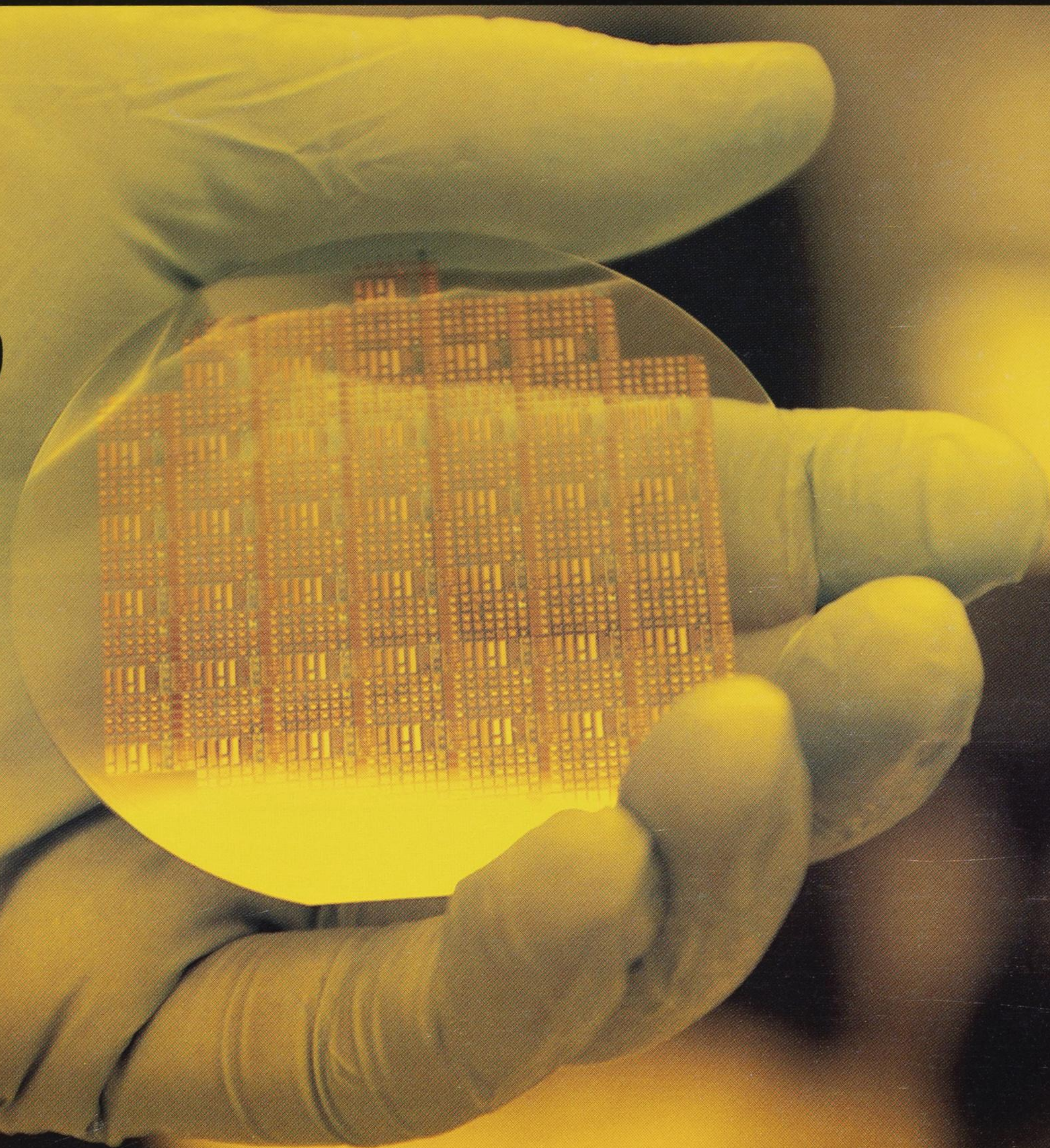


COMPOUND SEMICONDUCTOR

July 2006 Volume 12 Number 6

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

GAN ELECTRONICS
**Big guns take
aim at
wide-bandgap
sector**



HEADLINE NEWS

**Cree kicks off SiC
consolidation with
Intrinsic deal p5**

TECHNOLOGY



Integration

Telecom-boom trend makes a reappearance in optical networks. **p14**

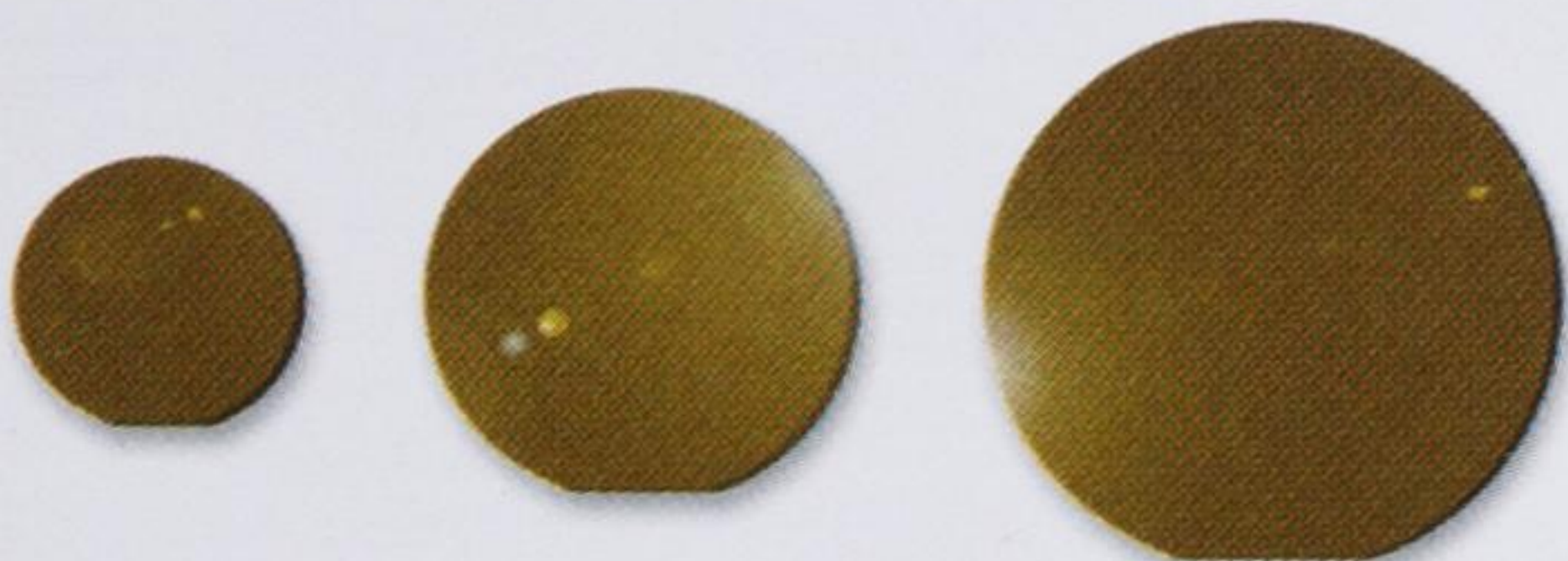
CONFERENCE REPORT



French fancy

ISBLLED delegates get a taste of non-polar GaN in Montpellier. **p20**

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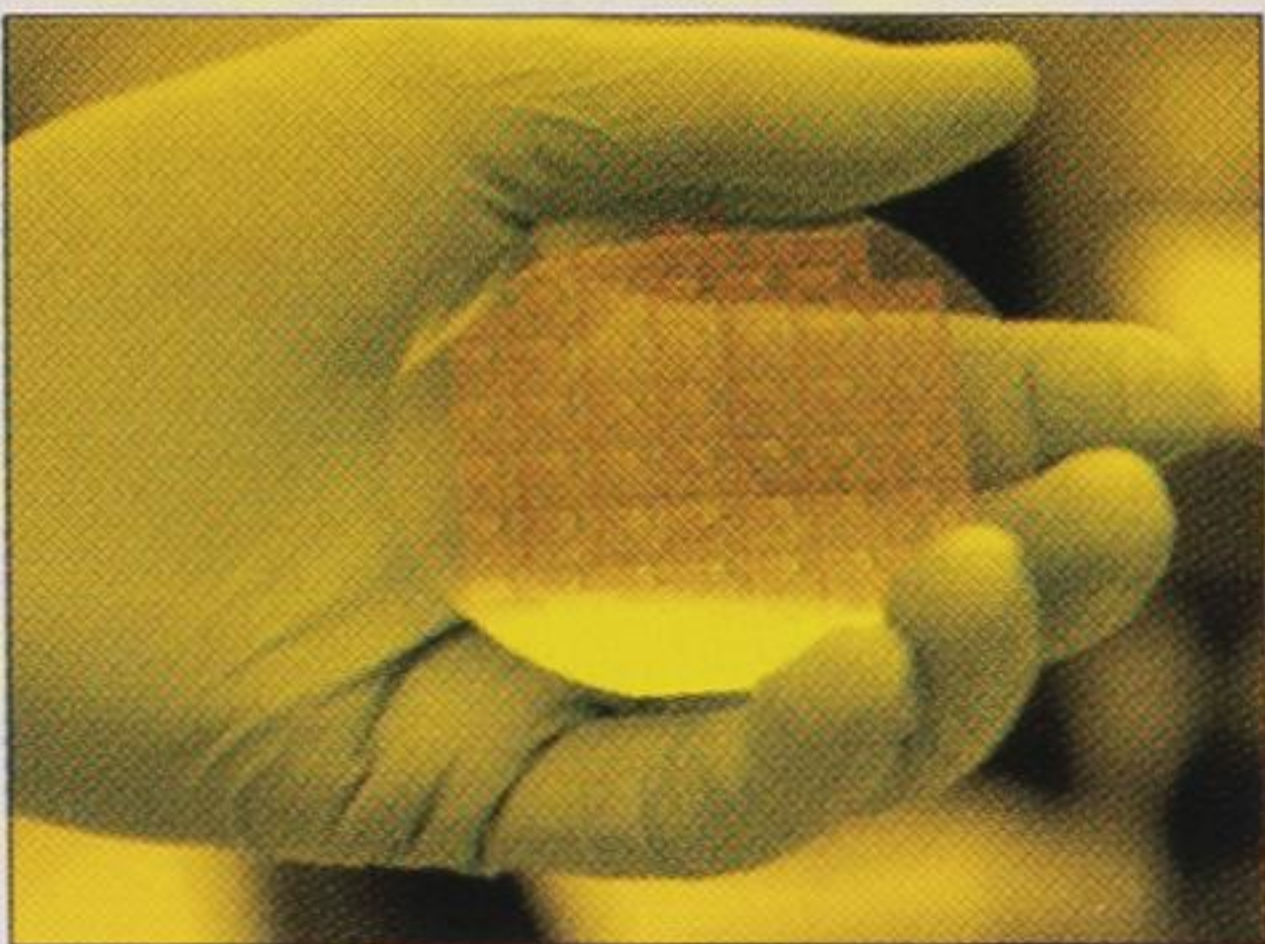
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INDUSTRY

5 **Headline news:** Novalux bags \$22 million finance with supply deal...Cree prepares to buy Intrinsic for \$46 million...Japanese firms target new GaN FET applications.

