

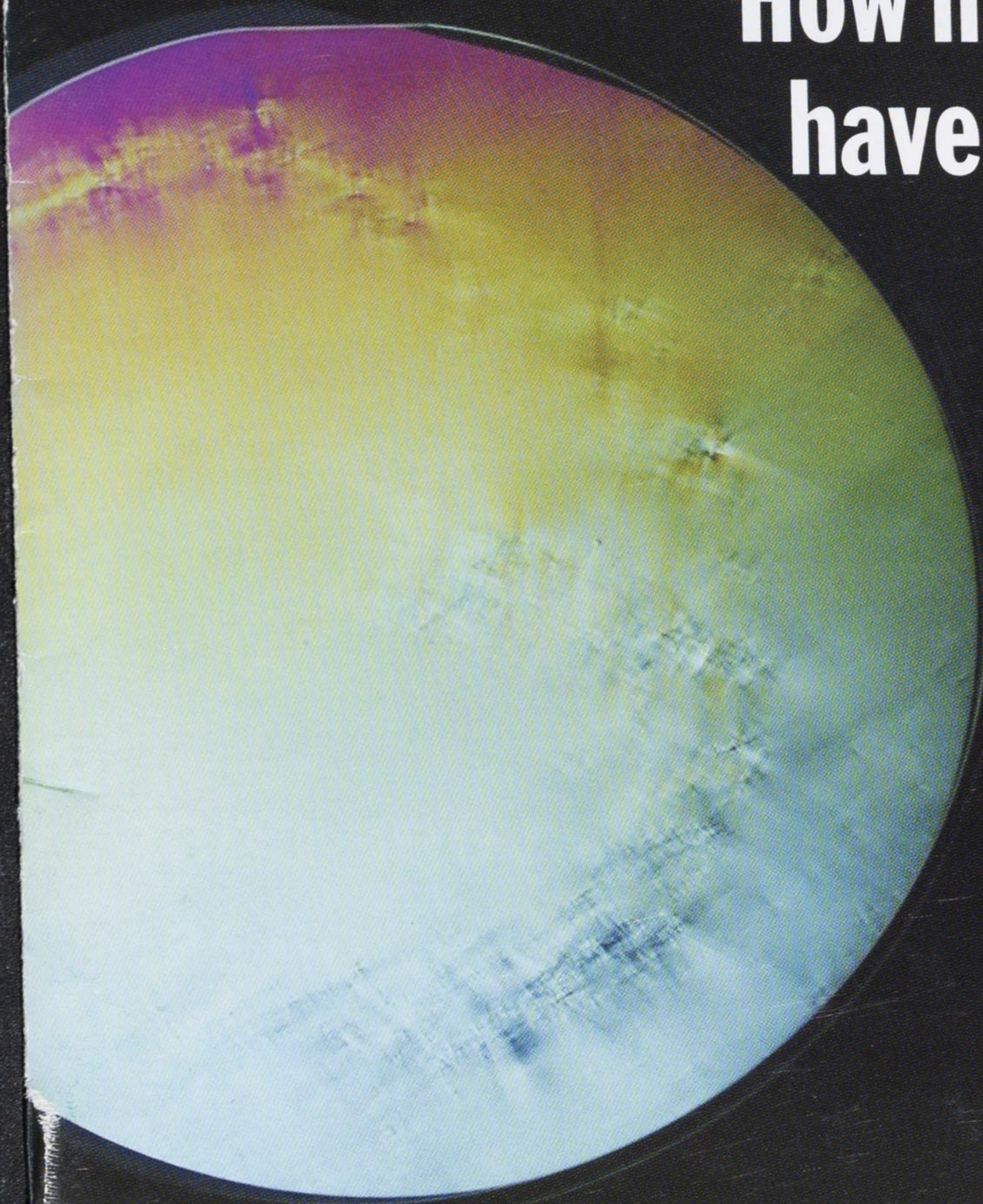
COMPOUND SEMICONDUCTOR

November 2006 Volume 12 Number 10

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

SIC SUBSTRATES

How many defects
have yours got?



HEADLINE NEWS

**UK defense
chiefs feel the
need for GaN** p5

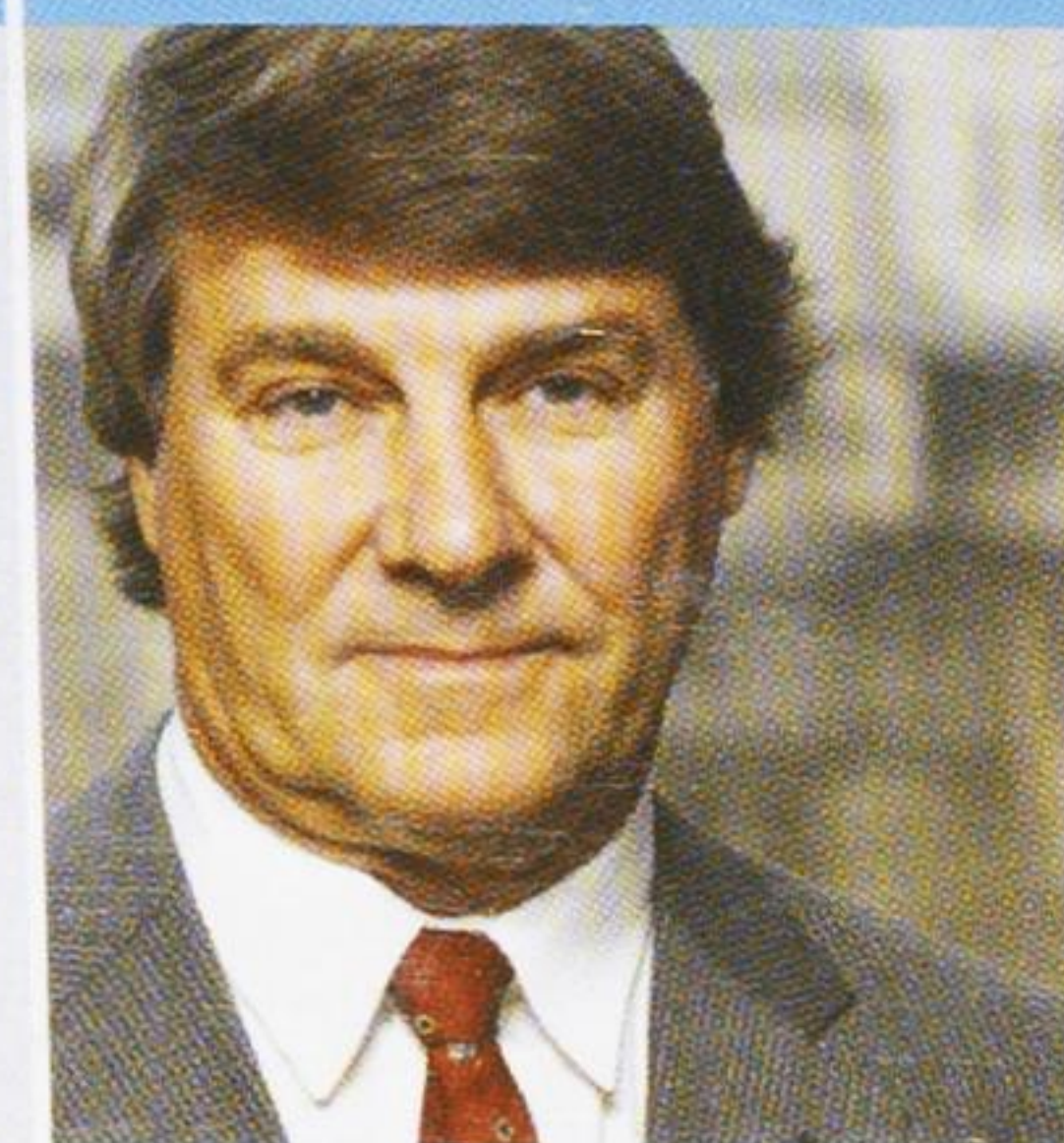
HB-LEDs



Sixties throwback

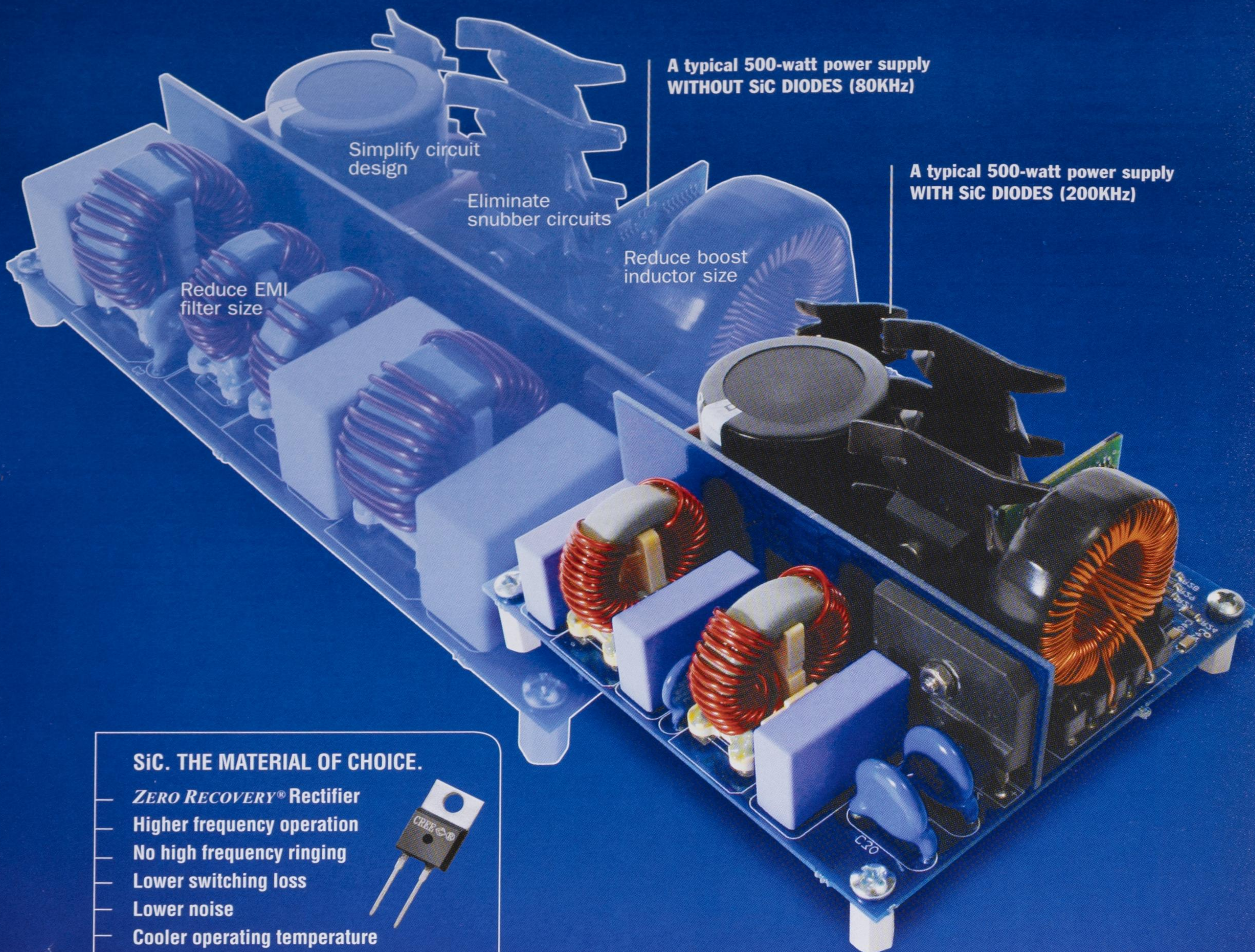
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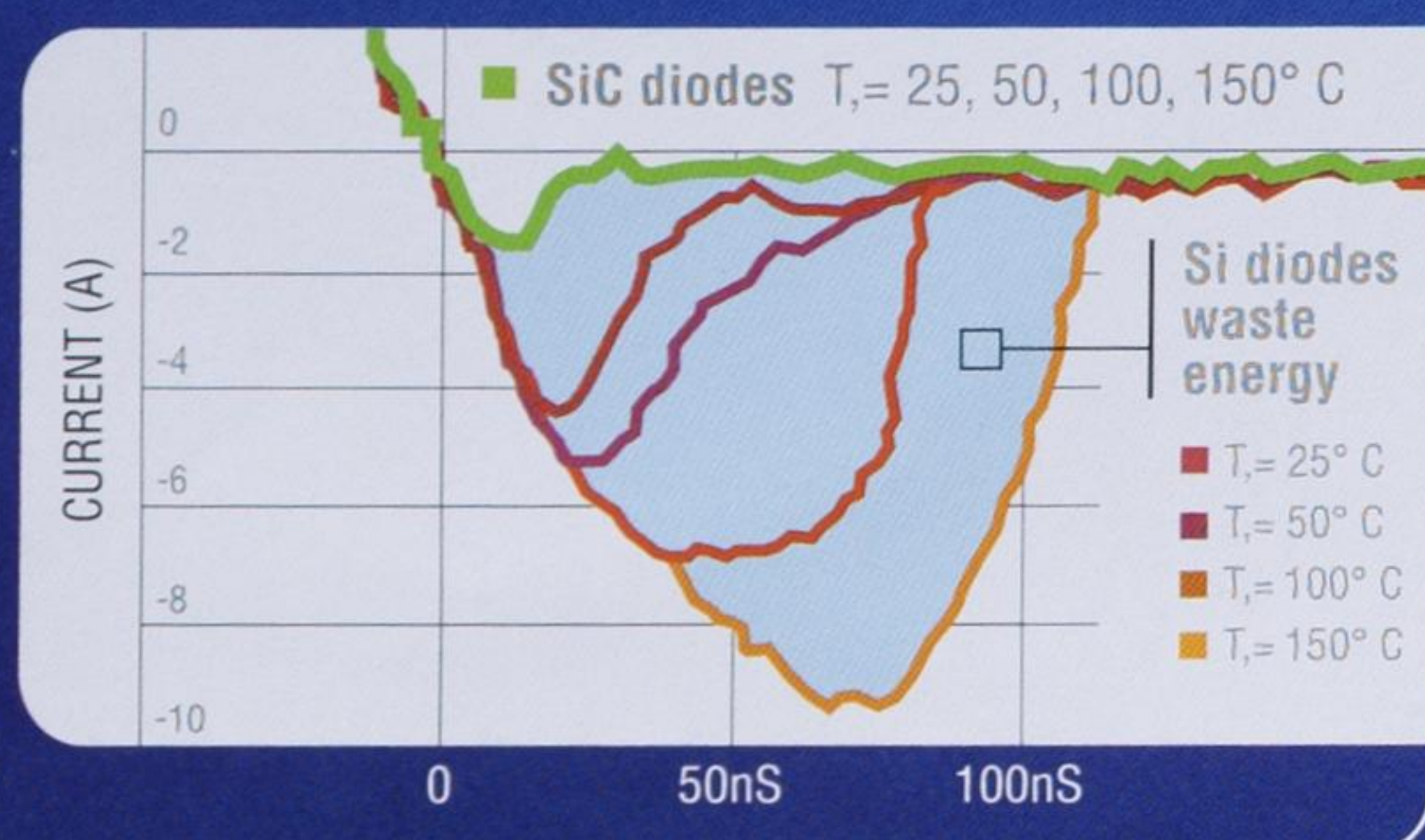
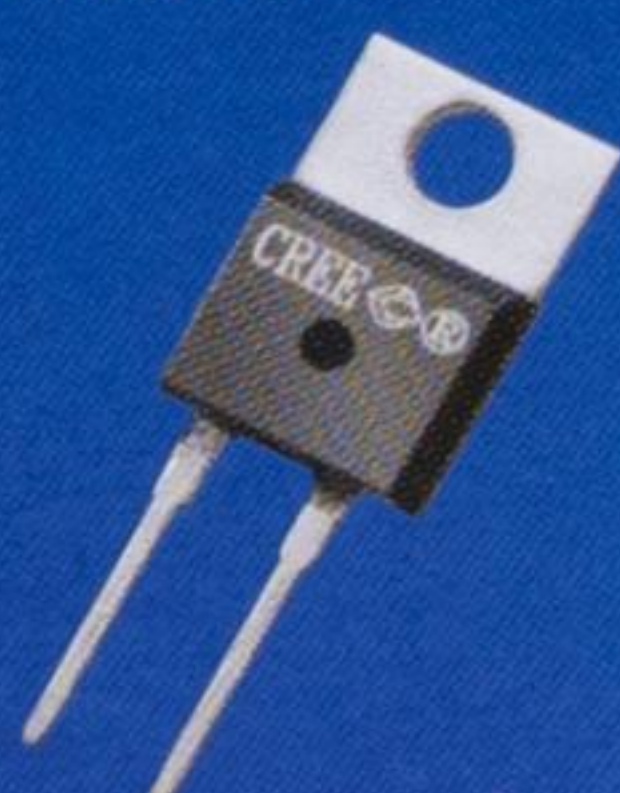
David Jordan explains why making GaN LEDs on a glass substrate makes sense. p12



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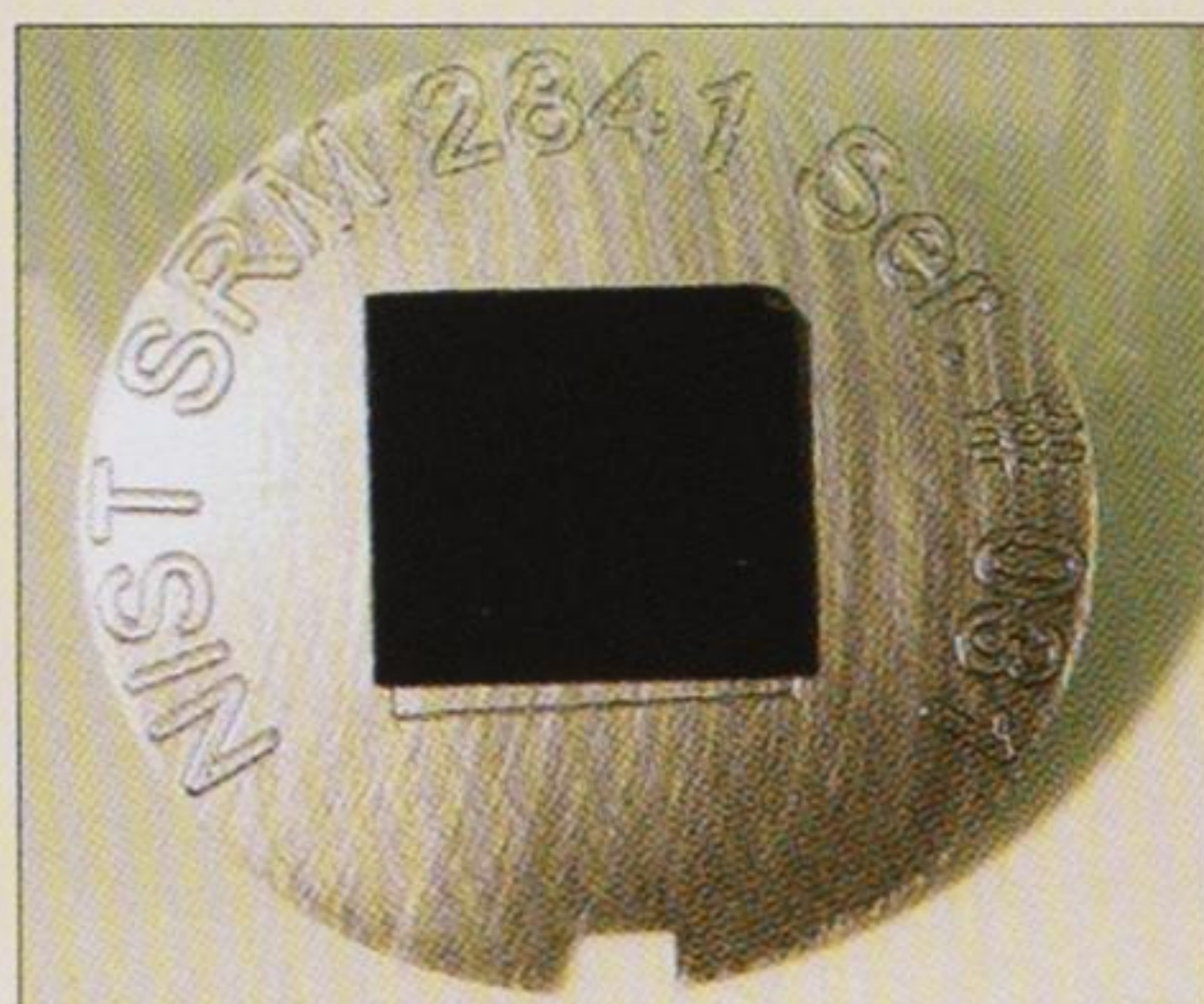
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INDUSTRY

