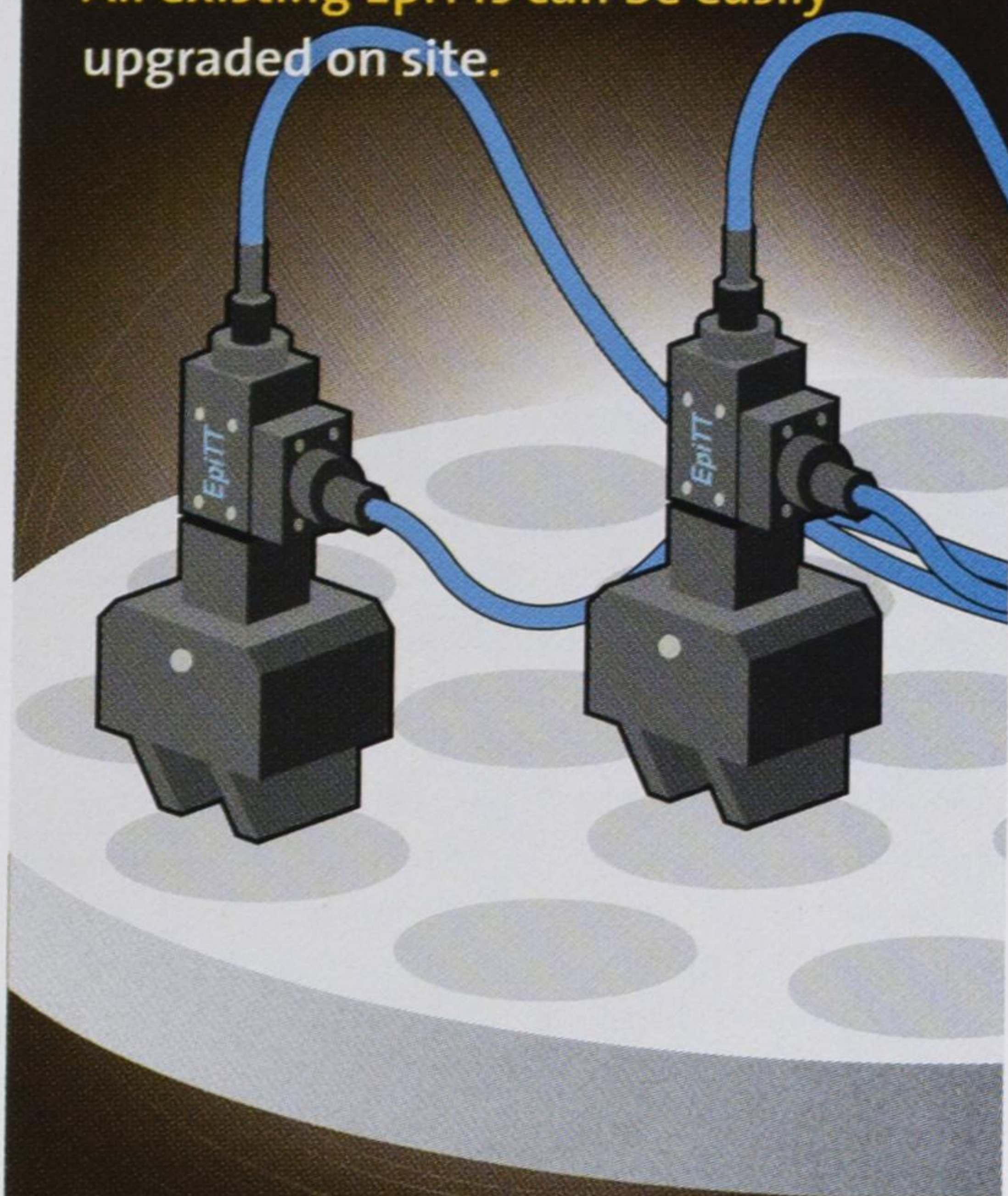
While RFMD has already begun sampling 50 W GaN-based amplifiers for wideband-CDMA base-station applications, Bruggeworth revealed that first-responder emergency services were also investigating power ICs based on the wide-bandgap material, for use in public mobile radios.

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INDUSTRY THE MONTH IN RFICS

SUBSTRATES

Nitronex supports GaN-on-diamond bid

Diamond wafer specialist sp3 Diamond Technologies has received \$750,000 from the US Missile Defense Agency (MDA), to pursue work on a diamond-based substrate material suitable for wide-bandgap electronics.

In collaboration with GaN wafer and component developers at Nitronex, the Santa Clara, CA, materials firm will use the phase II MDA contract to provide GaN on silicon-on-diamond (SOD) technology. The key benefit of diamond is its high thermal conductivity – 10 times that of silicon and more than double that of SiC, the most common substrate for GaN electronics.

In Phase I of the project, sp3 developed SOD wafers with a GaN top surface. It also performed detailed computer simulations, suggesting that a HEMT built on diamond would reduce junction temperature in the transistor by 80 K and increase power output by 37%. Nitronex, from Raleigh, NC, specializes in GaN-on-silicon devices and will be working with sp3 on future

development. “Nitronex will build active high-power devices as part of this phase,” said sp3.

“The ability to integrate a diamond thermal layer into our GaN-on-silicon strategy is of great interest,” commented Nitronex CTO Kevin Linthicum. “The fact that sp3 is offering us a known silicon interface on 100 mm wafers provides an easy migration to future productization and a pathway to scale to 150 mm wafers,” added Linthicum.

TriQuint Semiconductor will also be joining forces with sp3. Its team will model GaN-on-SOD to see how the material could help to generate the big increases in power and device efficiency needed by the US military.

sp3 is not the only company that is working on the development of diamond as a substrate solution for GaN electronics. Fellow Californian outfit Group4 Laboratories made the headlines earlier this year with the release of its GaN-on-diamond wafers.

AMPLIFIERS

TriQuint secures high-voltage US Navy deal

TriQuint Semiconductor is to improve the design and manufacturability of high-power, high-voltage amplifiers that operate in the S-band of frequencies. Armed with \$3.1 million from the Naval Research Laboratory, the chip foundry will first optimize the design of MMICs featuring advanced transistors, as well as a high-power amplifier operating at 2–4 GHz.

In the second part of the exclusive 20-month program, manufacturing improvements will be the major focus. This will include reducing cycle times and improving wafer and device yields.

The Hillsboro, OR, firm has been developing high-voltage PHEMTs since 2000 and has developed a similar process to fabricate devices that operate in the higher-frequency

X-band, which spans the 8–12 GHz range.

TriQuint's director of R&D Tony Balistreri says that the 24 V technology will provide the high power density and efficiencies required for near-term naval applications including phased-array radar, electronic warfare and covert communications. Gailon Brehm, the company's military business unit director, added: “This enhanced S-band technology provides the higher voltage needed for both military and commercial applications at frequencies below 6 GHz.”

TriQuint will carry out the developmental work at its GaAs facility in Richardson, TX, where it houses a 4 inch wafer fab. It also operates a 6 inch facility in Hillsboro, OR.

CONVERGENCE

\$7 million boost for III-V materials development

The US-based university–research consortium Semiconductor Research Corporation (SRC) has set up the Non-Classical CMOS Research Center to develop III-V materials for improving the capability of CMOS.

The center, which has \$7 million of funding over three years, will be headed by the University of California at Santa Barbara, and will draw on expertise from colleagues in San Diego and the universities of Stanford, Minnesota and Massachusetts-Amherst.

“We plan for the Non-Classical CMOS Research Center to ensure that Moore's Law will be alive and well for several generations,” said Jim Hutchby, director of the unit within the SRC that is responsible for narrowing the options for carrying CMOS to its limit.

“When the day comes that Moore's Law for classical silicon CMOS is no longer a viable solution, we'll have developed a new set of materials and devices for improvements to the speed and power of the historically successful CMOS technology,” he added. Results from the research are expected to have a big impact on chip manufacturing between 2012 and 2014.

This year's Key Conference will include a session dedicated to the convergence of III-V and silicon. See page 4 for details.

FINANCIAL RESULTS

Skyworks wary of weaker demand

US-based RFIC manufacturer Skyworks Solutions posted \$197.1 million in sales for the quarter that ended on 30 June, a sequential increase of 6% and a rise of around 3% on the same period in 2005.

That translated to a net profit of \$3 million, down from \$7.4 million a year ago. However, the Woburn, MA, company was hit by a stock compensation charge of \$3.7 million in the latest quarter, which decreased the net profit.

Despite the solid quarter and the promise of volume ramps for Samsung and Sony Ericsson phones, Skyworks financial chief Allan Kline warned that the company would see a weakening demand in the current quarter. Kline now expects sales for the final quarter of the fiscal

year to come in at around \$197–200 million.

Meanwhile, Skyworks' rival Anadigics enjoyed a sales increase of 68% on the year-ago quarter due to the strong market for high-end wireless components, including those based on its proprietary GaAs BiFET structures.

The Warren, NJ, GaAs chipmaker's second-quarter sales reached \$40.2 million, resulting in a net loss of \$2.8 million. CEO Bami Bastani expects the upwards momentum to continue and the firm to deliver a sequential increase in sales of 7–9% in the current quarter.

Although this is not forecast to result in a formal net profit, Anadigics could break even or post a slight profit, based on adjusted pro-forma accounts.



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...Romanek leaves Freiberger

Klaus Romanek, the CEO of leading GaAs substrate supplier Freiberger Compound Materials (FCM), is leaving the German company. Following three years at the firm, Romanek will be replaced by Hermann Schenk, who joined the company as recently as June. However, Romanek says that he will be supporting FCM for the remainder of 2006.

...SiGe delivers Wi-Fi integration

SiGe Semiconductor, the Canadian manufacturer of wireless components for RF applications, is targeting the dual-band Wi-Fi sector with a highly integrated front-end module. The latest in its "RangeChargerT" product line, the SE2559L front-end is designed for the IEEE 802.11 b/g specification. It is 60% smaller than competitive products and claims to cut the typical bill of materials cost by 15%. The module integrates a power amplifier, power detector, two switches and matching circuitry.

...InAs PHEMT clarification

On page 28 of our July issue, we reported that NRL researchers had broken the record for microwave amplifier efficiency with a new InAs PHEMT design. This was incorrect – the device actually showed a record low dissipation, but it had insufficient gain to qualify as an efficiency record.

...Picogiga on the up

GaN-on-silicon wafer specialist Picogiga saw sales rise sharply for the quarter that ended on 30 June. According to its parent company Soitec, its wide-bandgap subsidiary made sales of €2.7 million (\$3.4 million) into RF applications,

up 110% on the same period last year.

Soitec itself launched the industry's first strained-SOI wafers at July's Semicon West show in San Francisco. The French firm says that the wafers are available now for sub-65 nm CMOS processing.

...Skyworks on EDGE with Samsung

Skyworks says that it is supplying Samsung with its Helios EDGE radios as the Korean electronics giant pursues an aggressive ramp-up of 20 different mobile handsets. The Helios subsystem from the Woburn, MA, GaAs chip manufacturer comprises an RF transceiver, power amplifier (PA) and PA controller. Samsung is the world's third-biggest maker of mobile phones, behind Nokia and Motorola.

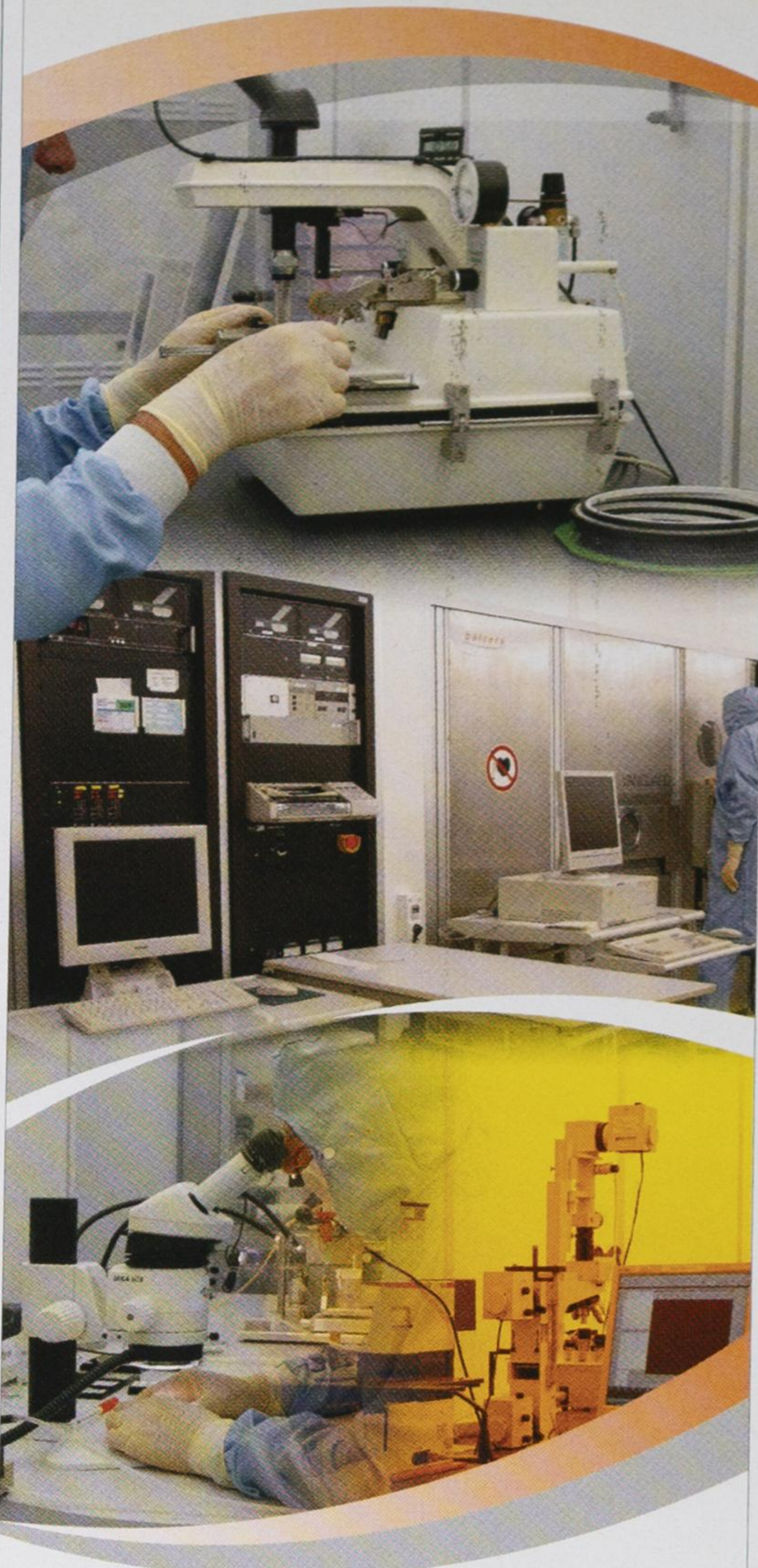
...RFMD powers iconic gadget

Sharp Corporation's "Sidekick 3" mobile device, the follow-up to the iconic handheld platform popular with US fashionistas, features GaAs-based components from RF Micro Devices. The gadget is expected to have a monthly production run of 100,000, and features one of the Greensboro, NC, firm's dual-mode EDGE power-amplifier modules. RFMD also provides the RF modulator and driver, as well as Bluetooth functions.

...3G China boost for Anadigics

GaAs chipmaker Anadigics is supplying InGaP heterojunction bipolar transistor power amplifiers (PAs) to Chinese handset maker ZTE for use in its F866 wideband-CDMA phone. The AWT6252 4 × 4 mm PA module optimizes efficiency for different output power levels and offers a shutdown mode with low leakage current.

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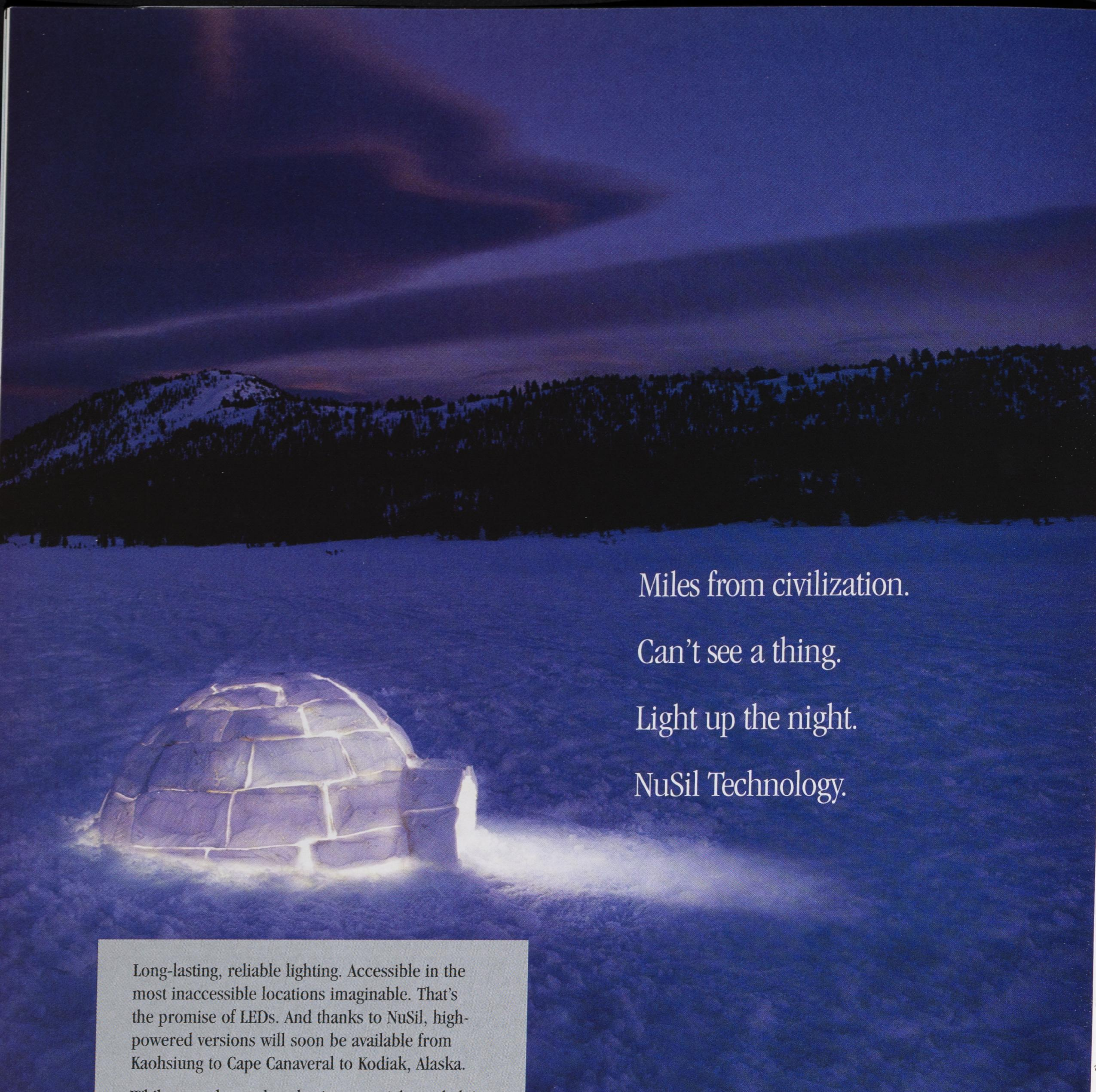
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EQUIPMENT

Backlights power Veeco revival

Epitaxy equipment vendor Veeco Instruments has revealed a sharp upturn in orders for MOCVD and MBE machines. The company, whose epitaxy divisions are located in St Paul, MN, and Somerset, NJ, posted just under \$18 million in sales of III-V process equipment for the quarter that ended on 30 June, up from \$15 million in the preceding quarter.

Although that represented only 16% of Veeco's total sales, its order book showed that a much stronger performance from the compound semiconductor divisions is in the pipeline. Equipment orders doubled since the same period in 2005 to reach \$27.4 million.

According to Veeco CEO Edward Braun, the strong order book has been bolstered by the emerging market for HB-LED backlighting of small-area flat-panel displays.

Meanwhile, high-brightness LED chip man-

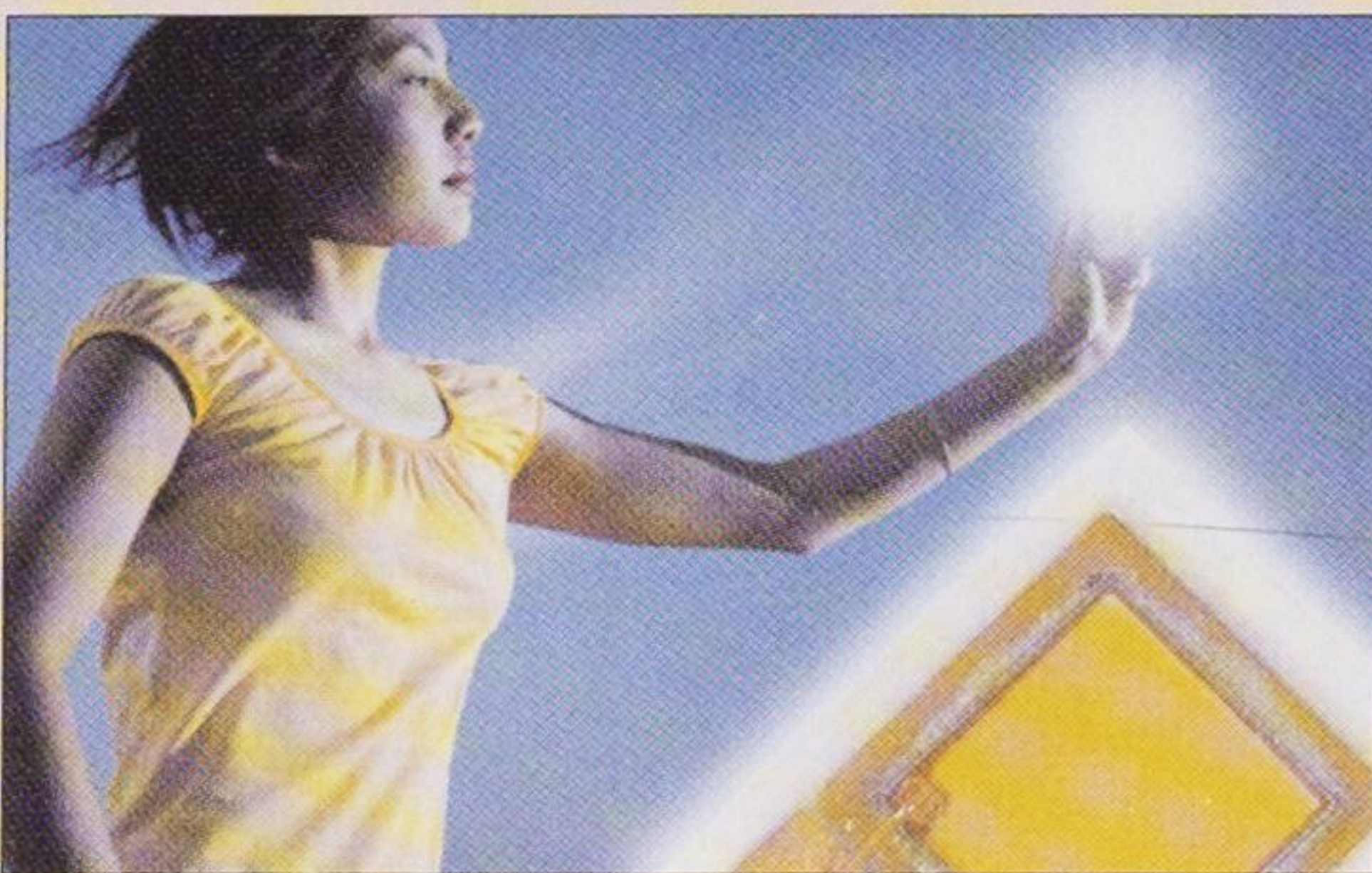
ufacturer Philips Lumileds has purchased another high-throughput MOCVD machine from Aixtron subsidiary Thomas Swan. The 30 x 2 inch CRIUS tool is the latest purchase of a four-year commitment to buy systems from the German firm and it will be used to manufacture GaN-based high-brightness LEDs.

CRIUS is the latest reactor design from the equipment vendor and uses Aixtron's "integrated concept" approach. Improved features are said to include its smaller size, easier operation and maintenance, and better reliability.

LED manufacturer Epitech has also ordered a 30 x 2 inch CRIUS platform to boost production volumes of ultra-high brightness GaN-based emitters. "Our new plans require a versatile, high-throughput machine to give us the increased capacity needed to meet growing customer demand," said president Semi Wang.

Two superbright LEDs for camera flash applications have been developed by Osram Opto Semiconductors. The German chip manufacturer says that the new Oslux and Ceramos products are ideal for use in mobile phones, where space is at a premium.

Both of the emitters are based on the company's 1 mm² ThinGaN chips. The Oslux operates at a high peak current of 1.5 A and with a luminous efficacy of 48 lm/W.



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...BridgeLux takes on bulbs

US-based high-power LED chip developer BridgeLux has introduced its KO family of blue devices, including what it claims is the only 1.5 mm chip available in production volumes today. When operating at up to 1.2 A in conjunction with a phosphor, the so-called "bulb buster" range of devices produce around 140 lm of white light, equivalent to an efficacy of around 40 lm/W.

...Lighting policies

The International Energy Agency (IEA) in Paris, France, has outlined the policies that will be needed to implement efficient lighting technologies, including LEDs, and help to reduce energy waste and CO₂ emissions. The IEA book, *Light's Labour's Lost*, documents the policies and is part of the response to the G8 Gleneagles Plan of Action agreed in July 2005.