6 **The Month in RFICs:** Nitronex attracts \$22 million in funding...Cree and RFMD launch a host of GaN transistors...Filtronic invests \$83 million in fab... Outsourcing strategies suit AWS and IQE.



Brave new world

Cree and RF Micro Devices have launched new ranges of GaN transistors, putting them in direct competition with each other for the first time. **p6**

8 **The Month in HB-LEDs:** Cool-white chip delivers higher levels of efficacy...US Department of Energy showers \$10 million on solid-state lighting... Avago aims for high-power sector...Highlink hikes up wafer capacity.

10 **The Month in Optoelectronics:** Californian optical component maker doubles wafer fab capacity in Texas...iSuppli analysis predicts Blu-ray player deadlock...Sharp urges III-V solar firms to co-operate... Ten-layer laser has broadband promise...Datacoms push upturn in active components market...IPG steps up capacity with Veeco MBE reactor kit.



High-power lasers

The Veeco MBE reactor kit will help IPG increase its diode manufacturing volumes in the future. **p11**

13 **Behind the headlines: Carolina's big guns board the GaN train** With some major developments at Cree, RF Micro Devices and Nitronex, there's no doubting where the push to commercialize GaN-based RF devices is coming from.

TECHNOLOGY

14 **Optical integration moves back onto the agenda:** Photonic integration was one of the hot new ideas that emerged during the telecoms boom, but it was subsequently shelved by cash-strapped component vendors. Now, as Roy Rubenstein reports, the technology could be set to make a big revival.



Photonics revival

Optical integration is back in fashion as transmission speeds increase toward 100 Gbit/s. **p14**

17 **Simulations provide additional insights into GaN HFET reliability:** GaN HFET reliability can be improved by adding field plates to the structures. This is believed to reduce carrier trapping at the surface, but simulations by Ric Borges, Nelson Braga, Bo Wu and Vidas Mickevicius of Synopsys show that it also decreases the electron temperature and bulk trapping throughout the device.

20 **Researchers seek material solutions to GaN deficiencies at ISBLLED 2006:** Researchers are turning to alternative capping layers and GaN and non-polar sapphire substrates to push the output power of LEDs to levels suitable for everyday lighting. Richard Stevenson reports.



Hot topic: materials

Richard Stevenson reports from the ISBLLED conference, which was held in Montpellier, France, in May. **p20**

23 **Fujitsu proves reliability of GaN HEMTs:** Fujitsu's GaN program has led to proven device reliability, a fabrication process using low-cost conducting 3 inch SiC substrates, and record output power from MIS-HEMTs, says Toshihide Kikkawa.

27 **Product Showcase**

28 **Research Review:** German collaboration extends room-temperature VCSEL emission to 2.3 μm ... Cermet makes ZnO LEDs on n-type substrates... InAs HEMT prototype breaks efficiency record.

Main cover image: RF Micro Devices is now utilising part of its Greensboro, NC, fab to manufacture GaN-based transistors on 3 inch SiC wafers.

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 **BPA** 9173 average total qualified circulation*
*December 2005 BPA audit statement

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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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Ready for prime time



It appears that GaN's time has come. The major compound semiconductor players in both Japan and the US have signaled their intention to attack the as-yet unmaterialized market for GaN-based microelectronic devices.

Some of the biggest names in the business – Cree, RF Micro Devices and Toshiba – have either firmed up plans for ramping up manufacturing, released products for RF applications or outlined development roadmaps, and the omens look good for the wide-bandgap technology. RFMD is traditionally regarded as a fairly conservative company, and would not be launching a raft of new GaN-based products for both WiMAX and cellular infrastructure applications without some seriously good information on the likely buying habits of its customer base.

If it all goes to plan, 2006 could well go down as the year in which GaN microelectronics started to hit the big time. RFMD is confident that its top-tier cellular infrastructure customers are now convinced of not just the

“Armed with a very convincing set of reliability stats, RFMD is turning on the evangelism.”

technological potential of the wide-bandgap material, but also the reliability of the products that are based on it. Now armed with what it believes to be a very convincing set of reliability stats, RFMD is turning on the evangelism.

Let's hope that the charm offensive works, because there are plenty of suppliers of SiC substrates who will be more than willing to

produce the wafers needed to support any future volume ramp. That supplier base is already starting to consolidate, with the news that Cree is to swallow up the Virginia firm Intrinsic Semiconductor, a pioneer when it comes to defect reduction in wide-bandgap material.

Intrinsic's zero-micropipe (ZMP) substrates represent the cutting edge of the SiC substrate industry, and could turn out to be a crucial technology for ensuring the reliability of electronic GaN devices that are fabricated on top of them. The only problem would have been the cost of producing them.

This is where the hook-up between Cree and Intrinsic really starts to make sense. Cree's volume manufacturing prowess, coupled with Intrinsic's technology, should lead to larger, lower-defect substrates, which will be ideal for the likes of RFMD to produce reliable, high-performance devices at a price point that the cellular industry will find hard to resist.