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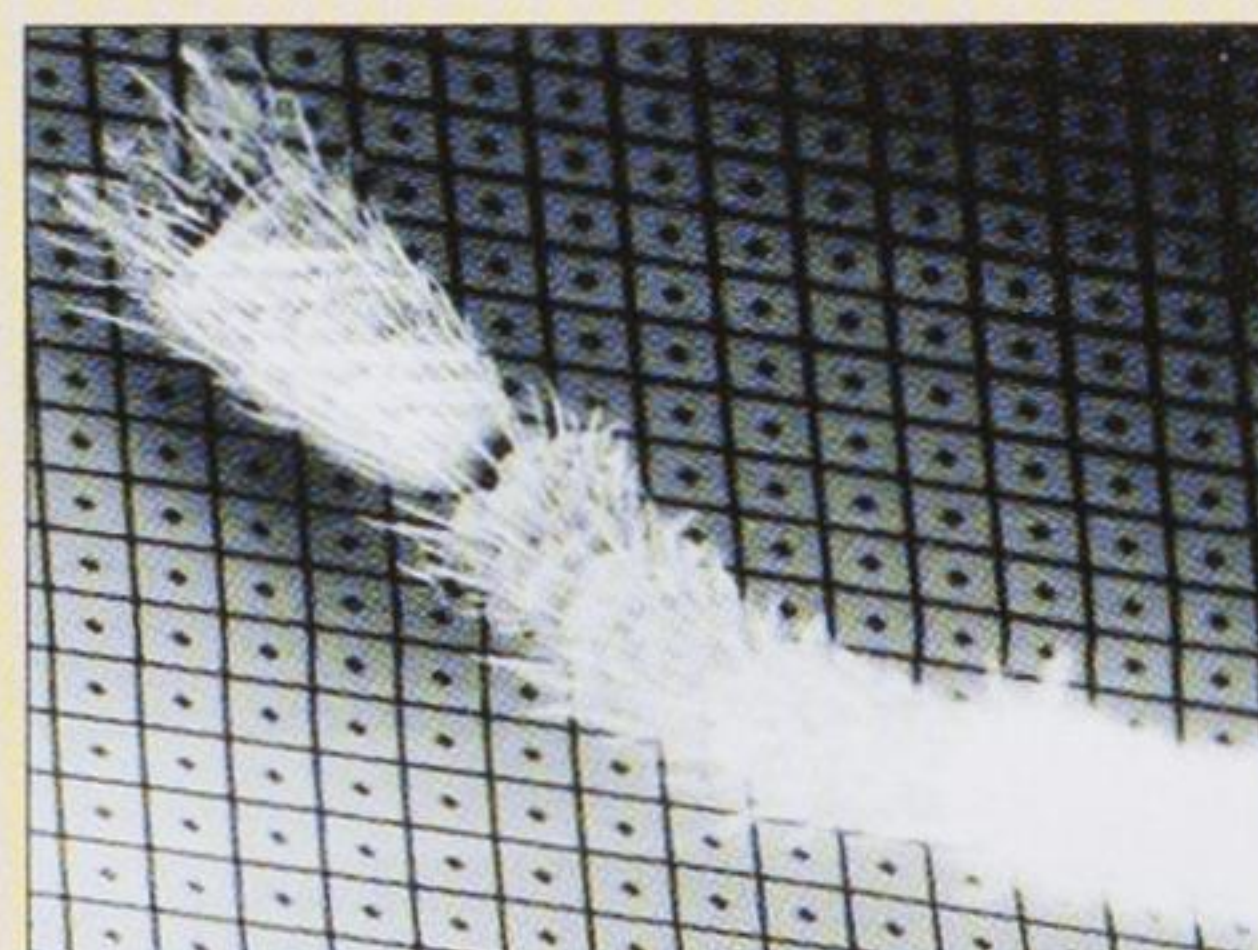


Small is beautiful

NIST has made available tiny pieces of AlGaAs that should help III-V manufacturers become more efficient. **p5**

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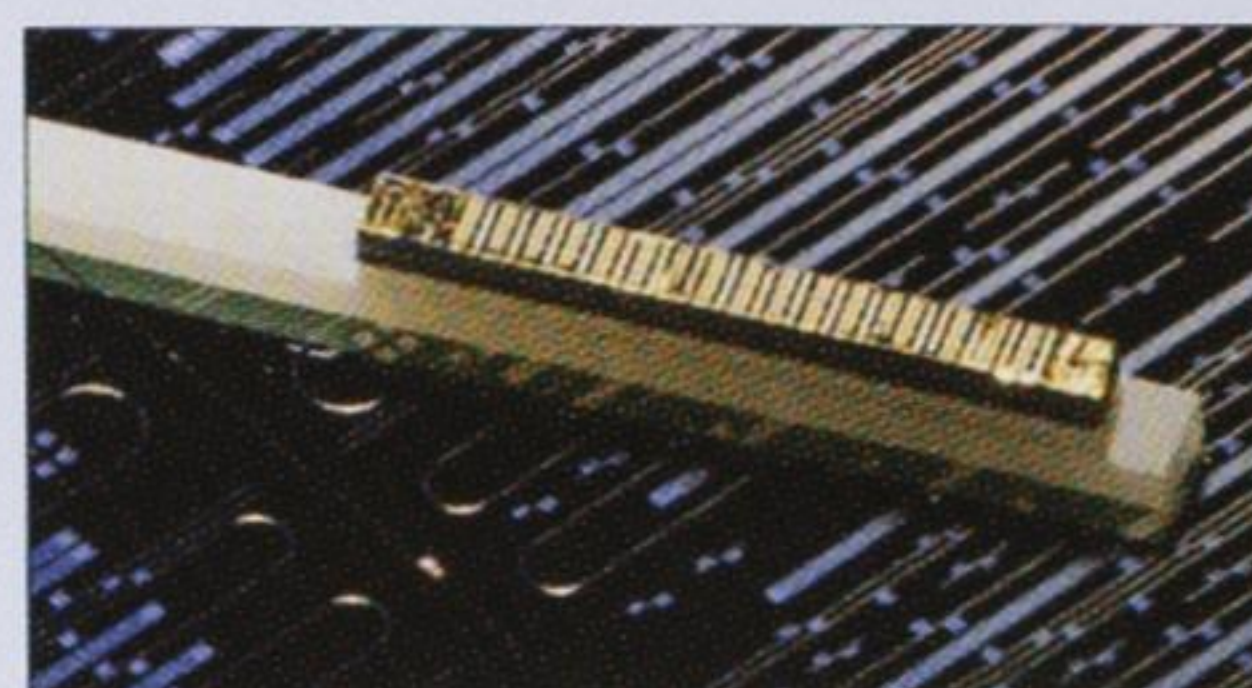
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Intel's new hybrid chip can integrate up to 36 lasers on a single die. **p17**

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Main cover image: Observed using cross-polarized light to highlight defects, the quality of these two SiC substrates might look completely different, but actually they both conform to equivalent SEMI standards for the material. As a result, some believe that the standards should be reviewed. Images courtesy of Northrop Grumman/Trans Tech Publications.

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US mailing information: *Compound Semiconductor* (ISSN 1096-598X) is published 11 times a year for \$148 by Institute of Physics Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK. Periodicals postage paid at Middlesex, NJ 08846. POSTMASTER: send address corrections to Compound Semiconductor, c/o PO Box 177, Middlesex, NJ 08846. US agent: Pronto Mailers Association Inc, 200 Wood Avenue, PO Box 177, Middlesex, NJ 08846.

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Global milestones



The daily churn of stories on our news service *compoundsemiconductor.net* last month included a couple of notable milestones in the world of commercial compound semiconductor device manufacturing. One of these came from Spectrolab, which specializes in multi-junction photovoltaic devices that are mostly used to power satellites, revealing that it had now made two million GaAs-based solar cells.

It's an impressive achievement. Having overcome the incredibly stringent technical demands of applications in space, Spectrolab's technology can now be found in more than half of all the satellites orbiting Earth, including the International Space Station. Its solar cells also feature in six of the seven craft still to be found either on the Martian surface or in orbit around the red planet, and have helped the Mars Global Surveyor and the Spirit and Opportunity rovers to operate way beyond their predicted lifespans.

A couple of weeks before Spectrolab, and a step up in terms of manufacturing volume, Finisar shipped its 50 millionth VCSEL. For that we

"The continued global craving for cell phones has prompted analysts to predict that a billion will be sold in 2006."

must also doff our hats to Honeywell, which began making the surface-emitting lasers commercially back in 1996. Finisar has emerged as a force to be reckoned with within the optical data communications sector, and has even commissioned a new epitaxy machine to meet the expected demand.

But do these admittedly impressive milestones really matter, or are they just nice, round numbers? Well, maybe here's one that does matter. The continued global craving for cell phones and, in turn, the GaAs transistors that sit at the heart of pretty much all of them these days, has prompted a number of analysts, including ABI Research and IDC, to predict another big milestone for 2006 – that a billion mobile phones will be sold.

One billion? It's the sort of number that is barely possible to conceive, and one that inevitably results in metaphors involving things being stacked end-to-end and stretching all the way around the world. Come to think of it, with the triple-junction solar cells in orbit, the surface-emitting lasers sending daily news updates around the world via optical networks, and the transistors deployed in phones from Africa to the Antarctic, it would be fair to say that the world has already been wrapped in compound semiconductors.

Michael Hatcher *Editor*

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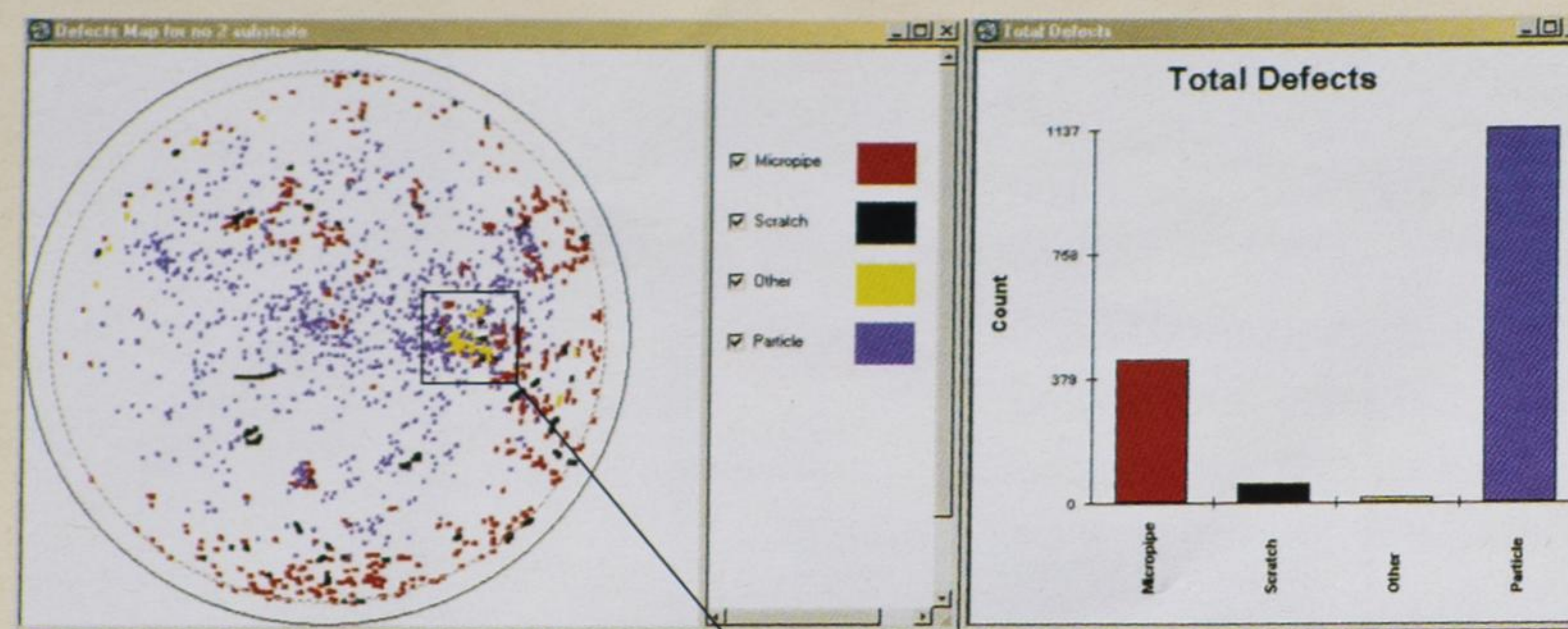
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13

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Summary Defect Report by Bin

Defect Count by Bin

Micropipe

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

Micropipe

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

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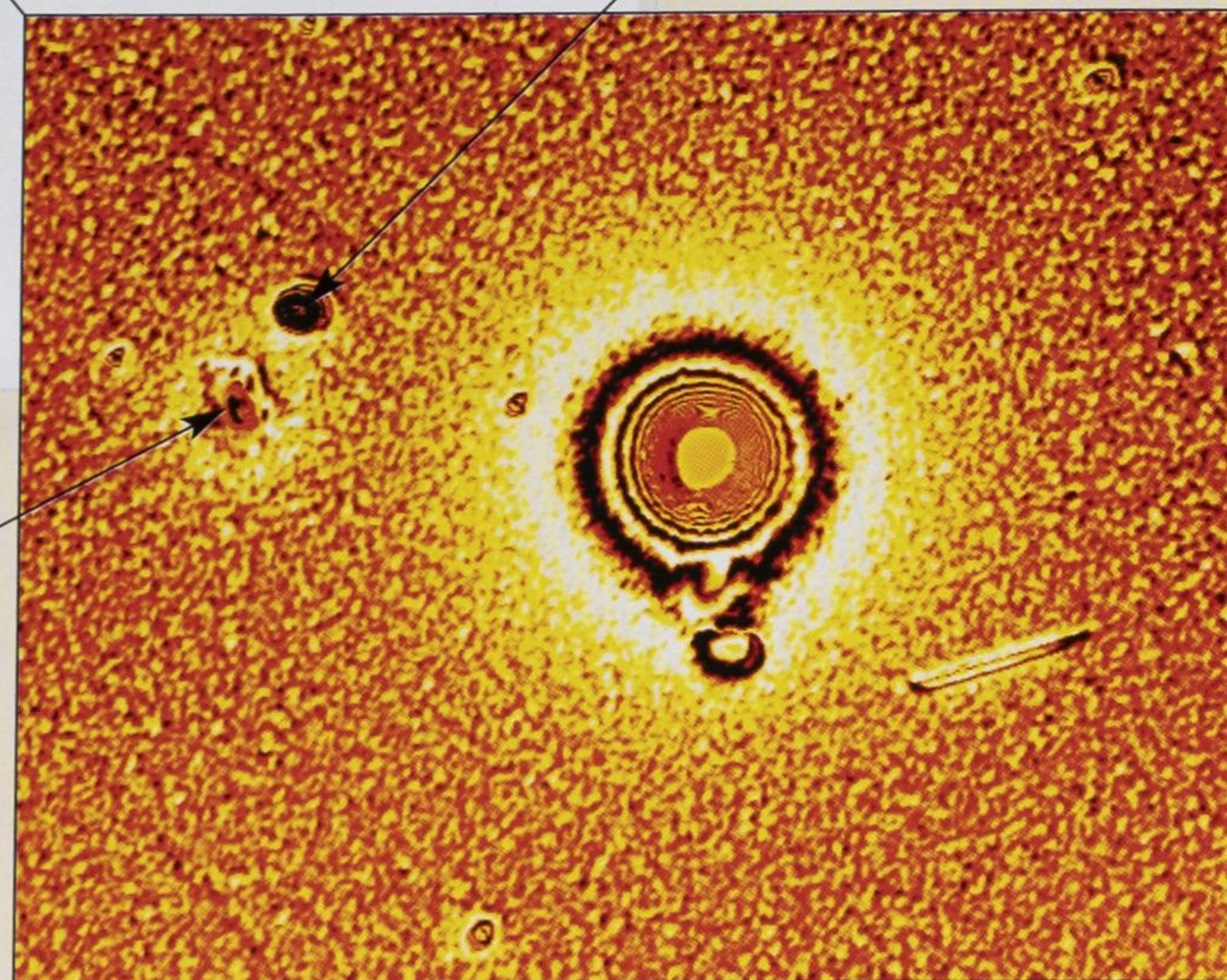
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NITRIDES

UK defense chiefs feel the need for GaN

GaN electronics has been specified as a priority technology by UK defense chiefs. In its Defence Technology Strategy (DTS), launched on October 17 by procurement minister Lord Grayson, the Ministry of Defence (MOD) highlighted GaN circuit technology as a key area of science and technology and one that demanded a domestic supplier.

According to the DTS document, the UK cannot currently guarantee on-shore access to GaN components, which the MOD believes will be crucial to the country's future military capability. "There is a need for the UK to ensure continued access to some critical advanced components and circuits," reports the MOD's strategy document. "The most important of these are the solid-state RF transmit/receive modules that are based on advanced semiconducting materials. It is essential that the UK maintains on-shore access to these technologies."

"[The] MOD will work with defense manufacturers and European procurement agencies to identify what UK investment is needed to ensure that UK companies will be able to access GaN technology within

Europe," claims the document.

Currently, the UK has a very limited GaN development program, although it is part of a European research effort focused on GaN HEMTs. The US and Japan are well ahead of Europe in terms of GaN electronics, thanks largely to central government investment in the technology, as well as being home to the incumbent GaN device manufacturers for optoelectronic applications such as blue LEDs and violet-blue lasers.

Part of the problem is that the UK currently relies on Filtronic as its only major III-V foundry for RFICs. This has been the case ever since Bookham decided to shut its Caswell GaAs line in May 2004 and concentrate solely on photonics components.

The MOD acknowledges that the very existence of the Filtronic foundry depends on the viability of that company's overall business, and the presence of a large non-defense market for its products.

With the UK's GaN electronics expertise currently limited to some leading university research groups and Qinetiq, the research and development company that was previously

part of the MOD, defense chiefs will need to invest some of the ministry's £2.6 billion (\$4.9 billion) annual research budget in the wide-bandgap material.

"The development of GaN can be considered as part of an ongoing systematic development of wide-bandgap materials, including diamond," the MOD said. "This is likely to lead to a range of new components."

Although GaN expertise is relatively scarce in the UK, one domestic company that could provide some of the required material is IQE. Its new Somerset, NJ, division has plenty of experience in GaN-based epitaxy for RF applications. The US location is not expected to prove any barrier to the MOD, just as IQE has been involved in US Department of Defense applications for many years.

"GaN HEMTs feature as key products on IQE's roadmap, and while the major driver is currently dominated by defense-related applications, we believe this has the potential to help refine GaN processes for RF components and drive down costs to open up commercial opportunities in the longer term," the company said.

STANDARDS

AlGaAs standard to make industry 'more efficient'

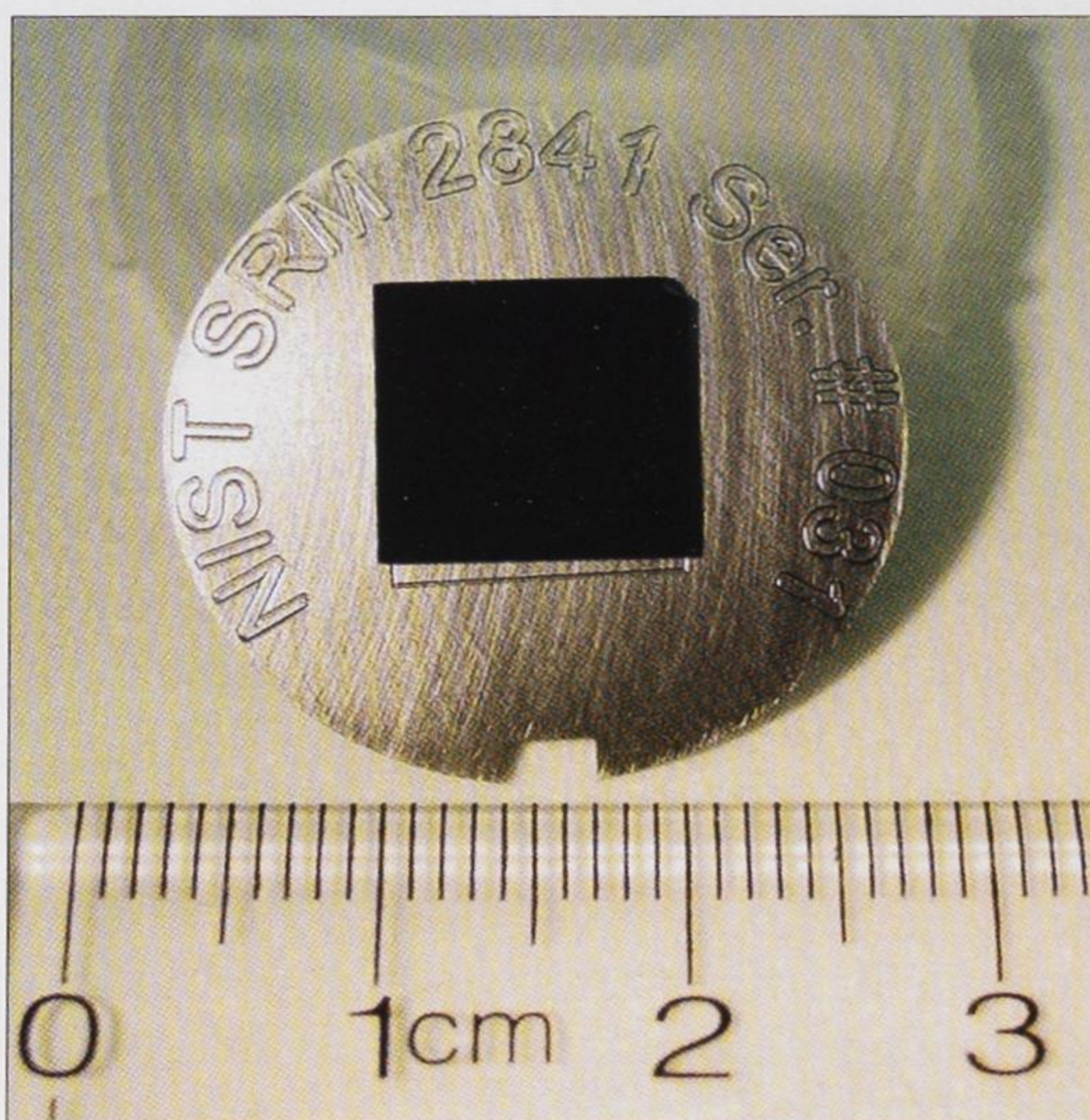
Compound semiconductor manufacturers will now be able to measure the composition of AlGaAs films more accurately than ever before, thanks to a new material standard issued by the National Institute of Standards and Technology (NIST).