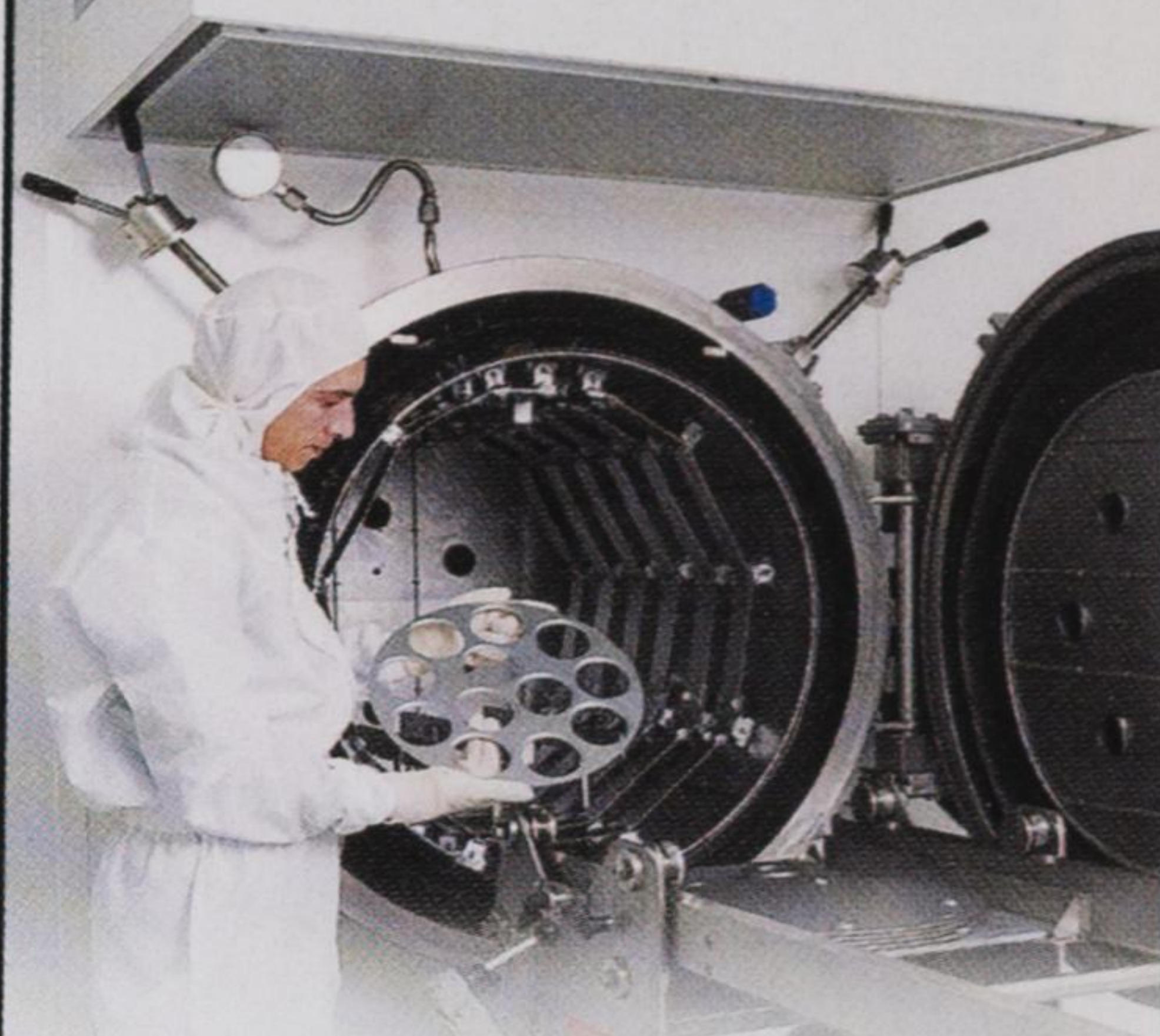
...Cree warning

LED giant Cree blamed production limitations and a change in sales mix as it warned investors of a lower-than-expected profit in its latest financial quarter. "We knew that this was going to be a transition quarter, but it proved to be more challenging than we expected," admitted CEO Chuck Swoboda.

...DoE offers more funding

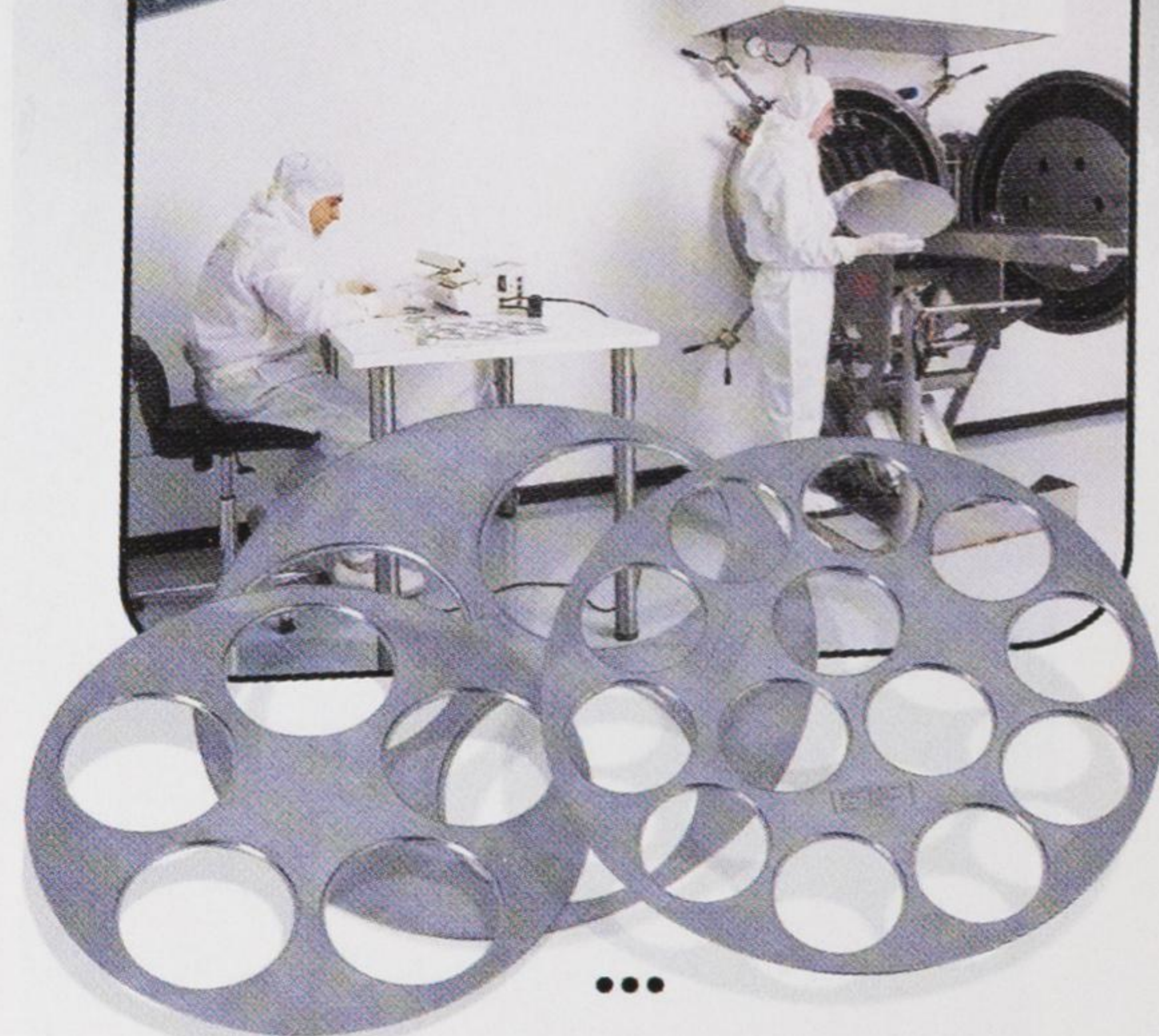
The US Department of Energy (DoE) is seeking more applications for funding from the LED community under its solid-state-lighting development initiative. Jim Brodrick from the DoE says that it is particularly keen to receive applications from industrial organizations for high-priority product development work. "Technical activities are to be focused on a targeted market application with fully defined price, efficacy and other performance parameters," he added.

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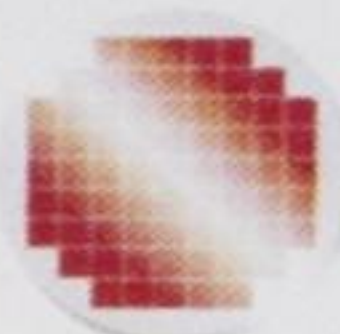
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MERGERS AND ACQUISITIONS

OCP snaps up Taiwan's Gigacomm

Optical Communication Products (OCP) is to acquire Taiwan-based laser, detector and module vendor Gigacomm for \$20 million in cash.

Based in Woodland Hills, CA, OCP closed its dilute-nitride VCSEL operation earlier this year, but hopes to fulfill its intention to move into the emerging market for fiber-to-the-home (FTTH) equipment through the deal.

Gigacomm is said to be the leading supplier of FTTH modules in Japan, the world's largest market for such gear. NTT has a vigorous plan for deployment of the technology and a recent market report from *Heavy Reading* predicted that by 2011, 86 million households will be hooked up with an FTTH link globally.

The Taiwanese firm is located in the Hsinchu Science-based Industrial Park, and also sells III-V optical components including VCSELs, edge-emitting lasers and photodiodes to some of Japan's leading communications equipment

vendors, including Mitsubishi Electric.

OCP's chairman Muoi Van Tran said, "The acquisition gives us increased capacity through [Gigacomm's] integrated manufacturing facility, an important second – and competitive – source of lasers, and a talented pool of engineers and management."

Mitsubishi Electric's purchasing department has bought more than a million modules from Gigacomm over the past year. With investors including Epistar and Taiwan's Industrial Technology Research Institute, Gigacomm will become a wholly-owned subsidiary of OCP. Gigacomm CEO Jacob Tarn will remain in charge of the operation.

● For the quarter ending 30 June, OCP posted revenue of \$14.9 million and a net loss of \$0.4 million. Interim CFO Philip Otto has been promoted to become the company's new CEO, while Muoi Van Tran shifts to become CTO.



The UK's Centre for Integrated Photonics (CIP)

has won a contract to develop optoelectronic parts that could form part of a portable DNA analyser for crime-scene officers.

CIP, which has a rich heritage in III-V optoelectronics expertise, received £215,000 (\$396,000) from the Engineering and Physical Sciences Research Council in the UK to integrate micro-fluidic and active optical components and create a disposable device.

After DNA is separated by a chemical technique called electrophoresis, an LED and photodiode will create and detect fluorescence in the sample. If it works, the "lab-on-a-chip" could allow DNA evidence to be extracted from a crime scene prior to contamination.

DETECTORS

Advanced Photonix projects rapid sales growth

Optoelectronic component manufacturer Advanced Photonix says that it expects sales of its detectors to grow by between 15 and 20% in the next 12 months.

The company, which makes silicon-, GaAs- and InP-based avalanche photodiodes and PIN detectors, currently runs wafer fabs in both Camarillo, CA, and Dodgeville, WI, but it is in the process of consolidating its chip-making operations to a single facility in Ann Arbor, MI.

In its fiscal 2006 results for the 12 months ended on 31 March this year, the company reported sales of \$23.6 million, up strongly from \$14.8 million last year and mostly a result of its March 2005 acquisition of Picometrix.

That deal has enabled Advanced Photonix

to penetrate the telecommunications market, while it has also witnessed strong growth for industrial sensing and homeland security applications of its detectors.

CEO Richard Kurtz commented, "Fiscal 2006 has been an exciting year. We have [gone] from a single product line to a three-product-line company. Looking forward to 2007, we are projecting revenues to grow by between 15 and 20% over 2006."

Overall, Advanced Photonix reported a net loss of \$3.5 million for fiscal 2006, compared with a net profit of \$5.3 million in the previous year. This was largely a result of increased research and development costs, and a variety of one-time charges and write-offs.

MARKETS

Ethernet boom to drive 10G ramp

A new analyst report claims that the market for 10 and 40 Gb/s optical communication modules based around semiconductor lasers and modulators will quickly expand from \$0.9 billion this year to reach nearly \$4.3 billion in 2011.

According to the forecasters at Communications Industry Researchers (CIR), the main reason behind the expected boom will be the deployment of products for use in short-range 10 Gb/s applications. "The biggest story for 10G is the growth in Ethernet port sales, fuelled by the need for aggregating the surging number of ports on both business and consumer computers," said CIR, citing recent increased optimism among optical networking equipment vendors and component manufacturers.

The impact of the Ethernet boom is apparent in CIR's detailed market projections. For example, in 2006 it expects sales of high-speed (10 and 40 Gb/s) modules for wavelength division multiplexing (WDM) and Ethernet applications to be in the same ballpark, worth \$266 million and \$398 million, respectively.

However, in five years the disparity between these two markets will be made clear. In 2011,

CIR predict that the WDM market will have grown a healthy 179% to reach \$743 million. But compare that with the Ethernet segment, which is expected to have grown a staggering six-fold to hit \$2.3 billion over the same period.

2008 will be the critical year when much of this growth occurs, with the Ethernet market for 10 Gb/s modules set to more than double from the 2007 figure to more than \$1.5 billion. Although the market for modules does not equate directly to that for manufactured semiconductor lasers, many module suppliers also make optical components based on III-V materials.

Chief among these are firms such as JDSU, Finisar, Avago and Opnext. Since it supports all the standard module platforms, and is also working on the new "SFP+" form factor that CIR expects to challenge today's standards, Sunnyvale-based Finisar may be in the best position to exploit the rapid market expansion. Avago and JDSU are currently regarded as the two biggest suppliers in the sector.

The report also predicts that 26 million ports for 10 Gb/s Ethernet will ship in 2011, equating to an average price just shy of \$90 per port.

UV LEDs

The Fox Group adds weight to ultraviolet push

US company The Fox Group has released a new series of products based on 350 nm LEDs. The products come in a number of forms, including 2 inch diameter epiwafers, 320 × 320 µm die, a "power pack" of 60 die and as packaged lamps.

The Deer Park, NY, firm says that the hydride VPE deposition process it uses to manufacture the devices ensures that the LED emission wavelength stays stable, despite changes in the drive current applied. The average output power of the LEDs is 200 µW for a drive current of 20 mA and a forward voltage of 4.5 V, rising to 500 µW at 50 mA. Applications include analysis of blood serum, as well as generating fluo-

rescence in biomedical detection systems.

Ultraviolet LEDs are becoming increasingly deployed in a range of applications, while AlGaIn epiwafer manufacturer Sensor Electronic Technology (SET) has signed a volume manufacturing and packaging deal with the Korean company Seoul Optodevice. Because of their shorter wavelength, SET's "deep-UV" LEDs can also be used to sterilize air, water or contaminated surfaces. These emerging markets are expected to realize sales of several million ultraviolet LEDs a year in the near future.

● See "Behind the headlines" on page 12 of this issue for further details.

VENTURE CAPITAL

Cascade Technologies bags \$4.6 m in funding

Cascade Technologies, the Stirling, UK, developer of quantum cascade laser systems for sensing applications, has gained an additional £2.5 million (\$4.6 million) in funding to develop further market opportunities.

Braveheart Ventures led the funding round by investing £1 million, alongside the Scottish Enterprise Scottish Co-investment Fund. Bank of Scotland Corporate's Growth Equity team

and Partnerships UK invested £750,000, with accountants Ernst and Young acting as advisors in the deal.

Cascade says it has developed and patented the world's first real-time technology for detecting gas, emissions and explosives through the use of quantum cascade lasers. The technology offers unprecedented levels of sensitivity and the ability to quickly analyse complex gases. "A number of commercial agreements have already been secured, proving that the commercially-focused management team we have in place is able to deliver," said chief executive John Fuller. Thanks to the investment, Cascade will create up to 14 jobs in the coming year.

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UV LEDs

Bug-killing chips set for production ramp

An equity deal and exclusive supply relationship between UV-LED innovator Sensor Electronic Technology and Korea's leading LED packager will spark a host of new applications by reducing the cost of the devices, writes **Michael Hatcher**.

One of the many futuristic applications touted for compound semiconductor devices in recent years has been the bug-killing capability of ultraviolet (UV) light emitters. Mercury lamps are already used to rid water and surfaces of bacteria, but concerns over mercury pollution, as well as the potential for semiconductor devices to deliver far more compact, efficient and portable systems, has prompted the development of AlGaIn-based LEDs.

Columbia-based start-up firm Sensor Electronic Technology Inc (SETI) and its collaborators in Asif Khan's research team at the University of South Carolina have pioneered the development of specialty deposition techniques, epiwafers, chips and even lamps to this end.

For the first time, that technology is now set to make the transition from development to industrial-scale production. When SETI looked to attract new investment recently, the Korean firm Seoul Semiconductor showed its interest. "We needed to find somebody to do high-volume chip manufacturing, and they wanted to become the number-one player in this emerging market," SETI CEO Remis Gaska told *Compound Semiconductor*.

Gaska struck an equity and supply deal with Seoul Optodevice Company (SOC), the chip-making subsidiary of the parent firm. While he has given up some of the equity in SETI, Gaska remains the majority shareholder. In return, SETI will supply AlGaIn-on-sapphire epiwafers to SOC exclusively, from which the Korean firm will process UV emitters operating at five key wavelengths between 340 and 255 nm.

Although SOC already does epitaxy for the visible-range LEDs that its parent company sells, SETI will retain this part of the operation when it comes to the UV devices. SETI's technology is highly specialized and the epiwafers are grown using the company's proprietary migration-enhanced MOCVD approach.

SOC's executive vice-president Jaejo Kim says that the company currently produces around 60 million chip die per month, and that this is set to ramp to 100 million. Exactly how much of that increase will be attributable to UV LED production is difficult to predict at this early stage, but Kim expects that applications such as air and water purification will demand "several tens of millions" of chips per year. At those volumes he believes that the deep-UV LEDs could be manufactured for as little as \$10 per piece, depending on the precise wavelength required.

That kind of price should attract the interest of UV lamp and system developers, who have indicated to *Compound Semiconductor* that a price lower than \$10 for a 0.5 W lamp would ultimately be required for applications such as portable disinfection systems to become economically feasible.

"The price of UV LEDs will [now] go down much faster than if we had decided to do all of the production in-house," admits SETI's Gaska, although he points out that the cost will be highly dependent on the specific nature of the application, and the lamp design.



Clean drinking water is critical to life, and deep-UV LEDs could one day be used in portable lamp systems to disinfect supplies. Here, Church World Service staff are inspecting a village well in Indonesia after an earthquake in late May.

Now focused on production issues such as yield improvements, a ramp-up in epiwafer manufacture and extending device lifetimes, SETI is also set to move up the value chain to improve lamp designs.

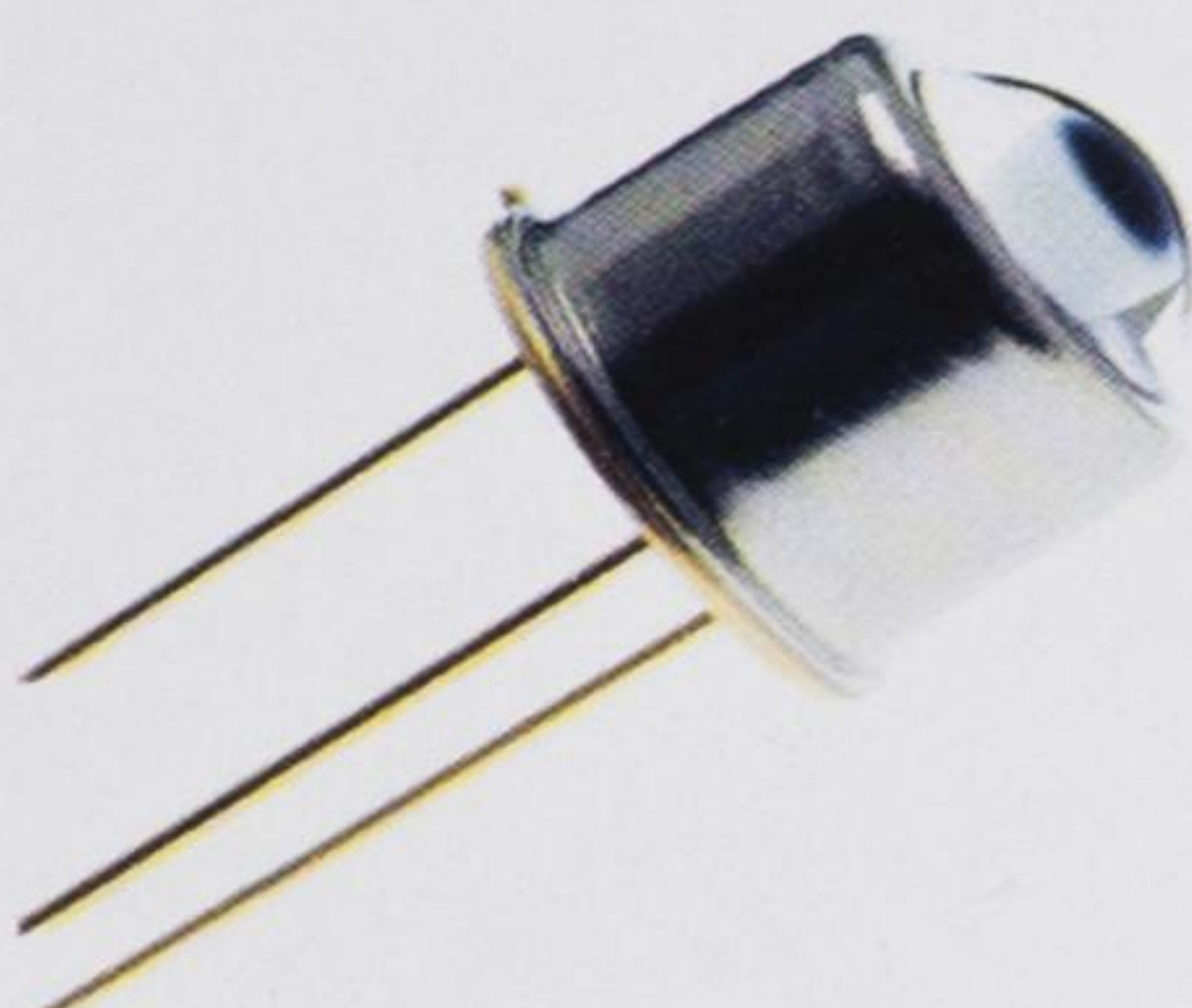
Confident of demand for SETI's epiwafers ramping up before the end of this year, Gaska says that there is still a major need to educate potential customers about the wavelengths that are suitable for the different applications that UV LEDs could serve. This is, at least in part, because of the restrictions inherent to using a mercury lamp, which produces light centered at 254 nm but is used for a wide variety of applications that this particular wavelength may not actually be best suited to.

Devices emitting at 340–365 nm can be used to detect biological species, and for the UV curing of materials such as adhesives. Because the aluminum content of the LED is not so high in this range, the devices are somewhat easier to produce. With less strain in the resulting epiwafers, their production can be scaled up more easily.

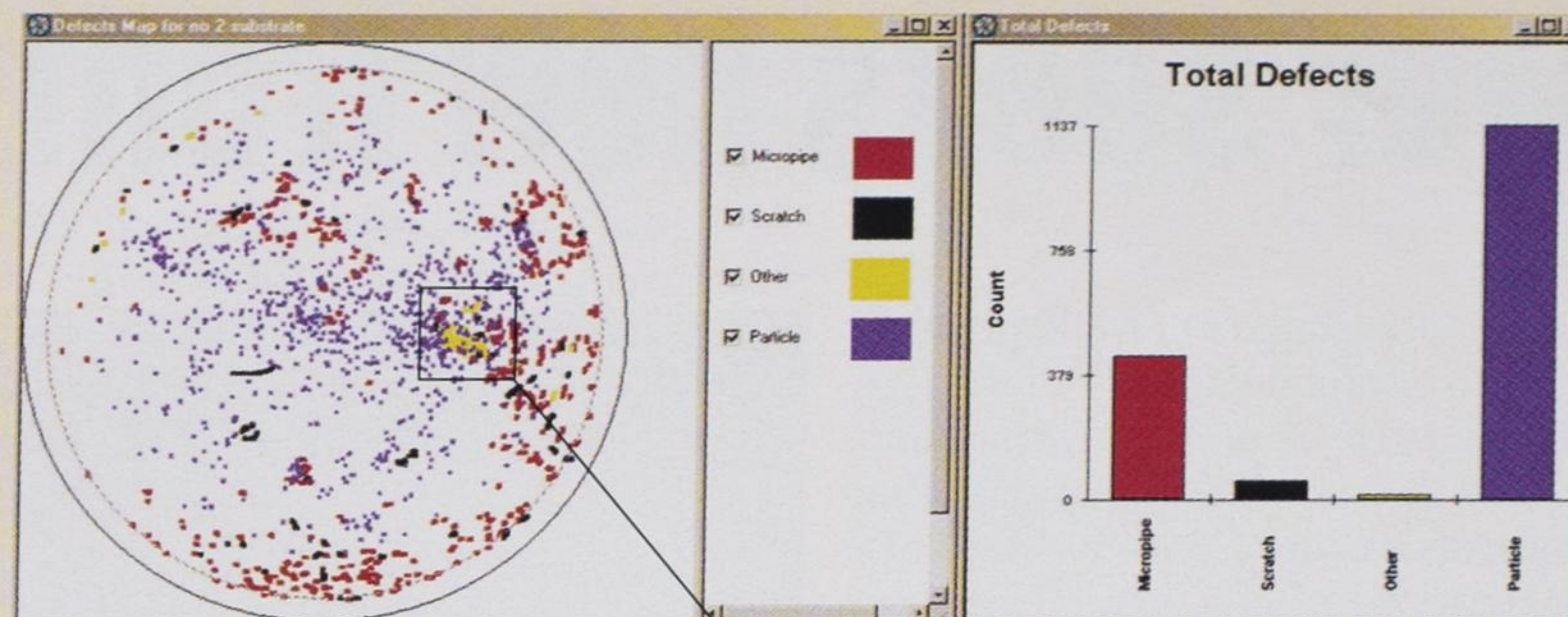
Between 280 and 320 nm, biomedical applications such as protein analysis are possible. Gaska says 310 nm could become a critical wavelength, because this is the light to which human skin is most sensitive. It could be useful for treating medical conditions such as psoriasis. Radiation below 280 nm is the critical region for germicidal applications such as water purification, and this is the range where UV LEDs are ultimately expected to find their biggest market.

Gaska and colleagues are now focused on improving the lifetime of 280 nm devices, and hope to set a benchmark of 5000 hours by the end of 2006. They are also looking to demonstrate the feasibility of a germicidal lamp based on their own design. "We are looking at the effectiveness of the 254 nm line – there may be a better wavelength to use," Gaska said.

SETI and SOC both have a number of obstacles to overcome, but a successful partnership between the two could unlock the emerging market for deep-UV LEDs.



The deep-UV LEDs set for volume manufacture at Seoul Optodevice Company.