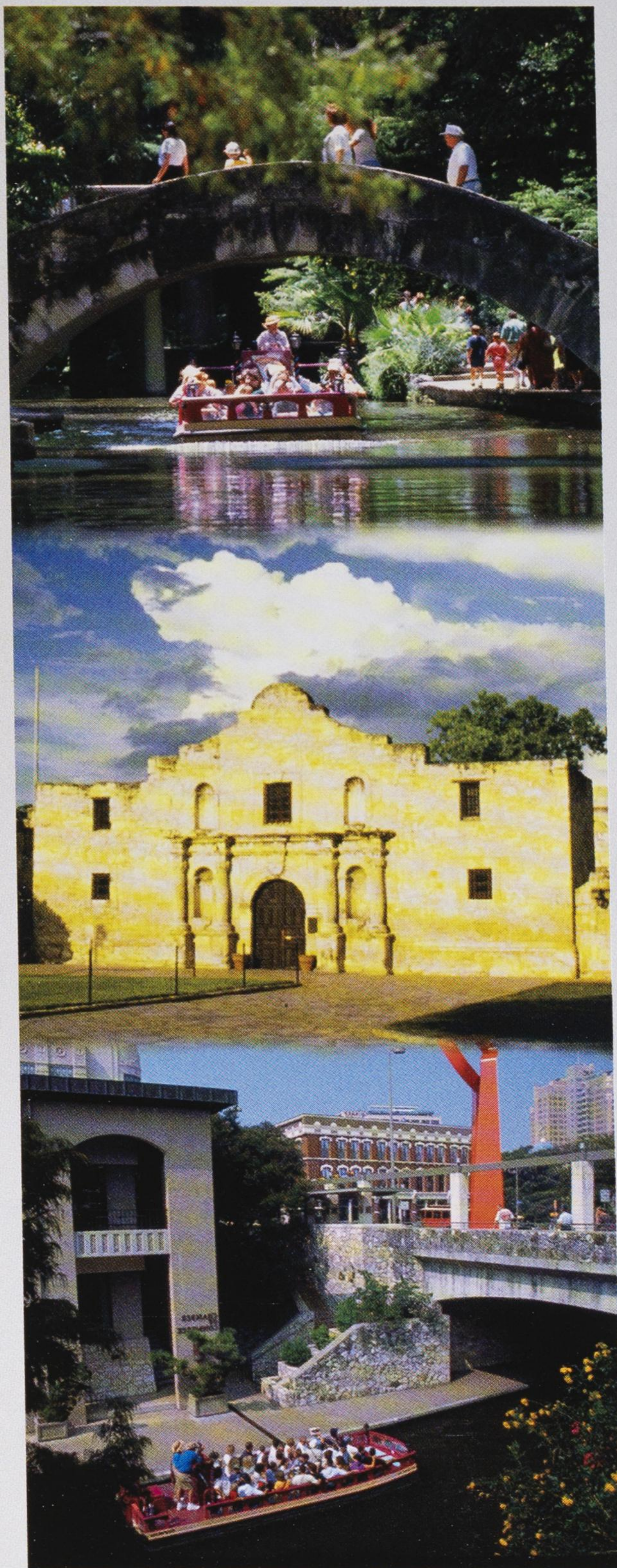
Michael Hatcher *Editor*

Advertisers' Index

Air Products & Chemicals Inc	4	ORS	22
Bandwidth Semiconductor	8	Raboutet	9
Cedova	7	Riber	16
CremIC	25	Shiva Technologies	26
CS Week	3	Synova	25
INTRINSIC Semiconductor	IFC	Taylor Hobson	26
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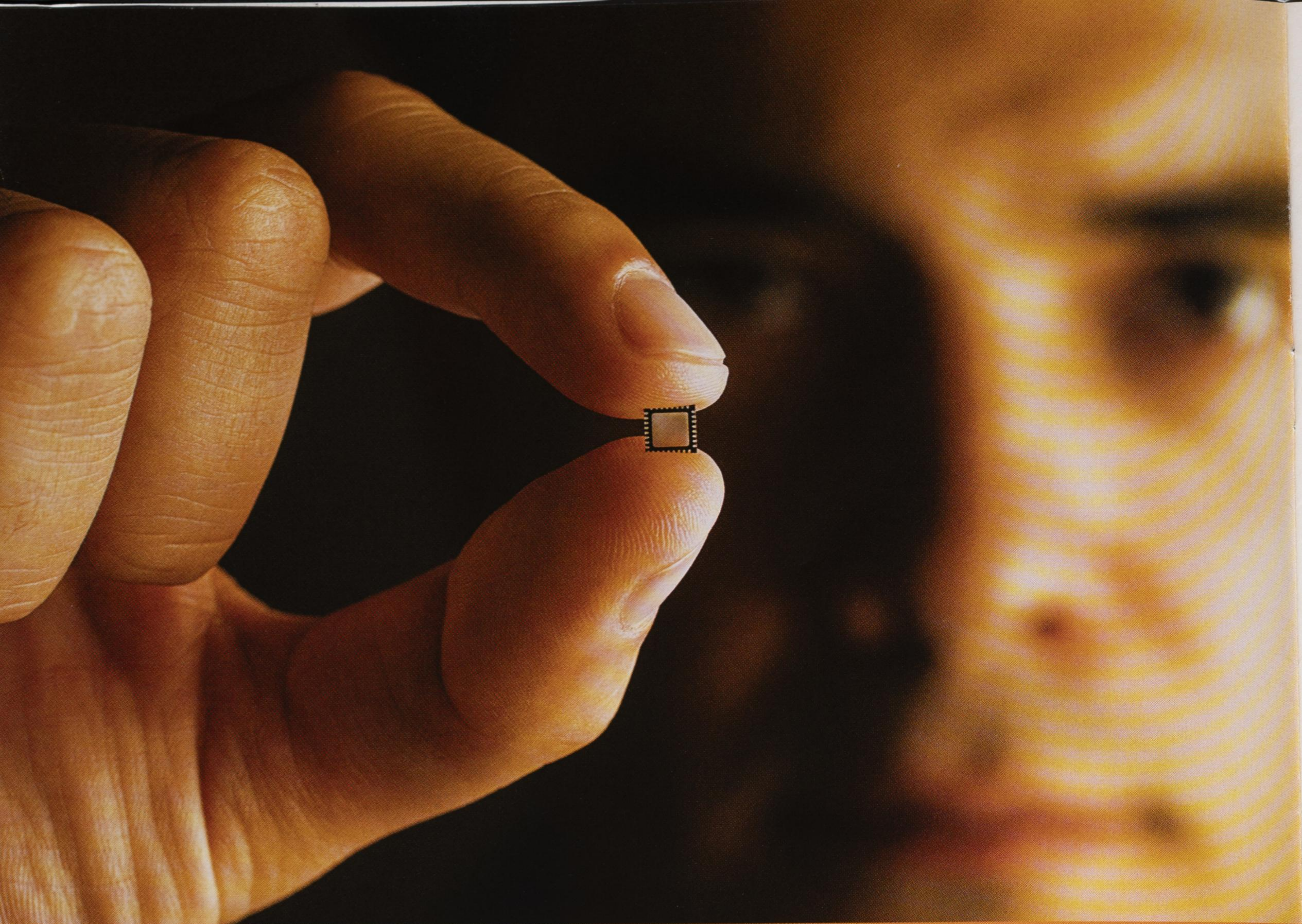
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MATERIALS

Cree prepares to buy Intrinsic for \$46 million

Cree is to acquire fellow SiC substrate developer Intrinsic Semiconductor in a deal that is valued at \$46 million. The Durham, NC-based chipmaker will stump up \$43.5 million in cash, while the remaining \$2.5 million is to be paid out through the assumption of outstanding Intrinsic stock options.

Although both companies manufacture and sell SiC substrates, Intrinsic has pioneered the development of so-called "zero-micropipe" material, a high-performance product line that has enabled the development of advanced SiC microelectronics.

Cree says that the acquisition will combine that expertise with its own volume manufacturing experience, stimulating the development of large-diameter SiC wafers beyond the 3 inch material that is starting to become widely used today, enabling high-quality 4 inch and possibly even 6 inch production.

Cree itself has almost completed the conversion of its LED production lines to 3 inch material, while RF Micro Devices will manufacture its new range of GaN-based products on wafers of the same size.

"These substrates should not only support our cost roadmap for LEDs, but – more importantly – they should also enable us to more rapidly commercialize higher-power devices for motor-control applications and hybrid [electric] vehicles," commented Cree chief Chuck Swoboda.

Cengiz Balkas, the man who has led Intrinsic until now, added that the combination of Cree and Intrinsic expertise would yield a unique opportunity to make a new generation of cost-effective SiC devices earlier than had previously been expected.

Intrinsic, which is based in Dulles, VA, recently began sampling 4 inch SiC substrates and has device prototyping capability. Like Cree, the company uses a physical vapor transport method to produce its substrates.

VENTURE CAPITAL

Novalux bags \$22 million finance with supply deal

Laser chip developer Novalux has completed a new round of equity financing worth "up to" \$21.7 million.

This includes a substantial investment from Unaxis Optics, which is based in Liechtenstein. The two companies have also signed a development and licensing agreement under which California-based Novalux will supply Unaxis Optics with red, green and blue laser chips.

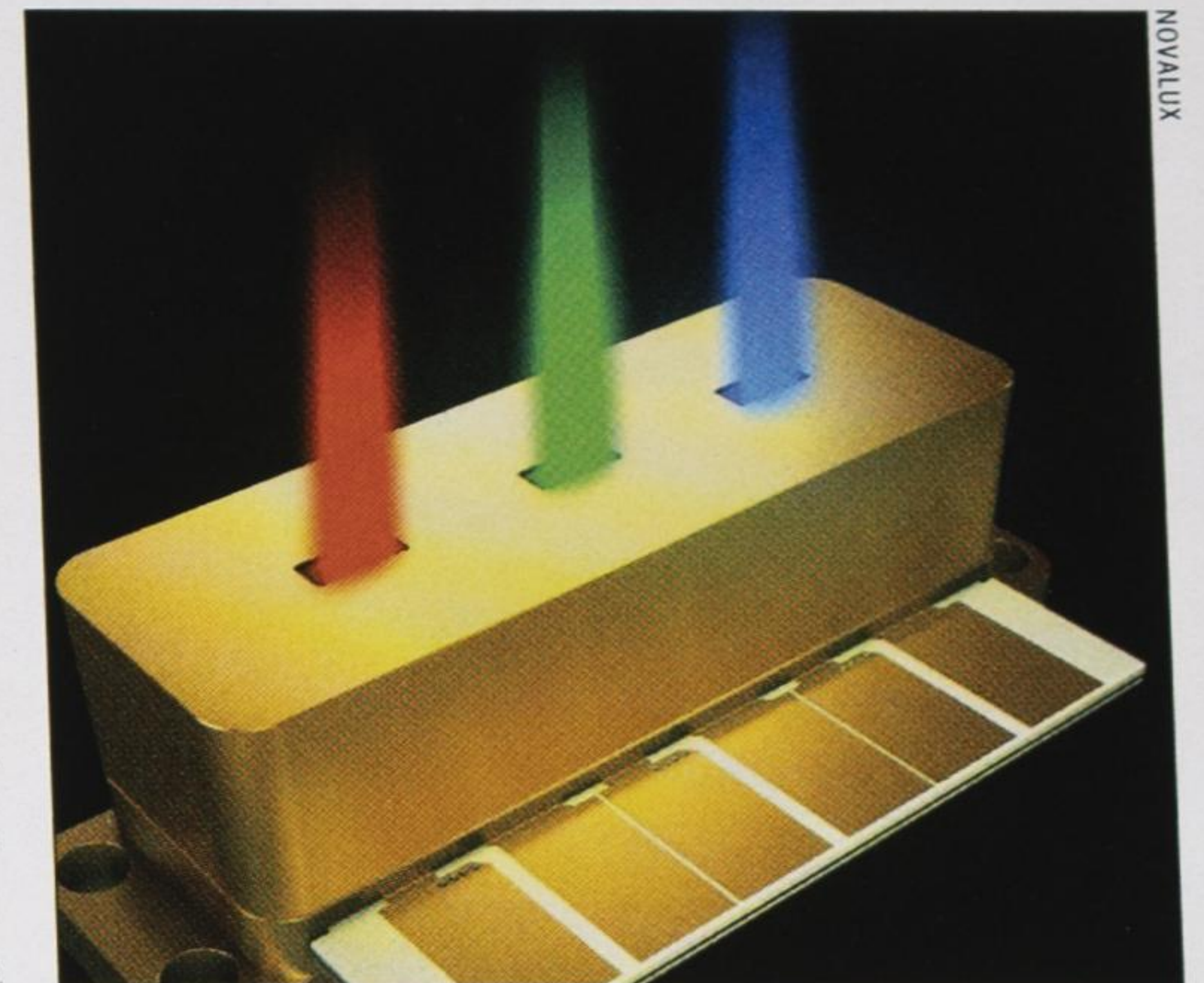
The European firm will mass-produce modules based on the lasers and distribute them throughout the display industry for applications including high-end televisions and personal projectors.

Earlier this year Novalux, which owns a GaAs wafer fab in Sunnyvale, CA, joined forces with display industry giant Seiko-Epson, to which it is also supplying laser chips.

Features provided by projector systems powered with Novalux's extended-cavity surface-emitting lasers (NECSELs) are said to include images with brighter, truer colors than those from "conventional" lamp systems, and higher reliability. Novalux laser sources can reduce the total number of components required and this could allow volume production of top-performance optical devices at more competitive prices, Unaxis Optics stated.

As well as large displays and micro projectors for high-definition TVs, the laser modules could also find applications in cell phones and gaming consoles, mini projectors, and head-up displays that project driver information onto vehicle windscreens.

"The laser technology from Novalux is an ideal addition to our own technologies and products," said Thomas Limberger, CEO of Unaxis. "This development is an innovation



Unaxis Optics will mass-produce television backlight modules featuring the RGB laser sources from Novalux.

that should reshuffle the market for front and rear projection displays and represent the future direction of projection systems.

"The partnership with Novalux makes sense for Unaxis since the technology is complementary to our product portfolio and can be applied across the range of micro display and scanning devices," he added.

"Our NECSEL technology is ideal for many current and future projection display applications," said Jean-Michel Pelaprat, chair and CEO of Novalux, adding: "The new arrangement will provide consumers with a lower-cost, longer-lifetime solution than other light sources, along with an unmatched viewing experience. This partnership positions both companies to launch RGB laser lighting into the projection display marketplace."

● Matthew Peach is a contributing editor at Optics.org.

GAN ELECTRONICS

Japanese firms target new GaN FET applications

Among a raft of new GaAs- and GaN-based products aimed at the wireless communications infrastructure business, the International Microwave Symposium, held in San Francisco in June, saw Toshiba reveal details about its plans for the development of wide-bandgap microelectronics.

The Japanese company says that having proved the basic design concept with its development of GaN-based power FETs with an output of 174 W at 6 GHz, it is currently

refining the technology to overcome heat dissipation issues. It then plans to develop a series of GaN products for satellite and point-to-point communications.

But perhaps surprisingly, the first application area that Toshiba is considering is medicine. "Initially, our plans are to develop an X-band device in the 9 GHz, 50 W range for medical applications, targeted for the third quarter of 2006," said Ichizo Kobayashi, senior manager at Toshiba's electronic systems

department. Kobayashi believes the devices could be used inside RF heating systems to treat tumors.

Meanwhile, Panasonic researchers have come up with a new vertically-arranged transistor structure that is said to reduce the device area to just one-eighth that of a conventional planar device. "This is the world's first demonstration of a GaN vertical transistor applicable to high-power switching devices," said the Osaka-based firm.