The Boulder, CO, authority says that the 1 cm² AlGaAs/GaAs pieces (denoted SRM 2841) will improve the accuracy of AlGaAs film composition analysis by 10 times compared with current methods.

AlGaAs layers are used widely in both microelectronic and optoelectronic device applications, in particular for the red lasers that are deployed in optical disc drives. Kris Bertness, the NIST scientist who led the standards development, told *Compound Semiconductor*: "There really have not been any absolute standards in the past."

"People are much more used to thinking in terms of how reproducible their measurements are, but that does not address the absolute accuracy of the measurement."

As a result, Bertness says, the III-V industry has been operating largely on knowing how the material they grow one day compares with what they grew the month before. "Most lab-



Tiny pieces of AlGaAs/GaAs like this one are now available from NIST, and the standards authority believes that they should help III-V manufacturers become more efficient. The NIST team that developed it is also beginning to work on standards for GaN material.

oratories have an internal reference system that works as a bootstrap standard," she said.

Comparisons between the way that differ-

ent laboratories measure AlGaAs compositions have shown that not only is there a variation in the calibration equations used, but also a tendency by the experimentalists to ignore absolute calibration of their own measurement equipment.

In response to an initial request from members of the Optoelectronics Industry Development Association, and with NIST funding, Bertness and colleagues set about the task of developing the standard back in 1998. The new standard is certified with reflection high-energy electron diffraction (RHEED) growth-rate measurements and photoluminescence.

The photoluminescence measurement is calibrated against both RHEED and two direct chemical analyses – one made using an electron microprobe, and another based on inductively-coupled plasma optical emission spectroscopy.

Bertness believes that the SRM 2841 standard will reduce wasteful duplication of reference wafers and increase the free exchange of thin-film materials between vendors and their customers. "We hope to make the industry more efficient," she concluded.

WIDE-BANDGAP TRANSISTORS

Silicon process update prompts Nitronex ramp

RF power transistor maker Nitronex says that its GaN-on-silicon manufacturing process is now fully qualified for volume production. The Raleigh, NC, developer has released several products manufactured with the "NRF1" process for applications in WiMAX connectivity and general wireless infrastructure.

While most GaN transistor makers, including RF Micro Devices and Cree, use SiC substrates, Nitronex believes that its use of silicon provides economic benefits without sacrificing transistor performance. Just over a year ago, Nitronex revealed that it had signed a deal to supply the Korean company RFHIC with GaN-on-silicon transistors for WiMAX applications, but since then it has refined its manufacturing process. Chris Rauh, the vice-president of sales and marketing at Nitronex, explained: "We made the decision to improve upon the process that was used to make the early samples."

"It was clear to us that our product lines would be improved by moving from 0.7 μm gates to 0.5 μm gates and by adding a source field plate to the process."

Those changes required a complete reliability study and qualification, which pushed back the release of the new Nitronex transistors until now. The new products, which are aimed at WiMAX infrastructure applications, include a 50 W/28 V device with an average power of 6 W over 3.3–3.8 GHz.

Two transistors producing 15 W and operating at 28 V have also been released, one of which covers the lower frequency band of 2.3–2.7 GHz. According to some commentators, these lower frequencies will remain the preserve of silicon LDMOS power transistors for the foreseeable future. Rauh's response is that while LDMOS is now viable for frequencies up to 3.5 GHz, this is only part of the story: "The real test is when you look at the carriers demanding 200 MHz of bandwidth, as well as very tough linearity requirements, and 25 W average OFDM power amplifier output with efficiencies greater than 10%," he remarked.

"Higher-frequency markets (more than 3.8 GHz) are clearly in our sights, so I am not in disagreement that there is a strong play for GaN at these frequencies, but I don't believe that the game is completely settled at 2.5 GHz and 3.5 GHz for WiMAX."

Rauh is expecting the process qualification to have an immediate impact on Nitronex sales. He believes that although the notoriously conservative wireless infrastructure market has had its fingers burned in the past by adopting new power transistor technology too early, the reliability data that Nitronex can now present meets or exceeds customer needs. "They can now fully embrace GaN technology because they can review the completed reliability and qualification report."

a major impact on its finances. AXT says that Chinese authorities are planning to impose custom duties on purchases of certain raw materials, as well as eliminate refunds of value-added tax for these transactions. Currently, the list of affected materials includes gallium and arsenic.

"The combination of these actions could significantly increase our costs," warned AXT in its financial outlook. "Lobbying efforts are being made to remove gallium and arsenic from the list of materials, but there is no way of knowing whether these efforts will have any impact on the final form of the regulations."

AXT may decide to restructure its Chinese operations, which includes five joint-venture firms that produce raw materials and key manufacturing equipment, in light of the new tax laws. On the positive side, CEO Phil Yin still believes the supply of both 4 and 6 inch semi-insulating GaAs substrates to be "severely" constrained, and that AXT's decision to expand its capacity will reap rewards in the near future.

COMPANY STRATEGY

Skyworks' switch increases focus on GaAs products

GaAs chip manufacturer Skyworks Solutions, of Woburn, MA, has ceased the operation of its baseband business unit. The move, which does not affect the firm's compound semiconductor operations directly, will result in a 10% drop in total headcount, equivalent to 425 employees.

The switch will, however, increase Skyworks' focus on advanced GaAs-based products for current cell-phone handset applications and emerging markets such as broadband wireless access. Skyworks claims to have increased its worldwide market share for power amplifiers used in cell phones from only 30% in 2002 to 42% currently.

Encouraged by this rapid pace of growth and increasing dollar content in phones through higher levels of integration, coupled with the development of BiFET components, Skyworks is focusing squarely on this as its core business. "We will partner with, rather than compete against, leading baseband suppliers such as Texas Instruments, Qualcomm, Freescale and Infineon," explained Skyworks' CEO David Aldrich.

"We are implementing a strategic restructuring to... realize our vision of becoming the global leader in semiconductors enabling mobile connectivity," Aldrich explained. Ultimately, the switch will provide a massive boost to Skyworks' bottom line. Pro forma profit for fiscal 2007, in which the restructuring charges are ignored, should now be at least \$0.55 per share, or double the estimate that was made before the restructuring.

How exactly that profit will be spent is not yet known, but it is possible that Skyworks is considering ways to increase its GaAs capacity to meet the expected ramp in demand for broadband wireless connectivity.

● Skyworks accounted for the restructuring in its latest financial quarter, which ended on September 29. Including the various severance and inventory charges, bad debts and license write-downs associated with the company restructuring, Skyworks posted a net loss of just over \$96 million on total sales of \$193 million. Excluding those one-off charges, the company made a profit of \$11.6 million. According to the company, shipments of power amplifiers for wideband-CDMA handset applications more than doubled in the recent quarter, reflecting the strong demand currently being felt for advanced handsets with higher GaAs content.

SUBSTRATES

AXT to lobby against China tax changes

Fremont, CA, substrate vendor AXT reported \$12.5 million sales for the financial quarter that ended on September 30 – a sequential rise of 21% and more than double its revenue during the same period last year. And despite an operating loss of \$1 million, AXT made a small net profit of \$0.6 million thanks to the sale of shares in Finisar and an income tax benefit.

With demand for semi-insulating GaAs material rising strongly for use in HBT and PHEMT devices for cell phones, and sales of germanium substrates growing in line with the emerging market for multi-junction solar cells, the outlook for AXT is looking very positive.

However, the firm's management also warned that changes to tax law in China could have

COMPANY FINANCES

Hittite enjoys huge gain in profit

Hittite Microwave, the fabless Chelmsford, MA, company that sells a range of GaAs, SiGe and silicon-based ICs, has reported a huge gain in profit.

The firm posted sales of \$34.6 million during the three-month period that ended on September 30 – an increase of more than 60% compared with the same quarter in 2005. Thanks to its lean cost structure, Hittite translated those sales into a profit of \$11.6 million. That figure is more than double the \$5 million profit that it posted one year ago.

“Favorable market conditions and product mix allowed us to deliver strong results,” said

Hittite CEO Stephen Daly, who pointed out that the company had launched no fewer than 20 new products during the past three months. Those include a range of nine new GaAs MMIC receivers operating at up to 28 GHz. These receivers, which are available as bare die and manufactured at one of Hittite’s many foundry partners, are typically used in radio architectures for military and back-haul links, as well as satellite-based communication.

Hittite is ranked among the top 10 GaAs device vendors by market researchers Strategy Analytics. It is also the highest-ranked firm without its own chip fab.

OUTSOURCING

Epiwafer foundry IQE wins new deal

Epiwafer foundry IQE has won a contract to become the preferred external supplier of epitaxial material to an unspecified European radio-frequency wireless chip foundry. The foundry will use MBE-grown material from IQE to make GaAs PHEMT switches.

IQE says that it has signed a memorandum of understanding with the customer, to the effect that its material will be sourced if the customer’s demand for epiwafers increases. IQE told *Compound Semiconductor* that it is already supplying the customer in small quantities, with volume production expected to begin in the second half of 2007.

“It is anticipated that any increase in epiwafer requirements beyond the customer’s

internal capacity will flow directly to IQE,” said the Cardiff, UK, firm.

IQE’s US-based MBE operation already has a substantial contract in place with a US manufacturer of wireless chips based on GaAs, while the recent acquisition of Emcore’s RF epiwafer division, which employs MOCVD reactors, has significantly expanded IQE’s customer and technology base.

The latest deal is another sign that many III-V chip makers are taking a new approach to epiwafer production and sourcing strategies, believes IQE’s CEO Drew Nelson. “This demonstrates the strength of the outsource model, which is now becoming a key part of customer’s strategic considerations,” he said.



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...TriQuint and Anadigics on the up

Oregon-based TriQuint Semiconductor posted sales of \$103.3 million in its latest financial quarter, up 37% on last year and marking the firm’s best operating results since 2001. TriQuint and rival GaAs chip maker Anadigics, NJ, both reported their sixth consecutive quarters of sales gains, with Anadigics posting \$44.8 million.

...NBC uses Cree chips for football show

GaN HEMTs made by Cree are deployed in blimps and aircraft to transmit broadcasts of NBC’s *Sunday Night Football* television show in the US. According to Cree’s Jim Milligan, the Powerlinear devices have reduced the weight and size of amplifiers and doubled their energy efficiency.

...new chief at UK foundry

Filtronic, the UK-based GaAs chip foundry, has promoted its finance director Charles Hindson to CEO. The company also completed the sale of its filter-based transmit receive and power amplifier business unit to Powerwave.

...RFMD powers to record sales

Leading GaAs chip manufacturer RF Micro Devices posted record sales of \$246.9 million in the financial quarter that ended on September 30. The Greensboro, NC, company added that the current quarter will likely deliver sales of up to \$280 million. If that is an accurate forecast, RFMD will be on course to reach \$1 billion revenue for the full fiscal year.

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PATENT DISPUTE

BridgeLux retaliates with Cree lawsuit

Shortly after being accused of patent infringement by the major LED manufacturer Cree, BridgeLux has responded with a similar lawsuit of its own.

The Californian company, which specializes in elongated chip designs for high-power light emission, has filed a motion to dismiss the action brought by Cree and Boston University, and alleged that its North Carolinian rival has infringed US patent 6,869,812.

Cree sued BridgeLux first, citing infringement of a number of US patents, including 6,657,236 and 5,686,738. The '738 patent, filed back in 1997 and assigned to Boston University, details an MBE-based method for making GaN films. GaN LEDs are generally produced using MOCVD. The more recent '236 patent lists Stephen DenBaars from the University of California, Santa Barbara, as one of three inventors, and is concerned with improving LED light extraction through the use of "optical elements".

BridgeLux's patent was filed more recently still, in May 2003. Entitled "High power AlInGaN based multi-chip light emitting diode", the patent is attributed to Heng Liu of Sunnyvale, CA, but does not mention either

BridgeLux or eLite Optoelectronics, the firm's former incarnation.

Meanwhile, BridgeLux has released a product line based on smaller die in a bid to penetrate the mobile handset market in which Cree has become such a dominant player.

The firm claims that its "BSV" series of side-view products will allow designers of cell-phones, digital cameras and other portable electronic devices to develop thinner displays. The new chips are based on elongated die measuring 10×18 mm and 10×23 mm that are manufactured at BridgeLux's volume production facility in Taiwan.

BridgeLux says that these new products are already being sampled, and the chips are set to be ramped into volume production by the end of the year. CEO Bob Walker says that the aim of the launch is to apply high-quality, high-power LED technology to mobile applications.

Mobile devices are still the key application market for high-brightness LEDs, accounting for around half of the total value of the sector. However, it has become a somewhat commoditized business. With the declining selling price of HB-LEDs used in mobile phone backlights now outweighing the market's growth,

chip manufacturers are pushing to penetrate higher-value applications such as large-area backlighting for high-definition television.

This trend was highlighted in Cree's latest financial quarter. The Durham, NC, company posted revenue of \$103.9 million during the three months ending September 24, equivalent to only a 1 per cent increase on the same period last year.

That was because an increase in unit shipments of 32 per cent was heavily off-set by a 26 per cent decline in the average selling price of Cree's emitters. This has had a massive impact on the company's bottom line, with Cree delivering a net profit of only \$13.3 million in the recent quarter compared with \$21.7 million one year ago.

While revenue from LEDs has remained largely flat for the past year, Cree has had more success with its SiC wafers and high-power product lines.

Sales of high-power devices such as SiC Schottky diodes rose to \$4.5 million in the latest quarter, up more than 35 per cent since last year. Meanwhile, Cree's wafer revenue hit \$6.6 million – representing a yearly rise of nearly 30 per cent.

CHIP MANUFACTURING

SemiLEDs scales up GaN production

US-headquartered SemiLEDs has ordered a high-volume MOCVD reactor with which it intends to scale up the manufacture of its vertical-design GaN LEDs. The 24×2 -inch Aixtron machine will be installed in the company's facility at the Hsinchu Science Park in Taiwan, alongside its existing range of MOCVD equipment.

SemiLEDs has pioneered a unique chip design that is based on the use of copper-alloy substrates. The novel substrate material aids heat dissipation and enables the chips to be driven at a very high current to increase light output without degrading efficacy (see *Compound Semiconductor* September 2006, p16).

SemiLEDs initially grows its blue, green and ultraviolet emitters on sapphire substrates, before transferring the epitaxial layers onto the metal alloy. The devices deliver an optical output of 75 lm/W at 350 mA drive current, and can withstand a drive current of more than 3 A without any noticeable light output power saturation, claims the company.



Automotive lighting and high-definition televisions are two critical applications that the German LED maker Osram Opto Semiconductors is trying to penetrate with its latest chip designs.

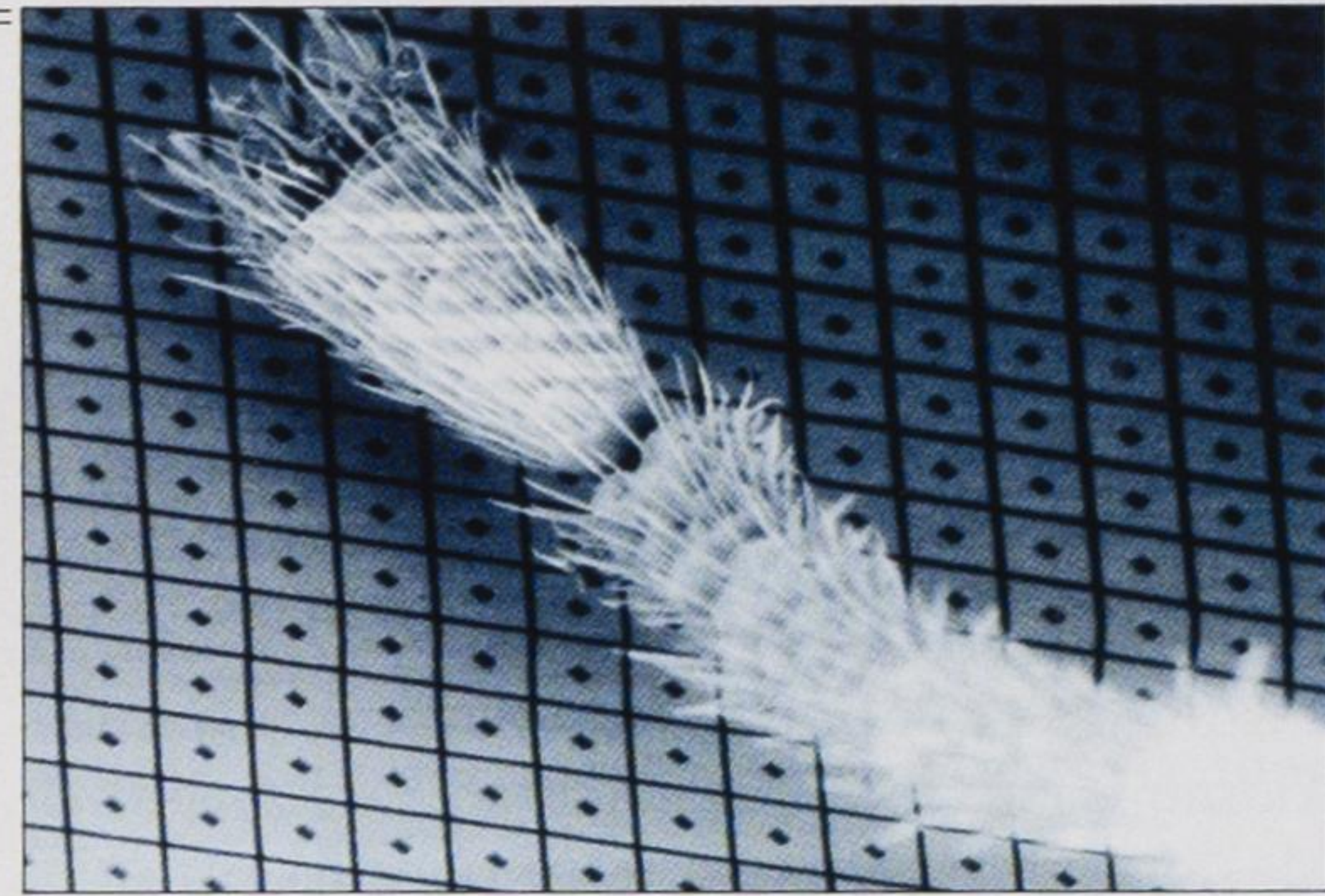
The company is focusing its marketing effort on the benefits of its O-Star, TopLED and new Platinum Dragon HB-LEDs. For example, Osram offers an optical module that features one red, one blue and one green O-Star HB-LED. Together, the three chips output 300 lumens, enough to backlight a 56-inch television screen.

O-Star LEDs have also featured in a partnership between Osram and Volkswagen that has updated the German motor company's Type 2 Transporter – the 1960s favorite also known as the "hippy bus" – for the 21st century.

The concept vehicle's headlamps are powered by O-Star LEDs, while its daytime running lamps feature Osram's Golden Dragon chips. TopLEDs were used in the front and rear turn signals, making this vehicle the first to be built with LEDs in all the major exterior lighting functions.

APPLICATIONS

Luminus samples super-bright chipset



The digital light processors made by Texas Instruments feature millions of tiny mirrors no larger than an ant's leg – as this microscopic image shows.

Luminus Devices, the Woburn, MA, LED manufacturer that has made a big splash with its “PhlatLight” chipsets for television back-lighting, has now introduced a 1500 lm white-light (RGB) source.

The Massachusetts Institute of Technology spin-out's new PT120 product has been optimized for use with Texas Instruments' hugely successful digital light processor (DLP).

Texas Instruments has already sold more than 10 million DLP subsystems for applications such as high-definition projectors. Each features up to 2.2 million tiny mirrors that switch thousands of times per second to deliver crisp, full-color images on a large screen.

The PT120 is currently being sampled to makers of microdisplay projection televisions, and Luminus says that it has already been designed into a number of high-definition televisions based on the DLP. “Several models from various manufacturers will be commercially available in 2007,” said the company.