Particle on-epi:
 ➤ bright scatter
 ➤ dark reflected
 ➤ same optical size

Candela

Recipe: Recipe 3

Wafer:

Instrument ID:

Total Defect Count

	Microscope	Scratch	Other	Particle
Count	432	58	13	1138

Summary Defect Report by Bin

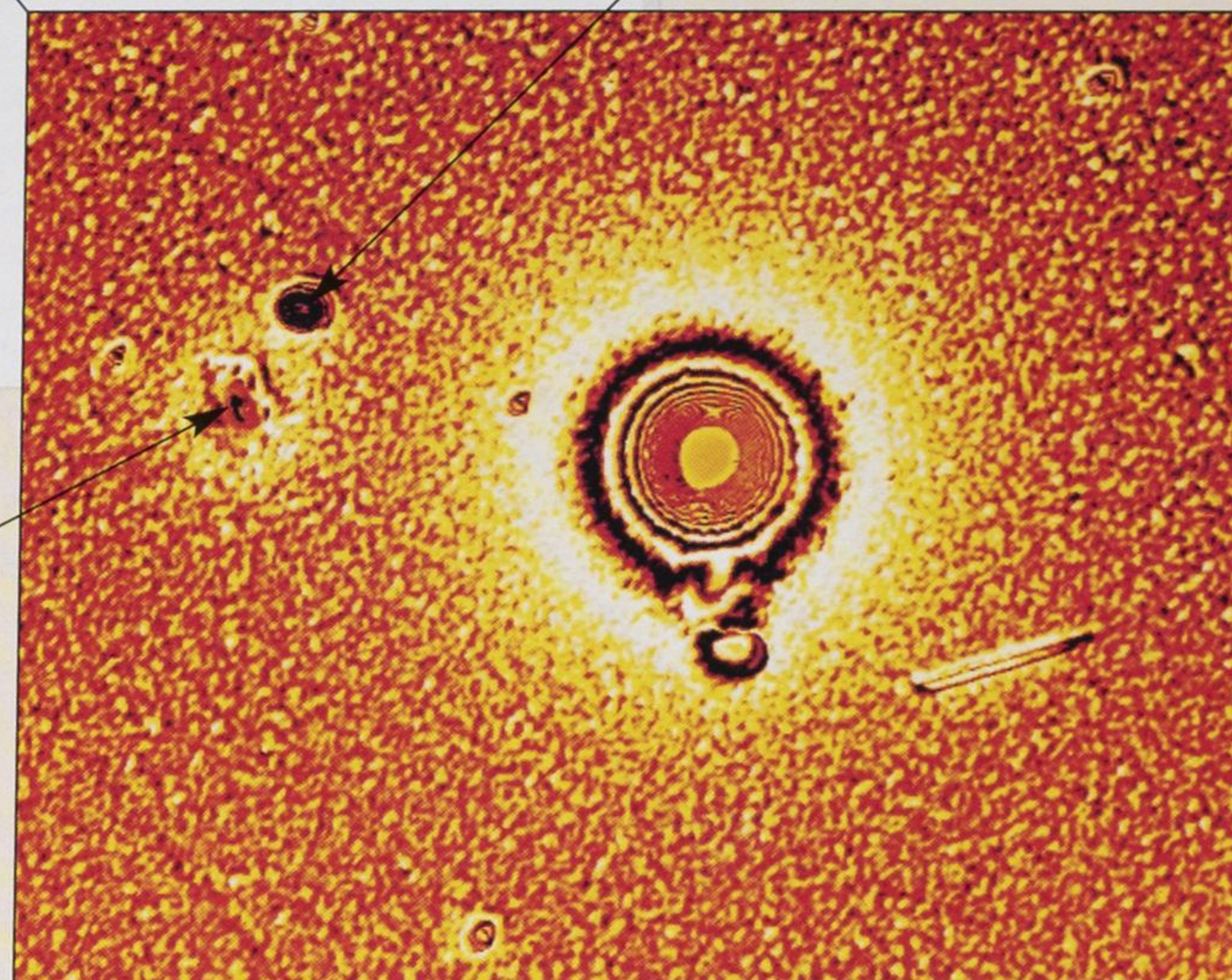
Defect Count by Bin

	Microscope	Scratch	Other	Particle
Bin 1				641
Bin 2				387
Bin 3	196	23		85
Bin 4	115	11		25
Bin 5	121	24	13	
Total	432	58	13	1138

Bin Size Legend

	Microscope	Scratch	Other	Particle
	Area(μm²)	Area(μm²)	[Pixels]	Area(μm²)
Bin 1	1000.00	1000.00		300.00
Bin 2	2000.00	2000.00		500.00
Bin 3	5000.00	5000.00		1000.00
Bin 4	10000.00	10000.00		2000.00
Bin 5	15000.00	15000.00		5000.00

Particle in-epi:
 ➤ bright scatter
 ➤ dark reflected
 ➤ smaller scatter signature
 (film thicker over particle)



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OPTOELECTRONICS

Photonic power seeks new frontiers

Despite distinctly *Star Trek* undertones, photonic power conversion is a very real technology. More than 10,000 systems are already deployed and a number of promising new applications are in the pipeline, hears **Michael Hatcher**.

You might think that by Googling “photonic power”, you’d find references to exotic weaponry of the like found on board the *USS Enterprise* and fired at the command of Captain Kirk. You’d be wrong, though. What Google actually throws up is a lot of links to details of a technology whose main application is far more prosaic.

Photonic power has been around for 10 years now, with more than 10,000 system deployments. Many of these are at electric utilities companies, where the technology provides a useful way to help measure the very high current delivered along power transmission lines.

The basic idea is to provide power to the measurement system photonically rather than electrically. Power can be delivered via an optical fiber instead of a regular copper cable. For utilities companies, the main advantage is a significant reduction in the weight and size of the measurement system.

Like any photonic system, it relies on three components. One to emit the light, a second to transport it over the required distance and a third to collect photons. In a photonic power system, the key element is the light collector and this is the III-V device that has been developed and tailored to a specific function. That’s because the requirements are somewhat different from both conventional detector and solar-cell technology.

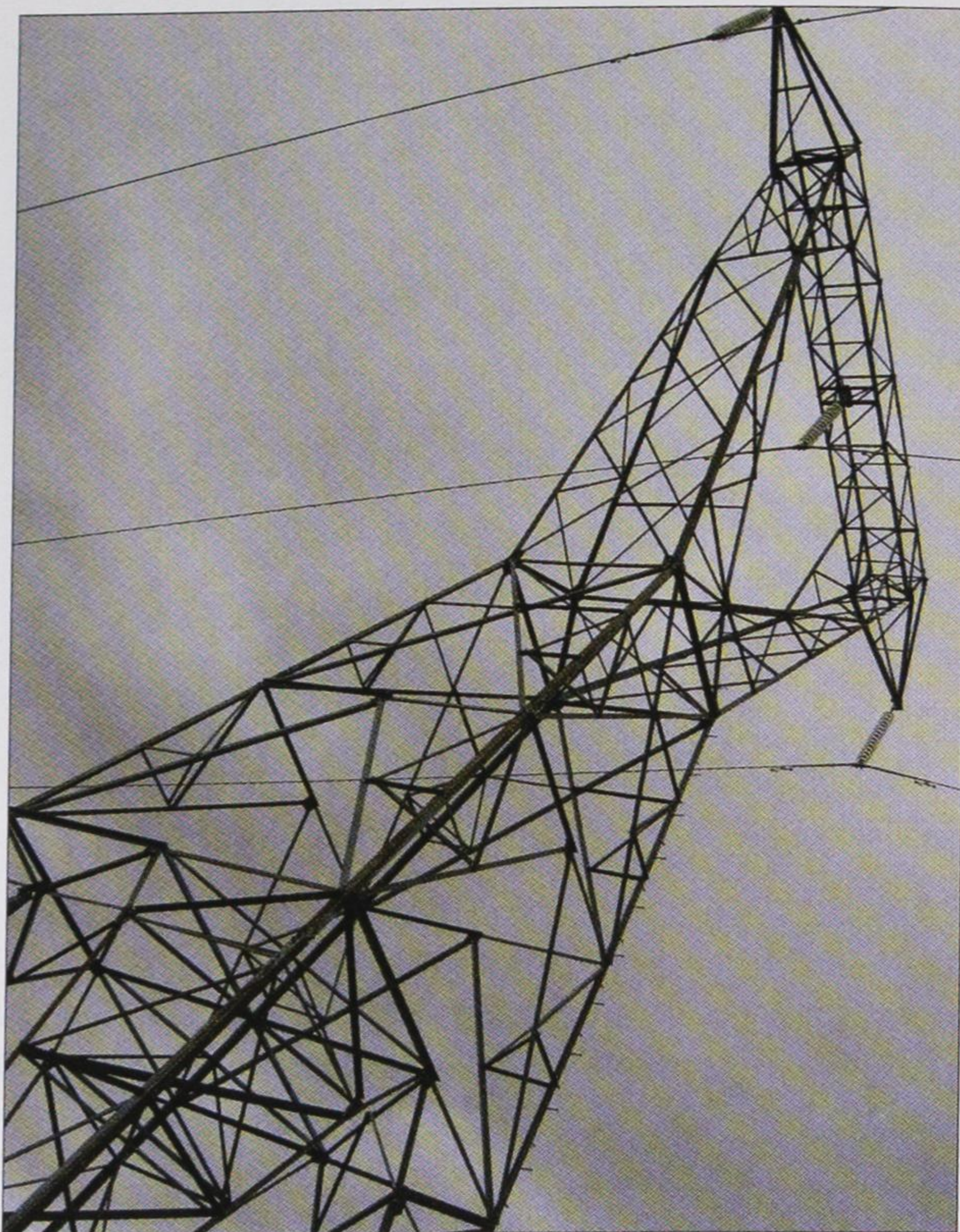
To be a useful detector, the photonic component only has to convert light into electrons to produce a measurable current. Because power also relies on voltage, the make-up of the light collector has to be adapted from the simple detector structure. And whereas a solar cell is designed to respond over a wide spectral range, a photonic power converter has to concentrate only on the very narrow part of the spectrum in which the laser or LED light source is operating.

The chief exponent of photonic power is Jan-Gustav Werthen, an engineer with a background in the development of multi-junction solar cells at Varian before it exited the semiconductor business. After that, Werthen set up his company Photonic Power – at the time a two-person operation involving just the engineer and his wife.

An innovative force

Last year, JDSU acquired Photonic Power. “I think that this is the best thing I’ve ever done,” Werthen said of the deal. “It’s just terrific. We’re a very innovative force within JDSU and we’ve been well received. I can see a long list of good things going forward here.”

Werthen explains that most of the systems already deployed are used to power sensors in environments that are either not suited to power delivery via copper cables, or where very bulky equipment would be required. “For an electric power utility application, you want to measure a current of maybe 1000–3000 A and a voltage of 100–500 kV,” he said. “The normal way to do that would be to use an instrument transformer to go from a high current and high voltage to almost no voltage and a very low current.”



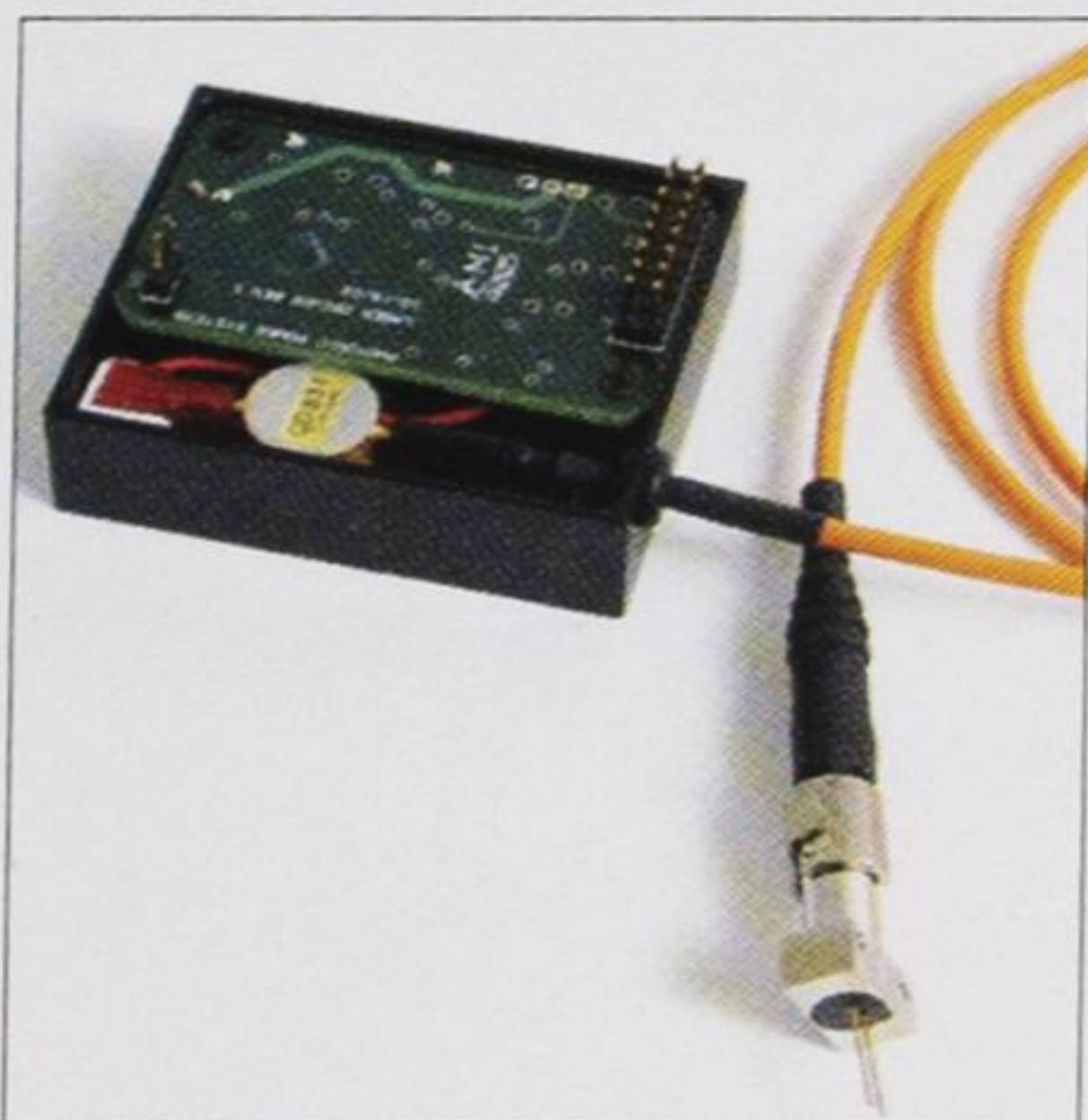
Using photons to provide power dramatically reduces the size and weight of the current-measurement systems that are used to monitor electrical transmission networks.

“The alternative that we provide to systems integrators like Siemens is for this very-high-end application. The advantages are that they get a lightweight system of less than 50 kg replacing something very bulky, of the order of 2000 kg.”

With a consumption of only 50–150 mW, sufficient power can be provided very comfortably by a 0.5 W laser and the converter, which has a typical efficiency of around 30%.

“Fiber-optic [power] installations happen in places like China, India and South America,” said Werthen, explaining that it is the relatively new power transmission networks in the developing world that provide the biggest market opportunity because the lower transmission voltage of 100 kV is increasingly used in these geographies. He estimates the total available market to be in the region of hundreds of thousands of systems per year, which translates to an annual market value for systems worth more than a billion dollars.

Since the JDSU acquisition, the number of applications being targeted is increasing to include electromagnetic field sensing. “People do care about the electromagnetic fields that are emitted from a hairdryer, a radio next to your bed, or a cell phone,” Werthen said. “These industrial sensors have hitherto been battery powered, but it can be a hassle to change the batteries.”



Most photonic power systems use a 0.5 W laser and have a photovoltaic efficiency of 30%.

That application might require as many as 50,000 units per year over the next four to five years, estimated Werthen. "It's considerably smaller than the utilities market, but on the other hand it is a sizeable market for anything involving lasers in the 0.5–1 W range."

The third market that has emerged over the last couple of years is in the field of medicine and has arisen because of the increasing use of MRI scanners. Because these scanners rely on very high magnetic fields of 3 Tesla or more, metal components such as copper wires are not welcome inside the imagers, so doctors need to find an alternative way to power sensors used to monitor patients. "The value proposition is that fiber cannot only power the sensors, but also send information back," Werthen said, "and you can add more channels to increase the resolution and sensitivity of the system."

The smallest of the three current commercial markets, photonic power systems could in theory be deployed in the installed global base of around 15,000 MRI scanners and expand as their use continues to grow.

Material options

It is the details of each specific application that determine the types of device and materials that Werthen and colleagues design into their components and systems.

Around 90% of deployed systems are designed to operate near 810 nm, because this is where sufficiently powerful lasers can be found at the cheapest prices. The power converter chip used for this wavelength is based on AlGaAs/GaAs. If the power requirement for a given application is higher than normal, the preferred solution shifts to a longer wavelength. "If you go to 940 nm then you have a plethora of lasers at 5 or 10 W available, so it becomes a question of power."

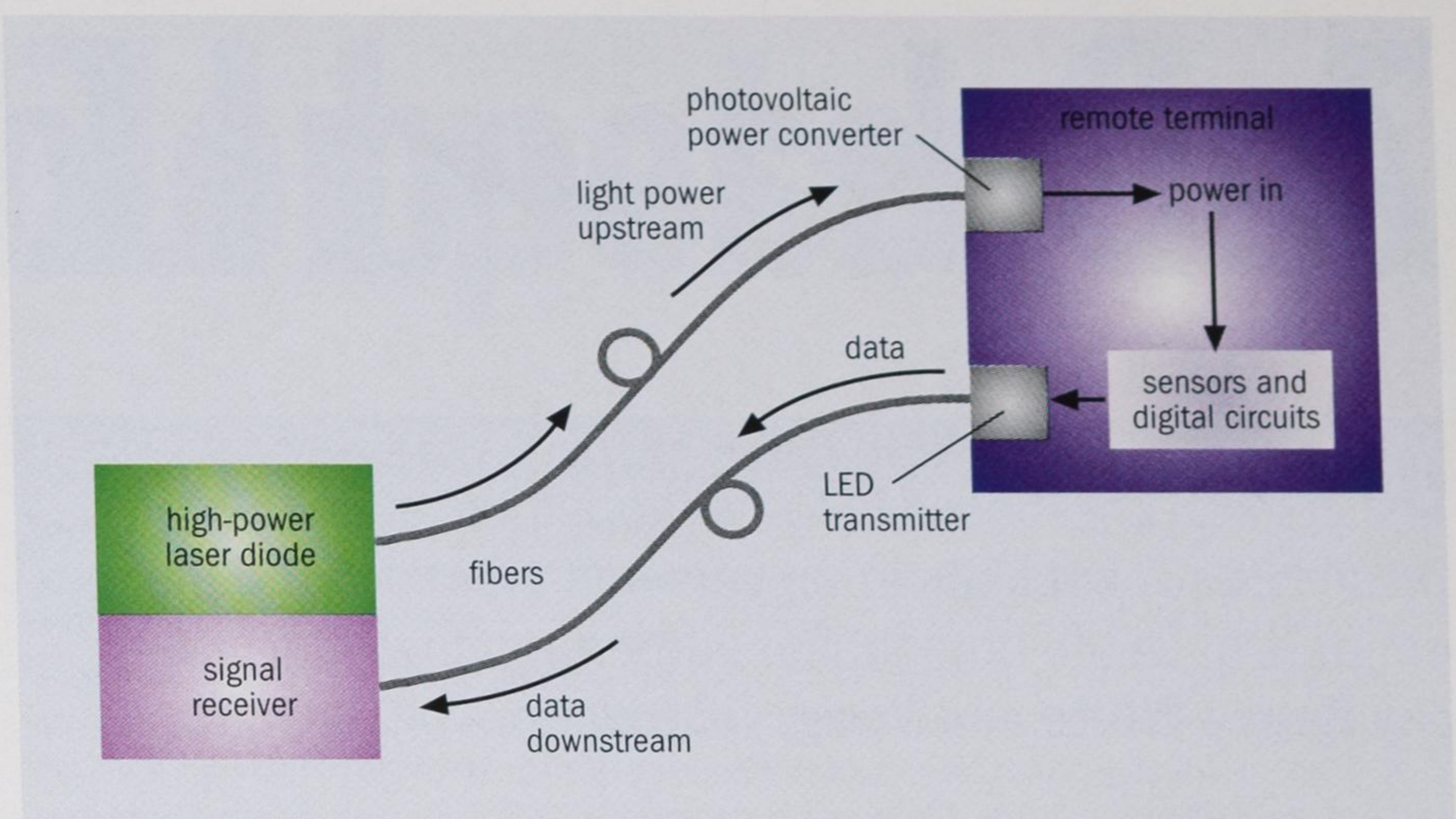
One such high-power application could be found in the wireless infrastructure sector. "Many of the existing antenna applications are pretty power hungry, so you might need a Watt or more out of the converter," explained Werthen. "This translates to 3 W or more on the laser side." Shifting to this longer wavelength demands a change in the converter chip material to an InGaP compound mismatched onto a GaAs substrate.

The third option is reserved for "long haul" applications, where the sensor is to be powered from a remote location. In these cases the best option is to use single-mode lasers in the 1310–1550 nm region, and a converter featuring InGaAs or InGaAlP on InP.

Whatever the specifics of the application, the physical appearance of the converter remains the same: "If you think of a pizza, that's what our converter looks like," said Werthen. "The pizza box is a 1 × 1 mm or 2 × 2 mm square, and the active area inside it is round and has been sliced up into segments."

Epitaxial growth is by MOCVD on a semi-insulating substrate and the segment boundaries are etched down to isolate each p-n junction. "Then you have to use proprietary technology to access the p- and n-side and re-connect them back in series. It's somewhere between an IC and a simple photodiode."

Mostly performed on 3 inch wafers, the process to manufacture the converter features around a dozen individual steps. It is well developed and not something that Werthen is particularly tempted to tamper with, mainly because the conservative electric utilities industry is



The photovoltaic power converter is the key element in the photonic power system. It must be tailored to the emission wavelength of the high-power laser diode, and to produce a voltage and current.

focused largely on reliability. But work to improve conversion efficiency continues, and 50% has been demonstrated in experiments.

Converter chip fabrication has now switched to JDSU's headquarters in Milpitas, CA. Being under the JDSU umbrella also means that the parent company's lasers are used in the bulk of the systems. JDSU's acquisition suggests a belief that photonic power is an application that can drive plenty of volume through the parent company's III-V wafer fab in the future.

Werthen certainly envisages a couple of application areas that could deliver this. "If you think of a situation where everybody has a wireless [internet] connection, then eventually there's going to be a need for fiber going to the point of that wireless transmitter," he reckons. "At that point, needing to use both a copper wire for power and a fiber for data is cumbersome and impractical."

"You could have just one fiber going to the point of the transmitter to provide both the power and the data. There are indications that there will be such a scenario, because everybody is going to demand the high bandwidth," Werthen said.

The other possibility that Werthen foresees is power for an electro-mechanical switch that could be used to re-route access to a passive optical network. "If it gets cut then you want to be able to switch to another one quickly. You might want to have a switch out by the passive optical network, but where do you get the power to drive it?"

Werthen admits that this futuristic application is somewhat speculative, but dreaming up such ideas are all part of the evangelistic approach that he is adopting in a bid to educate both the market place and the technical community within the semiconductor business to the potential of photonic power.

"If you think of a pizza, that's what our converter looks like."

Jan-Gustav Werthen
JDSU Photonic Power

ZnO-based LEDs begin to

Start-up company MOXtronics has recently produced the first colored ZnO-based LEDs. Although the efficiency of these LEDs is not high, improvements are rapid and the emitters have the potential to outperform their GaN rivals, say **Henry White** and **Yungryel Ryu** from MOXtronics.

The attractiveness of ZnO LEDs stems from the potential for phosphor-free spectral coverage from the deep ultraviolet to the red, coupled with a quantum efficiency that could approach 90% and a compatibility with high-yield low-cost volume production. These LEDs could even one day outperform their GaN-based cousins, which offer a narrower spectral range, thanks to three key characteristics – superior material quality, an effective dopant and the availability of better alloys.

The superior material quality is seen in the low defect densities of ZnO layers. At MOXtronics, our development of a viable p-type dopant has provided hole-conducting layers for ZnO-based devices. And our growth of BeZnO layers has shown that it is possible to fabricate ZnO-based high-quality heterostructures (see “The advantages of ZnO over GaN” box for further details).

ZnO also promises very high quantum efficiencies, and ultraviolet detectors based on this material have produced external quantum efficiencies (EQE) of 90%, three times that of equivalent GaN-based detectors. The physical processes associated with detection suggest that similarly high efficiency values should be possible for the conversion of electrical carriers to photons. So it is plausible that ZnO LEDs will have an EQE upper limit that is three times higher than that of GaN-based devices.

Finding the right dopant

However, ZnO is yet to fulfill all of its promise because of the delay in developing p-doped material. Early progress throughout the community was hampered by focusing efforts on using nitrogen as a p-type dopant. Nitrogen was the first choice because it was an effective dopant in ZnSe, and also because it was deemed, erroneously, to be of a suitable size to sit on an oxygen lattice site. Although we also tried to obtain p-type doping using nitrogen, a switch to arsenic enabled us to report the first successful p-type doping of ZnO in 1997. By 2000 we could produce hole concentrations into the 10^{17} cm^{-3} range with this approach.

Later in 2000 we reported our hybrid beam deposition (HBD) process that offers a viable approach to growing doped and undoped ZnO films, alloys and devices. The HBD process is comparable to MBE. However, it



MOXtronics has recently produced the first-ever ZnO-based LEDs emitting in the development of ZnO-based materials, such as the alloys CdO, CdSe and CdS, could

uses a zinc oxide plasma source, which is produced by illuminating a polycrystalline ZnO target with either a pulsed laser or an electron beam, and a high-pressure oxygen plasma created by a radio-frequency oxygen generator. Additional sources for either doping or ZnO-based alloy growth can be added to the growth chamber by conventional evaporation or injection methods.

We used the HBD process to fabricate the first ZnO-based ultraviolet detectors (see “Highly efficient detectors” box, p18), ultraviolet LEDs, FETs (Ryu *et al.* 2006), and red, green, blue and white phosphor-coated LEDs. Our LEDs incorporate BeZnO (see figure 2, p18), an alloy that allows bandgap engineering into the ultraviolet and the formation of multiple quantum wells and other heterostructures.