VENTURE CAPITAL

Nitronex attracts \$22 million in funding

GaN-on-silicon specialist Nitronex has closed a \$21.8 million venture-capital funding round. The Raleigh, NC, company, which agreed a deal to supply GaN-based power amplifier products for WiMAX applications to a Korean customer late last year, says that it will use some of the new funds to expand its manufacturing operations.

Several new products for WiMAX and cellular applications are said to be in the late stages of development, reliability testing and assembly qualification, while Nitronex also plans to accelerate recruitment in all areas of the business.

The latest funding round was led by Alloy Ventures and included new investors ARCH Venture Partners, Diamondhead Ventures and Intersouth Partners.

Nitronex CTO Kevin Linthicum told *Compound Semiconductor* that the latest funding round would be the company's last, as it now has the money to switch to a larger, state-of-the-art manufacturing facility. Although the new location isn't yet confirmed, epitaxy operations are set to be switched first, with the

move expected to be completed in early 2007. Staff numbers at the company are expected to double to reach 60 people by then.

The investment in Nitronex is the latest sign that the market for GaN-based RF transistors such as HEMTs and HFETs is set to become a significant one in the near future.

While its major rivals will manufacture their products on SiC substrates, Nitronex takes a different approach, using a proprietary GaN-on-silicon solution. Linthicum added that Nitronex would be building its own 6 inch wafer-capable deposition tool so that some chip processing stages would be easier to out-source in the longer term.

According to its supporters, the use of silicon substrates will ultimately mean that GaN-based transistors can be manufactured at a competitive price. However, others, including Cree and RFMD, contend that the thermal management benefits of SiC substrates outweigh the advantages of silicon, especially now that many suppliers are offering 3 inch SiC and 4 inch is becoming more available.

Linthicum's response is that while using a

silicon substrate does pose some thermal difficulties, these can be overcome through the use of innovative packaging solutions that effectively dissipate excess heat.

Despite the attentions of Cree and RFMD, Linthicum says that the extra competition is good news for the GaN RF business: "We see it as a plus. Commercial customers will want more than one supplier." The CTO added that success in the emerging market would ultimately be determined by having the most manufacturable process, and by being price-competitive with silicon LDMOS technology. Linthicum sees the Japanese company Eudyna Devices as its major competitor currently in the GaN RF space.

Korea-based consumer electronics giant Samsung is driving a move towards the convergence of cellular and WiMAX technologies for "beyond 3G" that could create demand for GaN-based RF components in the long run, suggested Linthicum. He believes that the drive is towards orthogonal frequency-division multiplexing, an approach that almost eliminates interference between channels.

WIDE-BANDGAP TRANSISTORS

Cree and RFMD launch a host of GaN transistors

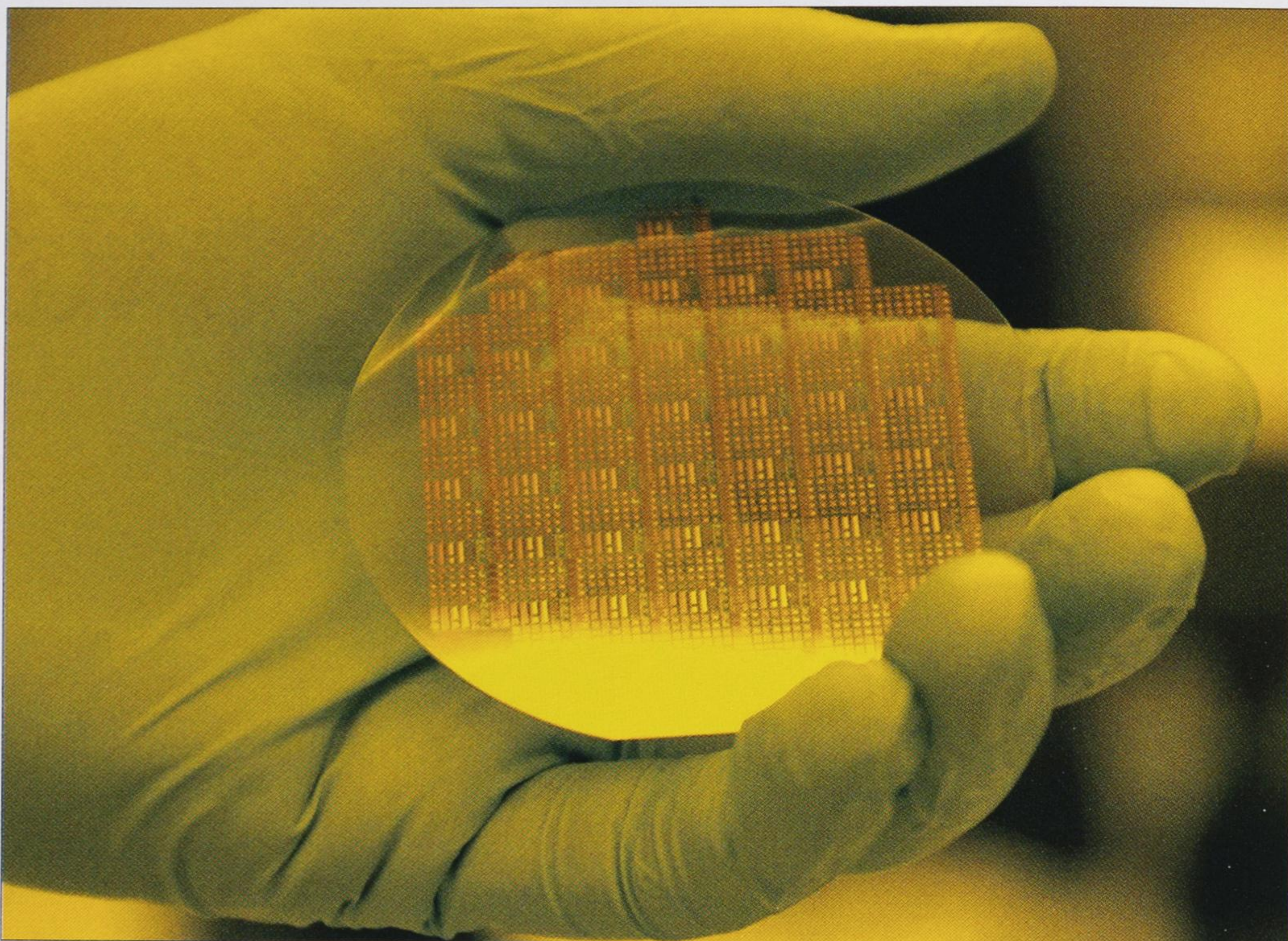
Compound industry heavyweights RF Micro Devices (RFMD) and Cree used the MTT-S event in San Francisco in June to launch their new ranges of GaN-based transistors designed for applications in wireless communications.

The two North Carolina companies, which have never previously been in such direct competition with each other, are targeting both the cellular infrastructure market and the emerging market for amplifiers in WiMAX base stations and customer premises equipment.

RFMD already has a business unit dedicated to cellular infrastructure applications that, although small, operates at a very healthy profit margin. The Greensboro firm will be seeking to build on existing good relations with top-tier base-station equipment vendors, as well as the high-volume manufacturing capacity provided by its large fabrication facility.

Durham-based Cree has rather less experience in the cellular base-station business, but has the advantage of control over the supply of SiC substrates that both it and RFMD use to manufacture GaN-based transistors. However, Cree is not believed to be RFMD's primary supplier of substrate material.

● See "Carolina's big guns board the GaN train" on p13 for more details.



Cree and RFMD's entry could mark the beginning of the commercial GaN RF sector. RFMD is using part of its existing GaAs fab to manufacture its wide-bandgap transistors on 3 inch SiC substrates, one of which is shown here.

GaAs MANUFACTURING

Filtronic invests \$83 million in fab

The compound semiconductor business in the UK is set to receive a huge boost from the sale of Filtronic's wireless infrastructure unit to Powerwave Technologies.

US-based Powerwave is set to purchase the unit in a cash-and-stock deal valued at around \$345 million. Should it get the go-ahead from Filtronic's shareholders and regulatory authorities, the UK firm will receive \$150 million in cash and 20.7 million Powerwave shares.

Filtronic has indicated that much of that cash will be invested in its GaAs fabrication facility in the north of England. The facility is currently used primarily to manufacture PHEMT switches for RF Micro Devices in the US.

"[The Filtronic board] has committed to a plan to expand the semiconductor facility to give Filtronic the potential to increase the size of this business by up to three times in the next two years, at an estimated cost of £45 million (\$83 million)," said a Filtronic spokesperson.

The huge increase planned by Filtronic is a response to the burgeoning demand for GaAs-based PHEMT switches that are increasingly used in cell-phone handsets to switch between frequency bands. It said that the large investment is needed to meet demand forecasts from various cell-phone handset module suppliers and also to support its supply agreement with UK-based defense firm Selex, which makes

electronics systems for military applications.

Because advanced handsets increasingly operate in as many as four bands, and future handsets are expected to feature yet more as wireless local-area network and WiMAX connectivity become standard features, the demand for PHEMTs is rising fast.

Filtronic added: "The [compound semiconductor] division is seeing strong long-term market growth for switches based on GaAs PHEMT technology, with the expectation that they will be used in around 80% of handsets produced by 2008."

While Filtronic is keeping its defense electronics business unit, which also utilizes GaAs technology, it seems clear that the firm's focus will be on exploiting the full potential of its 6 inch wafer fab in Newton Aycliffe to become a giant supplier of GaAs-based products.

In a trading update, Filtronic added that its compound semiconductor business had met a target of break-even operations in its most recent quarter, with revenues up 45% on the previous year. "A key part of the strategy for the group is to achieve further substantial value in compound semiconductors," said the company. "We have considerable opportunity to increase our supply of switch components for mobile handsets. The aim is to enhance our position as the number one supplier."

such as IQE are no longer seen just as a way to "top up" excess wafer demand when required.

Instead, says IQE, device manufacturers are building consistent levels of foundry outsourcing into their manufacturing strategies. IQE is seeing the strongest growth in its MBE operations in the US for wireless applications, and in particular for GaAs PHEMT switches that are finding increased application in cell-phones operating in various frequency bands.

Meanwhile, Taiwan-based AWSC is reportedly planning to expand its weekly capacity of 4 inch GaAs wafers from 1100. The local *DigiTimes* news website reports that AWSC will near-double this production to 2000 wafers a month by year-end, and to 3000 wafers a month by the end of 2007. The company's monthly sales have more than doubled since 2005, according to Taiwan Stock Exchange figures.

Again, demand is driven by advanced cell-phone architectures, and in particular the requirements of the US company Skyworks Solutions. Skyworks has been using AWSC's capacity extensively to ensure that it can meet rapidly rising demand without the need for a major fab upgrade of its own or a switch to manufacture on larger-size wafers.