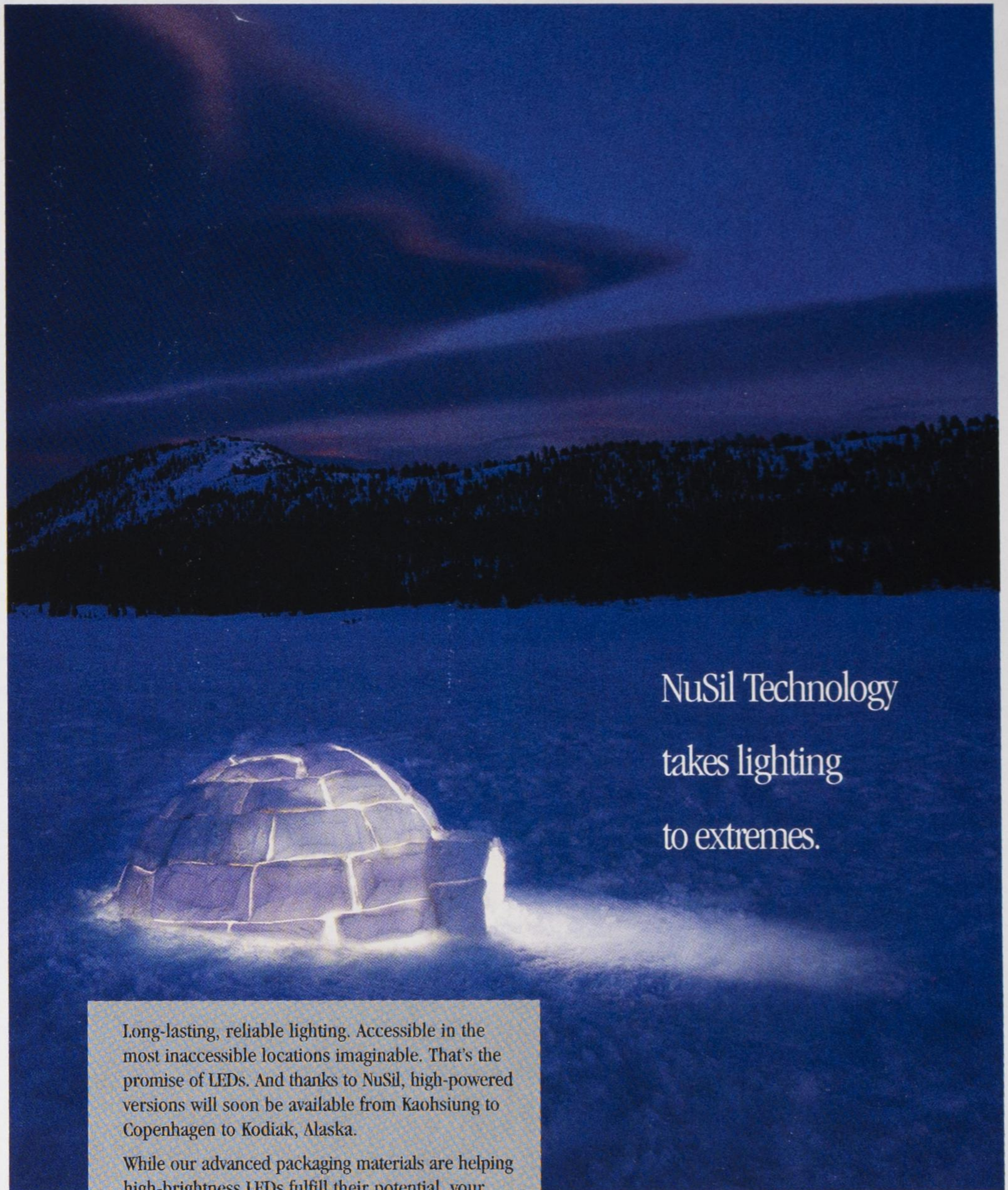
One of the critical advantages of using LEDs in place of fluorescent sources in television applications is the speed with which the solid-state emitters can be switched. “In a DLP high-definition television, the red, green and blue PhlatLight LEDs can cycle at 2.9 kHz, which is 48 times faster than traditional television frame rates – providing superior motion quality,” explained Christian Hoepfner, VP of products at Luminus.

Recently, Luminus has been issued with six US patents covering its photonic lattice technology, an approach that results in its LEDs operating with high light extraction efficiency. One of those patents dates from late 2004, but the other five were all awarded since August 2006. Before the end of this year, the company also expects to receive more of the 100 or so additional patents that it has applied for.

Claiming to have invested more than

\$10 million in its intellectual property portfolio, Luminus will soon be looking to penetrate beyond the relatively limited market for high-specification televisions. Luminus founder and CTO Alexei Erchak said, “There

are unlimited opportunities for LEDs using photonic lattice technology today and in the future. Luminus...will also support other LED applications through collaborations and licensing agreements.”



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...Spectrolab passes two million mark

Boeing subsidiary Spectrolab has manufactured its two millionth multi-junction GaAs-based solar cell. The company began working on the high-efficiency converters in 1983 and estimates that its cells power 60% of all the satellites currently orbiting the Earth – including the International Space Station. In total, Spectrolab cells have powered 525 satellites or interplanetary missions such as the Mars Global Surveyor.

...brighter UV-LEDs

The latest AlGaIn-based ultraviolet LEDs made by Seoul Semiconductor are twice as bright and twice as reliable as the previous generation, according to the Korean company. At a drive current of 20 mA, the latest components have a maximum optical output power of 1.5 mW at 280 nm. Just four months ago, volume device maker Seoul and AlGaIn epitaxy specialist Sensor Electronic Technology, US, signed an equity-based partnership to develop and sell UV-LEDs. The devices have a number of potentially very high-volume applications, chiefly surface decontamination and water purification, where they could replace mercury discharge lamps.

...JDSU's Kwong joins Binoptics

Ithaca, NY, laser chip developer Binoptics has appointed Norman Kwong as its new executive vice-president of business development. Kwong previously worked at JDSU, where he was director of advanced technology, and has also enjoyed stints at Ortel (now owned by Emcore) and Archcom Technology. Binoptics' lasers are made using a proprietary etched-facet process – the kind of innovation that Kwong believes will be important for meeting customer expectations for low-cost, high-reliability, high-performance lasers.

...Avanex shells another CFO

After less than seven months in his post, Avanex CFO Cal Hoagland has left the struggling optical component and module manufacturer. Giving no reasons for the sudden departure, the Fremont, CA, company has appointed Marla Sanchez as its new CFO. Sanchez previously worked as corporate controller at the laser diode manufacturer SDL. Yves Le Maitre, formerly VP of Avanex's optical components division, has been promoted to the unusual role of chief marketing officer. Avanex has also posted another loss-making quarter, recording sales of \$50.9 million for the three months that ended on September 30.

PHOTOVOLTAICS

Sumitomo Chemical sets up joint venture to exploit split-band material for solar energy

A joint venture company is aiming to become the first to commercialize ZnMnTe and InGaIn semiconductors for solar energy applications.

Japanese conglomerate Sumitomo Chemical and US start-up RoseStreet Labs have set up a new firm called RSL Energy in Phoenix, AZ, to develop, manufacture and sell what they describe as full-spectrum solar cells.

Having signed exclusive technology licenses from Cornell University and Lawrence Berkeley National Laboratory (LBNL), RSL Energy believes that the novel materials could be commercialized for solar energy production within the next three years.

Wladyslaw Walukiewicz and Kin Man Yu have developed the ZnMnTe material system at LBNL. They found that the conduction band of ZnMnTe can be split by adding oxygen to the semiconductor alloy. The bands split so that the normally single-band material becomes multi-band, with the energy levels widely spaced so that the three energy transitions fall within the range of the solar spectrum.

This means that by tailoring the exact proportion of oxygen impurities in the alloy, the

energy levels can, in theory, be tuned to produce triple-band material capable of more than 50% conversion efficiency. According to the research team, the energy bands could be further split to yield quadruple-band semiconductors with up to 73% calculated efficiency.

RSL Energy also has a license to commercialize a different approach that was developed through a collaboration between LBNL and Cornell. This has focused on InGaIn as a material that can be used in more conventional multi-junction solar cells. The joint venture company believes that the InGaIn approach could produce solar cells with practical efficiencies of more than 48%.

The US Defense Advanced Research Projects Agency has also identified InGaIn as a promising photovoltaic material, with a quantum efficiency of up to 60% in the ultraviolet range.

With a start-up capital of \$6.6 million, RSL Energy is 50% owned by each of Sumitomo Chemical and RoseStreet Labs. Sumitomo's subsidiary Sumika Electronic Materials has the first right of refusal to produce the compound semiconductor materials required.

MANUFACTURING

50 million and counting: Finisar honors VCSEL milestone in Texas

As it celebrated the official opening of its newly renovated manufacturing facility in Allen, TX, optical component and module manufacturer Finisar revealed that it has shipped 50 million VCSELs.

The Californian company has been restoring the Allen fab for more than a year at an estimated cost of \$13 million. With an additional MOCVD reactor now refurbished and a second wafer fabrication line in place, the facility is ready to support the production of 4 Gbit/s products to upgrade storage area networks (SANs) and 10 Gb/s VCSELs for local area network applications.

"This state-of-the-art facility will enable us to power more of our customers' applications, including video-on-demand, high-definition TV, and mobile computing," said Finisar chief executive Jerry Rawls. Over 300 people now work at Finisar's Allen site, which is expected to easily meet the firm's production needs.

The 50 millionth VCSEL was officially sold to high-profile customer HP. At the ribbon-cutting ceremony to celebrate the

renovated chip fab, Edward Flynn, the director of the SAN infrastructure unit within HP's StorageWorks division, described the milestone as an extraordinary achievement.

Commercial production of VCSELs began at Honeywell Labs' Richardson, TX, facility in 1996. Finisar acquired Honeywell's VCSEL business, including the Richardson facility, in March 2004 and turned it into the autonomous Advanced Optical Component (AOC) division.

Unlike many of its rivals in the same sector, Finisar has enjoyed very strong growth in demand for its data communications products over the past couple of years, culminating in the expansion of AOC's production capacity. "We worked our way back from one of the most difficult market downturns in history and succeeded in achieving our plan for returning to profitability," explained Rawls.

● In a deal that it says will free up its operational cash flow between now and 2010, Finisar has agreed to exchange \$100 million worth of existing "outstanding notes" for a new series of convertible notes.

EPITAXY

Hydride VPE suitable for quantum wells

Hydride vapor phase epitaxy (HVPE) can be used to produce very thin layers of GaN and AlGaIn quantum wells, according to US-based materials specialist Technologies and Devices International (TDI).

Until now, this method, which can deposit material much more quickly than either MBE or MOCVD, had only been suitable for growing very thick semiconductor layers.

Engineers at the Silver Spring, MD, company say that a new HVPE machine is able to slow down from its normal deposition rate of around one micron per minute by more than two orders of magnitude.

This means that the same machine can be controlled to grow sharp heterostructure layers just 1 nm thick, as well as thicker layers like

that of the GaN material in GaN-on-sapphire templates. One application of the approach could be in nitride laser manufacturing.

TDI president Vladimir Dmitriev said: "This opens up a completely new path for the formation of low-defect substrate materials and device structures."

Scientists at Virginia Commonwealth University and Arizona State University (ASU) have already characterized material grown in the novel HVPE machine. Subhash Mahajan from ASU was surprised by the success: "We never expected this technology to produce nanometer-thick GaN layers and multi-layer structures. However, our transmission electron microscopy measurements proved that it [has been] achieved."

APPLICATIONS

Shell turns to cascade lasers for oil prospecting

A cross-disciplinary UK team is working on a £2.4 million (\$4.5 million) project to develop an optical system for oil and gas prospecting that is based on quantum cascade lasers (QCLs).

Comprising the III-V foundry Compound Semiconductor Technologies (CST), the universities of Sheffield and Glasgow, Shell Global Solutions and laser system specialist Cascade Technologies, the consortium has received just over £1 million from the UK government's Department of Trade and Industry. The industrial partners are providing the other £1.4 million. Shell will fund field testing of the instrument once the development is completed.

The detection system will be based on photoacoustic spectroscopy, a method that can be used to measure gas concentrations with extreme sensitivity. CST commercial director Wyn Meredith explained that ethane (C_2H_6) is the key hydrocarbon that gives a clue to the location of an undiscovered field of oil or gas.

Ethane and methane (CH_4) are produced when larger hydrocarbons – typically found in oil and natural gas reserves – "crack" into smaller molecules. Unlike methane, however, ethane is not produced by biological decay and so it is a much more reliable indicator.

Shell already uses a system that is based on a mid-infrared lead-salt laser to probe for ethane in its "LightTouch" prospecting equipment.

However, because they require cryogenic cooling, these are relatively bulky systems whose mobility can be a problem. By using III-V-based QCLs instead, their size could be greatly reduced.

"Employing the photoacoustic spectroscopy approach, we hope to produce an instrument that has an ethane sensitivity of around 100 parts per trillion," said Meredith.

Researchers at the University of Sheffield will grow QCL structures using novel antimonide-based epitaxy to reach the crucial $3.35 \mu m$ absorption band of ethane. Current QCLs operate at longer wavelengths than this.

CST will fabricate laser devices from Sheffield's epiwafers, while Cascade will provide module-level packaging and control electronics.

Glasgow's physics department will then develop the photoacoustic detection system with Shell until it is ready for field trials.

"The long-term aim is to set up a UK supply chain – from design to packaged device to system implementation," explained Meredith. "This is strengthened by Cascade securing the rights to source QCLs from foundry manufacturers," he added, in reference to a recent intellectual property relating to QCLs deal signed by Cascade and Lucent Technologies. QCLs were invented at the US company's Bell Labs research facility.

While QCLs are only in the very early stages of commercial deployment, they could end up being as useful to cancer specialists as they may be to oil prospectors. That is because ethane gas and other hydrocarbons are released when cancer causes free radicals in the human body to break down cell membranes.

CST is now looking at a number of III-V device technologies that could turn into a valuable business opportunity for the foundry over the next five years.

"Once the baseline technology is established, the foundry model will allow rapid prototyping of novel designs for new product development and embed this technology firmly in the UK," Meredith concluded.

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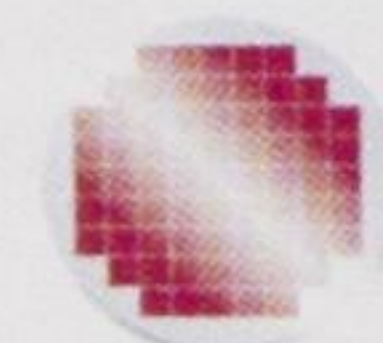
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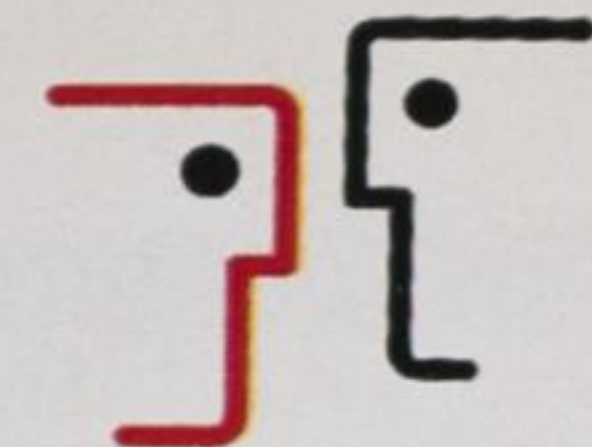
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BLUGLASS

Industry veteran aims to steer GaN from start-up to mass production

BluGlass's low-cost GaN deposition method has already won favor among Australian investors. **Jon Cartwright** catches up with CEO David Jordan to find out what direction the company is headed for next.



CEO David Jordan will be drawing on many years of experience in both the silicon and solar power industries as he looks to revolutionize the GaN epitaxy sector with Australian start-up firm BluGlass.

The shrewd investors who snapped up the shares of Australian GaN epitaxy start-up BluGlass must be basking in their blue-tinted glory. After the company was floated on the Australian Stock Exchange in mid-September, its share value jumped 67% from AUS\$0.30 to AUS\$0.50 (US\$0.39). And flicking through their corporate presentation it's easy to see why. Over the past 10 years the GaN industry has grown more than a hundred fold and by 2009 forecasters predict it will be worth more than US\$7 billion (Strategies Unlimited).

BluGlass is still in its infancy. The firm was conceived in July via the acquisition of Gallium Enterprises, a company originally set up by the commercial arm of

Macquarie University in Sydney after a decade-long research project to develop low-cost GaN epitaxy. Immediately afterwards, BluGlass launched an initial public offering (IPO) of shares to raise AUS\$6 million. However, as the deadline drew closer, unrelenting demand pushed BluGlass to release a supplementary prospectus to attract even more cash. All told, BluGlass raised AUS\$10 million through the IPO.

Pioneering technology

This capital now rests in the hands of the new CEO, David Jordan, for whom the semiconductor industry is second nature. "Most of my time before BluGlass has been almost exclusively spent in the photovoltaics and silicon semiconductor field," he says.

"In my previous role at BP Solar I managed to interface research and development programs and high-volume manufacturing worldwide. I very much see that as the basis of what we're doing here at BluGlass. We are taking a very promising, university-based technology and examining its potential as a business case, with the hope of taking it on to full commercialization and high-volume production."

Most GaN material produced today is manufactured through MOCVD. Though an effective, industry-proven method, MOCVD requires high temperatures in the region of 1000 °C and the use of highly toxic ammonia gas. The technology that BluGlass is pioneering, called remote plasma chemical vapor deposition (RPCVP), requires no ammonia and proceeds at the slightly more benign temperature of 700 °C. This means that hardy but relatively expensive wafer materials such as sapphire or SiC can be substituted by glass (hence the company name) at a fraction of the cost. French firm Saint-Gobin Recherche, which supplies both glass and sapphire for LED production, has just signed an 18 month deal to co-develop specially engineered substrates for BluGlass.

RPCVP is the subject of two international patents and one Australian patent held by BluGlass. These describe passing nitrogen plasma over the heated gallium. "The gallium is transported into the reaction chamber in a nitrogen carrier gas stream through a trimethyl gallium buffer," explains Jordan. The BluGlass team has already reduced the surface roughness of its thin films from 9–13 nm down to 1 nm, thus improving crystallinity and suggesting that a high-quality GaN layer is produced.

"We are also attacking the scalability," Jordan says. "BluGlass can already deposit at 4 inch diameters, whereas most of the MOCVD industry deposits on a diameter of 2 inches. And there's no reason why we can't extend that to 8 inches, 16 inches or beyond."

If this scale-up can be achieved, it points to a high

throughput of cheaper GaN devices, which have become ubiquitous in consumer technology. For blue LEDs, the mainstay of the GaN market, 68% of applications are in LCD backlighting such as mobile phones and digital cameras. Just 4% are in general lighting, but this could all change if BluGlass can make an impact. Every year, a fifth of the global electricity supply is used in lighting applications, most of which is still provided by inefficient bulbs. When it is possible for white LEDs to be mass-manufactured at a much lower cost, this huge market beckons.

"There is no doubt that in terms of efficiency white LEDs are currently on a par with compact fluorescent tubes and are significantly better than incandescent bulbs," says Jordan. "Compared with the light from fluorescent tubes, which is fairly harsh, white LEDs can be tuned to give a much softer light. In five years or so LEDs are set to take a very significant proportion of the general lighting market," he predicts. "All we have to do is to address the cost, which is still too high. Once the cost comes down, the market will open up."

There is another emerging market that could benefit from economic GaN optoelectronics: high-definition (HD) video. Found in Sony's new Playstation 3 games console and Blu-ray Disc players, HD discs can store 10 times more data than a regular DVD. The technology has been slow to take off because of problems making blue laser diodes and their resulting high cost. BluGlass's epitaxy could offer an attractive, lower-cost alternative to MOCVD-based laser diode production and help to

"We are taking a very promising, university-based technology and examining its potential as a business case, with the hope of taking it on to full commercialization and high-volume production."

David Jordan

ensure that HD discs fulfil their potential as the natural successor to DVDs.

Despite the three patents under its belt and ample investment, Jordan is revealing no definite indication of how exactly BluGlass is going to generate sales revenue. "We will be working with strategic partners, either licensing the technology once it's proven, or forming joint ventures with different groups," says the CEO. "But that's down the track, and we need to prove that we are able to hit the targets of cost-structures and device performance that we believe this technology offers us."

Having already demonstrated a functional single p-n junction LED using the RPCVD method, the next step for BluGlass will be to complete a pilot production plant in collaboration with cleanroom specialist M+W Zander. "This is an 18 month to two-year program," says Jordan. "We envisage moving into the pilot production plant at the beginning of next year, and then the commercial tools that we will use to implement the technology will be put in place in the first and second quarter. All of those things are required and they're coming together now."

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IoP

Extended VCSEL wavelengths offer

Markus Ortsiefer from Vertilas explains why long-wavelength tunable VCSELs are a better option for gas sensing than the lead salt, quantum cascade and diode-pumped solid-state lasers that are used today.

Gas sensors are employed for numerous applications, including detecting moisture, monitoring gas leaks and greenhouse gas emissions, searching for toxic and hazardous species, and optimizing combustion processes. Although many of these tasks can be carried out with chemical detectors, there is now a growing interest in optical systems that have several inherent advantages. These include rapid data collection and a non-contact approach that is more suited to the awkward measurement conditions in power stations and chemically reactive environments. And in contrast to chemical sensors, which only detect gases at a fixed location, optical techniques can monitor target molecules anywhere within the detection path of the measurement system.

At Vertilas, in Garching, Germany, we have been developing a unique VCSEL structure that can provide the source for a modern sensing technique – tunable diode laser spectroscopy (TDLS). Our lasers cover the wavelength range 1300–2300 nm and have been used to determine the presence of numerous gases.

With the tunable laser as a source, individual gases are identified by their unique optical absorption fingerprint. By focusing on a specific wavelength where a gas has a characteristic absorption, the amount of light absorbed reveals the concentration of the gas.

TDLS has frequently been applied to wavelengths outside the range covered by our lasers. By analyzing the strong absorption lines in the mid-infrared region (2.5–50 μm) the technique can determine the concentration of common gases such as water vapor, carbon dioxide and ammonia. These lines are associated with so-called “rovibronic” ground energy transitions, a term that describes the combination of molecular rotations and oscillations. The absorption strength of these transitions enables detection of gas concentrations even in the parts per billion range.