Why BeZnO beats MgZnO

BeZnO alloys of varying composition have provided a significant boost towards the development of the deep ultraviolet high-power LEDs. These alloys do not phase segregate, because BeO and ZnO have the same hexag-



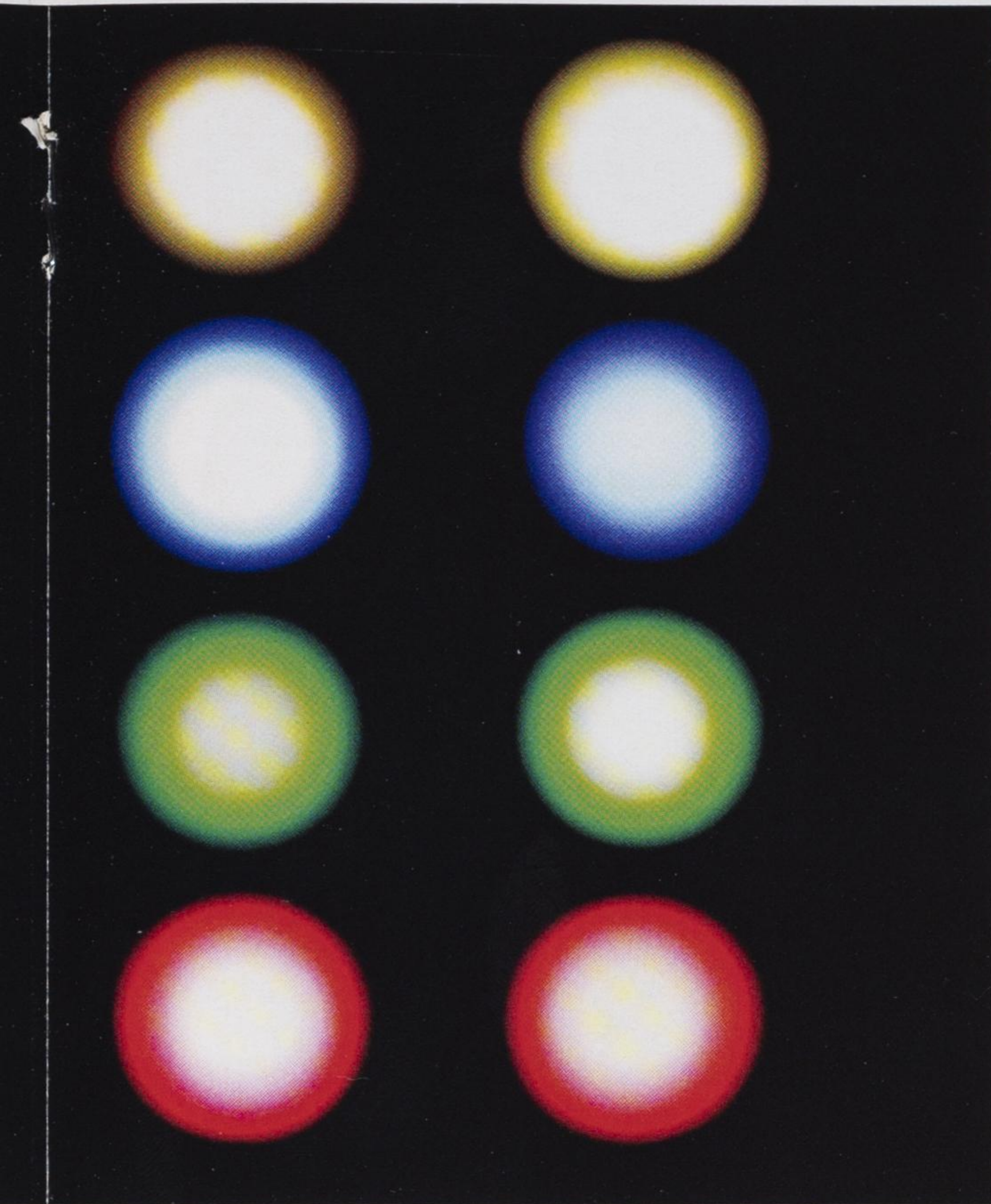
About the authors

Yungryel Ryu (left) (ryuy@moxtronics.com) is president and CEO of MOXtronics, and was a member of the company's original start-up team.

Henry White (right) (whiteh@moxtronics.com) is chair of the MOXtronics board, and a professor in the Department of Physics and Astronomy at the University of Missouri, MO. He was also a member of the company's original start-up team.

MOXtronics Inc was formed in December 2000 as a spin-out company of the University of Missouri. Subsequently, it has obtained Phase I and II Small Business Innovative Research grant funding from both the Office of Naval Research and NASA, and has raised funds through equity sales.

show full-color potential



the white, red, blue and green, by attaching phosphors to its devices. The further could lead to phosphor-free ZnO LEDs serving all these colors.

onal crystal structures, and the extremely high-energy bandgap of BeO could potentially lead to devices emitting at just 117 nm. Ultraviolet LEDs containing BeZnO alloys produce a narrow spectral profile, with very little emission in the visible, suggesting that the alloy is of high crystal quality.

Until we had produced BeZnO films, the primary choice for a compatible higher bandgap alloy was ZnMgO, a material developed by a group at Tohoku University, Toyo University, Tokyo Institute of Technology, and Japan's Institute of Physical and Chemical Research. In 1997 this team reported that crystal phase separation occurs between MgO and ZnO when the atomic fraction of magnesium exceeds 0.33, which corresponds to a bandgap of 3.99 eV. The separation is driven by different crystalline structures; MgO is a cubic structure with a lattice spacing of 0.422 nm, while ZnO is a hexagonal wurtzite structure with a lattice spacing of 0.325 nm.

We recently produced and characterized the first ultraviolet LEDs made from ZnO and BeZnO (figure

The advantages of ZnO over GaN

The three major benefits of ZnO over GaN are:

- superior material quality, which has been demonstrated by the growth of high-purity ZnO with defect densities below 10^5 cm^{-2} , a value typically associated with the best GaN films.
- improved doping performance, which results from the arsenic p-type dopant that has an activation energy of 119 meV in ZnO films, far less than the 215 meV for magnesium-doped p-type GaN. This lower activation energy produces a 10-fold increase in the proportion of activated acceptor atoms that are needed for electrical conduction (assuming the same atomic dopant concentrations are used), and also reduces the number of defects for a given hole carrier density.
- the availability of better alloys, due to our recent development of high-quality BeZnO films. These layers have driven the fabrication of LEDs, lasers and transistors that have less disorder than the structures produced using the AlGaIn/GaN material system. The reduced disorder is a consequence of the large difference in bandgap between ZnO and BeO, and enables only small changes in the alloy's composition to produce relatively large changes in bandgap. In comparison, a much larger shift in aluminum composition is required to produce the equivalent changes in AlGaIn, and this leads to greater disorder. The ZnO-based material system could also be extended into the visible using alloys such as CdO, CdSe and CdS.

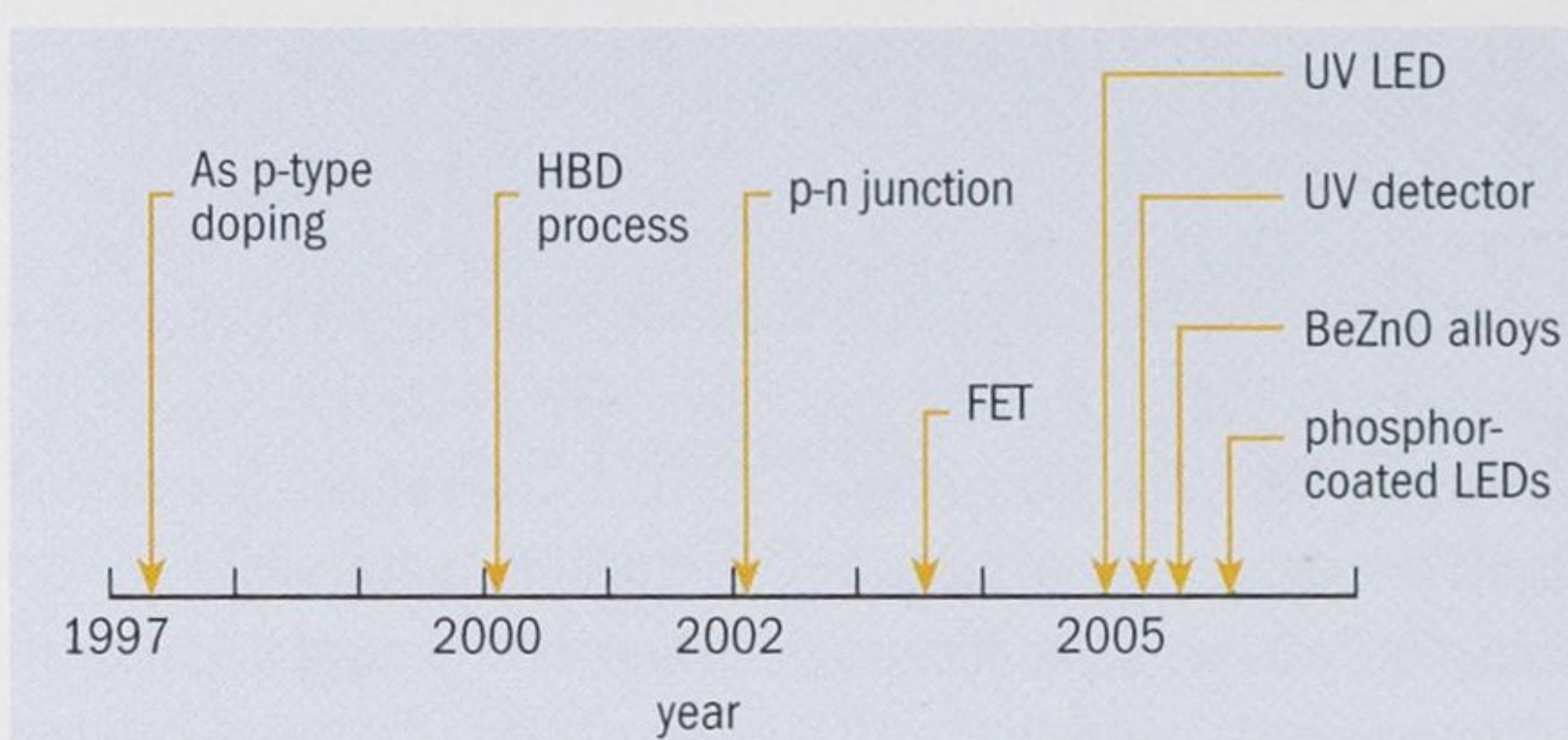


Fig. 1. US-based MOXtronics has pioneered the development of ZnO materials and devices. The company produced the first p-doped ZnO in 1997, and since then has fabricated the first p-n junctions, FETs, ultraviolet LEDs, ultraviolet detectors, and red, green, blue and white phosphor-coated ZnO LEDs.

3, p18). The device's emission can be tuned from the deep ultraviolet to around 380 nm, the wavelength associated with ZnO. Our devices have been built with several different active layer structures, including double heterostructures and single or multiple quantum wells, to try to improve efficiencies and optical output powers.

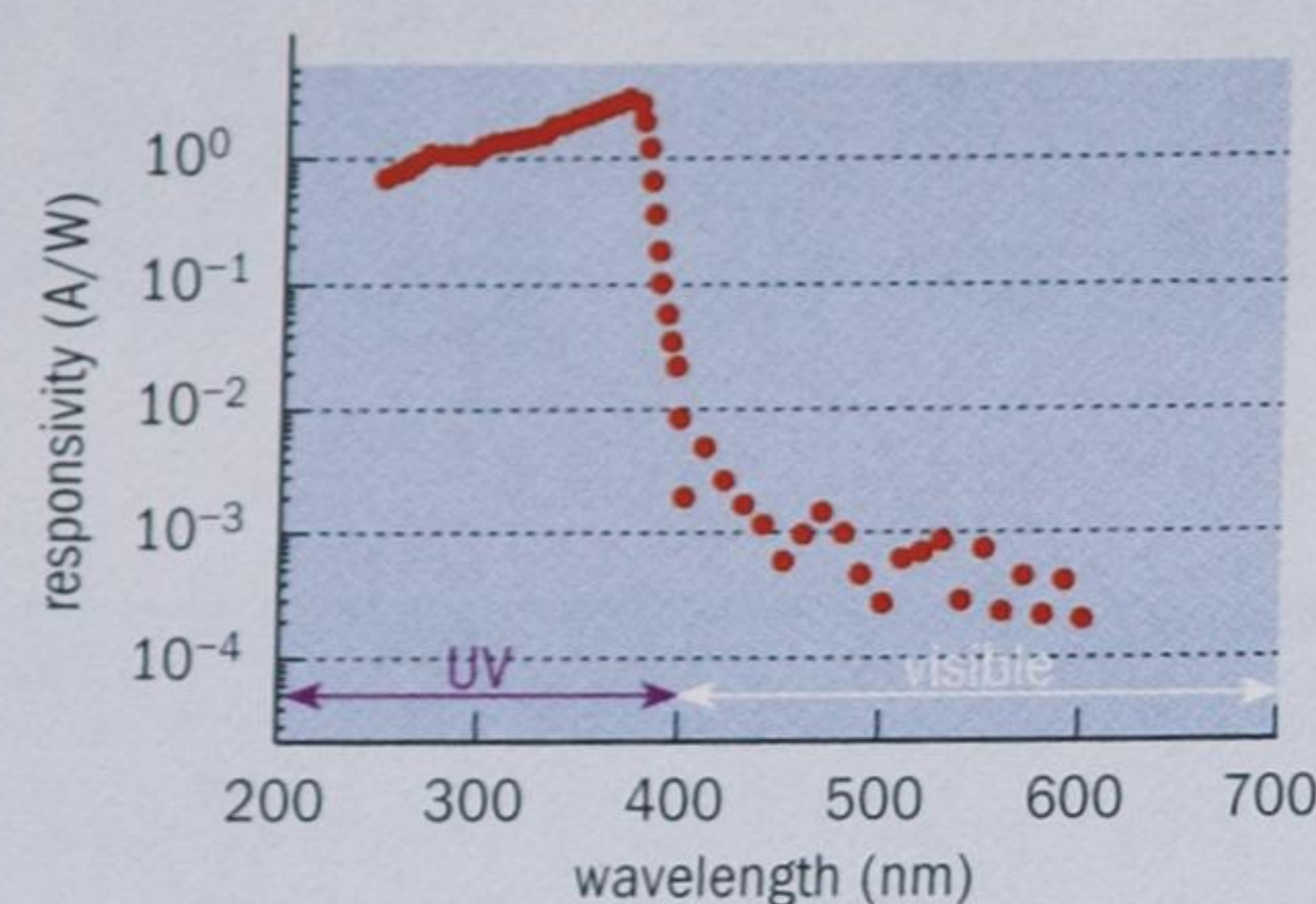
Our latest ultraviolet LEDs have a typical wall-plug efficiency of 0.1%, which would equate to an efficacy of 0.6 lm/W if the emission were in the visible spectrum. Although the efficiency is far lower than that of GaN LEDs, we are making rapid progress by addressing the various phenomena that degrade device performance. If progress continues at the same rate we will produce LEDs with a 1% wall-plug efficiency within one year, 1–5% within two years, and about 10% or more within three years (see figure 4, p18).

Our ZnO LED development program has used various substrates manufactured by several vendors, and has shown that the LED's performance is directly dependent on the substrate's material type and crystalline quality. Single-crystal ZnO produces the best

Highly efficient detectors

MOXtronics has also developed the first ultraviolet detectors based on ZnO. The sensitivity of these devices is three times higher than that of any other ultraviolet solid-state detector, and they have a responsivity of 0.27 A/W at 372 nm (see figure, right). The detector's noise floor at visible wavelengths is four orders of magnitude lower than its response in the ultraviolet, making it an attractive option for visible-blind applications. The device's temporal response is typically 50 μ s, but it can be shortened considerably and approach the theoretical limit of 10 ns by optimizing the structure and the electrodes' dimensions.

MOXtronics expects to develop high-speed focal-plane arrays, with pixel dimensions of typically 128×128 , by the end of next year. These arrays, and single-element detectors, should become



MOXtronics' highly sensitive ultraviolet detectors have a very fast response time and can be used to analyze the change in fluorescence spectra over very short time scales.

important components in both portable ultraviolet spectrometers, and in the ultra-fast ultraviolet spectrometers designed for the analysis and temporal de-convolution of fluorescence spectra.

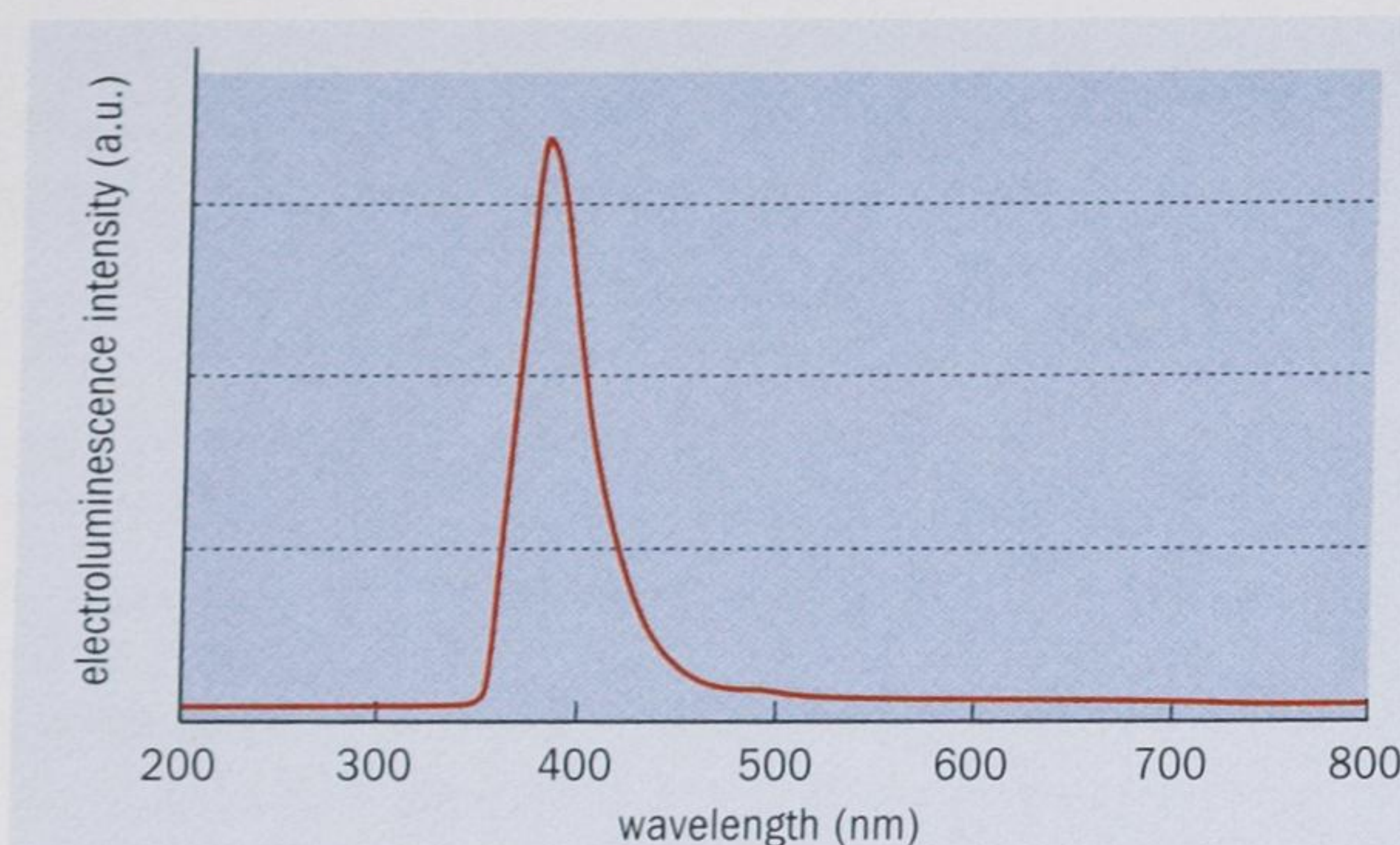


Fig. 3. The latest ultraviolet ZnO LEDs from MOXtronics, which contain BeZnO layers, produce a strong emission peak at 385 nm.

devices. This material has been available for many years, and interest is rapidly increasing for the growth of high-quality single-crystal ZnO with a diameter of 50 mm or more that could be used for ZnO-based LEDs and other optoelectronic devices.

Major improvements in the efficiency and power output of ZnO ultraviolet and visible LEDs are still needed to enable these devices to compete in the market place. Advances will depend on the availability of higher quality single-crystal substrates and improved processes for producing reliable and highly-ohmic electrical contacts to various different layers. Additional bandgap engineering development is needed for the ultraviolet C-band (100–280 nm) and visible region, along with optimization of the multiple quantum well and related structures in the device's active region.

Looking ahead

With the output power of our ZnO LEDs increasing rapidly, these devices appear to have a promising future. We expect them to first be deployed in white-light lamps and replace incandescent sources in appli-

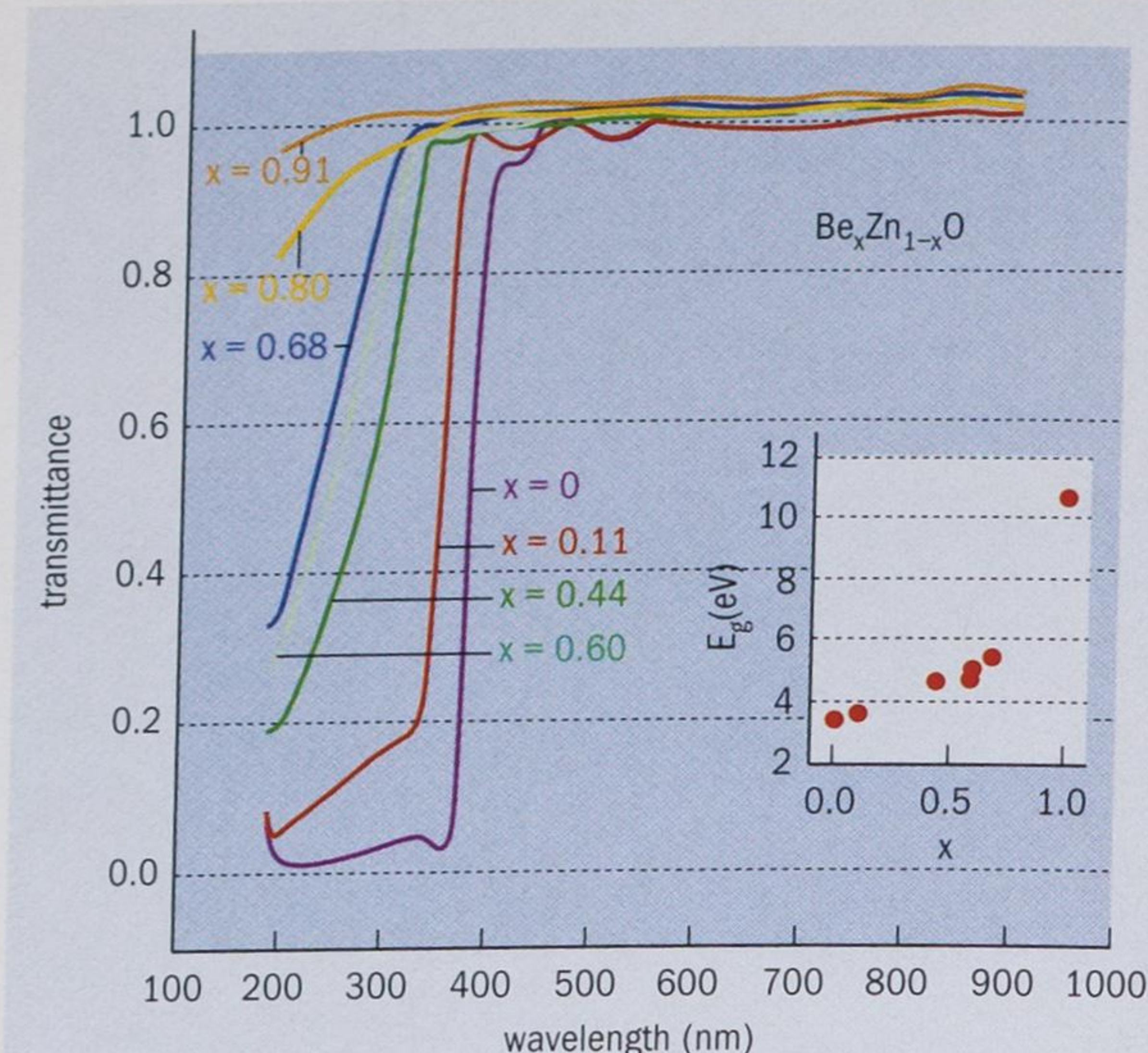


Fig. 2. The bandgap of BeZnO can be varied from 3.3 to 10.6 eV, which allows its transmittance to be tuned over a wide wavelength range. The material also benefits from the same hexagonal crystalline structure as ZnO, and, unlike its rival MgZnO, it does not phase-segregate into BeO and ZnO.