FOUNDRIES

Outsourcing strategies suit AWSC and IQE

Taiwan's Advanced Wireless Semiconductor Company (AWSC) and UK-based IQE both appear to be benefiting from a move by GaAs chip manufacturers to outsource more elements of the semiconductor fabrication process to pure-play foundry operations.

With wafer volumes now back close to the levels seen in 1999, and manufacturing efficiencies thanks to larger wafer sizes and reduced overheads, many foundries are hopeful of producing profits in the near future.

According to IQE, the upturn in orders and sales reflects a maturation of the industry since the boom of the late 1990s. In hindsight, the fragmentation of the compound semiconductor business at that time resulted in very poor future sales visibility for foundry companies, with apparent demand for products much higher than the real demand.

Thanks to consolidation across the business and a change in the approach to foundry usage by the larger device manufacturers, companies

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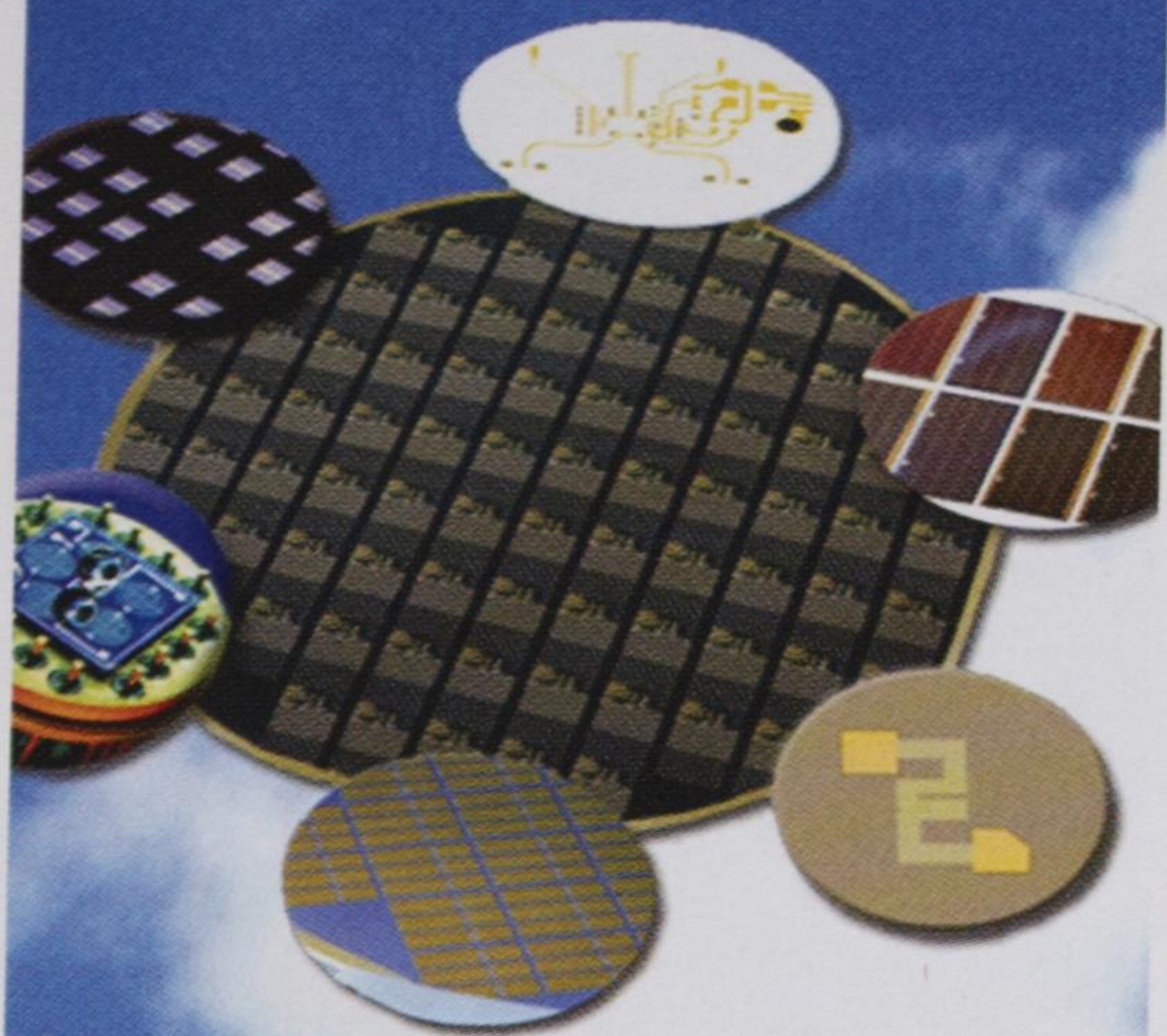
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INDUSTRY THE MONTH IN HB-LEDs

DEVELOPMENT

Cool-white chip delivers higher levels of efficacy

LED manufacturer Cree has revealed LED efficacy test results for a cool-white LED of 131 lm/W, measured at 20 mA. The correlated color temperature was 6027 K and the US National Institute of Standards and Technology in Gaithersburg, Maryland, confirmed the results.

Although the result is for a prototype device and does not reflect the performance of current production LEDs, it certainly points the way to commercial LEDs in the near future with efficacies exceeding 100 lm/W.

Tests were performed using prototype white LEDs using Cree "EZBright" LED chips that measure less than 0.3 x 0.3 mm. These chips are designed to be incorporated into white LEDs, which are used in backlighting applications in LCD screens on mobile phones, PDAs, televisions and monitors, as well as for indoor and outdoor LED display, camera flash,

gaming and indicator applications.

Cree sells EZBright chips to external customers, but does not use them for internal white LED production. Its high-power XLamp LED products incorporate 1 x 1 mm chips and these larger devices are designed to operate at a current of 350 mA. As a result, they have a lower efficacy than the smaller-chip devices.

"This is the highest level of efficacy that has been publicly reported for a white LED and raises the bar for the LED industry," explained Scott Schwab, Cree general manager, LED chips. "This result once again demonstrates Cree's leadership in LED technology and provides a glimpse into the future as to why we believe LED-based lighting products could not only save energy, but also change the way people use light."

• Tim Whitaker is editor of LEDs Magazine.

FUNDING

US Department of Energy showers \$10 million on solid-state lighting

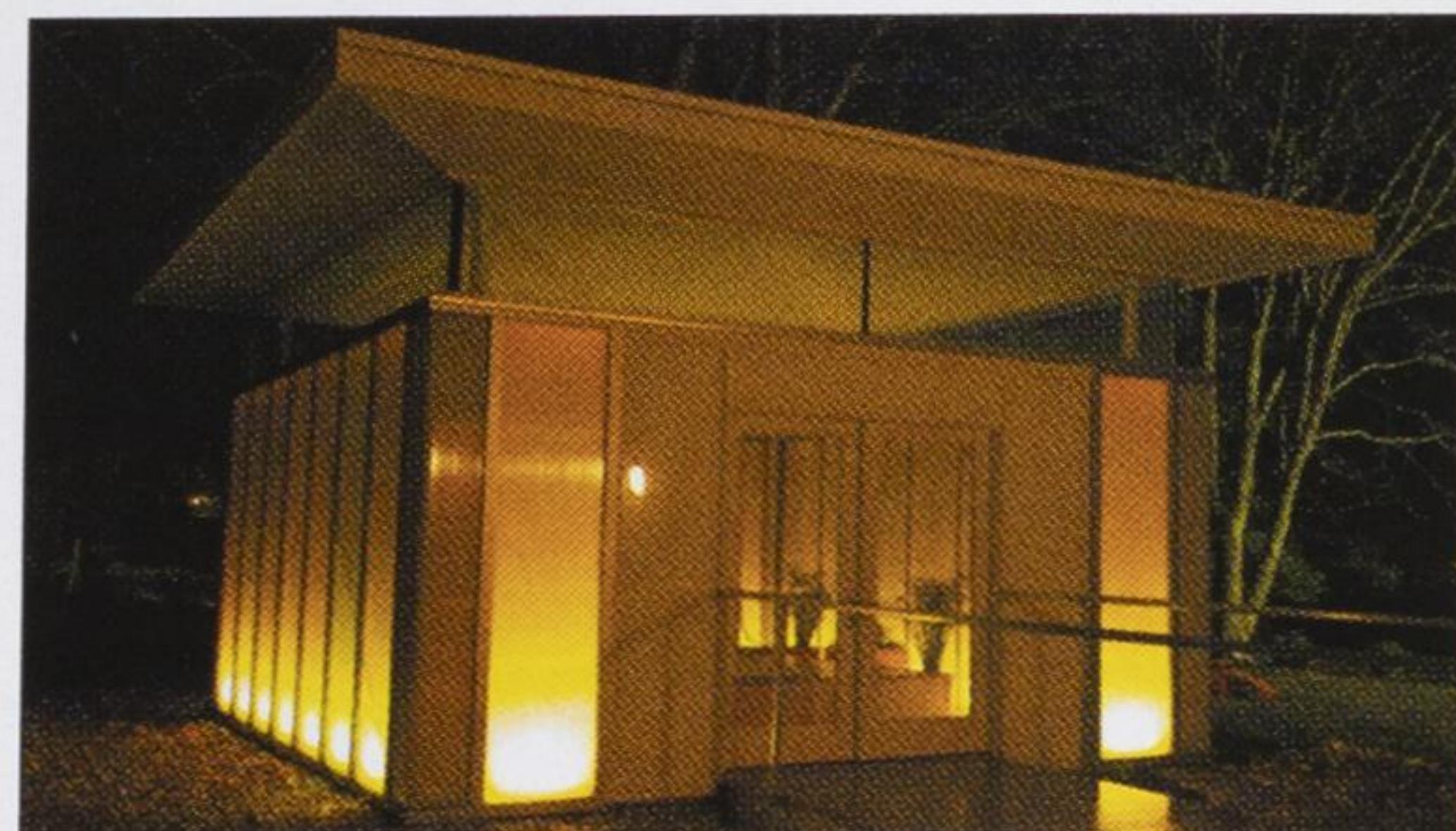
The US Department of Energy (DoE) has announced details of five projects that it is funding under its solid-state lighting product development program. The projects, which include a 30% cost share, total \$10 million in value and feature three efforts that are focused on III-V LED technology and two based on organic LED materials.

Awarded via the DoE's National Energy Technology Laboratory, the projects are expected to contribute to achieving the DoE's target of developing solid-state lighting with a product system efficiency of 50% by 2025.

Color Kinetics, General Electric Global Research and Osram Sylvania have been awarded the three projects that incorporate III-V LED technology.