However, the various lasers that are used to probe these gases at mid-infrared wavelengths, including lead salt, quantum cascade and diode-pumped solid-state lasers, tend to be either expensive or inconvenient to use. This can be avoided by focusing on alternative transitions in the near-infrared (800–2500 nm). The absorption strength of these transitions is one to two orders of magnitude weaker than that of the rovibronic transitions. However, more reliable, cost-effective and easy-to-use sources are available that draw on the technology associated with lasers used for telecommunication or data storage. Sensing in this spectral range is



Vertilas is currently developing single-mode versions of its 2.3 μm VCSELs. These la

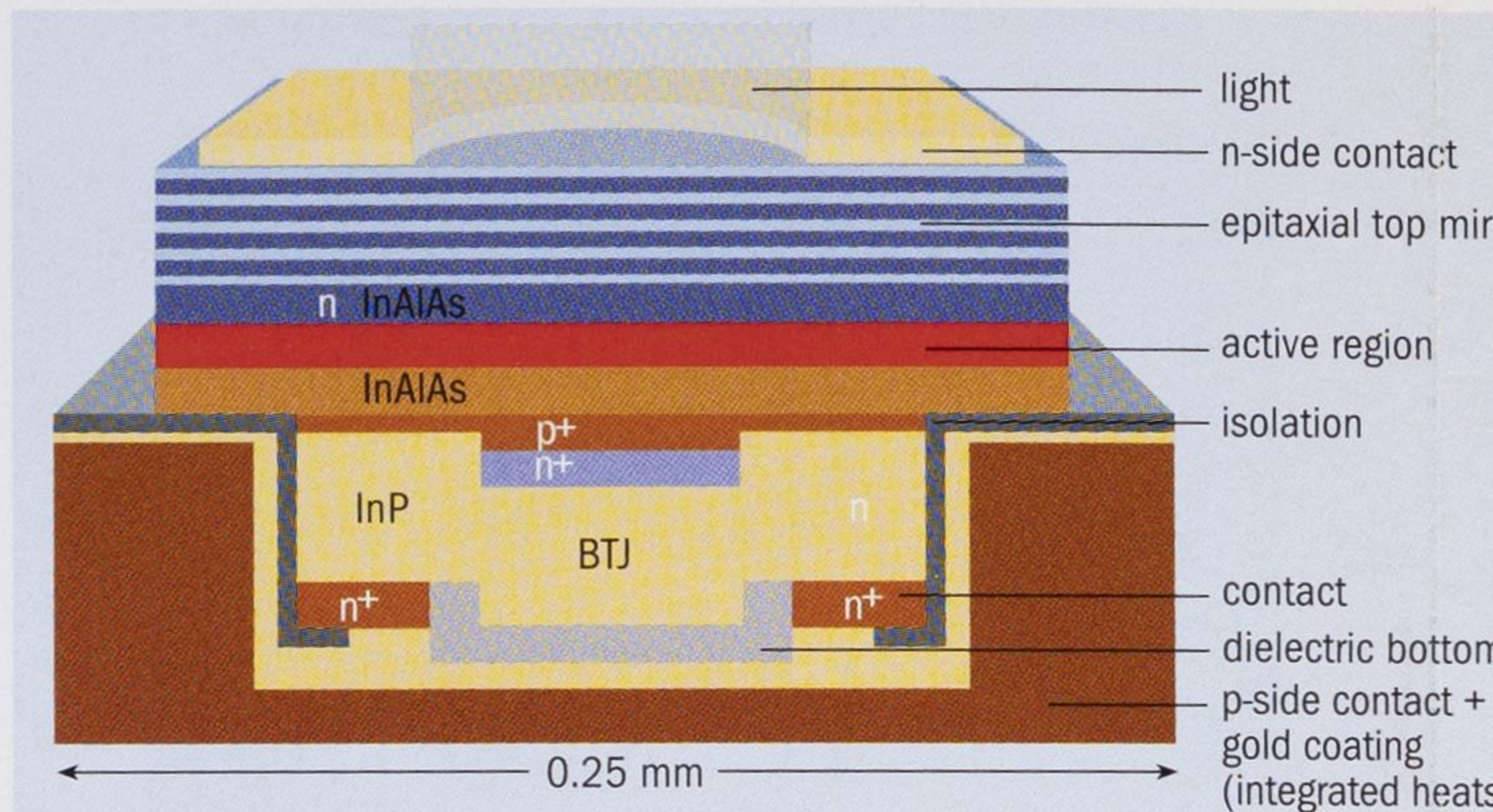


Fig. 1. Vertilas' VCSELs feature an InP-based active region, a buried tunnel junction, a dielectric mirror. The emission of these devices can be varied from 1.3–2.3 μm by a the composition and thickness of both the active region and epitaxial and dielectric

also an advantage because uncooled high-sensitivity detectors are available that can partly offset the weaker absorption strength of the higher order transitions.

VCSELs versus edge emitters

The first TDLS systems operating in the near-infrared used conventional edge-emitting distributed feedback (DFB) lasers, but improvements to the performance of VCSELs operating at 1.3 μm and above have made a better source for gas sensing (see table on p16 for the benefits of VCSELs over DFB lasers for TDLS applications). These VCSELs have a tuning range that can extend to several nanometers, which is much wider than that of a DFB laser. This is because VCSELs have a much smaller active region, so that their internal temperature is much more susceptible to increases in drive current

er convenient source for gas sensing



These lasers could be used to detect the carbon monoxide produced by car engines.

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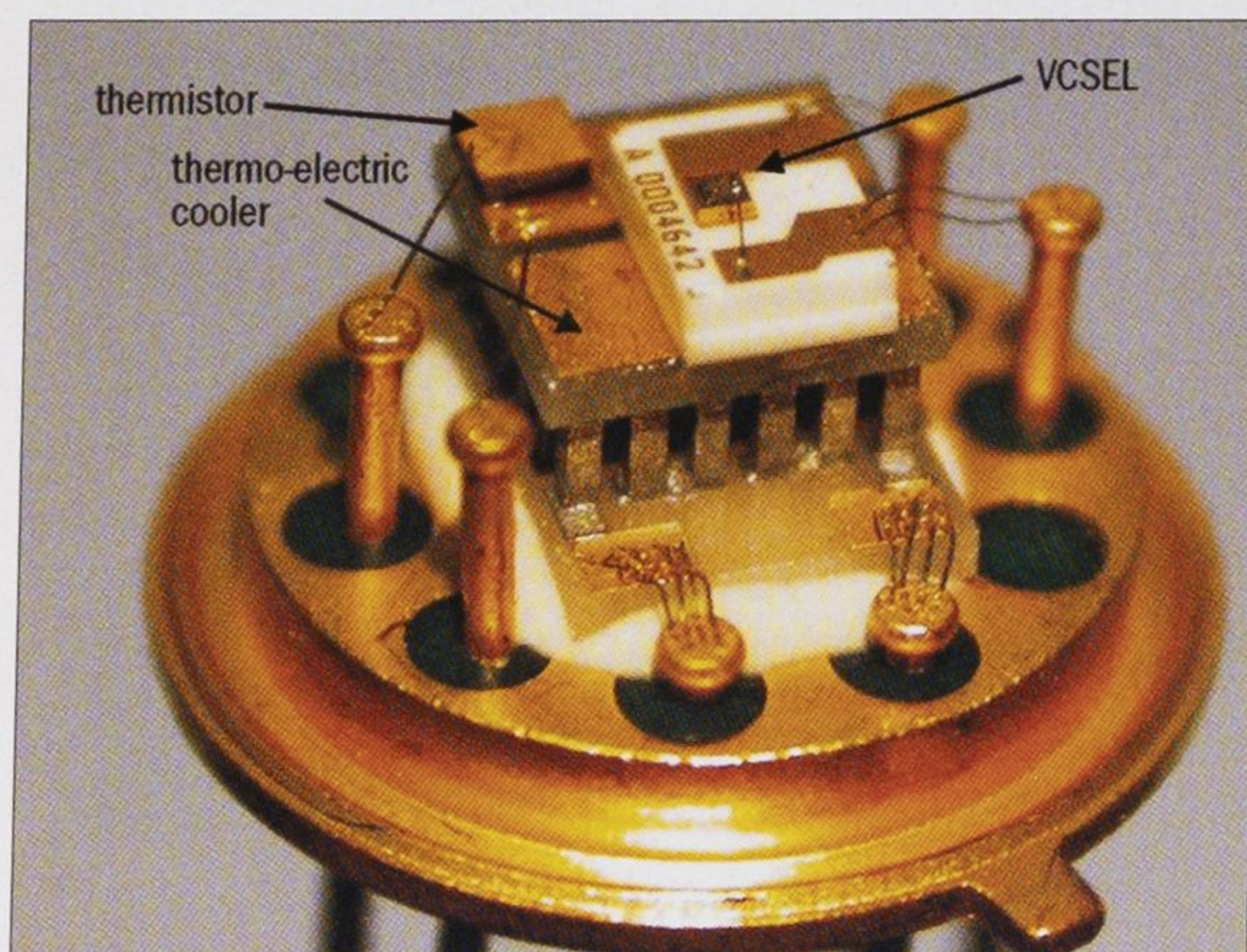


Fig. 2. Using a thermistor and thermo-electric cooler stops drift in the emission wavelength of the buried tunnel junction VCSEL.

than a DFB laser. The tunability yields a wider range of measurements. For example, pressure-broadened absorption lines can be examined, several lines relating to one species can be observed simultaneously and multiple species can be detected in a gas mixture. The VCSEL wavelength can also be tuned through the absorption line several million times per second, enabling real-time monitoring of rapid combustion processes.

Although GaAs-based VCSELs for optical communication applications are made in their millions, their use in TDLS systems is restricted to the detection of oxygen, which has an absorption line at 760 nm. Emission can be extended to 1300 nm while maintaining an adequate level of performance, but this is still short of the absorption lines for important species such as methane (1651 nm), carbon dioxide (2004 nm),

Coping with heat

Optical gain in InP-based lasers is very sensitive to temperature variation, so internal heating has to be suppressed to produce sufficient performance. Vertilas' buried tunnel junction (BTJ) design addresses this issue by reducing the thickness of the p-doped layers. Low-resistance, n-doped layers are used because of their negligible absorption. Thermal characteristics are also improved by attaching a hybrid gold-dielectric mirror to one side of the VCSEL. This decreases heat resistance by almost an order of magnitude compared with the ternary and quaternary InP-based semiconductor Bragg mirrors, and has no detrimental effect on reflectivity.

The dielectric mirror on the bottom of the BTJ VCSEL can be made with electrically insulating materials, which opens up the design space to pairs of materials with greater refractive index contrast. The upper mirror carries no heat flow, which means that this part of the VCSEL can still be made from normal semiconductor alloys.

The dielectric mirrors typically have a total reflectivity of 99.5–99.9% and are constructed from either 2.5 or 3.5 periods of $\text{CaF}_2/\text{a-silicon}$ (refractive index difference, Δn of 2.1) or CaF_2/ZnS (Δn of 0.9) that are coated with gold. The VCSELs also feature an electroplated metal layer on the bottom of the structure that provides mechanical stability and serves as an excellent heatsink. Finally, the InP substrate is completely removed from the device.

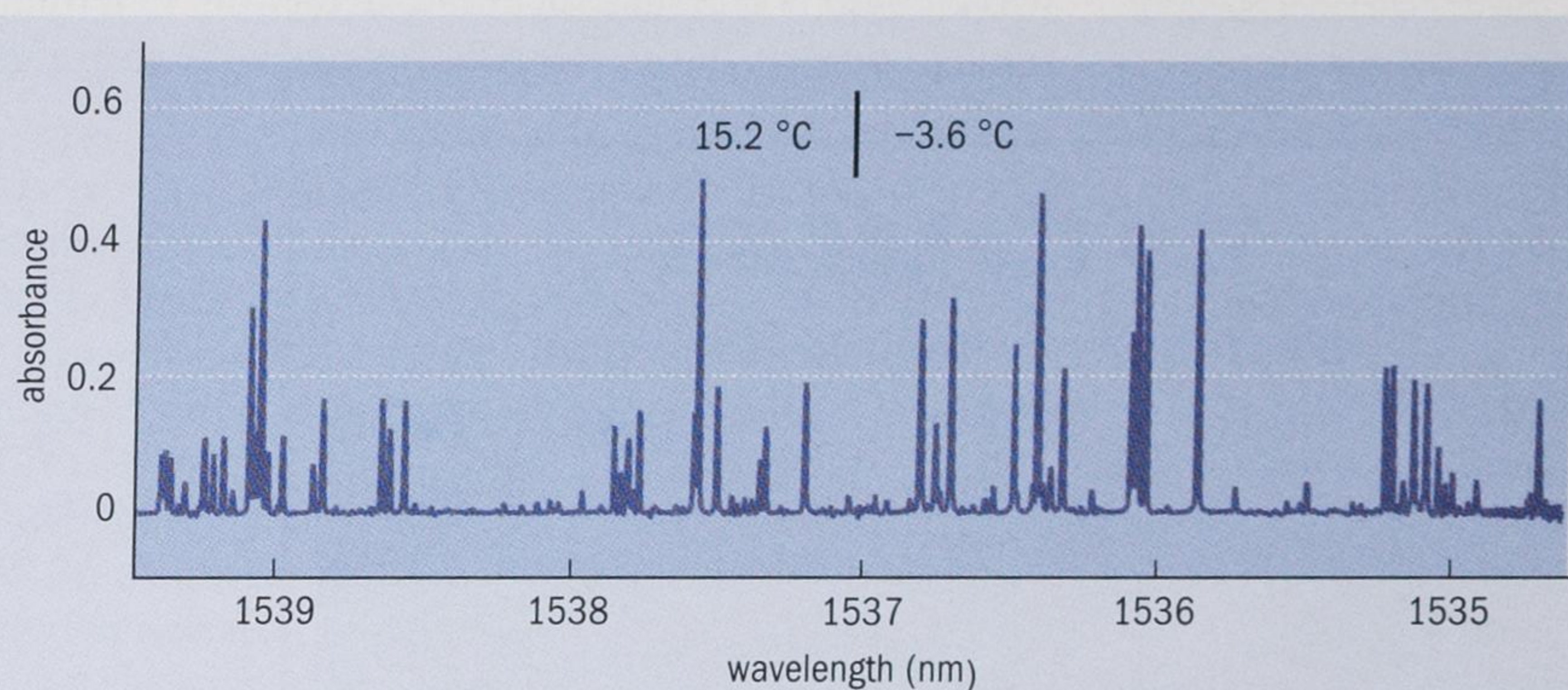


Fig. 3. By setting the operating temperature of the laser to 15.2 °C and -3.6 °C, Vertilas' VCSEL can be used to investigate the absorption spectrum of ammonia. The measurements were made on ammonia gas contained in a 44 cm quartz tube and held at a pressure of 9.6 mbar. The absorption measurements are in excellent agreement with the simulated data taken from the database standard.

water vapor (1854 nm) and ammonia (1512 nm).

Unfortunately, the performance of the long-wavelength VCSELs has lagged behind that of their short-wavelength counterparts, due to technological difficulties linked with the different material system required. The ternary and quaternary InP-based compounds that are needed to reach the longer wavelengths suffer from a relatively small index contrast, which means that a very large number of mirror pairs are needed to produce the required reflectivity for the laser cavity. Thermal conductivity is also more than an order of magnitude below that of the AlGaAs/GaAs compounds, making thermal management a major problem. Despite efforts to improve thermal dissipation by attaching a heat sink to one of the mirrors, most of the long-wavelength VCSELs fabricated so far have poor performance characteristics.

The characteristics of VCSELs and distributed feedback lasers

Laser type	Threshold current (mA)	Output power (mW)	Current tuning rate (nm/mA)	Current tuning range (nm)	Temperature tuning rate (nm/°C)	Maximum frequency modulation (MHz)
VCSEL	0.5–2.0	0.4–3.0	0.3–0.8	3.0–5.0	~0.1	>1.0
DFB	20	10	<0.05	<1.0	~0.1	<0.1



About the author

Markus Ortsiefer is a co-founder of Vertilas GmbH and is responsible for the company's production and research and development divisions. He would like to thank M Lackner from ProcessEng for technical discussions.

Success is possible, however, if one turns to novel designs, such as our InP-based VCSELs that feature a buried tunnel junction (BTJ) and dielectric mirrors (see figure 1, p14). We demonstrated this approach in 1999 and since then have improved the performance of our devices and increased their spectral coverage. Our BTJ VCSELs now operate at over 100 °C, have good thermal management properties (see "Coping with heat" box, p15) and deliver singlemode output powers of more than 1 mW at 85 °C. They also have a wavelength tuning range of several nanometers, modulation speeds in excess of 10 Gbit/s and are compatible with high-volume manufacturing – the full-wafer processes we use today on 2 inch material can be scaled to larger sizes.

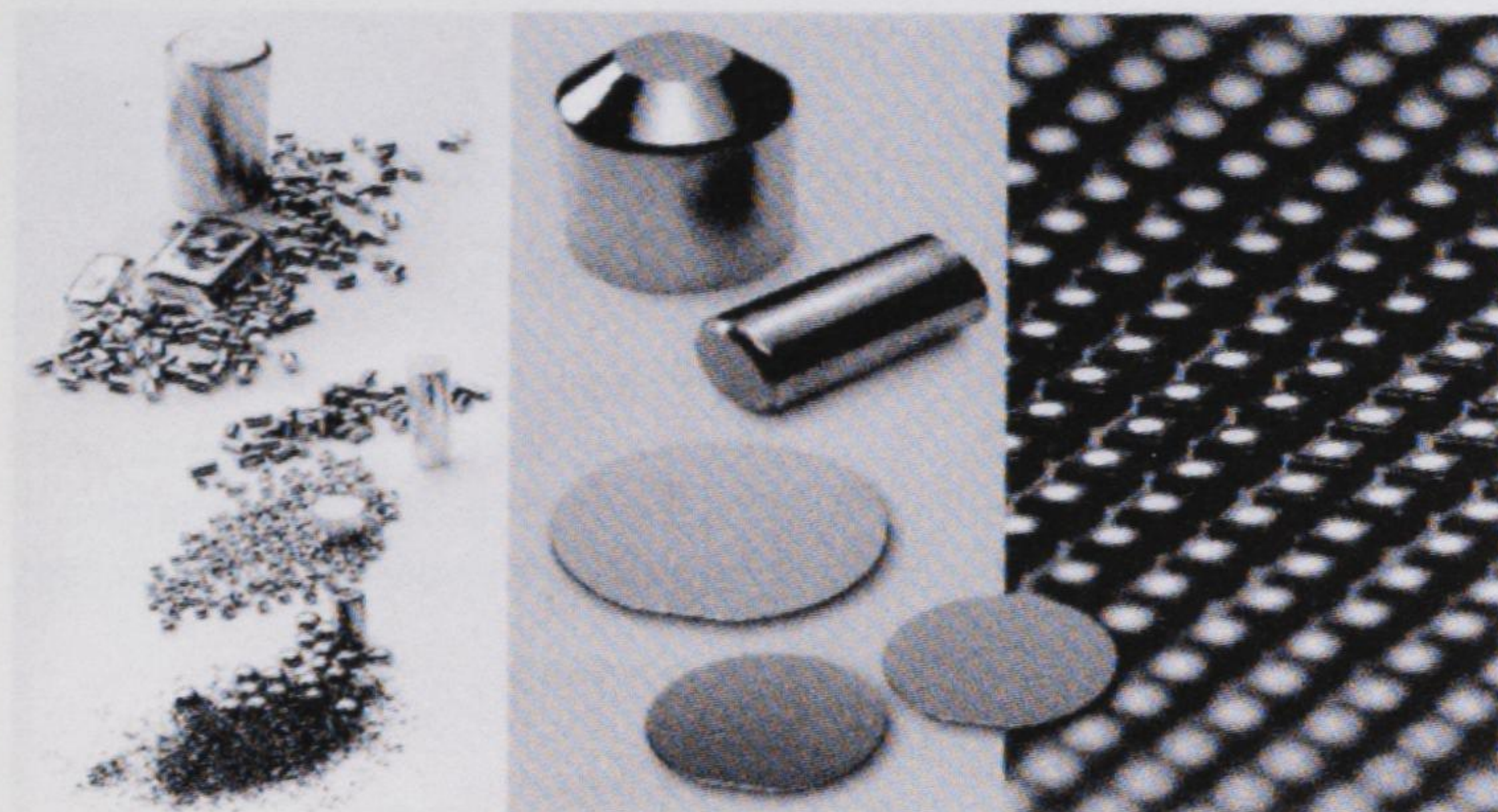
Our BTJ VCSELs are mounted on a TO-header with an integrated thermo-electric cooler and thermistor to monitor and control the laser stage temperature (figure 2, p15). Temperature stability is demanded by gas sensing applications because the temperature-dependent wavelength is crucial to accurate detection. In a final production step, the header is completed with a cap and

a wavelength-specific antireflection coating. The lasers' gas sensing capability has been demonstrated by absorption measurements of ammonia, which have shown many fine details (figure 3, p15). We acquired these spectra by operating the laser at –3.4 °C and then 15.2 °C to provide a coarse control of the emission wavelength and using current tuning for fine adjustments.