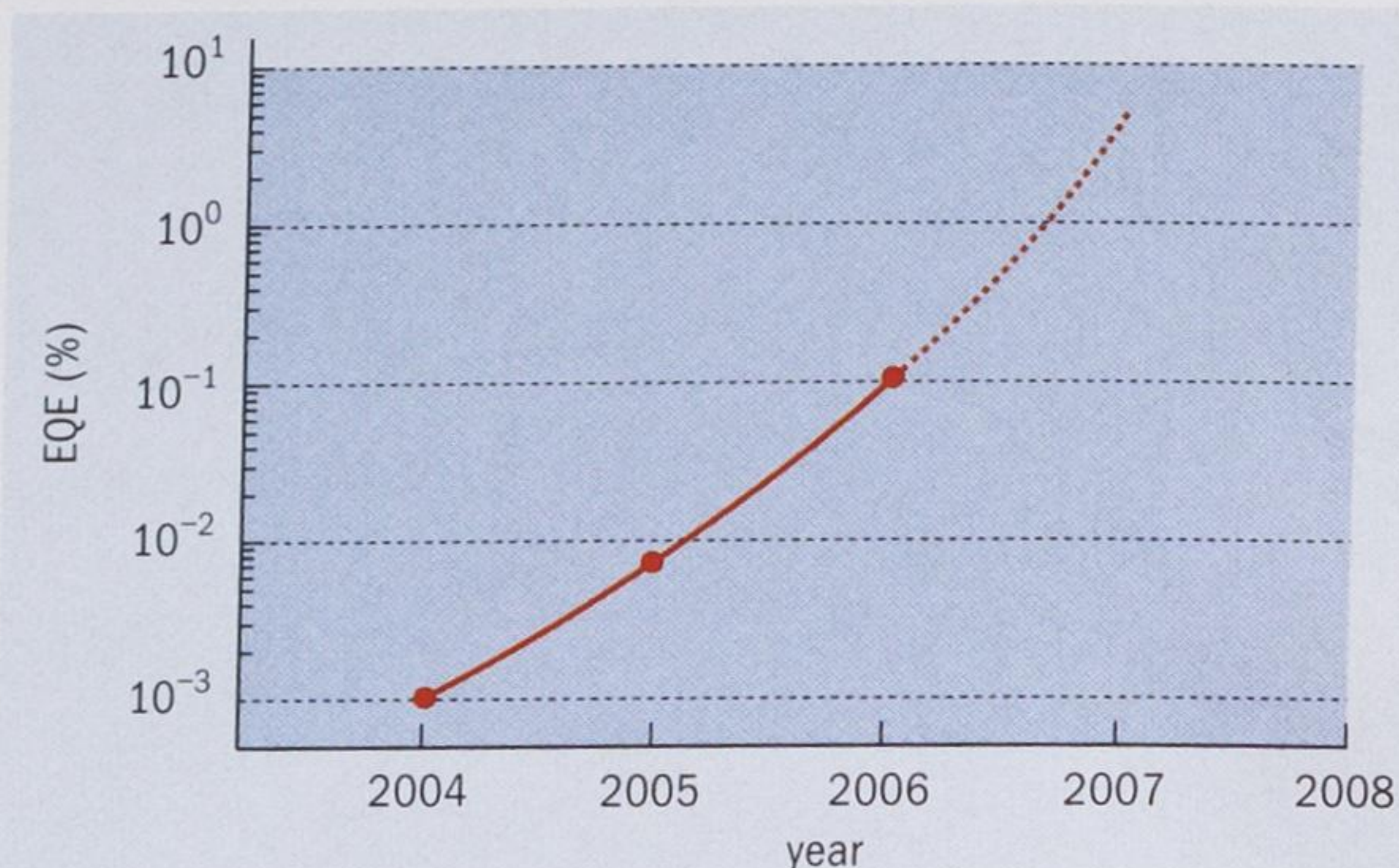


Fig. 4. MOXtronics has provided the only reports of external quantum efficiency (EQE) values for ZnO-based ultraviolet LEDs. Today, these devices can deliver an output efficiency of 0.1%, which corresponds to 0.6 lm/W if the emission were located in the visible spectrum. However, based on our progress to date, we expect to produce devices with efficiencies of around 5% by 2007 (the dashed line represents projected progress).

cations such as liquid-crystal display backlights. The promise of emission from the ultraviolet through the visible will then allow ZnO LEDs to target applications where no other single semiconductor material can operate today. At this time, for example, red–green–blue sources that are fabricated on a single wafer will offer unique advantages for the development of bright, compact displays and projectors. Laser diodes built from ZnO-based materials could also be produced that emit in the visible and ultraviolet, and offer compact alternatives for larger tube-type laser sources, ushering in a new era for color printing.

Further reading

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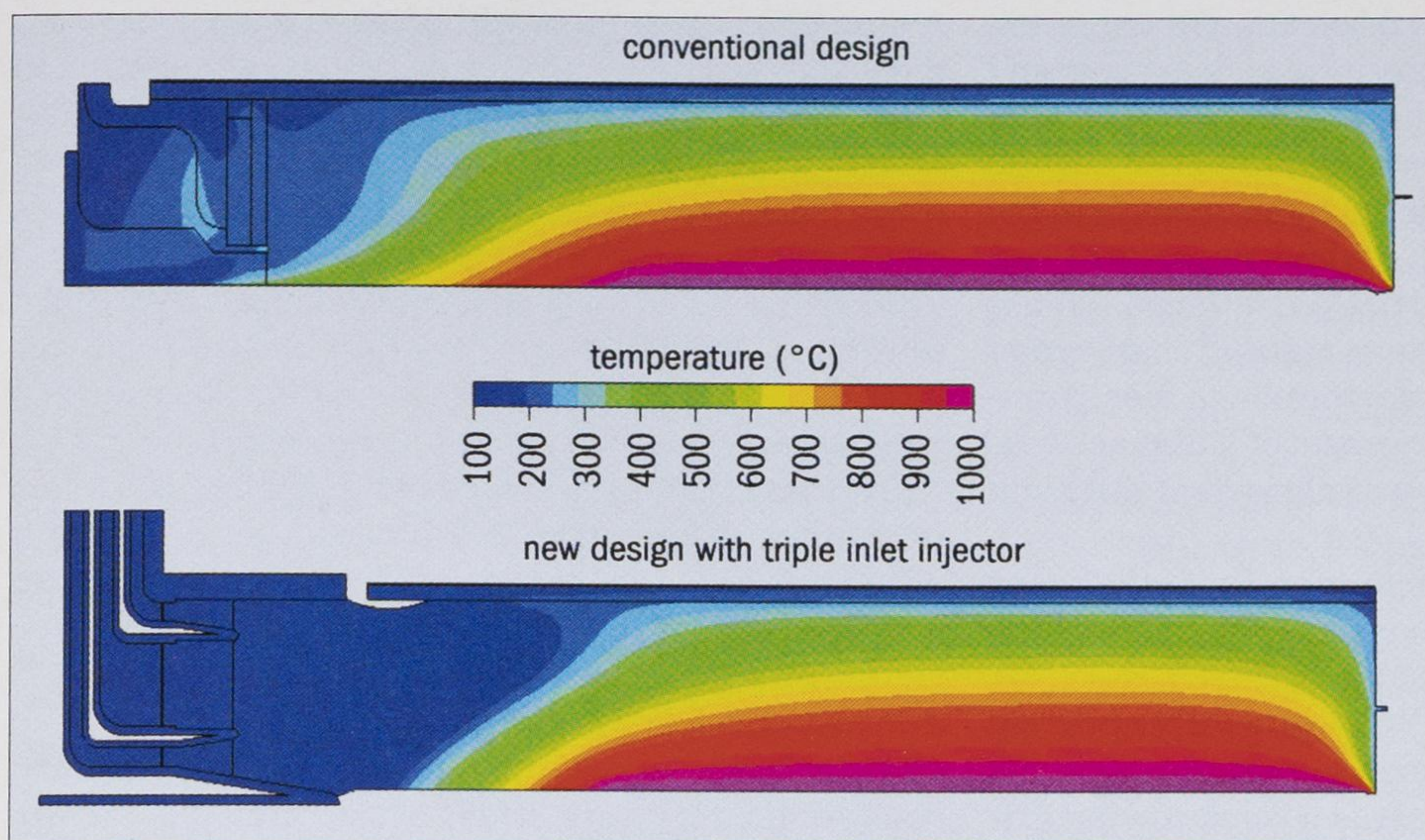
“We will produce LEDs with a wall-plug efficiency of around 10% within three years.”



MOCVD GROWTH

Revamped reactor targets higher yields

Aixtron claims that its latest GaN reactor can produce a higher LED chip yield through increased wafer capacity, improved temperature uniformity and greater ease of use. **Richard Stevenson** investigates.



Aixtron's latest reactor delivers a more laminar flow of gas and better growth uniformity, thanks to a new injector that has two separate inlets for group V gases and a single inlet for group III material. This new injector is held at a lower temperature, which prevents the build up of unwanted deposits.



Many LED manufacturers are looking to move on from making devices for mobile-phone backlights and keypads to producing chips for much larger backlight units. However, the new application places more stringent demands on the LED manufacturing process, as the acceptable spread in emission wavelength is much narrower than it was previously.



According to Rainer Beccard, director of marketing for Aixtron's compound semiconductor technology branch, the company's existing planetary reactors are unable to consistently produce a high enough proportion of LED chips within the specifications required for large backlight units. This has led the company to investigate various ways to improve the reproducibility and growth uniformity of its reactors, and ultimately to release a 42 x 2 inch reactor that can manufacture larger numbers of LED chips with a narrower distribution of electroluminescence wavelengths.



Aixtron's hardware changes include a new gas-injection nozzle (top), a wider water-cooled central region (middle) and a larger heating coil (bottom).

The improvements in emission uniformity resulted from changes to the reactor hardware that were assessed by monitoring the distribution of peak photoluminescence wavelengths from multiple quantum-well epiwafers, which is strongly correlated to the spread in electroluminescence of chips taken from the wafer. The reactor is also claimed to be far more "robust" and simple to use, which should boost the long-term manufacturing yield.

Beccard says that one of the problems with the company's existing reactors relates to the positioning of the

central gas-injection nozzle, which has to be regularly removed for cleaning. According to him, although Aixtron provides a very detailed description of how to adjust this part, the procedure can be carried out incorrectly. However, with the new design, misalignment is impossible because the central gas injection is mechanically fixed.

This new injector, which is water-cooled, also has two separate inlets for the group V gases, in addition to the single inlet for group III material. This is claimed to produce a more laminar flow than before, which improves growth uniformity, delivers greater control of the gas flows within the reactor, and cuts ammonia consumption by half for nitride growth.

Aixtron's latest planetary reactor is also designed to operate at a lower temperature in the center of the growth chamber (see figure, left). "The center is now water cooled and the susceptor is made of quartz, so inductive heating doesn't couple to the center plate," explains Beccard. This modification makes that central region too cold to drive reactions between the gases and prevents any growth of unwanted material on the injector that would have to be removed subsequently. The reduced deposition in the central region improves the run-to-run reproducibility, says Beccard, because it limits any changes in the reactor's thermal profile.

Aixtron's latest planetary reactor features these refinements (collectively referred to as yield+), and has already been ordered by Taiwanese LED manufacturers Highlink Technology and Epistar. However, the company can also update its existing 24 x 2 inch platform for customers who don't want to have to buy a new machine. Internal trials with these modifications have revealed an improvement in peak photoluminescence wavelength uniformity. The average standard deviation in peak photoluminescence from three wafers from one disk, taken over three consecutive runs and using an exclusion zone of 2 mm, fell from 2.70, 2.91 and 2.70 nm, to 1.20, 0.81 and 0.95 nm.

The down time for upgrading to a 24 x 2 inch reactor with the yield+ system is typically one week. "We replace the coil, put in a new set of graphite if it's not already there, and change part of the top-plate in order to fit the injector. That's it," says Beccard. Once Aixtron's engineers have made these changes they stay at the fab and help tweak the LED growth recipes for the upgraded reactor. "We don't want people to start from zero again," Beccard remarks, "so we teach them how the changes in the recipe will affect their uniformity."

Aixtron is hoping that its two options to improve GaN LED manufacturing yield – either installing a new 42 x 2 inch planetary reactor, or upgrading an existing 24 x 2 inch set-up – will tempt LED chip manufacturers to part with their cash. A surge in order-book activity will certainly be welcomed by the German outfit, which is hoping to see LED equipment sales recover after two difficult years.

New GaN faces offer brighter emitters

Robert Metzger explains why growing III-N material on a different crystal plane to form a non-polar structure should boost the output power of LEDs and improve the doping control in HEMTs.



LEDs are starting to be used for residential lighting needs, such as illumination in the 190 m high “Turning Torso” tower in Malmö, Sweden. There is still a long way to go before these devices really displace the light bulb, but the development of GaN devices on non-polar substrates could provide that much-needed hike in performance.

The tremendous improvement in III-N material quality has driven the commercial fabrication of lasers and LEDs emitting from the ultra-violet to the green, and aided the development of high-power HEMTs suitable for numerous telecom applications. However, despite these advances, GaN is hindered by its growth in the hexagonal wurtzite structure – which consists of two intermixed hexagonal closed packed lattices – and is highly susceptible to polarization-induced charges that can adversely impact device performance. For example, these charges can limit the output of LEDs and produce a shift in the emission wavelength at different drive currents.

The standard material orientation for GaN-based LEDs, lasers and HEMTs involves growth along the [0001] direction, which is also referred to as the “c”-direction (see figure 1). What is readily apparent from this diagram, and is a direct consequence of its wurtzite structure, is that there is a fundamental difference between the crystal A and B faces. The A face, or gallium face, is only terminated by gallium atoms, which have three unsatisfied bonds, while the bottom nitrogen face is terminated in an identical manner by nitrogen atoms.

Just beneath the gallium-face surface is a nitrogen layer. The gallium-nitrogen bond is highly ionic and the charge asymmetry, coupled with the lack of inversion symmetry in the *c*-direction, gives rise to a large spontaneous polarization along the *c*-axis. (This spontaneous polarization is greatly reduced in lattices with a high degree of symmetry, such as the GaAs or InP zincblende structures.) In addition to this spontaneous polarization, piezoelectric polarization is generated at interfaces between the III-Ns due to the strain that results from the different lattice constants (see “The properties of III-Ns” table).

The combined (net) polarization generates a polarization-induced electrostatic charge at alloy interfaces. While GaN and InN have very similar spontaneous polarization constants, in AlN it is almost three times larger. This difference produces a large spontaneous polarization-induced charge generated at interfaces between aluminum-rich and gallium- or indium-rich alloys, such as those that can occur in GaN-based HEMTs. For LEDs and lasers containing GaInN multiple quantum wells, the induced charge is dominated by piezoelectric effects arising from the large difference in lattice constant between InN and GaN. These induced interface charges bend the profile of the conduction and valence band, and consequently impact device operation.

Pulling the charges apart

A simplified quantum-well band structure that contains GaN barriers and GaInN wells, and is found in many LEDs and lasers, is shown in figure 2a. Electron-hole radiative recombination within the wells generates a photon with an energy equal to the GaInN’s bandgap, if we ignore energy-level shifts due to quantum effects in narrow wells. However, in the presence of polarization-induced charges at well-barrier interfaces, the bands will be bent by the electric field generated by these charges (see figure 2b).

This polarization-induced band bending leads to a phenomenon known as the quantum-confined Stark effect (QCSE). Electron and hole wavefunctions are displaced to opposite sides of their respective wells (see figure 2b), rather than residing in the center. This decreases the oscillator strength – the probability of an electron-hole pair recombining to generate a photon – because the electrons and holes are now physically displaced from each other. And the greater this polarization-induced electric field, the greater the displacement between the two different charge carriers.

The reduced oscillator strength decreases the light output from the active region. In addition, the GaInN bandgap across which the recombination process will take place effectively shrinks, because the smallest energy transition now occurs between an electron in the bottom-left-hand corner of the conduction band and a hole from the right-hand corner of the valence band. This red shift means that the energy of the emitted photon is lower than that of the GaInN bandgap.

The impact of the red shift on blue and green LEDs, as a function of drive current, is shown in figure 3 (p22). As the current increases, the emission shifts towards shorter wavelengths due to an increase in the screening of the polarization-induced field, until a point is reached at which the band structure approaches that shown in figure 2a. For LED applications, as emission is pushed to longer wavelengths by increasing the indium composition within the well, the size of the piezoelectric-induced charge also increases. As a consequence, longer wavelength green-emitting devices are more susceptible to the QCSE. In addition, for higher indium content quantum wells, the band-bending becomes steeper and the separation of the electron and hole wavefunctions further increases, which decreases the oscillator strength. These polarization effects mean that it is more challenging to make high-brightness green LEDs than blue ones, and explains why the brightest green LEDs typically generate only half the light output of their blue cousins.

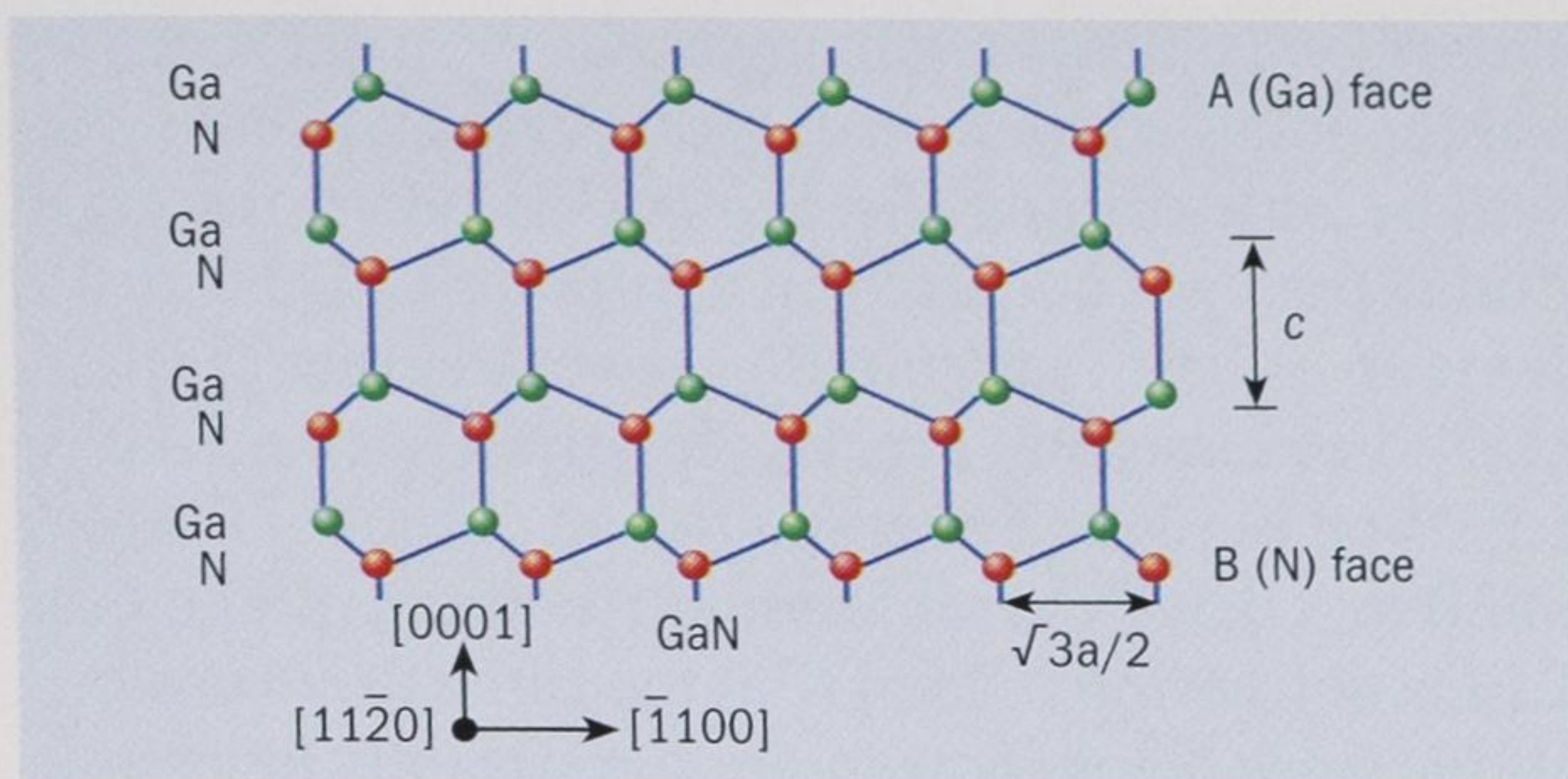


Fig. 1. Growth along the c -direction takes place onto either the a -plane of gallium atoms (the A face) or the a -plane of nitrogen atoms (the B face). The ionic nature of the gallium–nitrogen bond means that epilayers grown on this face have a high spontaneous polarization.

The properties of III-Ns

	AlN	GaN	InN
Lattice constant – a (nm)	0.311	0.319	0.354
Lattice constant – c (nm)	0.498	0.519	0.580
Bandgap (eV)	6.20	3.44	1.89
Spontaneous polarization (C/m ²)	–0.081	–0.029	–0.032

A potential remedy to these polarization-induced effects is to grow GaN films oriented in other directions that have either a reduced or no polarization fields in the growth direction. Figure 1 shows that such non-polar directions do exist in GaN, such as those directions perpendicular to the gallium or nitrogen face that are still in the plane of the figure. These directions produce a surface plane with equal numbers of gallium and nitrogen atoms, and eliminate the polarization effects.

Two non-polar directions are present in GaN, both perpendicular to the c -axis: the $\{11\bar{2}0\}$ plane, called the “ a ” plane, and the $\{10\bar{1}0\}$ plane, called the “ m ” plane. Devices fabricated on these planes should not suffer from the polarization effects currently observed in c -axis-oriented GaN. In addition to these two non-polar planes, there are several “semipolar” planes at different angles between the polar c -axis and the a - and m -planes that should have reduced polarization effects.

The growth challenge

Nearly two decades have been spent researching and developing the growth of c -axis polar GaN, and this has opened the way for the commercial production of GaN-based lasers, LEDs and HEMTs. However, while much of that experience can be applied to the growth and subsequent fabrication of GaN devices using a - and m -plane materials and semipolar orientations, there is still much to do to establish the optimum growth conditions for these orientations – especially with regard to the control of threading dislocations and basal-plane stacking faults.

The materials and electrical and computer engineering departments at the University of California Santa Barbara (UCSB) are at the forefront of this research. The first challenge in the growth of non-polar GaN films is to establish the growth regime for a smooth surface, which is not a trivial task. UCSB’s Paul Fini reports, “We’ve found in general that a -plane GaN has a smaller

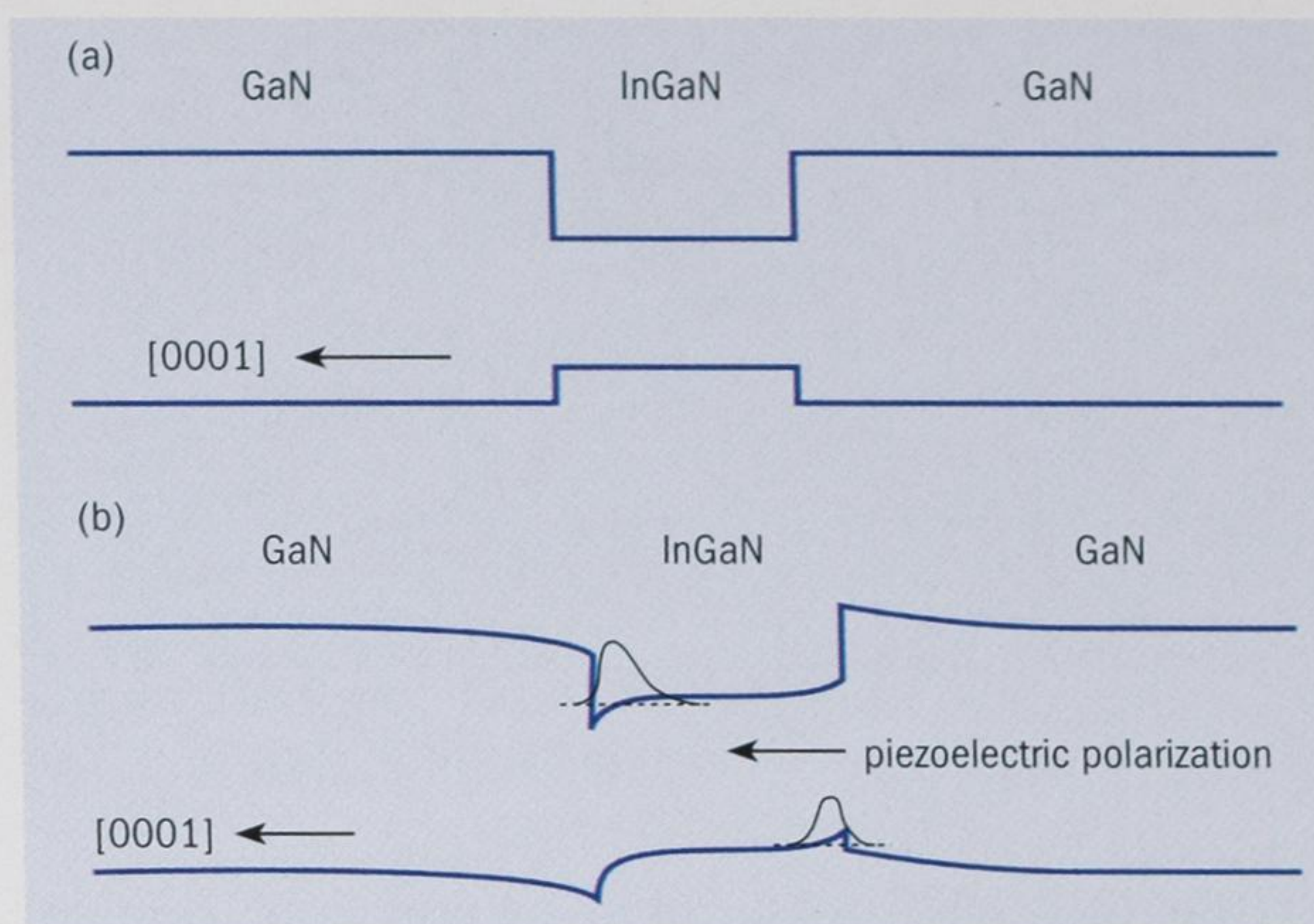


Fig. 2. A combination of spontaneous polarization caused by ionic bonding in III-Ns and a piezoelectric polarization resulting from the material strain can change the band-structure profile. For the simple quantum-well structure found in many LEDs or lasers (a), these polarization effects distort the band structure and push the electron and hole wavefunctions to opposite sides of the quantum well (b), which reduces the oscillator strength.

growth window for planarity than m -plane, semipolar or c -plane films.” The researchers have observed that the threading dislocation density is often more than $1 \times 10^{10} \text{ cm}^{-2}$, and that the stacking-fault density is greater than $4 \times 10^5 \text{ cm}^{-2}$, when growing a -plane GaN on sapphire or m -plane on LiAlO_2 . The threading dislocation density is similar to values obtained in the early days of c -axis GaN growth, but just like polar GaN, these defect levels have been reduced by the use of lateral epitaxial overgrowth techniques. Although these non-polar films do not have the same microstructural quality as c -axis polar GaN films, they can still be used to investigate the effects of non-polar orientations on device operation.