Color Kinetics plans to develop replacement lamps for existing 60 W incandescent bulbs with an efficacy of 80 lm/W. It will develop what it describes as a novel hybrid-LED source that combines direct emission with phosphor down-conversion.

General Electric's research wing will focus on using novel nanophosphors to convert violet LED emission into white light. Also planning to replace incandescent sources, it is aiming for an efficacy of 96 lm/W.



Color Kinetics, one of the recipients of funding under the DoE's latest solid-state lighting initiative, has installed a number of LED-based systems in residential settings, including this meditation room in the US.

Osram Sylvania's target is to increase external quantum efficiency using so-called remote phosphors and a multilayer thin-film coating technique to extract more light from LEDs.

The product development required under the project guidelines includes production of field-ready prototypes focused on a targeted market application with fully defined price, efficacy and other performance features.

All of the projects are covered under the DoE's "exceptional circumstances determination", which was issued in June 2005 and covers ownership of intellectual property.

CHIPS

Avago aims for high-power sector

Avago Technologies, the chipmaker formerly known as Agilent's semiconductor products group, has entered the high-power LED market with the first in a series of 1 W emitters.

Designed for use in applications such as outdoor lighting and display backlights, the In-GaN-based LEDs are available in blue, green and, when coupled with a color-converting phosphor, white. Previously, Avago concentrated on lower-power LED products and did not compete in such a direct manner with companies such as Lumileds, Nichia and Cree in

the high-power arena.

The ASMT-MX00 products are the first in a series of devices operating at 1 W power dissipation and 350 mA forward current.

The line-up features green emitters that produce a luminous flux of 40 lm, 10 lm in blue and 35 lm in white. White color temperatures ranging from 4500 K to 10 000 K are available.

Avago was sold by Agilent in 2005 to two investment banks, Kohlberg Kravis Roberts and Silver Lake Partners, while its 50% stake in Lumileds was sold to Philips.

MANUFACTURING

Highlink hikes up wafer capacity

Highlink Technology Corporation has ordered two huge MOCVD reactors in a bid to significantly step up its wafer fabrication capacity. The Taiwanese LED manufacturer will take delivery of the two Aixtron machines, which will be used to make high-brightness GaN emitters, over the next few months.

The AIX 2800G4HT tools are the largest-capacity offerings for GaN growth from the German equipment vendors and support 42 x 2 inch wafer manufacturing. As well as providing a large ramp-up in capacity, the tools feature an improved gas inlet that will improve both wafer yields and device uniformity.

Gary Yu, president of Highlink, commented:

"The build-up in customer demand means that we now require a major increase in production capacity."

Sales of MOCVD equipment to Taiwan-based LED manufacturers have picked up strongly in the first half of 2006, with Aixtron and its US rival Veeco Instruments reporting improved order books. The upturn follows a period of retrenchment and consolidation in the Taiwanese LED sector, caused by an overcrowded market and overcapacity of supply.

Mergers and acquisitions between some of the region's key companies, such as United Epitaxy Company and Epistar, have since stabilized the industry.



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...Veeco hooks up with KOPTI

Veeco Instruments is to deliver one of its latest GaNzilla MOCVD machines to the Korea Photonics Technology Institute (KOPTI) under a new collaborative relationship to help advance solid-state-lighting technology. Both KOPTI and other LED manufacturers in the country, including Samsung and LG Innotek, will be able to use the machine, get process support and liaise with key experts at the site.

...Nakamura wins gong

GaN pioneer Shuji Nakamura has won the Millennium Prize Foundation's second "millennium prize", following in the footsteps of Internet trail-blazer Tim Berners-Lee. As well as the gong, which will be awarded at a ceremony in Helsinki on 8 September, Nakamura receives €1 million (\$1.26 million). The biennial prize is awarded for technological innovations that improve the quality of human life.

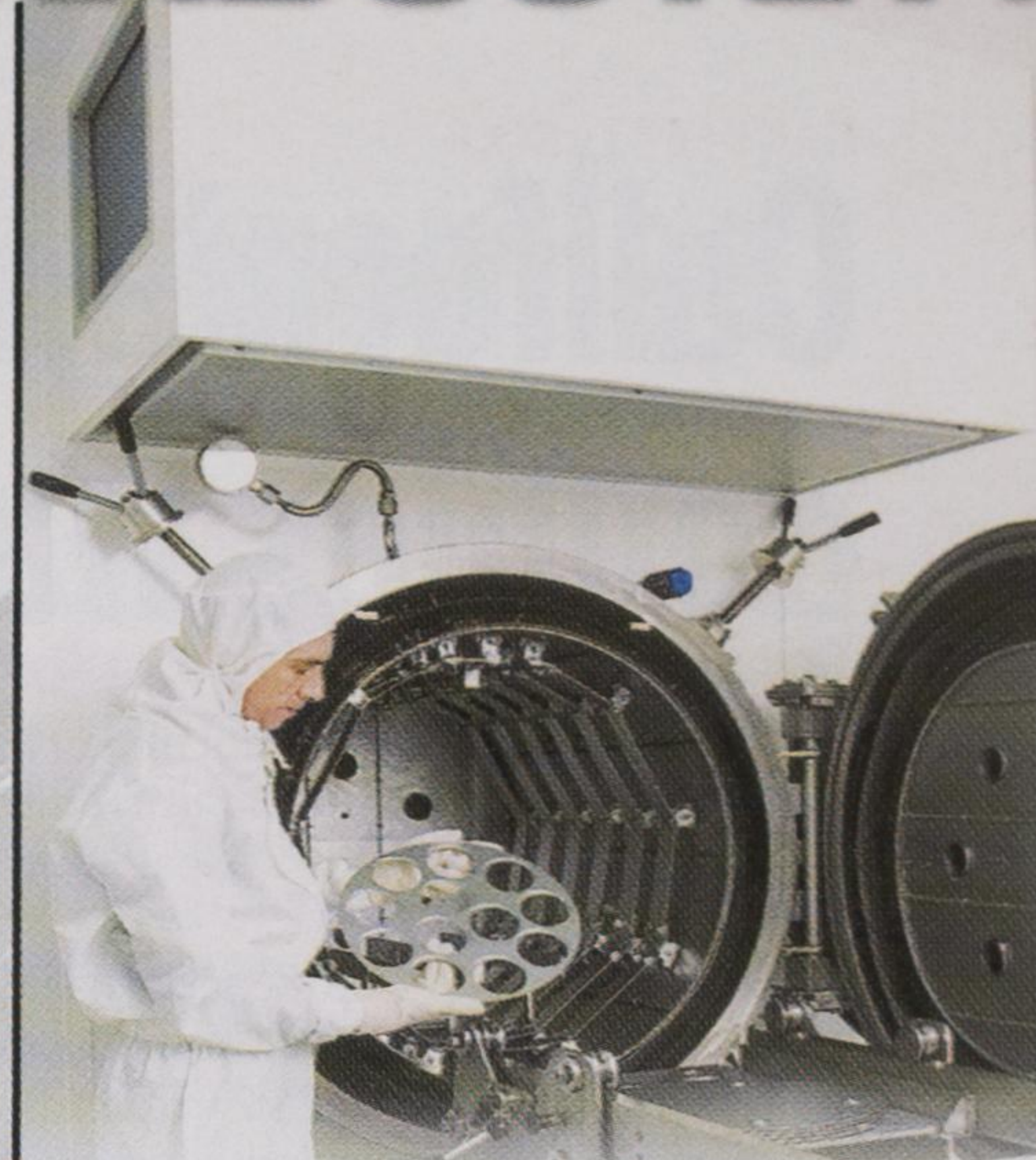
...Strategies Unlimited confirms slowdown

The latest report on the growth of the HB-LED market from Strategies Unlimited has confirmed its earlier assertion that the sector has entered a period of slower growth than it has experienced before. Forecaster Bob Steele revised his estimate of the value of the market sector in 2005 down slightly to \$3.9 billion. That represents annual growth of 6.2%, an effect caused by the market for cell-phone handset applications reaching saturation.

...Citizen plans ultra-bright chip ramp

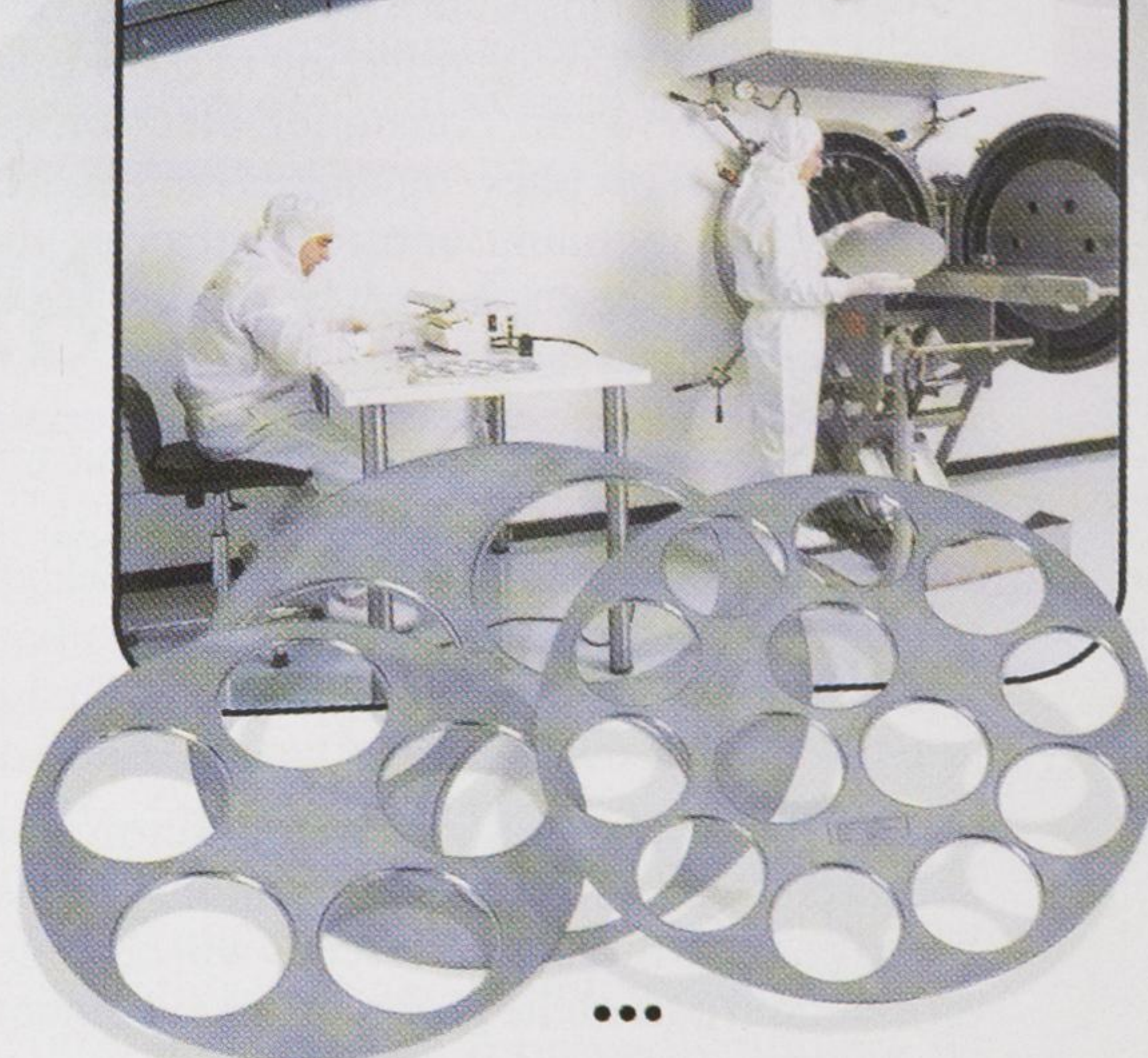
Japanese LED manufacturer Citizen Electronics is set to begin the mass production of 3.5 W white LEDs that produce 245 lm, claims a report in the *Nihon Keizai Shimbun* newspaper. Volume manufacturing will begin in September at a unit situated next door to the company's headquarters in Fujiyoshida, in the Yamanashi prefecture of Japan.