By adjusting the thickness and composition of the active region and epitaxial and dielectric mirror layers, we produced singlemode BTJ VCSELs operating from 1.3 to 2.05 µm. We also demonstrated the first electrically pumped room-temperature continuous-wave 2.3 µm BTJ VCSEL. This produces 1.47 mW at 0 °C and 0.74 mW at 20 °C, and a tuning range of 4.2 nm at room temperature. It only operates in a multimode fashion that is unsuitable for spectroscopy, but we are developing a singlemode version that could be used to detect carbon monoxide, which has a 2332 nm absorption line. This work will extend the range of our BTJ VCSELs, which can provide a cost-effective, tunable source and offer a good choice for a variety of gas sensing applications. ●

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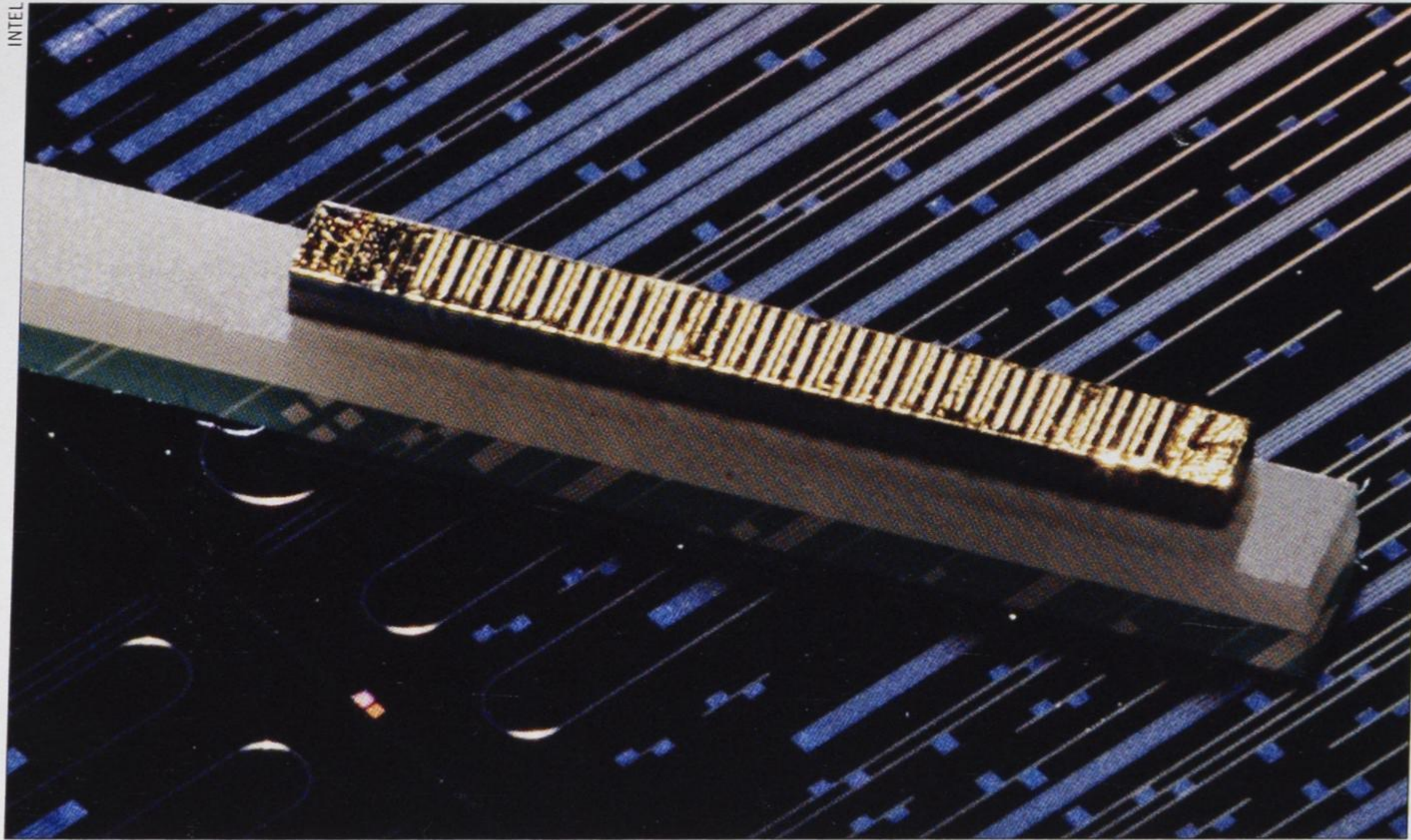
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OPTICAL INTERCONNECTS

Big step forward in silicon integration

The hybrid III-V/silicon laser manufactured by Intel and its collaborators may not represent true silicon photonics, but it is a significant development in optical interconnects for chip and board communications, discovers **Michael Hatcher**.



A slice of the hybrid silicon laser chip. Up to 36 lasers can be integrated into a single die and Intel envisages being able to build future chips with tens or even hundreds of emitters.

Until the last couple of years, research into silicon photonics had been moving at snail's pace. Now things seem to be happening at breakneck speed. "Silicon photonics is on fire!" is how Graham Reed, head of electronic engineering at the University of Surrey, UK, puts it.

"Just look at the number of *Nature* papers in the past two years," he said. "There is a daily increase in the number of groups and companies in this field."

One of those companies is Intel, the biggest player in silicon electronics bar none. But it is also at the forefront of the emerging silicon photonics research field. In September, it revealed details of an electrically pumped hybrid III-V/silicon laser, developed in collaboration with researchers at the University of California, Santa Barbara (UCSB). While many key optical functions have been demonstrated on a silicon platform, finding a suitable light-emitting source has posed the biggest problem – until now, it appears.

According to Intel, the breakthrough addresses one of the last major barriers to producing silicon photonics for use inside and around future computers and data center architectures. In essence, that means using components compatible with volume silicon manufacturing methods to generate, amplify, route, modulate and detect light in very high speed terabit optical interconnects of a suitable size for a high-performance computer.

Reed, whose credentials include initiating the field of silicon optical integrated circuits in the UK, concurs: "This device has a lot of potential" he said. "There's no doubt that it's certainly a very significant piece of the puzzle. While it's not truly a silicon laser, it's probably the next best thing".

The flurry of silicon photonics papers appearing in the leading science journals over the past couple of years

suggests that with the fundamental building blocks in place, integration of these various components in an optical system has now become the major challenge.

For example, electro-optic modulators are one of these key building blocks. Earlier this year a Danish team published details in *Nature* of just such a device. Using a silicon nitride layer to compressively strain the active layer of silicon, Rune Jacobsen from the Technical University of Denmark and colleagues discovered that this strain induces a linear electro-optic effect that can modulate light at high speeds. In theory, it could be used instead of an electronic "bus" to transport data in computer architectures.

Unlike some other approaches to optical modulators based on silicon, the device proposed by the Jacobsen team is not limited by any charge mobility or carrier recombination effects. They argue that this could be a critical advantage when it comes to commercial deployment of silicon-based photonics because these effects could limit modulation speeds.

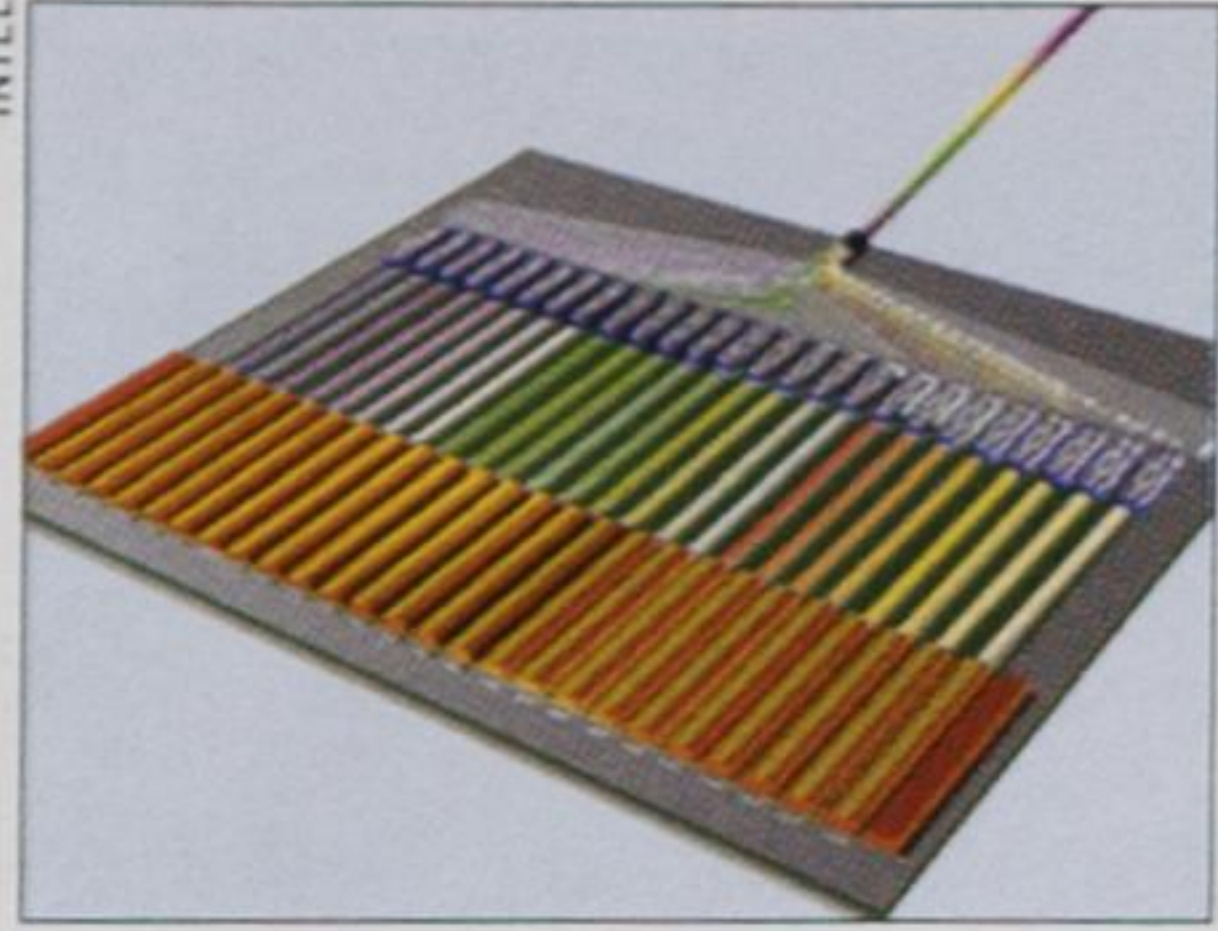
Despite the apparently different material platforms that the Danish team's modulator and Intel's hybrid silicon laser are based upon, Reed believes that these two devices could, in theory, function together as part of an optical system. "Most of the parts that are emerging are compatible at a high level because they are almost all based on a silicon-on-insulator (SOI) platform," he said.

Intel's hybrid laser is made by fusing together a AlGaInAs/InP quantum well structure and a silicon strip waveguide. That waveguide is first formed on the surface of an undoped SOI substrate. The "special sauce" that allows the laser to function is the way that the silicon waveguide and the active AlGaInAs layers bond.

Both surfaces are treated in an oxygen plasma reactive ion etch chamber, pressed together and annealed. The materials couple so well that the III-V and silicon elements each form a critical part of the laser structure, with the silicon waveguide fundamental to the lasing action. The degree of alignment between the two types of material does not require a particularly high level of precision. John Bowers from UCSB has been leading the research: "All of the optical mode confinement – in the laser, in subsequent modulators, in output waveguides and in a fiber holder – is determined by the same CMOS lithography step," he explained.

According to Graham Reed, the complexities of integrating lasers, modulators and detectors will always throw up issues of compatibility, particularly when it comes to processing optical and electronic parts in the same layer of material. For high-end applications capable of 40 Gbit/s communications, it will also be necessary to develop another part – a silicon-based optical isolator – that can be easily integrated into a circuit.

These high modulation frequencies will have to be



In its concept of a future integrated silicon optical transmitter, Intel proposes using 25 hybrid silicon lasers, each coupled with a silicon modulator and multiplexed together into a single output fiber.

achieved in Intel's vision for commercialization of "silicon" photonics, however. Although it is funding a big effort into the development of the hybrid laser, the chip giant's overall photonics strategy is difficult to understand given recent events. In September, Intel sold its optical networking components business (which makes control electronics, rather than optical communications modules) to venture-backed newcomer Cortina Systems.

So why the push to develop the hybrid laser? Intel knows that its commercialization at any level is at least five years away, but it is already talking about using integrated photonic chips as part of its terascale computing research program. This program is based on the idea of multi-core processing and Intel's plan is to house tens or even hundreds of these cores onto a single chip.

The problem arises when you try to move this amount of data around using conventional copper interconnects. While copper can support very fast interconnection speeds, it can only do this over a very short distance. To deliver terabit communications, it seems more than likely that photonic interconnections will be needed.

But what exactly would such a system look like? Intel has already proposed its idea of a terabit optical transceiver. It consists of a row of hybrid silicon lasers, all of which are tuned to operate at a slightly different wavelength. The individual wavelengths can be defined by altering the width of each silicon waveguide and its grating pitch, and can be tightly controlled thanks to the precision that state-of-the-art photolithography allows.



The Intel-UCSB team with hybrid silicon laser device –

left to right: Hyundai Park, UCSB graduate student; John Bowers, UCSB professor; Mario Paniccia, director of Intel's Photonics Technology Lab; Richard Jones, Intel researcher; and Alex Fang, UCSB graduate student and former Intel intern.

If 25 lasers are used and each of these individual data streams is modulated at 40 Gbit/s, the result would be terabit per second data transmission from a single chip. Even Intel's prototype hybrid die featured as many as 36 lasers, although only 26 actually lased.

With the hybrid laser and the other building blocks required for silicon photonics on the road to commercial development, the long-awaited marriage between optoelectronics and computing suddenly appears to be within reach. And not, as some had predicted, to the exclusion of compound semiconductors.

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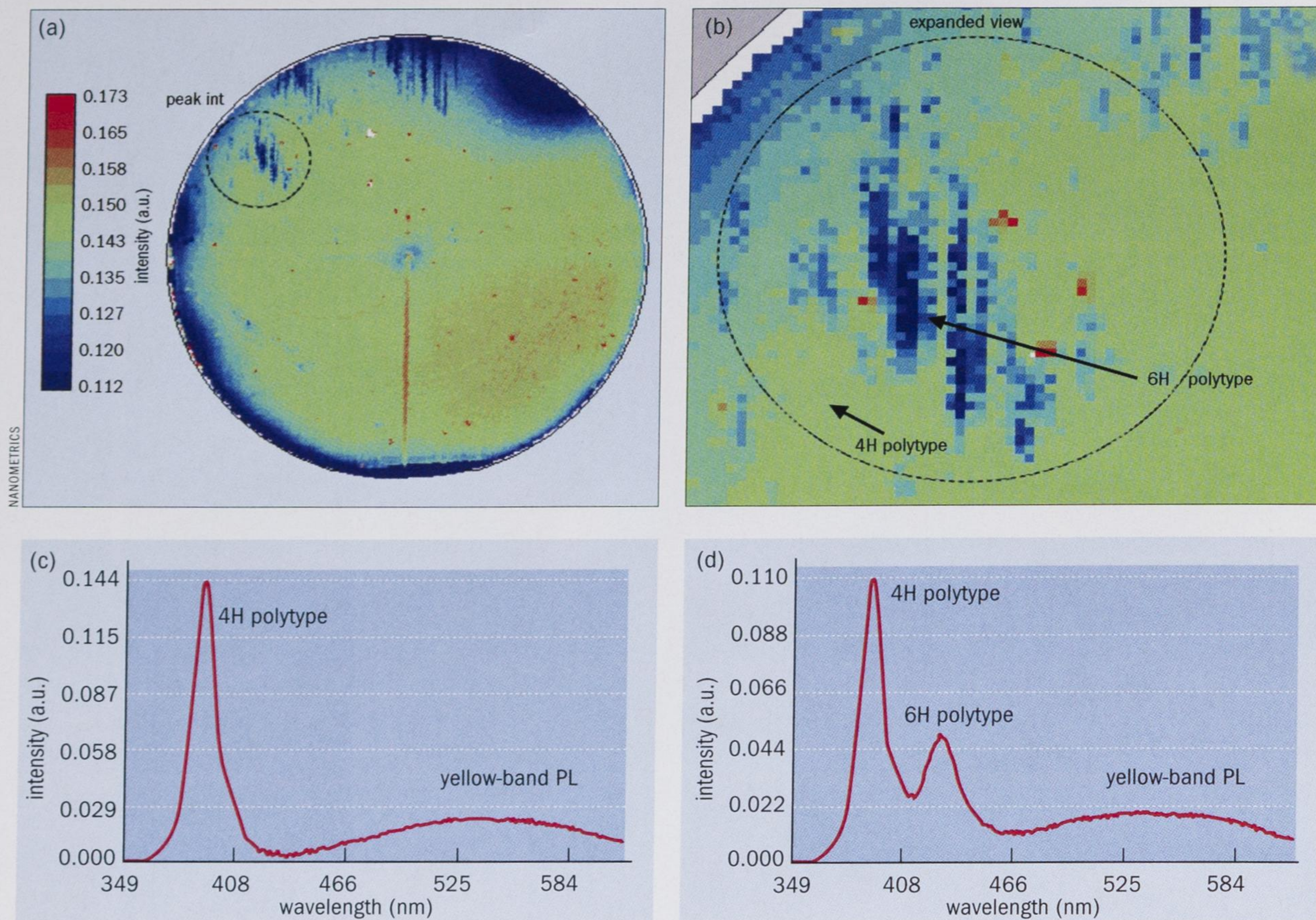
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Crossed swords over SEMI standards

Competition among SiC substrate manufacturers has boosted wafer diameters and eliminated micropipe defects in commercial SiC wafers. However, there is still some division over the effectiveness of the standards used to define the quality of the material, as **Richard Stevenson** discovers.

Fig. 1. Photoluminescence intensity mapping can identify unwanted 6H polytypes in 4H SiC substrates (see the whole wafer map (a) and the expanded view of a part of this substrate (b)). These maps were produced by measuring the photoluminescence intensity at 392 nm, the peak of the emission from 4H material. High-quality regions of the substrate with just 4H material produce relatively intense emission at this wavelength (c). Regions containing both polytypes have weaker emission at 392 nm, and an additional peak at a longer wavelength due to the 6H polytype (d).



Intense competition between rival SiC substrate manufacturers has been good news for their customers. Wafer sizes are up and the micropipe defects that kill devices and hit yields have been cut to very low levels, with “zero micropipe” material now available. So does this mean that very-high-quality substrates are routinely available from a wide variety of suppliers?

Well, not according to several researchers speaking at the recent European Conference on SiC and Related Materials (ECSCRM) in Newcastle, UK. In their opinion, today’s substrates contain high-density threading-screw dislocations, basal-plane dislocations and unwanted polytypes, and there is a huge variation in quality, not only between vendors but between many manufacturer’s nominally identical substrates. These discrepancies are not exposed by the Semiconductor Equipment and Materials Institute (SEMI) specifications, which has led some researchers to claim that these standards need updating.

One of these researchers is Tom Ryan, from char-

acterization equipment supplier Accent Optical Technologies, now part of Nanometrics. He and his colleagues have been assessing the quality of 2 and 3 inch 4H polytype substrates from seven different vendors. The team employed photoluminescence to identify electrically active defects and X-ray measurements that provide a metric for crystalline perfection. “The results blew us away,” says Ryan. “These nominally identical wafers are so different.”

Photoluminescence can distinguish between 4H and 6H material, and Ryan has also employed this method to identify boron-related defects. By altering the power density of the incident laser source he has produced whole-wafer maps that reveal 6H polytypes and stacking faults (see figure 1).

Ryan has also mapped smaller areas using a micro-photoluminescence tool that has a typical spatial resolution of 1 μm . By recording the intensity of the 4H band edge emission he has revealed lines that are associated with crystalline defects such as low-angle

“SEMI standards lack state-of-the-art measurements and are too simplistic.”

Tom Ryan
Nanometrics

Table 1. Variations in 4H substrates revealed by X-ray measurements

	Wafer size (mm)	FWHM average (arc sec)	FWHM min (arc sec)	FWHM max (arc sec)
Vendor A	75	21.3	14.5	61
Vendor B	75	21.2	15	55
Vendor C	75	267	74	700
Vendor D	75	130	47	275
Vendor E	75	460	118	1300
Vendor F	50	39	16.5	140
Vendor G	50	42	19.5	120

grain boundaries, threading dislocations and interfacial misfit locations (see figure 2).

Ryan's X-ray rocking curve studies involved whole-wafer mapping of the full-width half-maximum (FWHM) of an X-ray peak (see table 1). This value provides a measure of crystalline quality – perfect crystals have a theoretical FWHM approaching zero arc seconds, and this value increases through dislocations and grain boundaries that disrupt the lattice. The highest quality regions of the best SiC substrates have a rocking curve FWHM width of 14 arc seconds, which is only a little higher than that for typical silicon and GaAs material. However, even these SiC substrates have large regions with FWHM values of up to 100 arc seconds, where material is typically much more disordered.

Synchrotron measurements

Some of the defects responsible for this disorder have been identified by Patrick McNally from Dublin City University, along with colleagues at the University of Freiberg, Helsinki University of Technology, GE Global Research and the Institute for Synchrotron studies in Germany. Using a synchrotron source for X-ray analysis, the team investigated 2 and 3 inch substrates from five manufacturers and discovered what McNally described as “an alarmingly large variation in wafer quality” (see figure 3, p22).

Although SiC substrate and chip manufacturers might be interested to see McNally's results, they are hardly likely to install an X-ray synchrotron instrument in their foundries. “It is not something that you're going to find in a company's backyard,” says McNally. “It's a scientific tool.” However, SiC manufacturers could replicate the technique with standard X-ray kit configured for Lang topography, which can map out whole substrates for different types of defect at a lower spatial resolution than the synchrotron.

Also at ECSCRM, James Oliver from Northrop Grumman Electronic Systems' Advanced Technology Center presented the results from his survey of SiC substrates. He compared material from five vendors and found that variability in crystal quality is common, even within individual vendors. Although the best substrates are free of macroscopically observable defects, this is not the norm, according to Oliver. Polytype inclusions, low-angle grains, precipitates and strain can be seen in many substrates with the unaided eye using a cross-polarizer technique. Finer details can be gained using a cross-polarized light method and a

microscope (see figure 4, p22).

Oliver has also looked at substrate surface quality with an atomic force microscope. He believes that the surface roughness, which is typically less than 0.4 nm and at best 0.2 nm, is acceptable.