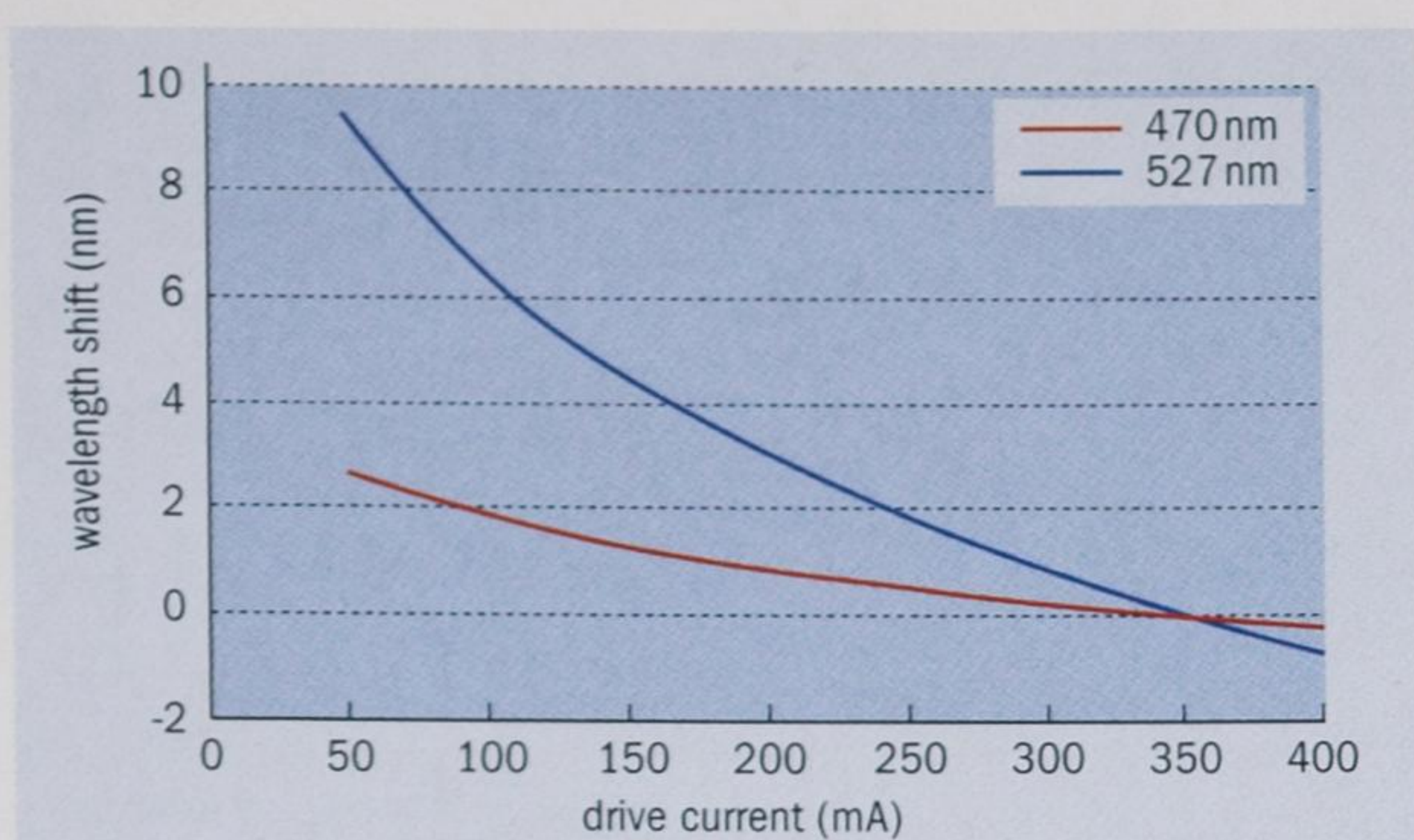
In fact, several groups have now produced devices that show the significant reduction in shift of emission wavelength that has been predicted. This 10-fold, or more, reduction in wavelength shift compared with polar quantum wells indicates the absence of polarization-induced charges in non-polar quantum wells.

The polarization-free interfaces can also have a significant impact on HEMTs. A typical AlGaIn/GaN HEMT built on polar GaN has a channel charge of more than $1 \times 10^{13} \text{ cm}^{-2}$, and all this charge is polarization-generated. With the elimination of the QCSE, HEMTs can be produced with two-dimensional electron gas formed by silicon-doping an offset electron donor layer, which is the approach used in GaAs- and InP-based devices. This switch allows the doping level in the two-dimensional electron gas to be independent of polarization effects that are highly sensitive to strain. The elimination of the QCSE also aids the fabrication of both enhancement- and depletion-mode devices, greatly simplifying the GaN-based logic devices. While this has not yet been reported, it should now be possible.

One of the toughest challenges for c -plane GaN device engineers is overcoming the limitation of p-type magnesium doping levels – the best reported electrically active levels are only in the $1\text{--}2 \times 10^{18} \text{ cm}^{-3}$ range. UCSB researchers have discovered that for m -plane GaN, it is possible to produce electrically active magnesium-doped levels of up to $7 \times 10^{18} \text{ cm}^{-3}$. These higher p-type doping levels are expected to lead to lower contact resistance, a reduction in p-n junction turn-on voltage and series resistance, and produce LEDs and lasers with higher optical output efficiencies.

“Non-polar GaN devices can target a niche that polar GaN cannot address.”

Fig. 3. Green LEDs contain InGaN quantum wells with a higher indium content. The additional indium makes these devices more susceptible to the quantum-confined Stark effect, and causes a greater variation in emission wavelength with drive current.



SOURCE: CREE

One other benefit of growth on non-polar orientations is the possibility of polarized light emission. This could be used directly for backlighting LCD displays and projectors, because a polarized light source can eliminate polarizing filters and lead to screens that are thinner, lighter and more energy efficient. UCSB and other groups have produced polarized light emissions from *m*-plane GaN LEDs with a polarization ratio of 0.17 (randomly oriented and totally polarized light have polarization ratios of 0.0 and 1.0, respectively). While more work remains to be done to improve this polarization ratio, initial work shows that *m*-plane GaN devices can target a unique niche that polar GaN simply cannot address.

While these results highlight the promise of non-

polar GaN, unless output power can meet or exceed the values obtained by devices grown on polar GaN, there will be little driving force to pursue non-polar GaN. Today the light output from non-polar LEDs is still at least an order of magnitude lower than that for polar GaN. For example, Fini has reported packaged blue LEDs on *m*-plane material with an output of 0.6 mW at 20 mA drive current, and on-wafer *a*-plane blue LEDs delivering 0.25 mW at the same drive current. While these output powers are significantly lower than what is currently available with polar GaN, it is important to remember that non-polar GaN development is still in its infancy. "Until that work is completed, directly comparing non-polar LEDs to polar devices is like comparing apples and oranges," says Fini. ●

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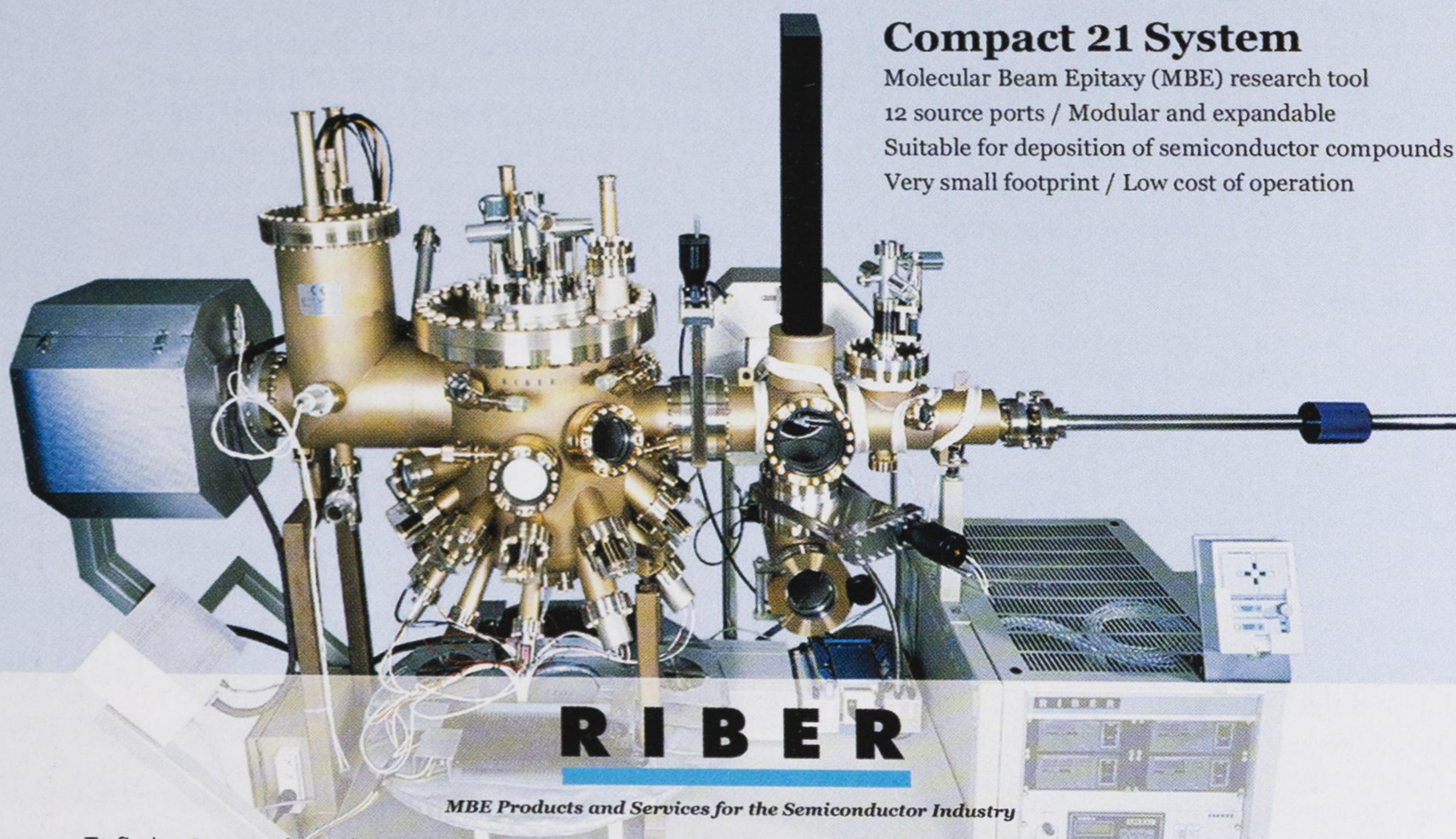
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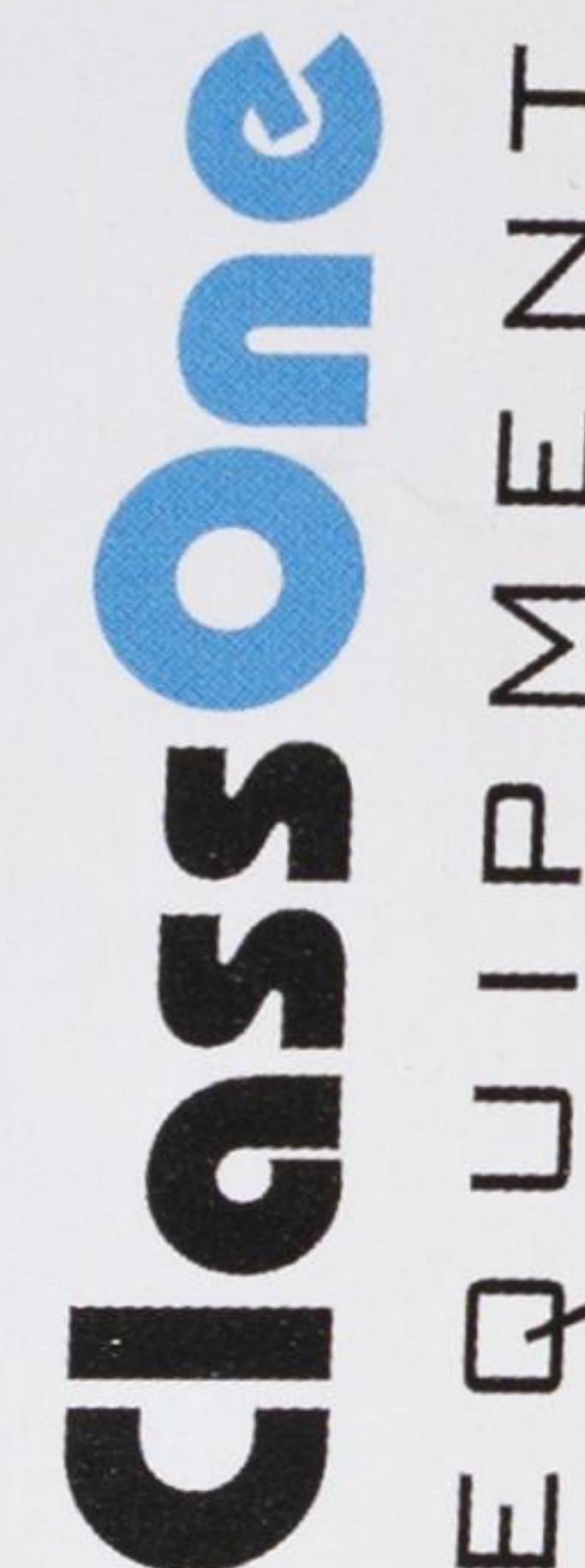


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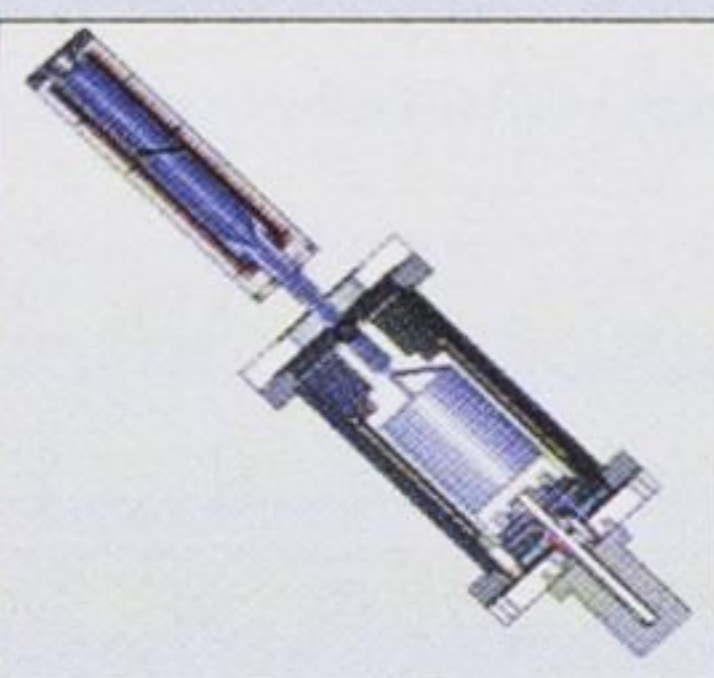


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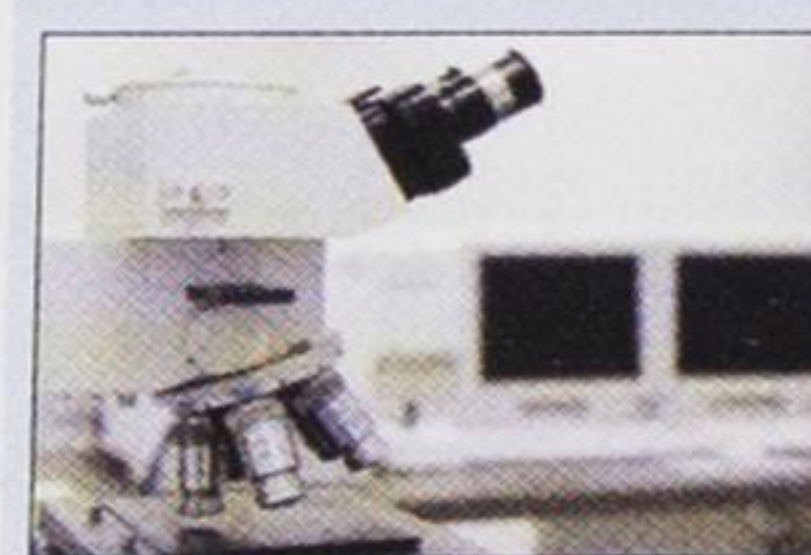
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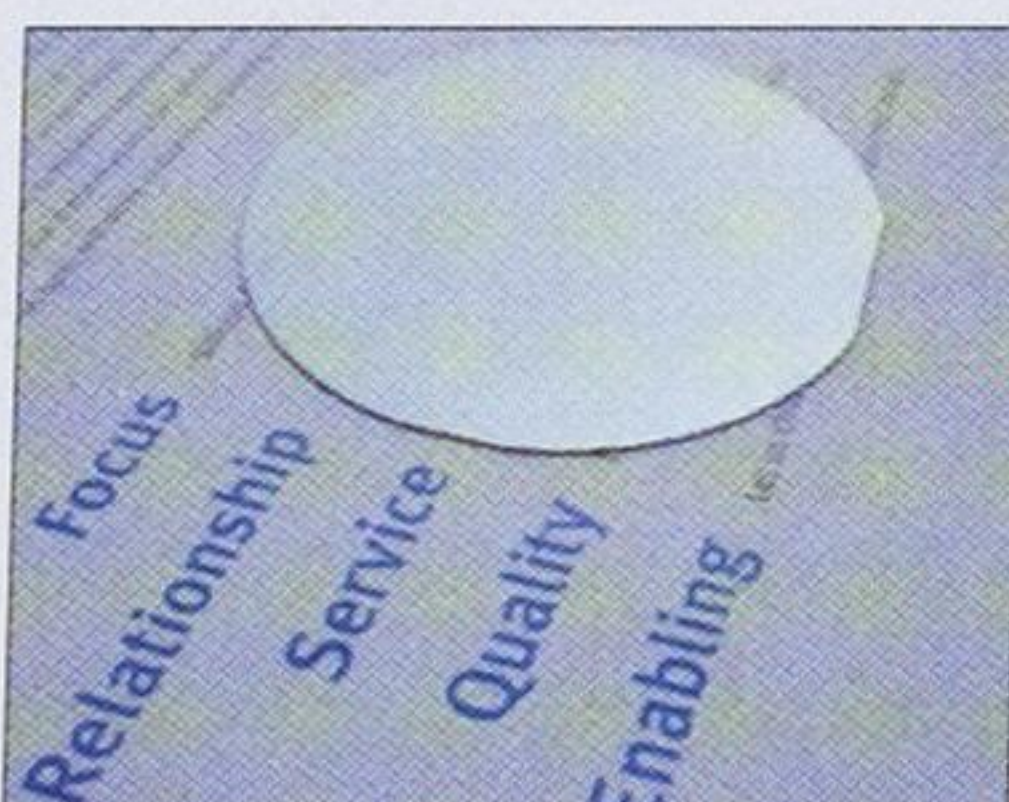


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Innovative tricks light up silicon

Practical, commercial silicon lasers are at least a decade away from reality, but other silicon optics could still impact the III-V optoelectronics industry, according to **Yvonne Carts-Powell**.

Don't expect to see commercial, electrically pumped silicon lasers within the next decade. But even if silicon never produces an electrically pumped laser, simple economics indicate that other active and passive optical devices made of silicon are likely to affect the III-V optoelectronics industry. Silicon devices can achieve almost all the necessary functions for integrated optical devices: amplifiers, modulators, switches and detectors. Only an electrically powered silicon light source, preferably a laser, is lacking.

One lure of silicon is the potential to integrate photonic and electronic components on the same chip. Microelectronics companies want to use optics, rather than copper, to ferry more and more data at increasing speeds in shrinking packages. Eventually, light could provide chip-to-chip or even on-chip communications.

Silicon also offers the potential to make photonics incredibly cheaply. Alex Dickinson, president of silicon photonics company Luxtera, calls it "the irresistible economics of CMOS". A high-volume silicon chip made via standard CMOS fabrication costs less than chips made from a more-expensive material using less-optimized and less-standardized processes.

Silicon offers technical benefits too. Bahram Jalali at the University of California, Los Angeles (UCLA), explains: "Silicon is the purest and highest quality crystal manufactured by mankind. In addition, it has the highest optical damage threshold of any popular crystal." The large index difference between silicon and SiO₂ also provides excellent optical confinement.

The US Defense Advanced Research Projects Agency (DARPA) funds research on CMOS-compatible silicon photonics through the Electronic and Photonic Integrated Circuits (EPIC) program. Its vision statement explicitly guns for III-V devices: "This would enable the integration of complex electronics and photonics circuits on a single silicon chip, eliminating the multiple materials platforms currently used to accomplish such functionality." The EPIC program has funded the work at UCLA, Brown University and Translucent mentioned in this article.

Extracting the light

Silicon is a terrible material for a laser. Lasers usually create a population inversion in which light emission is the most common relaxation path. Silicon, alas, has an indirect bandgap and an overlong spontaneous recombination lifetime. Free-carrier absorption hinders population inversion and Auger recombination reduces

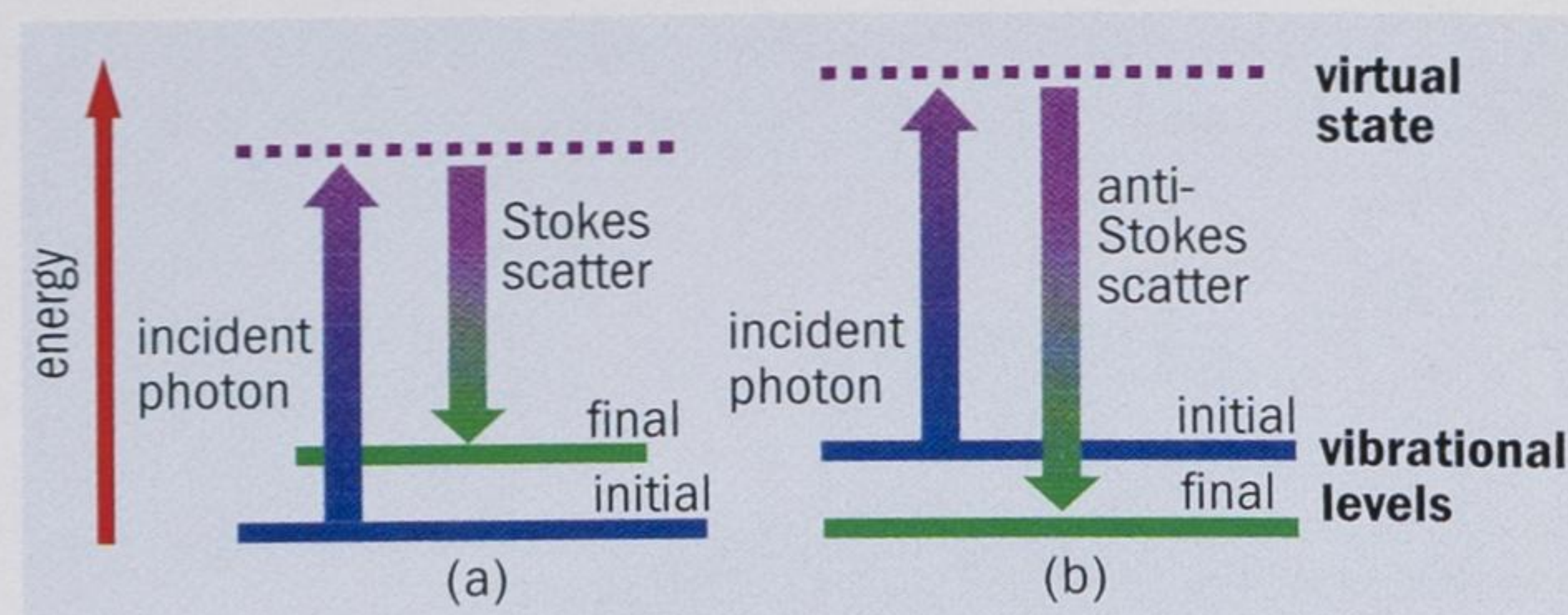
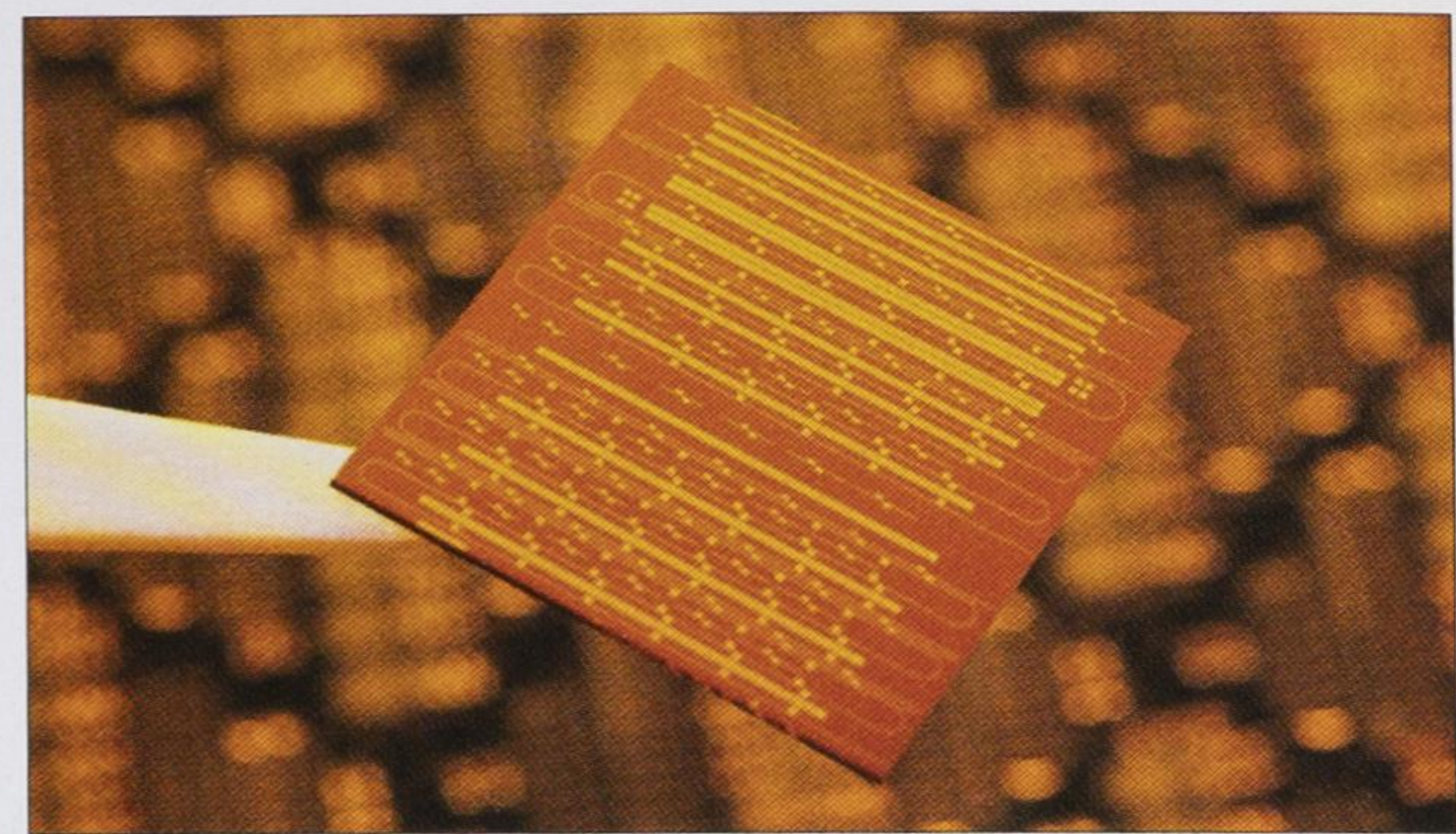


Fig. 1. Silicon lasers cannot operate using the same principles as lasers made from compound semiconductors, but can produce laser emission via the Raman effect. Lasing due to Stokes scattering can occur when energy from the photon-molecule collision is transferred to both photon emission and vibrational energy. Occasionally, vibrational energy and the pump photon combine to produce photon emission at a longer wavelength than the pump (anti-Stokes).