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MANUFACTURING

Californian optical component maker doubles wafer fab capacity in Texas

Finisar, the optical component maker based in Sunnyvale, CA, has posted another profitable quarter, with total sales for fiscal 2006 reaching \$364.3 million.

In the latest three-month period, ending on 30 April, revenue from sales of components and subsystems rose by 9.2% sequentially to \$91.9 million. Finisar reported a net profit of \$1.7 million for the quarter on total sales (including network testing gear) of \$102.4 million.

Those sales of optical components and subsystems represent a 42.5% improvement compared with one year ago. "Fiscal 2006 marked an important turning point for our company," said CEO Jerry Rawls. "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."

To meet what it expects to be a continued rapid increase in demand for optical components, Rawls says that the company is in the process of doubling its wafer fab capacity in Texas. Currently based in Richardson, Finisar is switching production to a brand new clean-room facility in Allen.

"The first reactor is plumbed and wired and doing the first calibration runs," explained Rawls. The existing Richardson fab will first be replicated with new equipment in Allen, before the company switches the Richardson

set-up to the same site.

The biggest growth for Finisar has been seen in sales to the local and storage-area network sectors, which have grown by 41%. Sales to metro access applications also rose by 27%.

For the full fiscal 2006 period, Finisar had a deficit of \$24.9 million, compared with a loss of \$88.6 million in the previous year.

Finisar, which has acquired Honeywell's advanced optical components division and much of the fiber-optic business previously owned by Infineon Technologies over the past few years, also operates a chip fab in California.

● A jury in Texas awarded Finisar \$79 m in damages from DIRECTV on June 26.

GaN LASERS

iSuppli analysis predicts Blu-ray player deadlock

Market analysts at iSuppli say that the next-generation DVD sector will drive demand for GaN-based blue lasers to at least 65 million devices in 2010.

This year, they expect the debut models from companies such as Sony, Toshiba and Samsung to result in the shipment of 1.6 million players and recorders, each one of which will require a blue laser diode.

However, unlike some commentators, iSuppli senior analyst Chris Crotty says that there will not be a clear winner in the battle between the Blu-ray and high-definition (HD) DVD formats. "This is not a repeat of VHS versus Beta," said Crotty, referring to the previous battle between consumer electronics giants. "The most likely outcome is stalemate, with the savvy manufacturers introducing dual-format players as early as the 2006 holiday season."



Samsung began shipping the industry's first Blu-ray disc player to hit the US market in late June. iSuppli expects that 1.6 million next-generation players featuring a blue diode laser will ship this year, rising to 65 million in 2010.

In a tear-down analysis of Toshiba's new HD-DVD player, iSuppli estimated the bill of materials at \$674, with the laser-containing optical drive unit accounting for \$200 of that total. Toshiba is clearly subsidizing its own player in a bid to steal a march on its rivals,

since it retails for just \$499 in the US.

Samsung and Philips have both launched Blu-ray players in the past month, while according to reports in the Japanese press, Toshiba has ditched any remaining efforts to unify the Blu-ray and HD-DVD standards.

SOLAR CELLS

Sharp urges III-V solar firms to co-operate

Sharp, the world's biggest manufacturer of solar cells, has said that concentrator systems based on III-V multijunction cells will become an essential part of the global effort to combat greenhouse gas emissions.

Takashi Tomita, corporate executive director at the Japanese electronics giant, is also urg-

ing companies in the photovoltaic industry to co-operate on the development and promotion of the technology to ensure that its advantages can be properly exploited.

Although Sharp focuses on silicon-based solar energy generation, the company produced multijunction cells with a conversion efficiency of 37% in its laboratories last year, a figure that is comparable with the best efforts of III-V specialists Emcore and Spectrolab.

Tomita says that although 85% of solar cells manufactured in 2005 were made from crystalline silicon, the higher conversion efficiency

and scalability of III-V cells means that the portion of the system cost attributable to the cell itself is relatively small. This means that overall system cost could be dramatically reduced through volume manufacturing in the near future, Tomita added.

Sharp has also identified the areas of the globe that would be best suited to concentrator systems based on III-V cells. These are regions where there is abundant solar irradiation through clear skies, and include southern Australia, southern Europe and northern Africa, Mexico and the Middle East.

DEVICE DEVELOPMENT

Ten-layer laser has broadband promise

Quantum dot (QD) laser specialist NL Nanosemiconductor has come up with a novel structure that delivers singlemode operation over a 25 nm-wide range of wavelengths.

The broadband laser chip will enable cost-effective integration of III-V components with silicon photonics such as arrayed waveguides and light modulators, says the company from Dortmund, Germany, which has just completed Series B funding to raise €5 million (\$6.3 million), and opened an office in San Jose.

As well as having potential applications in optical communications, the broadband source could be used in place of superluminescent LEDs for the medical imaging technique that is known as optical coherence tomography. In this application, the higher power of the laser should lead to better-quality images that could be used for the much earlier diagnosis of malignant tumors, for example.

"We managed to develop a way to get a laser

to lase with a very wide emission spectrum, which is of course the opposite of the fundamental nature of lasing – a very narrow spectrum," said company COO Alexey Kovsh.

To create the broadband emission, Kovsh and colleagues designed a special epitaxial structure featuring ten layers of quantum dots on a 3 inch GaAs substrate. "Each layer was grown under a different regime to make the gain spectrum broader," he explained.

Although this sounds like a very complex process, Kovsh says that the laser is compatible with a manufacturing environment. The maximum output power achieved in continuous-wave mode so far is 400 mW, while an emission of 150 mW over a wavelength range of 20 nm has been shown to be reproducible, Kovsh told *Compound Semiconductor*.

In the longer term Kovsh believes that the QD lasers under development could find widespread use in both optical interconnects and

optical clock systems for high-performance computing applications.

Acknowledging that such applications are unlikely to take off before 2010, Kovsh admits that the company is now searching for shorter-term market opportunities.

Although large volumes are not yet required, he says that the quantum-dot process is at a level of maturity where the laser could be switched into mass production if necessary.

Some improvements are still needed, however. For instance, the laser currently operates at up to 80 °C in a stable fashion. Operation at 100 °C will be required for final implementation in an uncooled system.

Kovsh says that the NL Nanosemiconductor team is working to optimize chip dimensions and the number of QD layers, and is carefully adjusting each of those layers to improve the overall device performance and extend the laser's emission band further still.

MARKETS

Datacoms push upturn in active components market

The rapid build out of fiber-based enterprise and access networks is expected to drive a sharp upturn in the market for active optical telecom components such as lasers, modulators and detectors.

According to analysts at Communications Industry Researchers (CIR), the value of the active components sector will near-quintuple from just under \$1 billion today to \$4.8 billion in 2011. "The big surge in growth is due to the rapid penetration of fiber into enterprise and access networks, and the larger bandwidth applications riding over them," said CIR.

Tunable lasers are now one of the key

growth engines, with tens of thousands of such devices being shipped annually. By 2011, this niche alone is expected to become worth more than \$460 million.

Meanwhile, the market-research company Heavy Reading is predicting a huge upturn in the deployment of fiber-to-the-home networks. "Over the next 15 to 20 years, copper access networks will largely be replaced by a fiber access network, creating massive opportunities," it claimed in a new report.

The emergence of complex, data-hungry services such as video delivery over IP networks has sparked the beginning of a mass

migration to fiber access in several countries, notably Japan, Sweden and the US already, with China, France, Korea and the Netherlands set to follow in the next couple of years.

That technology shift will boost demand for active optical devices at the access level of the network, as well as the need for more bandwidth in the optical backbone. The Heavy Reading report predicts that by 2011 more than 62% of Japanese residences will enjoy high-speed fiber access to services, equivalent to 31 million connected households. In the US it expects 10.3 million households to be fiber-connected, or 9% of available connections.