In addition to the studies comparing material from various vendors, Kurt Gaskill from the US Naval Research Laboratory in Washington, DC, presented the results of his investigation into 2 inch 4H-SiC substrates from Intrinsic, which is now part of Cree. Gaskill found large variations in the X-ray data and cross-polarization images of three substrates, which were off-cut at 4° towards (11–20) and had a micropipe density of 0–5 cm⁻². There was little correlation between the X-ray and cross-polarization images, which led him to conclude that cross-polarized light images may not be sensitive to crystalline imperfections in high-quality, low-micropipe substrates.

Sub-standard SEMI standards?

Although the substrates studied by Ryan, McNally, Oliver and Gaskill have a very wide range of characteristics, they all conform to SEMI's specifications for 2 and 3 inch material. This is because the standard does not set a value for the micropipe density, which must be agreed between customer and supplier, and requires no tests based on X-ray diffraction or photoluminescence. Included in the SEMI standards are the substrate's dimensions, including warp and bow figures and off-axis angle tolerances. SEMI also defines limits for the number of visible defects and pits on the surfaces, the number of cracks in the material and the proportion of crystallite area.

Ryan is critical of these specifications: “SEMI standards lack state-of-the-art measurements and are too simplistic.” Arnd-Dietrich Weber, the global task force manager for SEMI's SiC standardization committee and manager of test and metrology at substrate manufacturer SiCrystal, is not so sure: “It is known that if you look at the market – and the feedback from customers – that material from one vendor is not identical to that from a second vendor. But what is not clear at the moment is the impact of such variations on device production [and performance].”

Weber's is a point that all of the researchers agree with. In fact, many are now in the early stages of projects to find out whether there is a correlation between substrate quality and the performance of certain devices. Ryan and McNally both expect to find

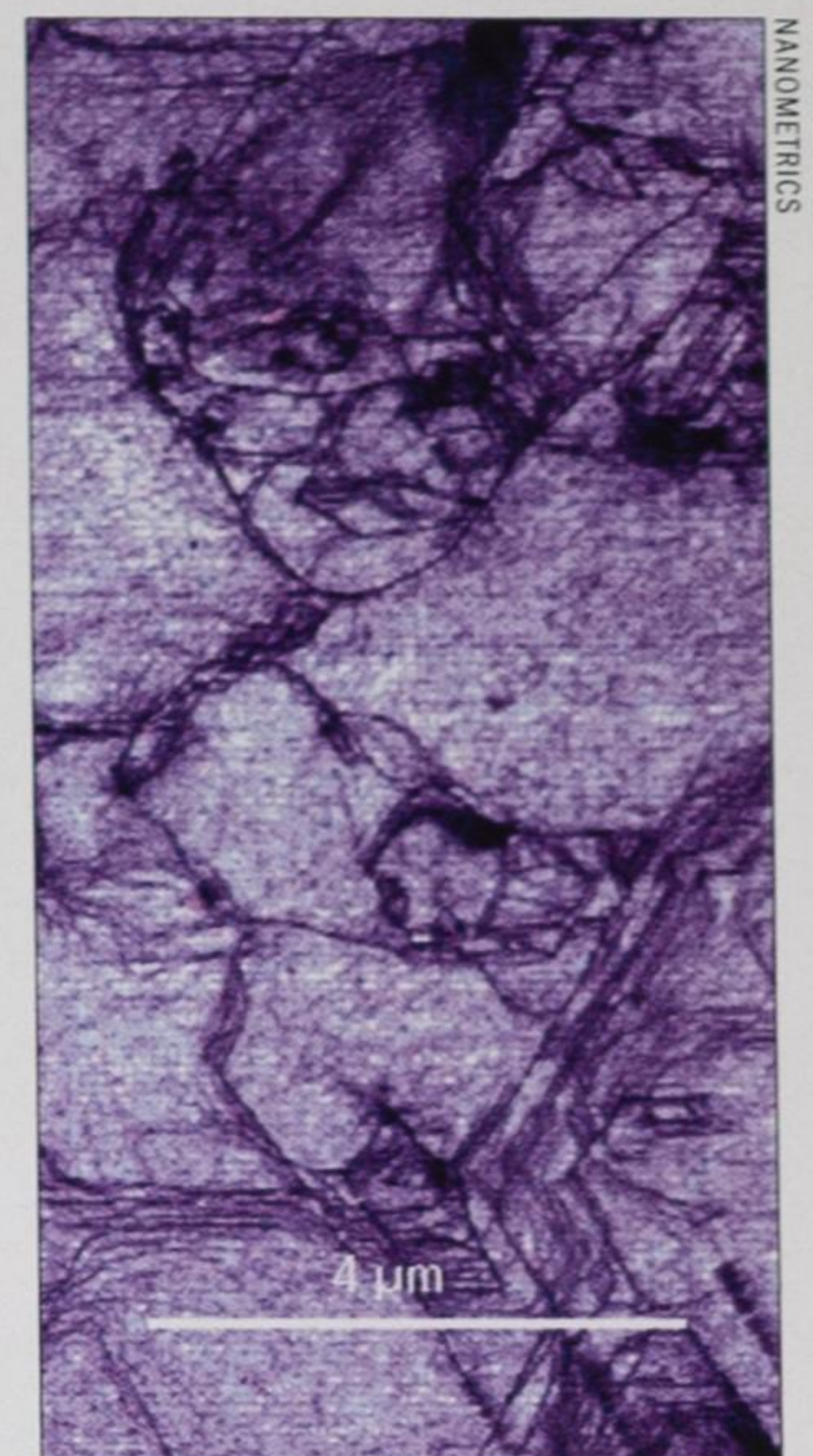


Fig. 2. Micro-photoluminescence maps of the intensity of emission at 392 nm, the band-edge of 4H SiC, can reveal lines associated with non-radiative defects. These dark lines identify low-angle grain boundaries, threading dislocations and interfacial misfit dislocations.

“The papers at ECSCRM are very interesting, but the SEMI standards are the requirements needed for economic success.”

Arnd-Dietrich Weber
Global task force manager, SEMI SiC standards committee

Fig. 3. Large-area white beam synchrotron back reflection X-ray topography can be used to analyze the density of threading-screw dislocations (a) and basal-plane dislocations (b).

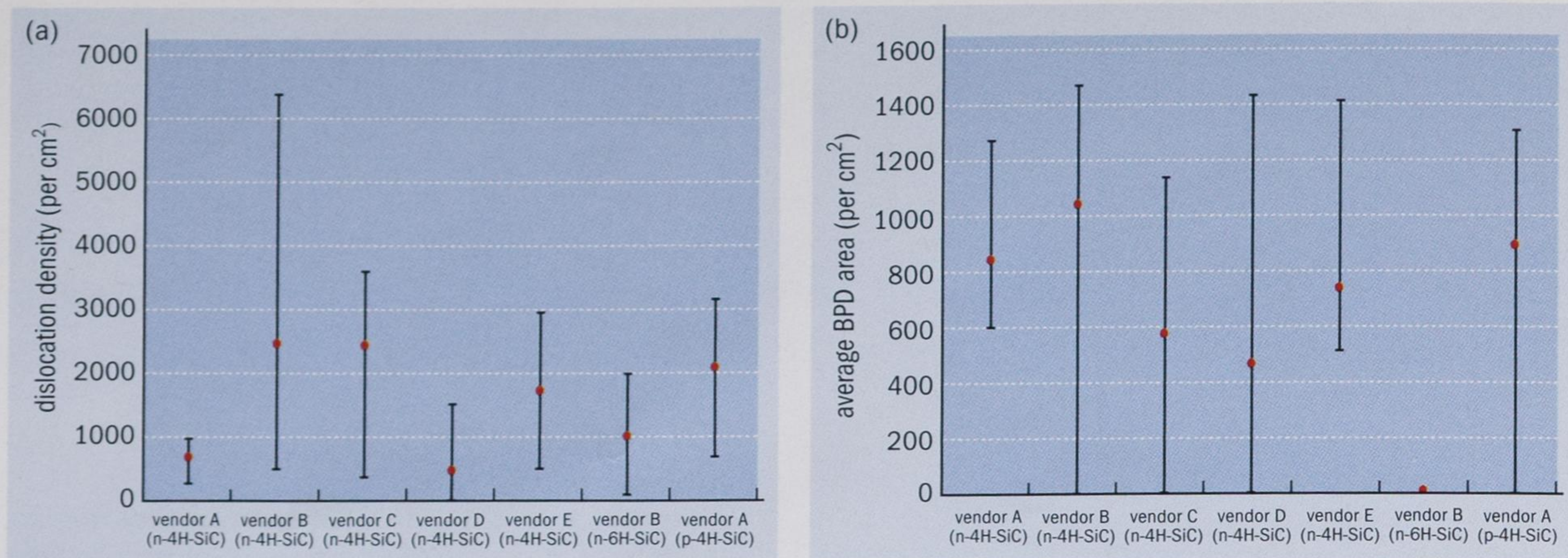
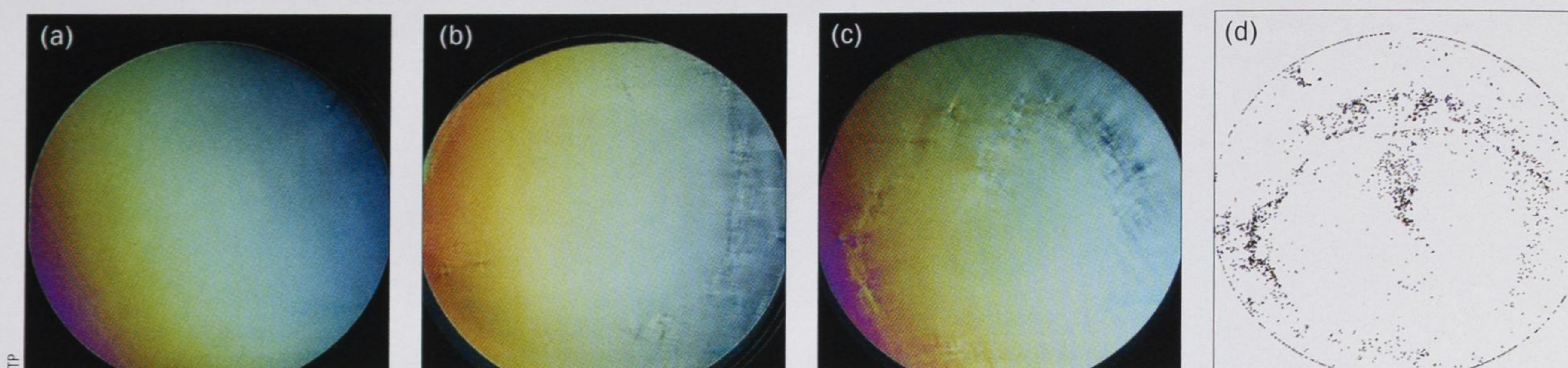


Fig. 4. Cross-polarized light images, which have been cropped to remove the laser markings, can reveal various features on SiC substrates. Substrates a and b have micropipe densities of 1.3 cm⁻² and 32 cm⁻², respectively. Substrate c, which is of poorer quality, has many features that can correlate to the micropipe map (d). Images courtesy of Trans Tech Publications (TTP).



this link. Ryan believes that the non-4H inclusions – such as basal-plane dislocations, stacking faults and threading dislocations – increase the leakage current in Schottky diodes and will influence MOSFET yields. McNally thinks that the threading-screw dislocations will affect the performance of reverse-biased devices, like photodetectors. Gaskill, however, is less certain and does not want to speculate on the outcome of investigations relating current substrate quality and device performance.

Weber points out that research findings can also lead to claims that ignore the economics of substrate production. “You have two completely different worlds dealing with the same material. The papers at ECSCRM are very interesting, [but] the SEMI standards are the requirements needed for economic success.”

The SEMI standards for SiC substrates were drawn up to reflect what is currently possible, explained Weber, and to provide a guideline that does not hamper future developments. He asserts that the SiC task force is not biased towards the material suppliers because it has representation from both these vendors and their customers. “It is a balanced composition that enables us to make good technical progress and produce a healthy document.” Without this document every manufacturer could generate its own standard and substrate, which would be bad for both customers and the industry in general.

The current concerns for Weber’s SiC task force are not the variations in substrate quality that are revealed by X-ray diffraction and photoluminescence, but agreeing a standard for 100 mm substrates and a method for counting micropipes. Substrate thickness has proved the sticking point for the 100 mm standard.

Customers want thinner material to improve device performance, but vendors say that this could lead to problems associated with warp, bow and other geometrical features.

The micropipe counting issue is being addressed by another organization, the American Society for Testing and Materials (ASTM). “Without a standard in place it’s impossible to compare the numbers published by different vendors directly,” says Weber. This has led customers to request different micropipe densities from different known suppliers in order to ensure a consistent benchmark for incoming material. Unfortunately, good standardization is a very slow process, often taking five years. The ASTM committee has only been meeting for two years, so a universal method for micropipe counting will have to wait.

A manufacturer’s perspective

SiCrystal’s European sales manager Thomas Kippes offers the most pragmatic perspective. He believes that the key test for SiC quality is not the X-ray or the photoluminescence results, but whether the substrate provides a platform for high-yield manufacturing. He relates the story of a customer making Schottky diodes. The customer focused on X-ray diffraction maps, but observed no correlation with device yield. “Maybe it’s a different story when you make a MOSFET,” said Kippes, before pointing out that a customer’s SiC experience and its individual process have to also be considered.

Today’s SiC substrates are far from perfect and riddled with imperfections. But this may not matter. The pertinent question for device makers is “how good does my substrate need to be?”

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ECSCRM: applications steal the show

Commercial applications and market penetration of devices dominated the recent ECSCRM conference in Gateshead, UK, which was held on the centenary of the first SiC paper. **Alton Horsfall** reports.

There was a shift in emphasis at the sixth European Conference on Silicon Carbide and Related Materials (ECSCRM). The characteristics of specific substrates and devices stopped hogging the limelight, and issues surrounding silicon carbide (SiC) in commercial systems emerged as the key talking point.

This theme was taken up by Peter Friedrichs, managing director of SiCED, the German joint venture between Siemens and Infineon. In his plenary talk he asked whether SiC was a suitable technology for investment. According to Friedrichs, the first commercially available SiC products suffered from signs of overheating, caused by circuit developers using the devices beyond their rated values.

This problem has been addressed by reducing the internal electric fields within devices, and the latest products now deliver a stability comparable with that of their commercial silicon counterparts. Friedrichs believes that this advance, allied to a doubling in the cost of silicon over the last two years driven by increased demand from the photovoltaics industry, has changed the commercial landscape for SiC. "Should we invest in SiC?" is probably not the pertinent question any more, argued Friedrichs, but rather "Is now the right time to invest?"

In a session that focused on industrial applications, Roger Bassett from energy consultant Areva outlined the benefits of using SiC devices in high-voltage functions, such as power transmission and distribution. SiC

offers low-loss switching of voltages in excess of 10 kV and this provides greater flexibility in the generation and distribution of electrical power. These attributes make the existing power network a major target for SiC devices – it could generate \$200 million in product sales by 2020. SiC devices can offer an additional benefit over silicon, says Bassett, because they can reduce the area of land needed for construction of large-scale power conversion facilities.

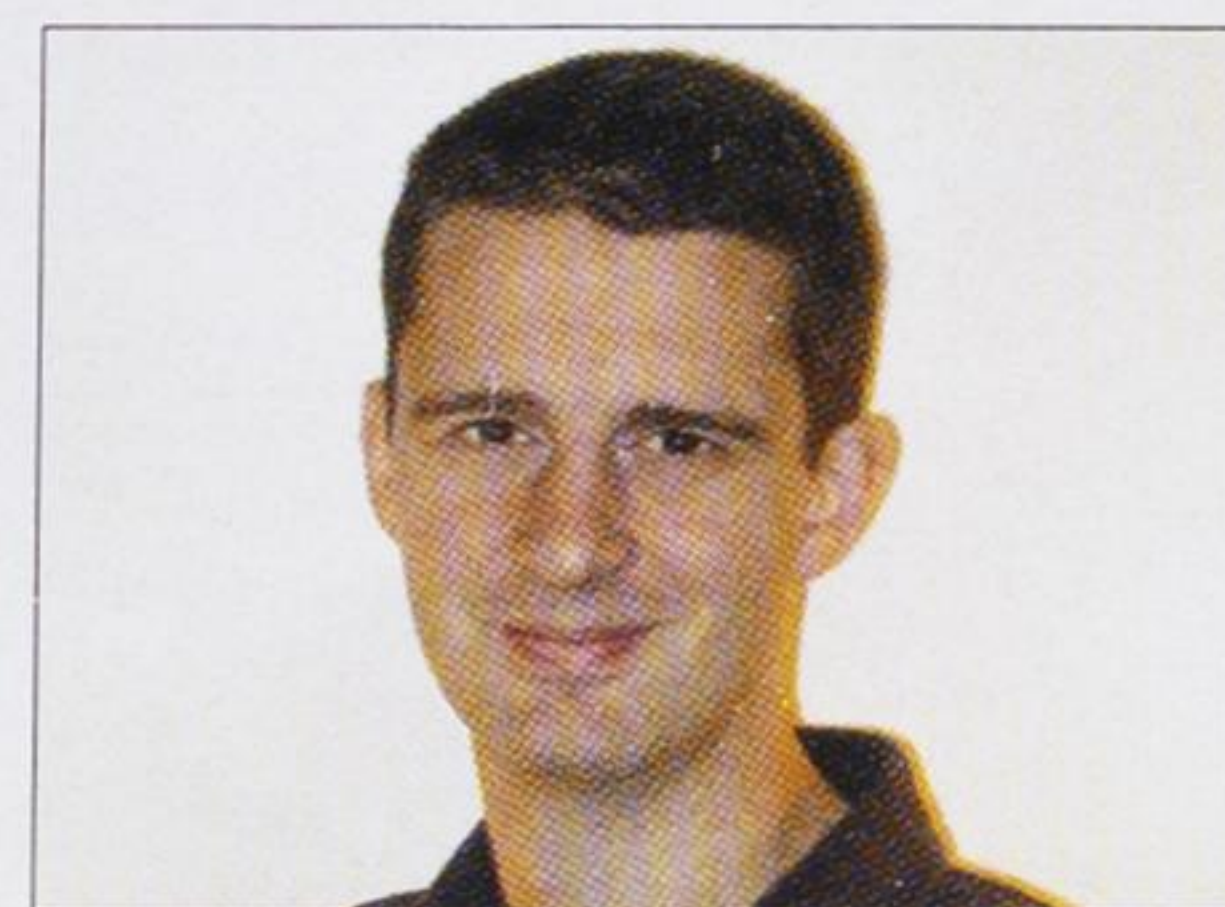
The use of SiC devices in circuit applications was discussed in other talks by Ty McNutt from Northrop Grumman and Leon Tolbert from the University of Tennessee. Both of these speakers said that the promised reduction in on-state losses in circuit applications can only be delivered by making dramatic changes to packaging technology that aids heat dissipation. The two research groups have already demonstrated inverter circuits featuring SiC switches and diodes.

At previous conferences the capabilities of SiC devices at high temperatures has been a strong theme. This year's meeting was no exception. NASA's Phil Neudeck revealed that SiC FETs can run at 500 °C for more than 2400 h, which means they can be deployed into environments where traditional semiconductor technology cannot function. These could include engine exhausts, the surface of Venus and aerospace applications such as aircraft. NASA researchers have also studied behavior of this type of device in an amplifier circuit operating at 500 °C.



ECSCRM 2006
Newcastle upon Tyne, UK

The sixth European Conference on Silicon Carbide and Related Materials, which took place at The Sage Gateshead on 3–7 September, attracted 420 delegates. A total of 293 papers were presented.



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100 years of SiC publications

This year's ECSCRM marked the centenary of SiC publications with a review by Nick Wright from Newcastle University. Some of the major breakthroughs over the last 100 years include:

- **1906** Henry Dunwoody patents a SiC-based wave responsive or detecting device', which could replace magnetic 'coherer' devices in radio receivers.

- **1907** First observation of the semiconductor LED, which was fabricated using SiC. Captain Joseph Round, personal assistant to Marconi, noticed that yellow light was emitted from certain crystals when biased at typically 100 V.

- **1908** Marconi used the wave responsive device in his transatlantic telecoms system.

- **1925** The wave responsive device was launched commercially by Carborundum Corporation.

- **1955** A method to grow SiC crystals of sufficient quality for electronic devices was developed by Lely. However, these hexagonal crystals were the wrong shape for semiconductor processing.

- **1960s** The first commercial SiC LEDs were released, just a few years before the launch of III-V devices.

- **1978** Tairov and Tsvetkov from the Ioffe Institute developed a seeded crystal growth technique for producing circular SiC substrates.

- **1991** Cree released the first commercial SiC wafers.

- **2001** Infineon launched the first SiC Schottky diodes.

- **2006** Cree ships micropipe-free substrates.



The Sage Gateshead, by the River Tyne in Gateshead, was the venue for this year's ECSCRM conference. The building opened in 2004.

For several years SiC has also been touted as a suitable technology for power devices operating in high radiation environments, due to the material's wide bandgap. At this year's ECSCRM Infineon Technologies' Gerald Soelkner presented the first analysis of device failure from cosmic radiation. His work demonstrates that SiC devices can deliver greater reliability than their silicon equivalents when the maximum electric field under blocking conditions is reduced enough. When this occurs, the effects of impact ionization are not important, says Soelkner.