Intel has produced chips with eight silicon Raman lasers, but these devices require optical pumping with infrared radiation and have a conversion efficiency of only a few per cent.

light emission. For every 100,000 photons absorbed, silicon emits only one. Inducing it to shed light at all requires invoking nonlinear or quantum effects.

In 2003 Jalali and others at UCLA achieved optical gain in silicon using spontaneous Raman scattering, a nonlinear effect in which light is inelastically scattered by molecular vibrations (figure 1). Raman scattering is a small effect, so one needs a strong pump and low losses to build a laser with this method. In 2004 Jalali's group demonstrated a pulsed Raman laser that emitted at 1675 nm when pumped at 1540 nm. Silicon is opaque through visible wavelengths, but turns transparent in the near infrared.

This Raman laser could only work in pulsed mode because continuous-wave (CW) operation led to a build up of excess charge carriers that impacted the light output. In 2005 researchers at Intel created a CW Raman laser in which the entire length of the waveguide was equipped with a reverse-biased pin diode that swept away the free charge carriers. The lasing threshold depends on the bias voltage in the diode, but this method generates considerable heat (the Intel laser produced

Opaque Translucent

Translucent, a company based in Palo Alto, CA, is developing active silicon emitters, as well as other devices for creating entire photonic circuits. In 2003 Translucent claimed to have achieved optical gain in room-temperature semiconductor-grade silicon, but specified little else. In late 2005 the firm announced that it had demonstrated electroluminescence (EL) at telecommunications wavelengths and at room temperature in "a new class of silicon-based semiconductors". Other groups have demonstrated EL, but only at cryogenic temperatures.

Achieving EL meets a milestone for DARPA's Electronics and Photonics Integrated Circuits program. DARPA awarded Translucent a contract worth \$1.2 million over four years, assuming that the company continues to meet milestone deadlines.

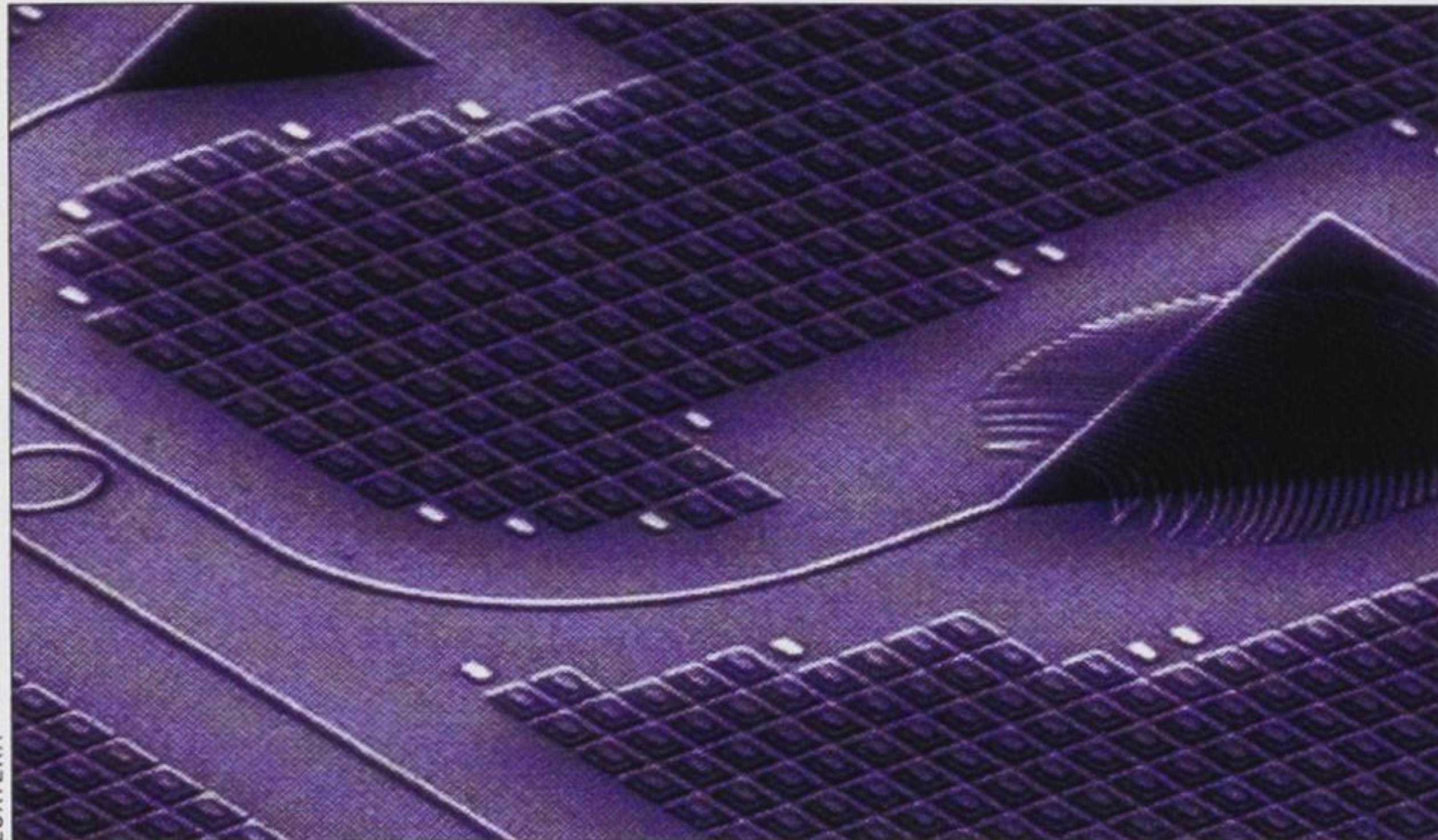
Last November Translucent CEO Petar

Atanackovic said that the EL result was, "an important step forward in our optical silicon integration program. The ultimate objective is to develop optically active devices, including an electrically driven silicon laser, which can be integrated with mainstream silicon chips." The company has, however, been elusive about the specifics.

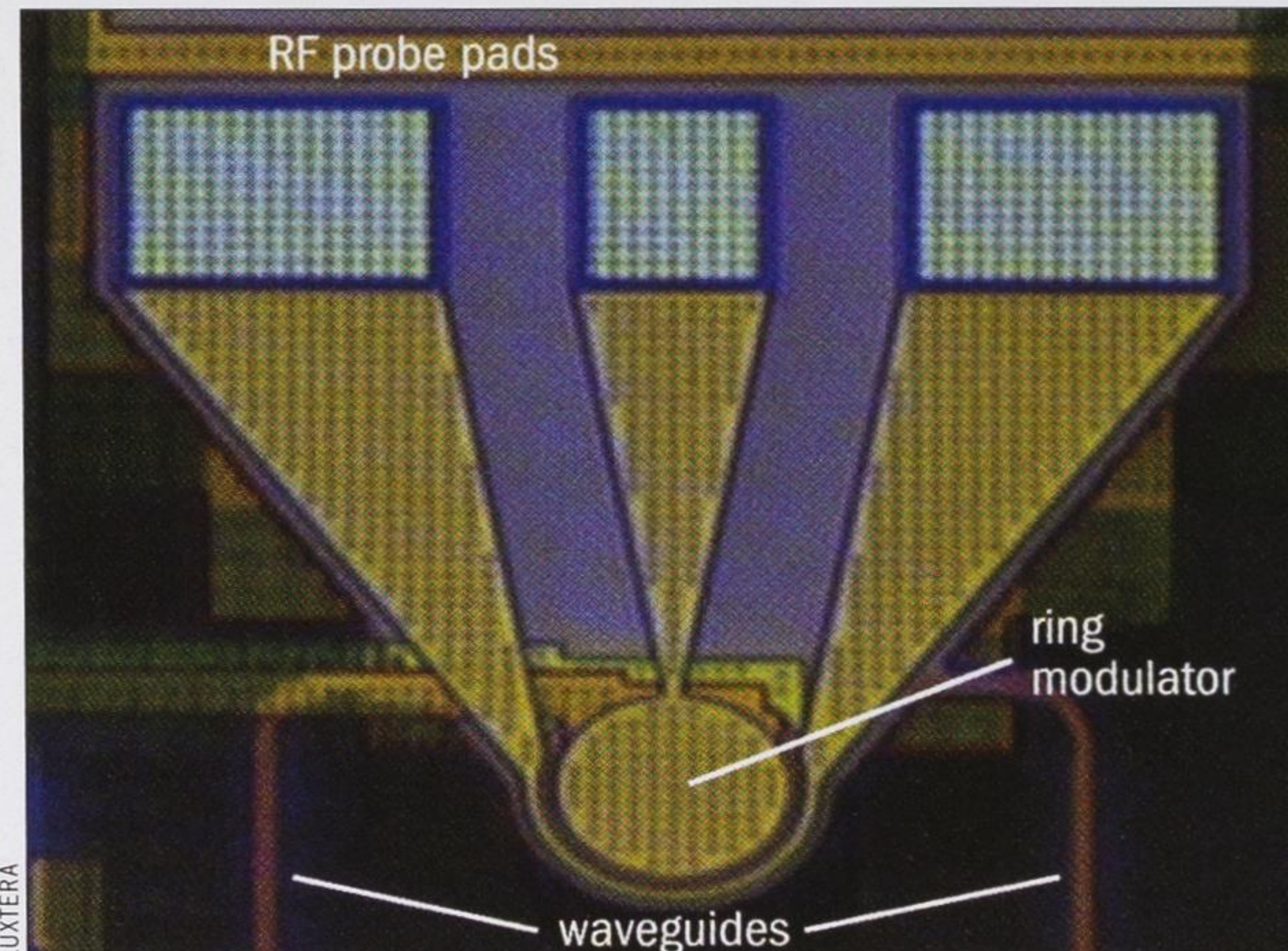
Translucent has not published or presented papers at public conferences. Press releases are available only through parent company Silex Systems Ltd, based in Australia. According to Silex's 2005 annual report, the company has made prototype silicon planar lightwave circuits at the Palo Alto lab, in parallel to the work being done for the DARPA project.

Despite repeated invitations, neither Atanackovic, nor anyone else at the company, agreed to be interviewed for this article. One can

speculate that Translucent may be shifting research priority away from achieving electrically pumped silicon lasers to focus on easier-to-commercialize applications of their materials. Translucent has developed two "spin off" projects from its optical silicon work since 2004: developing materials with high-dielectric constants, which are needed to replace silicon dioxide in the gates of CMOS transistors as miniaturization shrinks feature sizes to below 90 nm; and developing silicon-on-insulator substrates, which are needed for ultra-large-scale integrated circuits – these are likely to be the company's first commercial offering. In a further indication of veering R&D priorities, the company filed a patent application in June this year for an unusually efficient thin-film silicon solar cell design, and announced plans to develop a demonstration cell in the next year.



Luxtera's optical coupler uses diffractive optics and the prism on the wafer's surface to transfer laser light directed vertically downwards into the waveguides on the silicon chip.



Luxtera has produced

compact ring modulators based on CMOS technology that can provide optical switching at 10 Gbit/s. These devices, which will feature in the company's transceiver chips that will be available for sampling this year, are far smaller than the Mach-Zehnder modulators that are typically built from InP.

9 mW output power when pumped with 600 mW). In July, Jalali's group reported a method that recovers some of that energy as electricity, thus reducing heating.

Raman lasers are incapable of being electrically pumped, however. Several alternative routes are being explored, explains Sylvain Cloutier at the University of Delaware (Newark, DE), most of which require making silicon act like a direct-bandgap material.

While Cloutier was working in Jimmy Xu's group at Brown University (Providence, RI), they reported creating a silicon laser that works at cryogenic temperatures using sub-bandgap isoelectronic trapping centers. They drilled holes in a thin layer of silicon, pumped this material with a green laser at 514 nm, and extracted weak laser light at 1278 nm. The exact mechanism for the lasing is unknown, but the researchers suspect that the large surface allows a number of silicon-vacancy defects where trapped electrons and free holes recombine. Lasing was observed from 10 to 80 K, but whether the laser can be converted to a room-temperature electrically driven device is another question. The Brown group is also working on

manipulating phonons in the material.

Other researchers, such as Lorenzo Pavesi at the University of Trento in Italy, use quantum confinement and the surface-state recombination effects of nanocrystals or porous silicon. Nanocrystals are so small that their electrical structure begins to resemble the discrete energy levels in atoms. The size of a particle dictates the bandgap, and therefore the emission color. Thus, silicon nanocrystals emit light at visible wavelengths.

Nanocrystals have demonstrated electroluminescence with about a relatively excellent 1% efficiency, as well as optical gain. However, short lifetimes have been a problem for these materials. We still do not know what mechanism accounts for luminescence in this material. Pavesi suspects that it is a mixture of two recombination paths in the bulk and at the surface. His group is working on creating an electrically injected silicon laser that emits in the visible by overcoming losses and improving bipolar current injection.

The Trento researchers are also one of the groups combining silicon with erbium or germanium. (Another group is the California-based company Translucent,

see "Opaque Translucent" box, p27). Pavesi and co-workers are motivated by the potential of replacing erbium-doped fiber amplifiers with a smaller, cheaper, electrically pumped erbium-doped silicon amplifier. In this scheme some of the energy absorbed by the silicon is transferred to the excited state of Er^{+3} ions, and the erbium releases the light as it relaxes.

Hybrid chips

Silicon might take over all roles except light emission. Luxtera president Alex Dickinson says, "We know that compound semiconductors have a key role." But he adds, "We move a lot of the complexity over to silicon." Luxtera combines optical components with VLSI electronics on silicon chips, betting that the combination of integration and CMOS manufacture will dramatically lower costs. Every component except the flip-chip-bonded laser is made of silicon.

Luxtera sees a market opportunity in the move towards 10 Gbit/s Ethernet. Electrical cabling and power requirements get awkward at this point, but current optical transceivers are too expensive to make economic sense. Lower cost transceivers, especially if they incorporate simple optical connections, could be adopted quickly. Luxtera has intellectual property in a number of key areas, including packaging and modulation. The company is also testing at large volumes: it has made 150 km of silicon waveguides.

This year Luxtera researchers reported making a CMOS 10 Gbit/s DWDM transceiver chip that contains 50 optical devices and about 100,000 transistors, as well as on-chip lasers. If all goes as planned, the transceiver chips will sell for less than \$100. The company will offer sample volumes of transceivers this year, with production quantities available in 2007. These transceiver chips could feature silicon-based ring modulators for switching the light, which Luxtera claims are 25,000 times smaller than Mach-Zhender modulators that are typically made from InP.

Although the efforts at Luxtera show that silicon devices are starting to scratch away at III-V's domain, the impact will likely be small over the next few years. This could however all change if the silicon industry chose to back silicon photonics with multi-billion dollar R&D programs. This funding could improve the performance of many forms of silicon devices, but it is still debatable whether it will ever be possible to make electrically pumped silicon lasers, regardless of how much money is thrown at the problem. ●

About the author

Yvonne Carts-Powell is a freelance science writer based in Belmont, MA, who specializes in photonics, imaging, microtechnology and nanotechnology. E-mail: yvonne@nasw.org.

Further reading

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On-chip gratings add stability to high-power semiconductor lasers

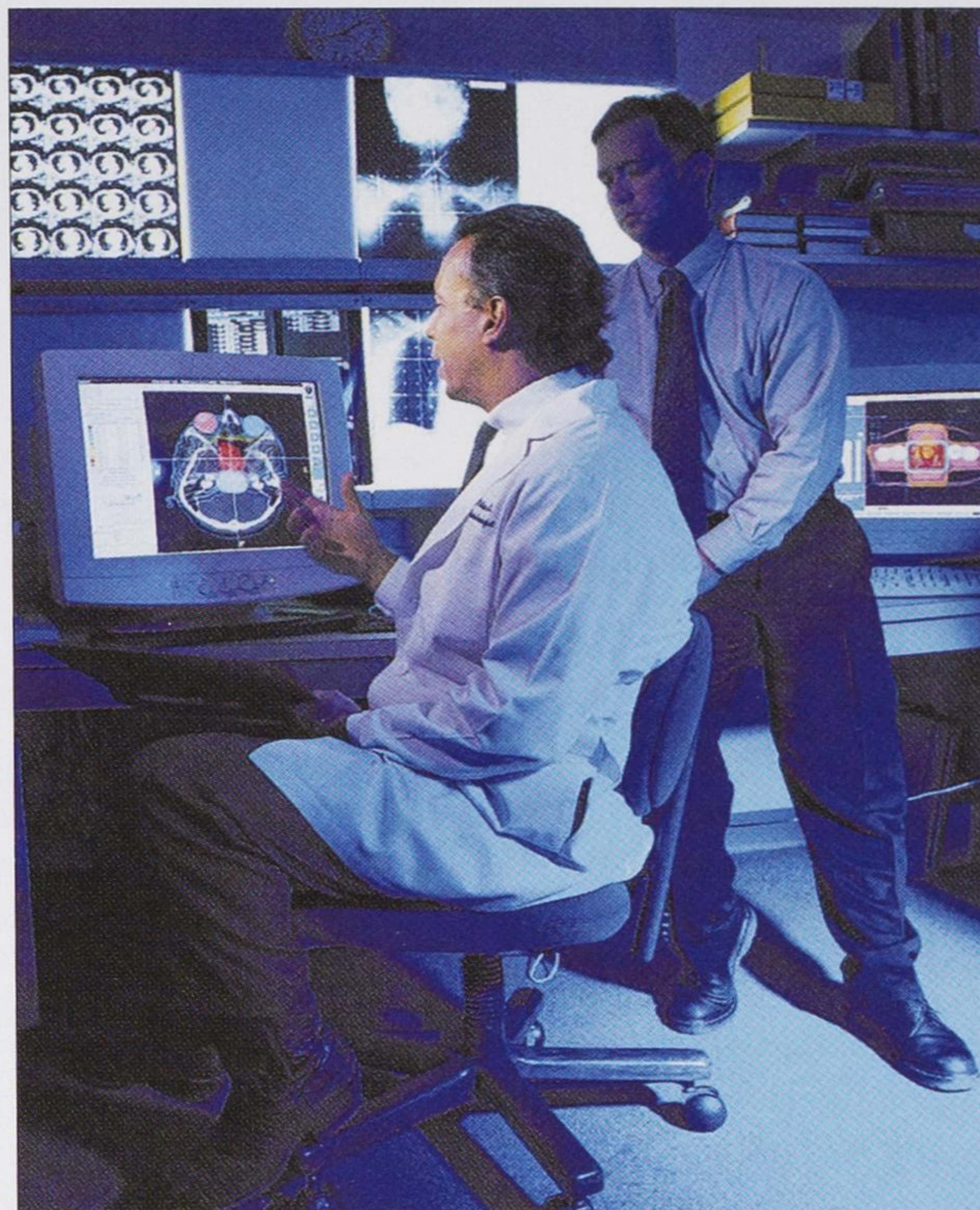
Quintessence Photonics has written gratings into its infrared laser diodes that narrow the emission spectra and reduce temperature sensitivity. This will lead to cheaper diode-pumped laser systems, and make the devices more attractive for medical imaging and Raman spectroscopy, says **Paul Rudy**.

The combination of compactness, low running cost and excellent electrical-to-optical efficiency has enabled high-power edge-emitting laser diodes to serve many applications in industrial, medical and defense markets. A growing number of these lasers are directly addressing “thermal” applications such as printing, medical and plastics welding, but the majority have well-defined spectral emission and are used as sources to pump solid-state and fiber laser systems.

The advantages of diode pumping over lamp pumping are well known, and include increased system efficiency, greater reliability and lower cost of ownership. However, these systems cannot deliver the temperature-independent performance of lamp-pumped designs because of the laser’s lack of stability. Instead, precise thermal management and temperature control of the diode is needed to precisely tune the emission wavelength, and even with this control insufficiently narrow linewidths are produced for some applications.

So it is critical to improve the stability and the spectral narrowing of high-power laser diodes so that they can simultaneously deliver the efficiency associated with diode pumping and temperature-stability provided by lamp pumping. If these objectives are met at a well-defined wavelength, then laser system designers can improve the system’s compactness, efficiency, power, and beam quality while reducing its thermal-management cost. The improvements will also mean that these lasers can be used directly for scientific and medical pumping applications, such as Raman spectroscopy and enhanced magnetic resonance imaging, which require precise tuning of narrow emission wavelengths to hit atomic or molecular absorption spectra.

Various methods have already been used to improve the spectral brightness, stability and accuracy of laser diodes. These approaches include various external techniques using either volume Bragg gratings, external lenses and bulk gratings, or seed lasers in master oscillator power amplifiers. However, all of these approaches require sensitive and high-precision alignment, costly additional lasers and/or optics and specially designed coatings. On-chip solutions are possible with internal distributed feedback gratings similar to those that are used in singlemode telecom lasers. However, it is difficult to transfer this technology to



High-power laser diodes with sufficiently narrow linewidths can be used for various medical applications, including pumping solid-state laser systems for “enhanced” magnetic resonance imaging.

high-power multimode lasers because multimode devices require more complex grating designs to capture and lock the large number of transverse modes.

Recently, Quintessence Photonics Corporation (QPC) has overcome these challenges and demonstrated a range of high-power lasers operating at 808, 976, 1470, 1535 and 1550 nm, which are fabricated at our headquarters in Sylmar, CA. These MOCVD-grown InP-based and GaAs-based lasers feature internal gratings that narrow the spectral linewidth, reduce wavelength-temperature sensitivity, and ensure that the device operates at the required wavelength.

High-power diode lasers are usually constructed by inserting a gain-producing active stripe into the device’s resonant Fabry-Pérot cavity. The cavity provides essentially no wavelength control, aside from defining a periodic “comb” of resonant frequencies, and the emission wavelength is controlled by the active layer’s gain spectrum. Unfortunately, this gain

Quintessence’s high-power grating-based lasers vs conventional designs

Single emitters	808 nm emitter		976 nm emitter		1470 nm emitter		1535 nm emitter		1550 nm singlemode	
	SD	IG	SD	IG	SD	IG	SD	IG	SD	IG
Power (W)	6	6	6	6	1.5	1.5	1.5	1.5	1	1
Wavelength tolerance (nm)	±3	±0.5	±5	±0.5	±10	±1	±10	±1	±10	±1
Spectral width (FWHM) (nm)	2	0.3	2	0.3	10	1	10	1	10	0.01
Temperature tuning (nm/C)	0.3	0.07	0.3	0.07	0.35	0.1	0.35	0.1	0.35	0.1

SD = standard device; IG = internal grating.

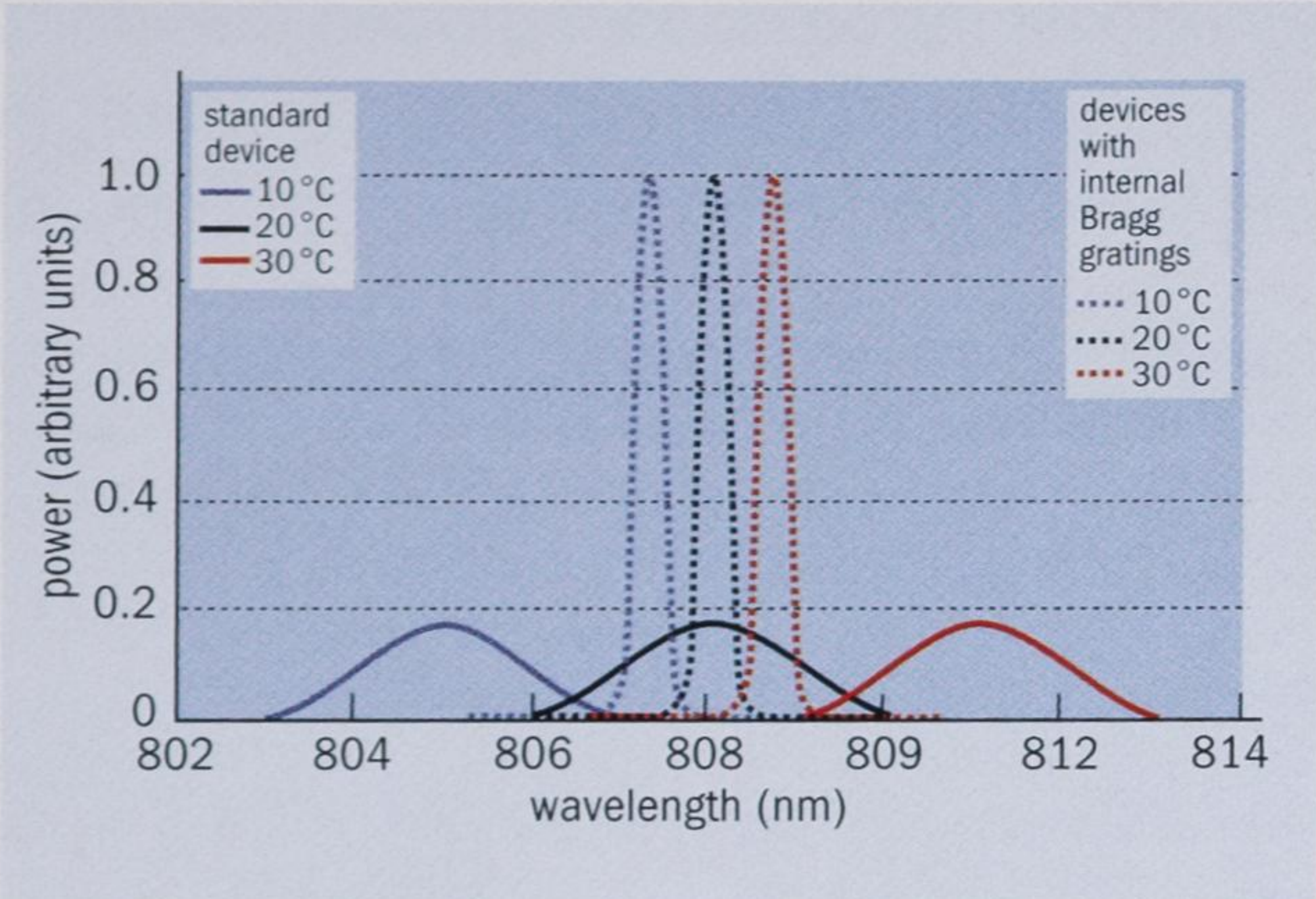


Fig. 1. Internal Bragg gratings (represented by the dashed lines) deliver a reduction in the shift in wavelength with temperature, and a narrower emission width, compared with standard lasers.

spectrum is “flat”, with a characteristic width of typically 20 nm, and is strongly temperature dependent. This makes for a spectrally broad laser output, particularly at high power fluxes, which is highly dependent on the operating temperature. The emission wavelength can typically vary by 0.3 nm/°C.