Another application for SiC devices is gas sensing in extreme environments. Our team at Newcastle University has shown, for the first time, that gas concentrations can be recorded at high temperatures by monitoring the leakage current through the sensor's capacitor. The research shows that sensor arrays can be built that determine the concentration of various gases in a mixture. The arrays are made by varying the capacitor's dielectric for each detector, which gives every element a unique and identifiable characteristic that can be used to trace specific gases.

Improving the oxide interface

SiC MOSFETs have the potential to deliver a low on-state resistance but progress has been limited by the quality of the SiC/SiO₂ interface. Typical device mobilities are 40 cm²V⁻¹s⁻¹, which is significantly lower than the silicon equivalents due to the high density of near-interface traps near to the conduction band edge.

Einar Sveinbjornsson, from Chalmers University, Sweden, said that this trap density is related to the presence of sodium in the oxide, which causes many deep interface traps (typically 1 × 10¹³ cm⁻²) that can lead to a large hysteresis in capacitance-voltage characteristics. The density of near interface traps can be reduced by oxidation in alumina because the sodium that is present from the processing converts these defects into deep traps, which can then be reduced by annealing in hydrogen gas. With this approach MOSFETs can be produced with mobilities in excess of 100 cm²V⁻¹s⁻¹.

While applications took center stage this year, progress in the quality and size of SiC substrates still

arouses intense interest. Cree, which acquired Intrinsic Semiconductor this summer, picked the event to launch its zero micropipe material. Cem Basceri, from Cree's Dulles site in Virginia that previously housed Intrinsic, says that the micropipes are linked to polytype inclusions, which propagate in the [11–20] direction. With careful control of the growth conditions the formation of these inclusions is suppressed and the micropipe density can be reduced to zero, says Basceri. The company is now transferring its technology to a 100 mm platform. Recent efforts have led to 100 mm conducting substrates with just seven micropipes and high-purity semi-insulating material of the same size with micropipe densities of 2.5 cm⁻².

Substrate quality is also improving at SiCrystal, says Thomas Straubinger, the firm's leader in the research and development of crystal growth. The German outfit has observed that substrate quality is dependent on the initial seed and has improved its production process by switching to a new generation of 3 inch seed crystals. Straubinger revealed that these efforts have concentrated on reducing the substrate's basal plane dislocation density because this type of defect has the greatest impact on power devices. The basal plane dislocations are linked to stress generated during the growth process and they can be substantially reduced by minimizing temperature gradients.

II-VI, a US manufacturer of SiC substrates, also reported improvements in material quality. Andy Souzis, the technology and program manager for the company's wide bandgap group, claimed that II-VI has cut the density of all types of dislocation in its 3 inch material by two orders of magnitude over the last 12 months. Typical values for comet counts are now 31 and total dislocation densities average 7 × 10³ cm⁻².

It is a safe bet to assume that further improvements in SiC material will be reported at the next International Conference on Silicon Carbide and Related Materials, which will be held in Nara, Japan, in October 2007. However, as production of this material matures and high-quality substrates become the norm rather than the exception, the increasing focus on applications is surely set to continue.

●



VCSEL PROCESSING

Steam generator purifies oxidation

A Californian start-up claims that its ultrapure steam generator can boost the production yield and speed the oxide aperture process used widely in VCSEL manufacturing. **Richard Stevenson** talks to the tool's inventor, Jeff Spiegelman.



Rasirc's Intaegeer ultrahigh steam purification system provides a controlled water vapor source for VCSEL oxidation that has only a few contaminants and is free from a carrier gas.

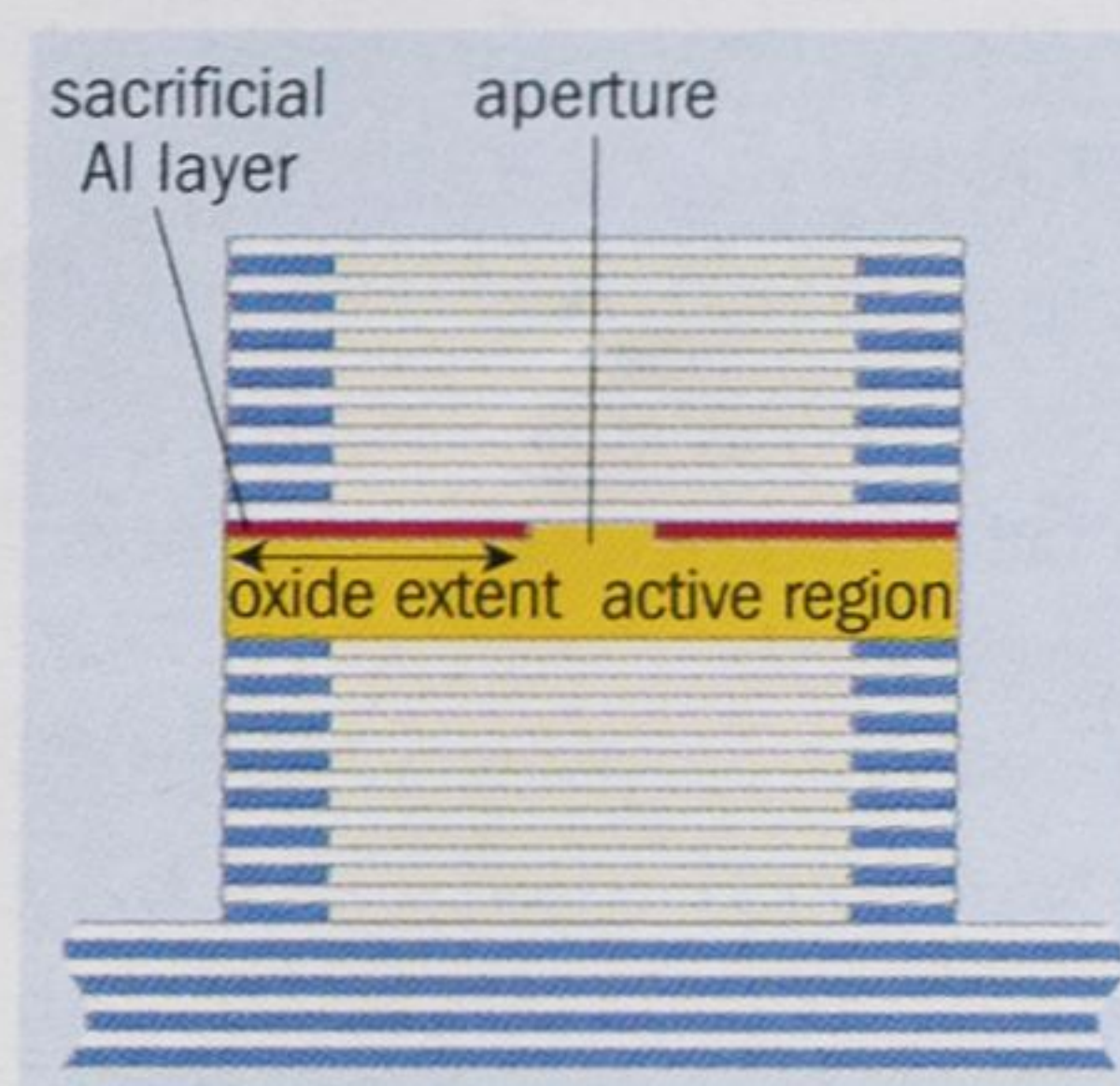


Fig. 1. Water vapor reacts with the sacrificial aluminum-rich layer to produce an oxide that forms on the outside of the device first, and moves towards its center. The rate of this step is key as it defines the size and position of the aperture – the remaining un-oxidized material. A uniform flow of high-purity water vapor ensures consistency between devices and a high yield.

Oxide apertures feature in most of the VCSELs deployed in optical mouse sensors and data communication networks. The structures deliver optical and current confinement (see figure 1), and are added by oxidation in a furnace with a controlled water vapor source.

The water vapor is generated by a bubbler or vaporizer. However, Jeff Spiegelman, president of Californian start-up Rasirc, says that VCSEL production yield and throughput improvements can be made if manufacturers switch to his company's steam purification system. "We are able to deliver [water vapor] at a rate and composition that gives us an advantage over everybody."

The water vapor source provides the furnace with a continuous stream of gaseous water at a well defined temperature and pressure. If this uniformity is achieved, all of the VCSELs on the various processed wafers are oxidized identically and yields are very high.

Spiegelman believes that bubbler-based water vapor sources compromise this uniformity. Water is absorbed during the process, but the carrier gas – typically nitrogen or argon – is not consumed, which leads to changes in the composition and pressure of the gas. These variations alter the oxidation rate, resulting in non-uniform

oxidation across the wafer. "The more nitrogen you have in your bubbler, the slower the growth rate and the worse the uniformity," claims Spiegelman.

Bubblers also suffer from contaminants in the gas stream. Any metallic or ionic contaminant in the gas can be absorbed by the oxide layer, which reduces the film's insulating properties and impacts the VCSEL's optical and current confinement.

According to Spiegelman, vaporizers, which are also known as clean steam systems, can also produce high levels of contamination. This is because metallic parts can corrode and release ions. In addition, their performance is hindered by incomplete vapor formation. "The water drops onto a heated surface and you get some vapor, but you also get a clump of water molecules that haven't gone into the vapor state," explains Spiegelman. "When they go into the furnace they vaporize. [You need] a lot of energy to go from a liquid to a gas, which can lead to non-uniformity."

Spiegelman believes that Rasirc's Intaegeer ultrahigh purity (UHP) steam purification system, which was launched six months ago and is based around a non-porous hydrophilic membrane, can address the shortcomings of vaporizers and bubblers. The machine can be fed with de-ionized water, which is relatively cheap, and contamination is also restricted by the membrane's selectivity. The membrane allows water molecules to pass through a million times more quickly than nitrogen molecules, thereby providing a source that is free from a carrier gas while removing contaminants such as other gases, ions, organic material, particles, viruses, bacteria and metals. Tests have shown that the Intaegeer system can reduce 67 different metal contaminants to levels below detectable limits, and "virtually eliminate" nitrogen and carbon dioxide.

Rasirc is yet to sell its first UHP Intaegeer steam generator to a VCSEL manufacturer, but it has increased oxidation rates at three silicon fabs. All of them have seen an improvement in growth rate of at least 14%, says Spiegelman. One fab reported a hike of 18%, which is equivalent to a time saving of four days a month. "That translates to three months or less for payback on the tool." Oxidation uniformity has also improved: one customer went from $\pm 5\%$ at best to $\pm 1.8\%$, based on data from three lots of 25 wafers, which included wafer-to-wafer, across the wafer and across the furnace variations.

Rasirc's steam generator is more expensive than a bubbler and closer to the price of a vaporizer. However, Spiegelman points out that once the capital expense has been met, running costs are as low as \$20 a year for the water, aside from the utility bill for boiling it. "And in these high-volume applications, like VCSELs, that cost differential is going to be critical."

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DETECTORS

Chinese Academy of Science researchers boost GaAs photodetector efficiency by factor of 10

Researchers from the Chinese Academy of Sciences' Institute of Semiconductors have boosted the detection efficiency of 1.55 μm GaAs photodetectors by more than 10 times by adding a resonant cavity into the structure.

This aids the development of GaAs-based receivers for optical fiber communication, which are preferable to the complex hybrid devices in use today that use silicon electronics and germanium or InP-based photonics.

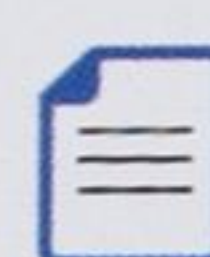
Absorption in the infrared is made possible by the existence of midgap arsenic-adatom defects in low-temperature-grown GaAs.

Until now, the low absorption coefficient for transitions between the midgap defect state and the conduction band has only produced efficiencies of 0.2–0.5 mA/W. The Chinese Academy researchers have increased this detection efficiency to 7.1 mA/W by adding two GaAs/AlAs-distributed Bragg reflectors that produce constructive interference and capture more of the incident light.

The team introduced the midgap defects in a GaAs absorption layer by growing the material by MBE at 200 °C and at a growth rate of 0.7 $\mu\text{m}/\text{h}$. Standard lithography was then used

to fabricate the device, which had top and bottom reflectors with 25 and 15 pairs of undoped AlAs/GaAs quarter-wave stacks, respectively.

According to the research group's leader, Qin Han, the addition of a resonant cavity would not add much to the detector cost, although as yet there are no plans for commercialization. "The structure of the photodetector is similar to a VCSEL – it can be grown all at once by MBE or MOCVD."



Journal reference

Q Han et al. 2006 *Appl. Phys. Lett.* **89** 131104.

RED LASERS

Osram investigates nonradiative defects

Optoelectronics manufacturer Osram and the University of Duisburg-Essen, Germany, have made the first detailed investigation of defects in red-emitting AlGaInP laser diodes generated during catastrophic optical damage (COD).

Understanding the formation of these defects, which are often seeded by enhanced non-radiative recombination due to surface states at the laser's facets, could aid the performance of AlGaInP lasers in high-power applications.

COD damage is caused by an avalanche-like process, which occurs at either the mirror facet or the adjacent semiconductor material. "Its occurrence is accelerated by local temperature at the mirror facet, the local current density in that region and the optical power density at the



Microphotoluminescence mapping reveals that enhanced nonradiative defects start at the output laser facet and then divide into a number of branches.

mirror," said Osram's Peter Brick.

The team conducted its investigation on MOCVD-grown 650 nm lasers 1200 μm long and 100 μm wide, which were grown on (100) GaAs substrates cut at 6° towards the (111) direction.

COD was instigated by turning up the continuous-wave driving current until the

laser's power output suddenly dropped. The n-doped AlGaInP cladding layer was exposed by selective wet etching and then a 488 nm laser was employed to map the surface's photoluminescence with a spatial resolution of 1 μm . This revealed that highly nonradiative defects originate from the front mirror of the laser, propagating in a direction perpendicular to the output facet for more than half the resonator length (see figure).

The team then used focused ion beam microscopy to examine the epitaxial layers that were affected by COD. Most of the defects were in the InGaP single quantum well active layer but some veered into the AlGaInP waveguides. The researchers also found that the defects were noncrystalline and that they can sometimes start from multiple locations on the facet.



Journal reference

M Bou Sanayeh et al. 2006 *Appl. Phys. Lett.* **89** 101111.

DEVICE DESIGN

Reflector increases InGaN LED emission

Rensselaer Polytechnic Institute, NY, in partnership with the Samsung Advanced Institute of Technology, South Korea, has increased the light extraction of its InGaN 400 nm LEDs by 38% by adding a GaN/SiO₂/Al omnidirectional reflector (ODR).

The team says that its latest ODRs are better suited to GaN emitters than silver mirrors, which suffer from low reflection and a high index of refraction in the near-ultraviolet.

Aluminum-based ODRs do not suffer the same limitations, although they do exhibit poor

conductivity. However, the researchers overcame this by using an array of NiZn/Ag microcontacts that reduced the resistance between the layers of p-type GaN and aluminum.

The InGaN LED structures were grown by MOCVD on sapphire substrates, and standard photolithographic patterning and etching was used to form the 300 × 300 μm mesas. 105 square microcontacts with dimensions of 4 × 4 μm , 6 × 6 μm and 10 × 10 μm , were patterned onto a quarter-wavelength-thick SiO₂ layer and etched to expose the p-type GaN layer. NiZn/Ag microcontacts were then deposited and annealed, before the final aluminum layer was deposited by electron-beam evaporation.

At an injection current of 20 mA, the GaN/SiO₂/Al ODR LED delivered an average of 16% and 38% higher light output than similar

LEDs fabricated with SiO₂/Ag ODRs and silver reflectors, respectively. At higher currents the effect was less noticeable. The size of the microcontacts also had a marked impact – devices with 10 μm wide microcontacts had a greater light output than those with microcontacts 6 μm or 4 μm wide.

Fred Schubert of Rensselaer thinks that the upper limit for the surface coverage of the microcontacts would be about 75% of the total area: "Beyond 75% it may be better to use regular broad-area metal contacts," he told *Compound Semiconductor*.

The ODR has now been licensed to an undisclosed US start-up firm for commercialization.



Journal reference

J K Kim et al. 2006 *Appl. Phys. Lett.* **89** 141123.

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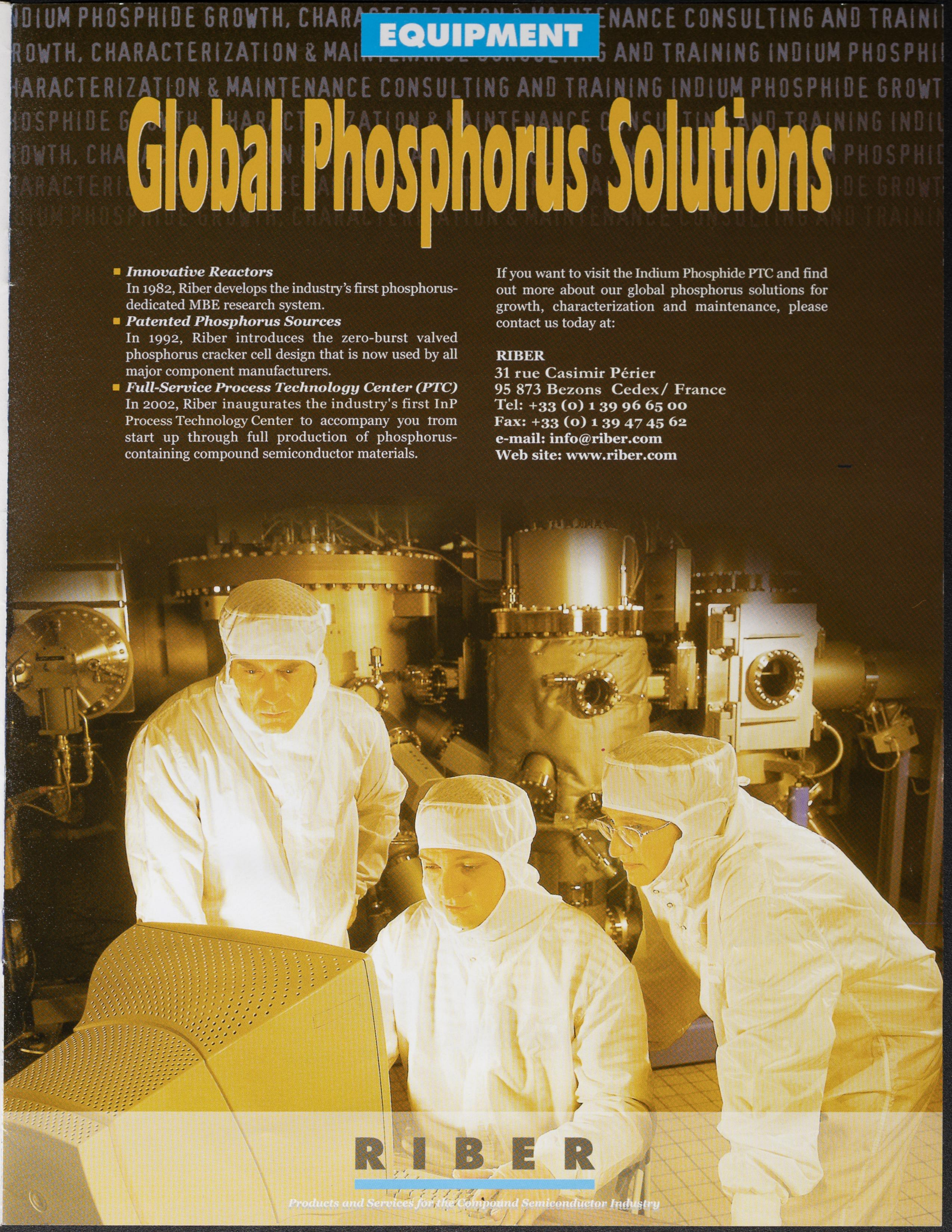
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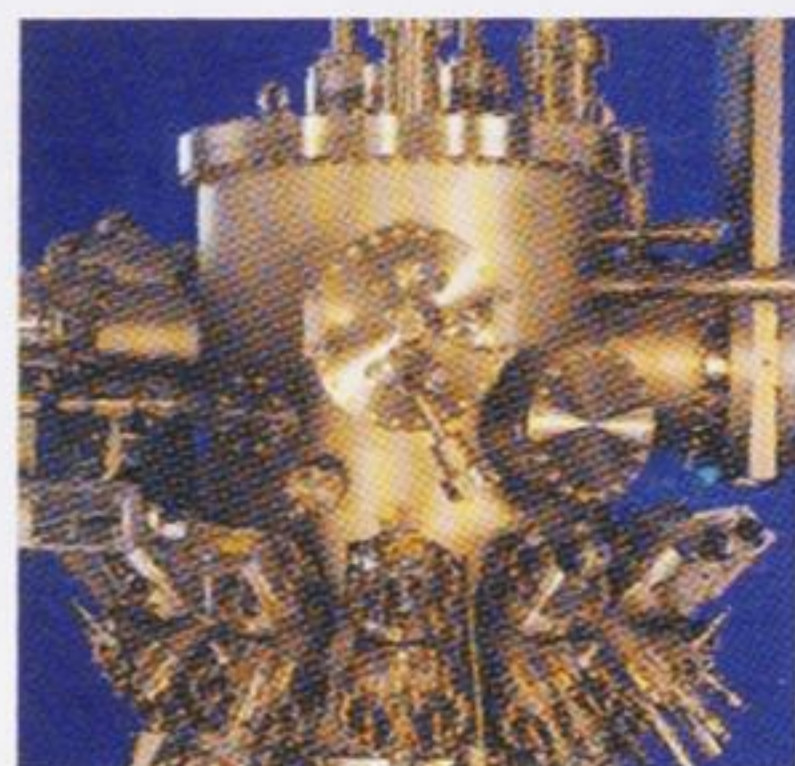
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