However, when the on-chip grating is added to select the longitudinal mode, temperature sensitivity is governed by the changes in refractive index of the grating region, and is reduced to 0.1 nm/°C or less. These devices are fabricated in a similar way to conventional laser diodes, with the gratings defined by optical lithography into a photoresist, followed by etching, or formed during a growth and re-growth process. The InP and GaAs lasers have different grating geometries that are designed through extensive modeling, but use similar processes to write the gratings. After the design has been optimized, the total processing time for the grating-based lasers is only slightly longer than that for conventional emitters. Our development has led us to believe that high-power grating-based lasers promise excellent manufacturing yields through improved targeting of the wavelength, which leads to reduced yield loss compared with conventional laser diodes.

When 808 nm pump lasers are sold, it’s typically with a 3 nm center wavelength tolerance, a spectral width of less than 2–4 nm and a 0.3 nm/°C temperature tuning coefficient. However, for common gain media, such as neodymium-based crystals, absorption peaks can be as narrow as 1 nm. This means that system manufacturers have to control the operating temperature to within 0.1 °C to correctly tune and maintain the appropriate

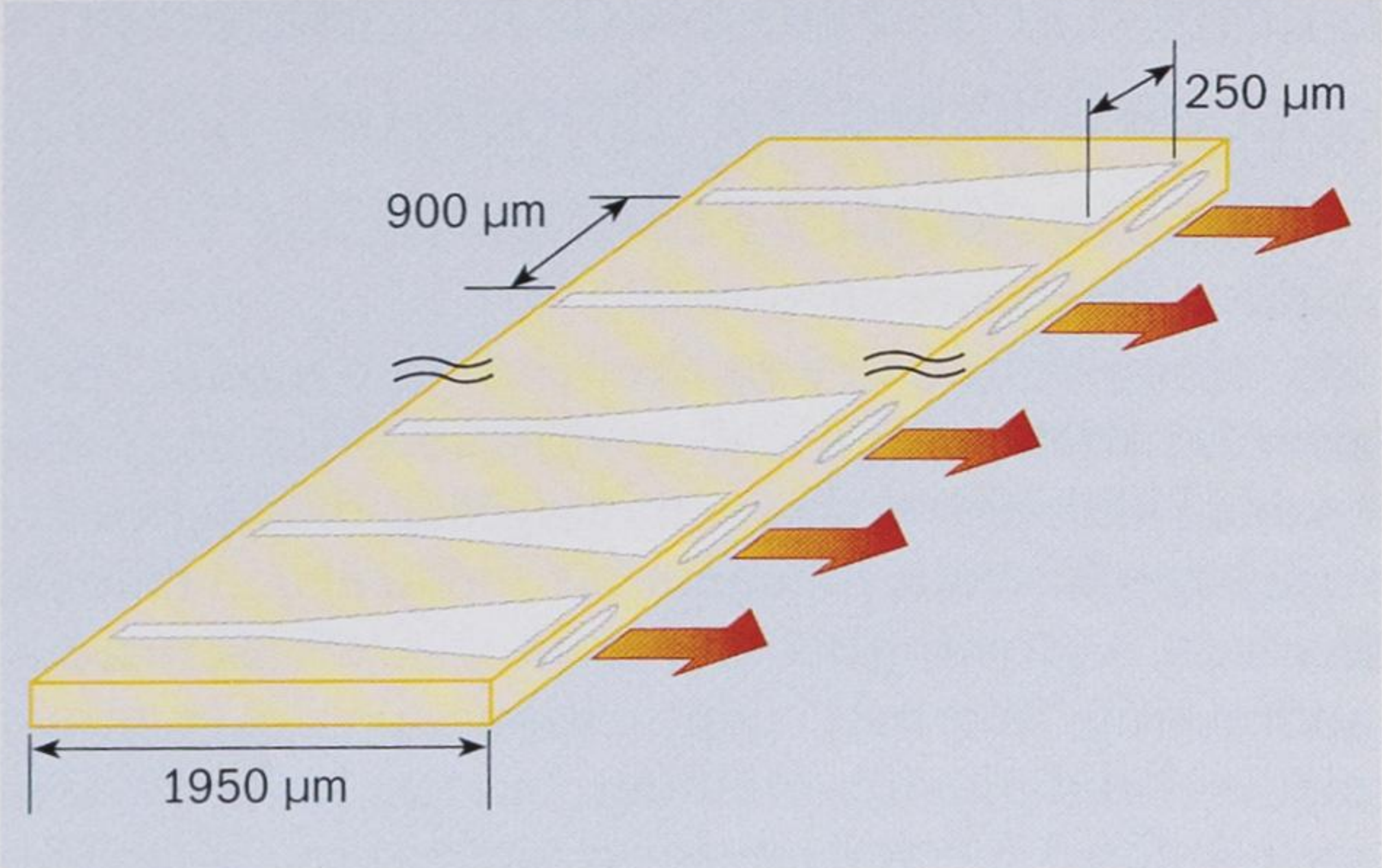


Fig. 2. QPC’s 1550 nm emitter features a buried heterostructure singlemode waveguide, which governs the operating mode. It is 750 μm long and typically 1.5 μm wide. This mode is then amplified with a 1200 μm long tapered gain region.

emission wavelength. Unfortunately, the diode red-shifts as it ages, and to maintain efficient lasing the diode has to be increasingly cooled, often until it reaches the dew point. Once this point is reached catastrophic damage to the laser’s mirrors can occur.

QPC has released 808 nm lasers this June with 100 μm wide stripes that avoid these issues by using internal gratings to deliver the performance described in the table above. These lasers have much narrower laser emission widths than their Fabry-Pérot cousins (see figure 1), and have great promise for Raman spectroscopy, pumping alkali vapors for medical imaging and atomic vapor lasers, and simplifying neodymium-based diode pumped systems.

In the 915–976 nm regime, high-power laser diodes are used to pump fiber lasers that have a typical center wavelength tolerance of 5 nm, a spectral width of less than 5 nm and a temperature tuning coefficient of 0.3 nm/°C. The fiber laser’s absorption spectrum has a relatively weak broad peak of 915–960 nm, and a three-to-four times stronger peak at 976 nm. Using this shorter wavelength peak is not ideal for a growing number of pulsed fiber laser applications, because longer lengths of fiber increase nonlinear losses. Until now, the choice has been between using an uncooled diode to pump the broad-but-weak absorption peak, or a temperature-controlled laser to excite the stronger and narrower 976 nm peak. However, our 976 nm single-emitting device shows that it is possible to enjoy the benefits of pumping strong-but-narrow peaks without the need for high precision temperature controls.

Diode lasers of 1.4–1.6 μm are used for various

applications, including pumping Er:YAG lasers that are used for range finding, materials processing and aesthetic medical treatments. These lasers, which emit in the eye-safe regime, are also becoming widely used to reduce the impact of potentially hazardous unintended scattered radiation from either laser sources, optical delivery systems or targets. Applications abound in the industrial, defense and medical markets.

For Er:YAG pumping, lasers operating at 0.9–1.0 μm can be used, but optical conversion is more efficient at 1532 nm where there is a 1 nm wide absorption peak. This peak can be pumped using typical high-power temperature-controlled InP lasers that have a 10 nm spectral width and 0.35 nm/ $^{\circ}\text{C}$ temperature tuning, but it can also be excited with increased efficiency with our grating-based laser bars.

Fiber laser sources

High-power fiber lasers often use several expensive amplifying stages, but this cost could be avoided with 1550 nm single frequency, single transverse mode diodes that can deliver sufficient power. At higher powers, singlemode operation has been demonstrated in tapered devices. However, producing more power while maintaining a near diffraction-limited performance and narrow linewidth is challenging, because of yield losses owing to beam quality deterioration at high powers, and filamentation at relatively low powers.

These issues have been addressed with QPC's high-power 1550 nm laser, which contains a buried heterostructure singlemode waveguide and a tapered gain region (see figure 2). The waveguide acts as a mode filter, but once the beam is fed into the tapered gain region the mode can freely diffract and be amplified by a tapered electrical contact. These lasers can deliver more than 1.5 W at 28% wall plug efficiency, using a 5 A drive current. Spectral linewidth is limited by the test equipment, but was measured at less than 6 MHz, and suppression of the sidemodes is more than 50 dB.

The combination of our range of diodes' spectral brightness, stability and spatial brightness opens the door to deployment in tasks such as the seeding and core pumping of fiber systems, as well as providing the source for second harmonic generation of light for biotech and display applications. And even higher output powers could be reached while maintaining diffraction-limited performance if emitters can be coherently combined. Our motivation is to expand the number of pumping and direct diode applications with enhanced performance, increased temperature stability and reduced system complexity, while maintaining the device's compactness, low running cost and excellent efficiency.

Acknowledgments

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DEVICE PROCESSING

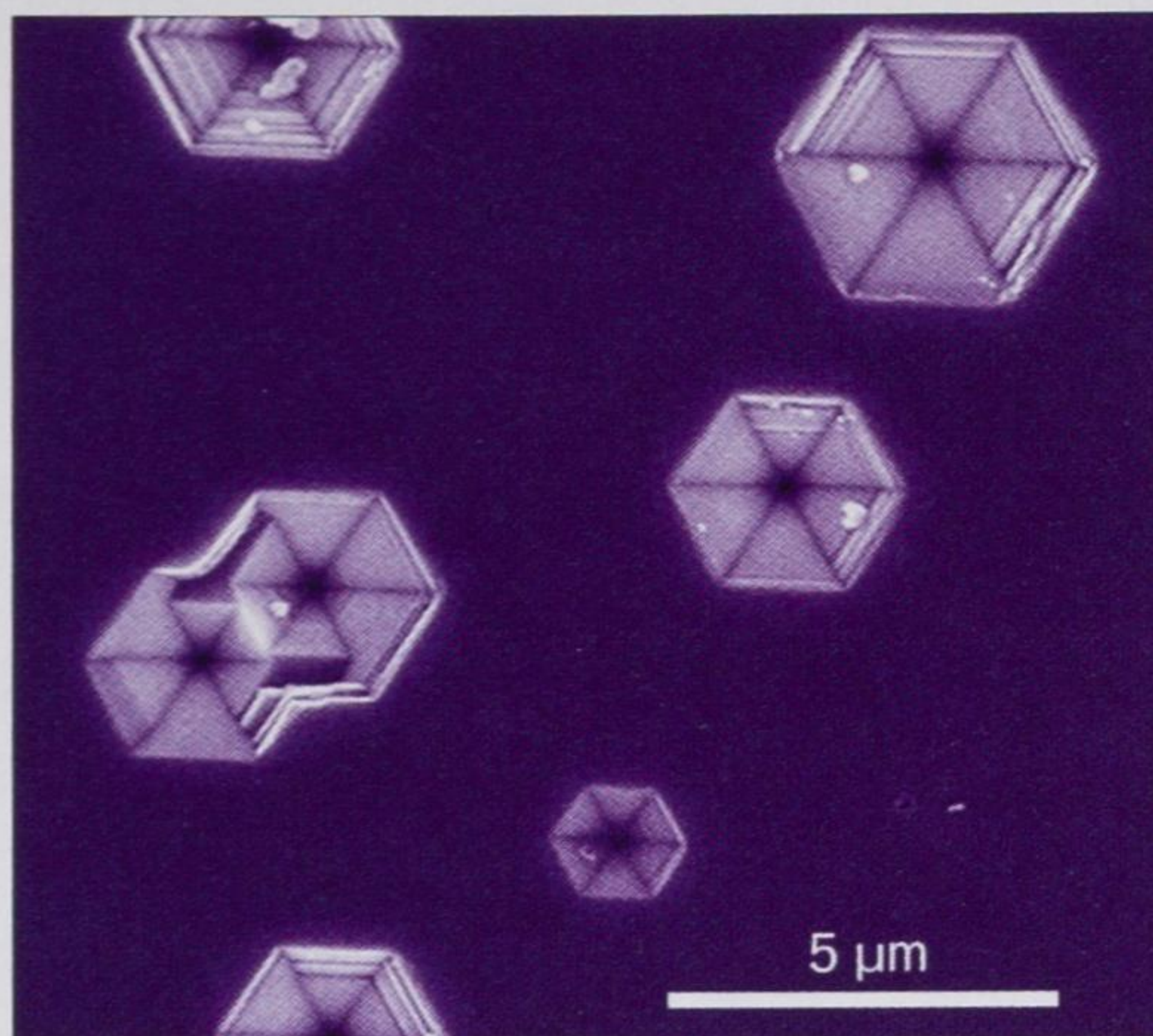
Etched hexagonal pits brighten GaN LEDs

A Korean partnership between Samsung Electro-Mechanics and Gwangju Institute of Science and Technology (GIST) has improved the electrical and optical performance of LEDs by etching into the device's p-type GaN layer.

Etching with a potassium hydroxide in ethylene glycol solution created hexagonal pits in the p-type GaN (see figure) that increased the light output by 29.4% at 20 mA drive current.

The new surface morphology increases the probability of photons escaping from the device. Other factors accounting for the improvements are a larger contact area between the electrode and the p-GaN layer, which reduces contact resistance, and an increase in hole concentration, which comes from the surface texturing.

The team says that its wet etching process should also greatly enhance LED lifetime, because it reduces the leakage current through

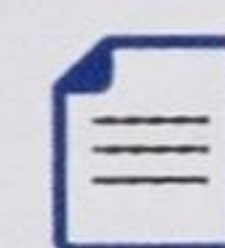


By etching hexagonal pits into the p-type layer, Samsung and Gwangju Institute of Science and Technology have increased the number of photons emitted by GaN LEDs and reduced the leakage current.

surface passivation and removal of threading dislocations from the p-type GaN layer.

The Korean researchers demonstrated the benefits of their process by comparing etched and standard $300 \times 300 \mu\text{m}$ LED chips that were grown by MOCVD on sapphire substrates and featured five InGaN/GaN quantum wells. Etching was carried out at 165°C for 30 minutes, and produced $0.5\text{--}3.7 \mu\text{m}$ hexagonal pits with a density of $4.7 \times 10^6 \text{ cm}^{-2}$ and a depth of $10\text{--}20 \text{ nm}$.

Seong-Ju Park from GIST believes that the wet etching process is suitable for volume manufacturing, and revealed that Samsung is continuing to develop this process for its next-generation LEDs.



Journal reference

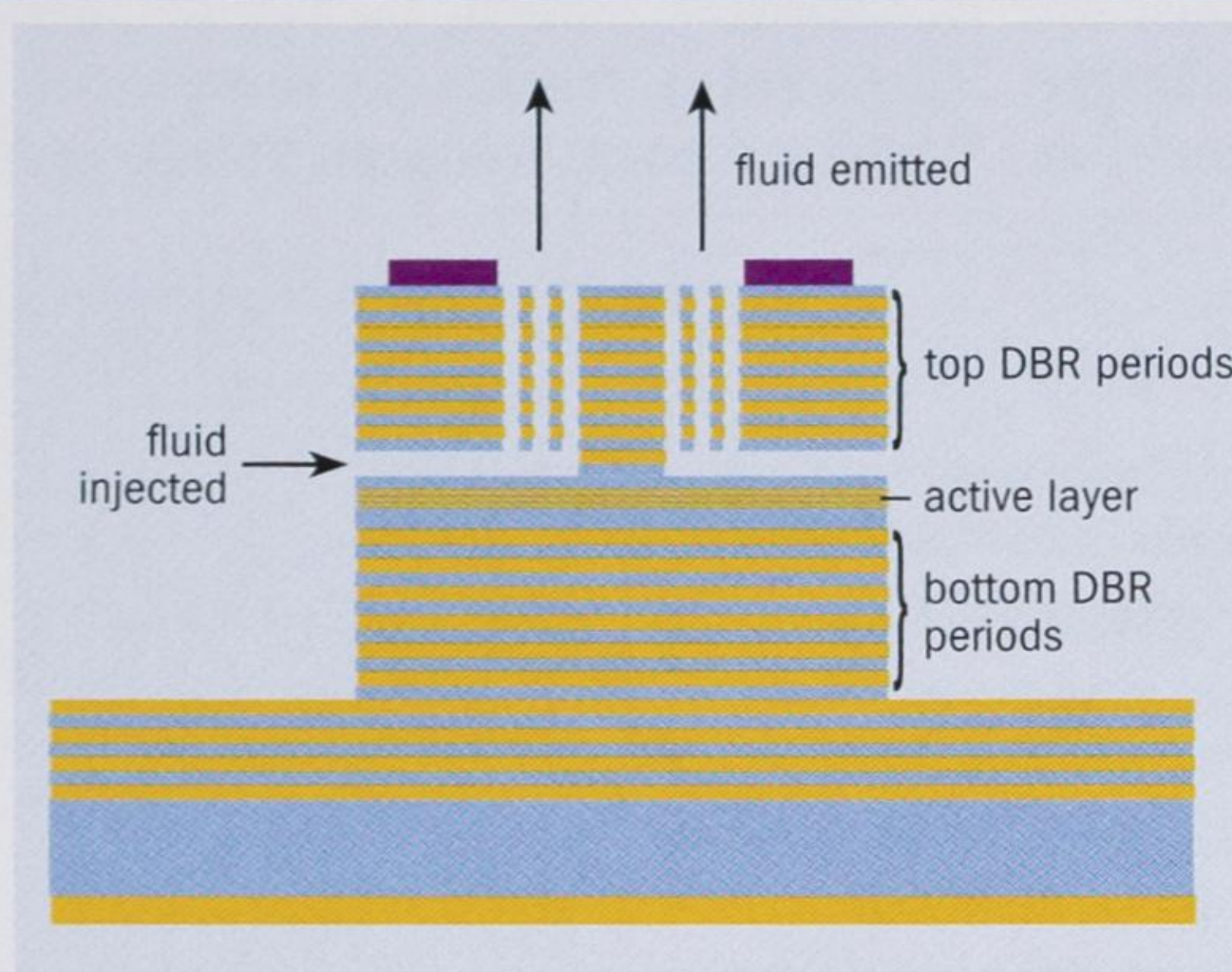
S I Na et al. 2006 *IEEE Photon. Tech. Lett.* **18** 1512.

LASER DESIGN

Modified VCSEL design detects various fluids

Researchers from the University of Illinois, Urbana-Champaign, have made the first monolithic photonic crystal VCSEL to feature horizontal and vertical micro-fluidic channels within the device (see figure). The scientists say that the 850 nm laser could provide highly sensitive detection of fluids, cells and particulates.

The devices are formed by first fabricating conventional VCSEL structures. Patterns of circular holes with diameters of $1\text{--}5 \mu\text{m}$ are then written by electron-beam lithography on to the top of the devices, before an inductively-coupled reactive ion etch step down to the oxide layer to form a photonic VCSEL.



The modified MOCVD-grown 850 nm VCSEL that contains AlGaAs distributed Bragg reflectors (DBRs), also features micro-fluidic channels, which are etched into the top part of the structure. The new device contains five GaAs quantum wells, an AuGe/Ni/Au ohmic backside contact and a Ti/Au top ring contact.

Horizontal channels are finally added by wet etching the oxide layer at $2.5 \mu\text{m}$ per minute, using potassium hydroxide.

To test the sensing ability of their VCSELs, Karthikraman Samakkulam and colleagues monitored the shift in emission wavelength produced when fluids are inserted into the device. Water and acetone were inserted into the horizontal micro-channel and these red-shifted the singlemode emission wavelength by 0.26 and 2 nm , respectively.

Although the researchers are unable to explain the sensing mechanisms in their micro-fluidic VCSELs, they believe that acetone's higher refractive index is responsible for the greater shift in emission wavelength.



Journal reference

K Samakkulam et al. 2006 *Electron. Lett.* **42** 809.

DILUTE NITRIDES

New III-V ratio set to benefit laser intensity

Researchers at Stanford University have doubled the photoluminescent efficiency of MBE-grown $1.55 \mu\text{m}$ GaInNAsSb quantum-well structures by reducing the flux of arsenic and antimony during epitaxy.

The team, working in partnership with Innovation Core SEI, a US-based subsidiary of Sumitomo Electric Industries that offers consultancy services for manufacturing optical components, believes that the new growth

conditions could improve temperature stability and reduce the threshold current density of dilute-nitride lasers that promise lower manufacturing costs than InP-based devices.

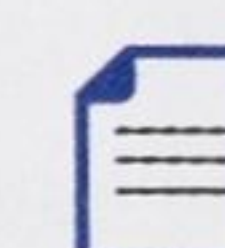
The researchers compared the photoluminescence of several samples that featured a 7.5 nm $\text{Ga}_{0.59}\text{In}_{0.41}\text{N}_{0.028}\text{As}_{0.942}\text{Sb}_{0.03}$ quantum well sandwiched between 22 nm thick $\text{GaN}_{0.03}\text{As}_{0.97}$ barriers.

The photoluminescence from structures dropped significantly when the arsenic/III ratio was cut from 10 to 2 (equivalent to a decrease in arsenic/antimony ratio of 50 to 10).

After fixing the arsenic/antimony ratio to 42, which gives relatively strong photoluminescence, the team investigated the influ-

ence of the combined arsenic and antimony content versus the group III material (As+Sb)/III on the photoluminescence intensity. When this ratio fell from 10 to 5, the intensity doubled.

Seth Bank from Stanford University told *Compound Semiconductor* that the team still has to fabricate lasers using the improved growth conditions. "We are very excited about the potential performance of lasers grown under reduced III/V ratios, because even the two-fold improvement in photoluminescence should significantly enhance laser performance."



Journal reference

S Bank et al. 2006 *Appl. Phys. Lett.* **88** 241923.



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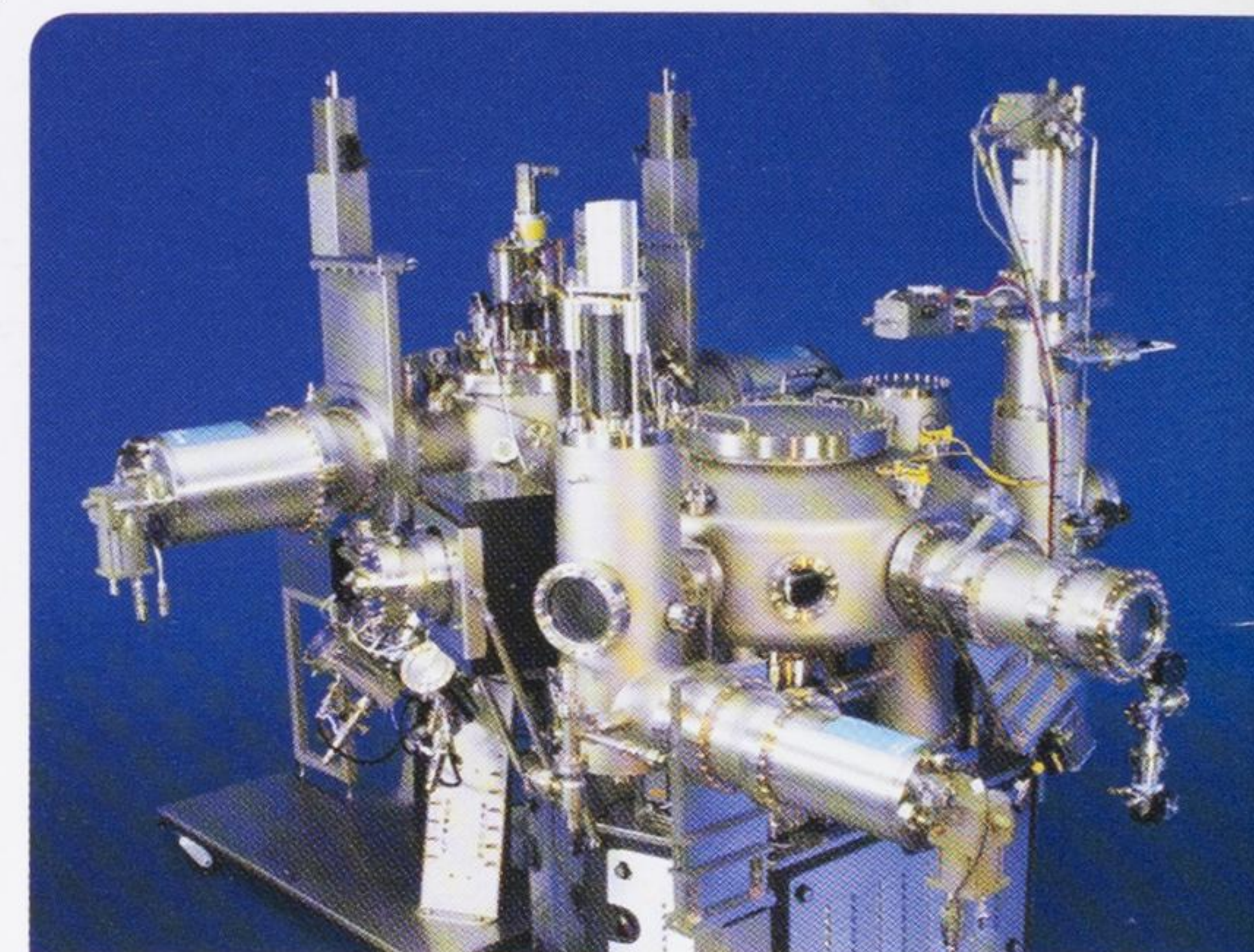
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