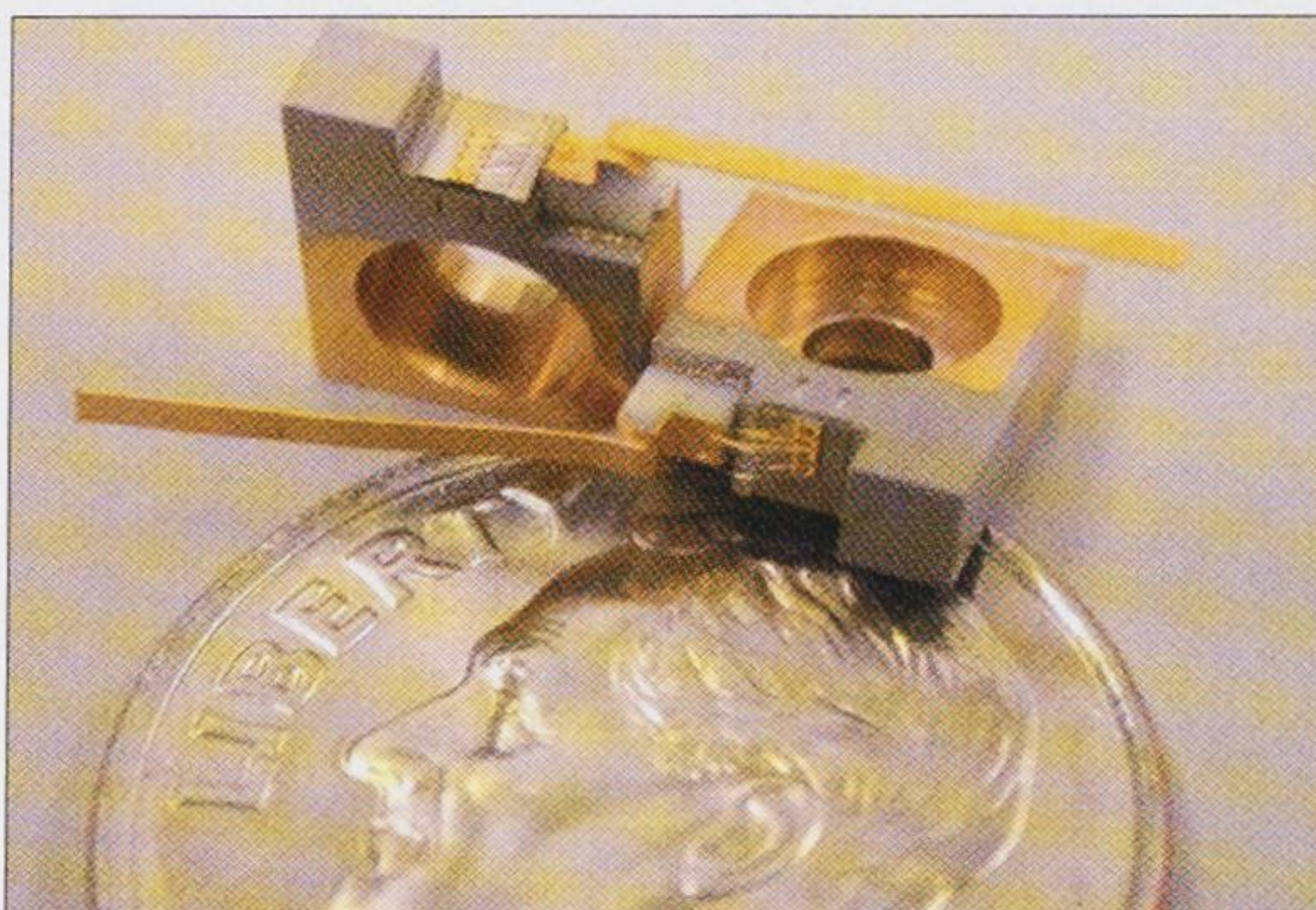
HIGH-POWER LASERS

IPG steps up capacity with Veeco MBE reactor kit

Fiber laser system integrator and laser chip manufacturer IPG Photonics is expanding its manufacturing base with the purchase of an MBE reactor from Veeco.

IPG, which owns a semiconductor fab in Oxford, MA, has become one of the world's leading manufacturers of laser diodes in the past couple of years thanks to booming sales of high-power fiber laser systems for applications in industrial machining.

The Gen200 MBE tool that it has ordered from Veeco enables 4 × 4 inch epiwafer production and will help IPG in its bid to increase

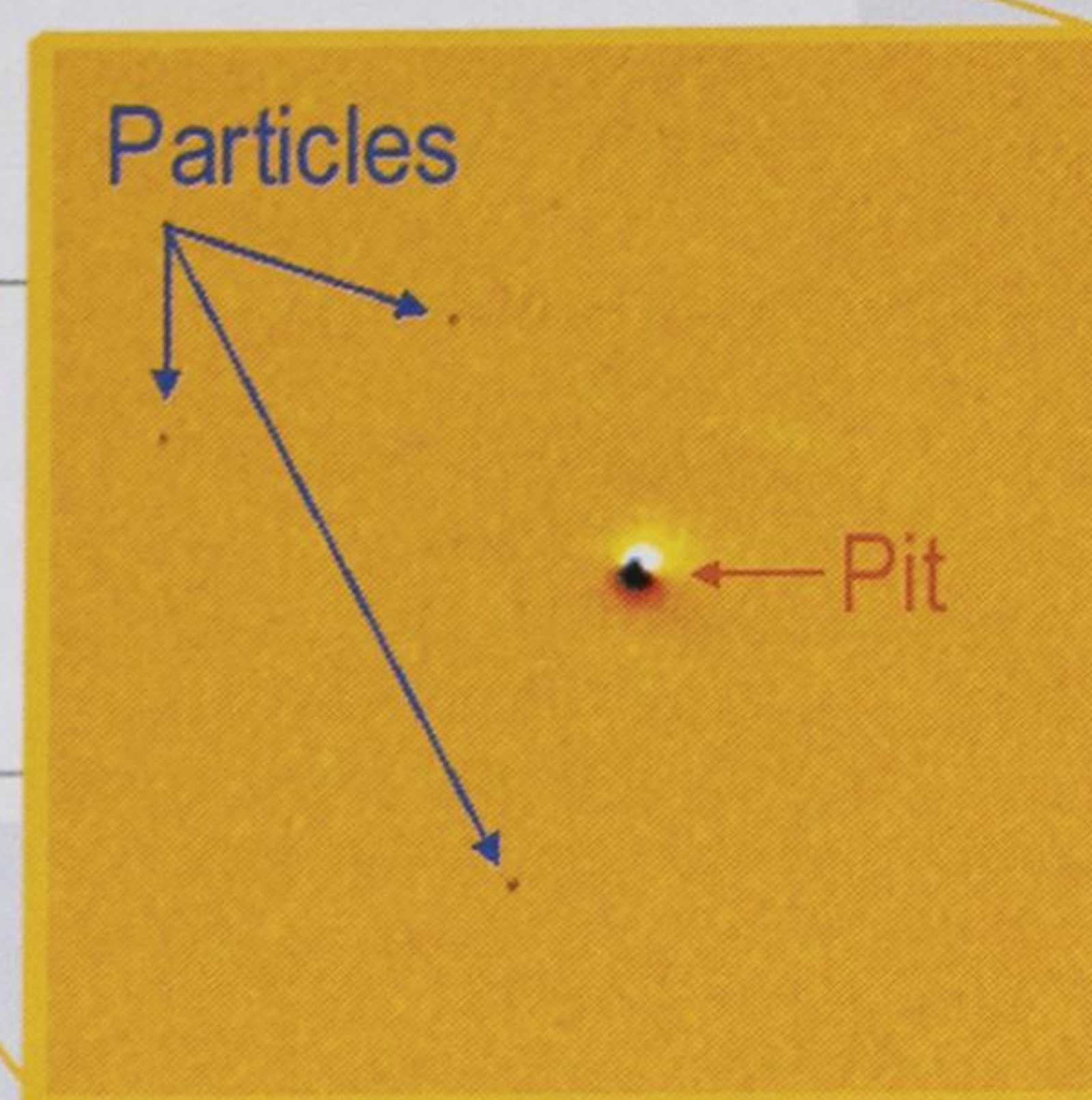
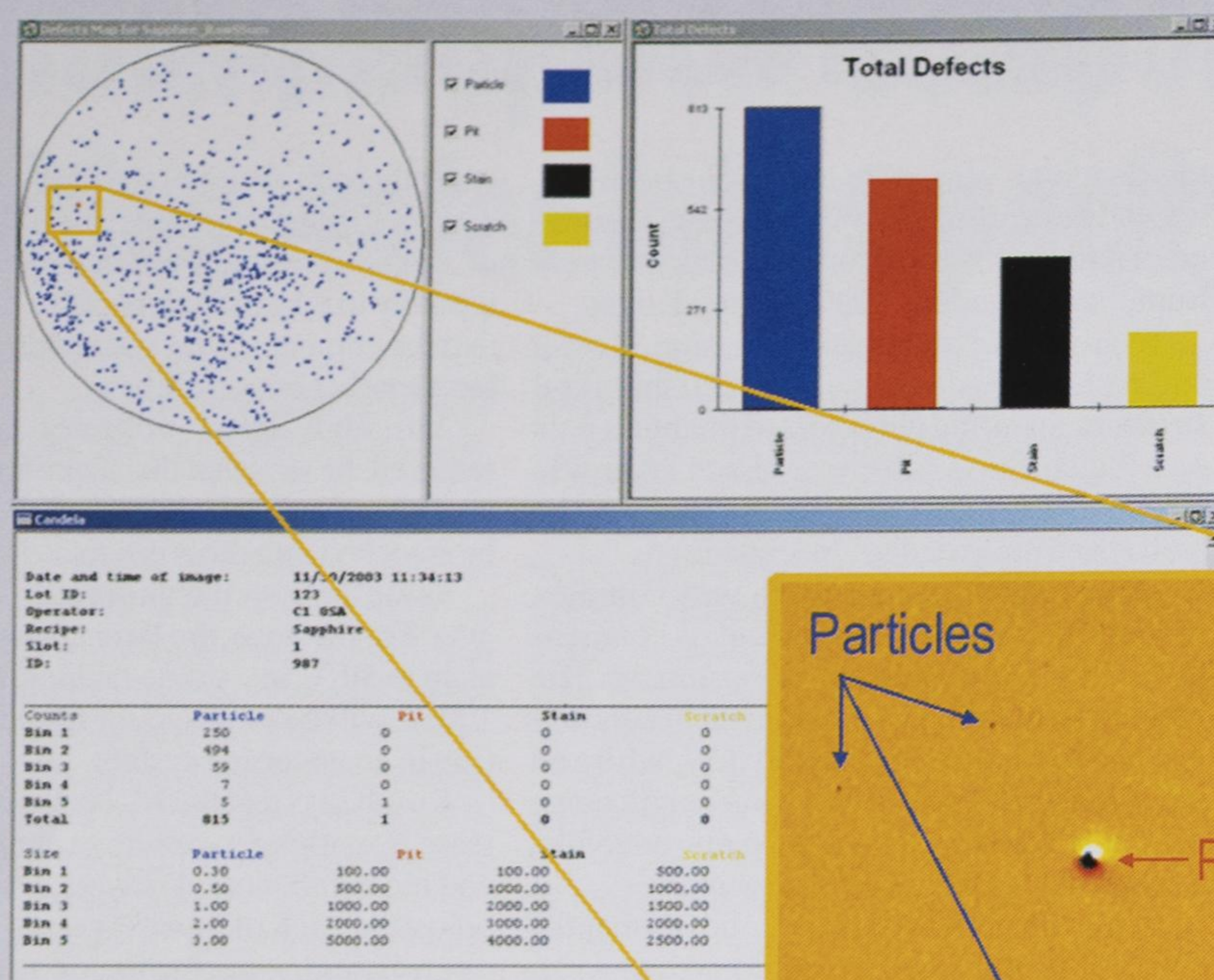


IPG makes 8 W laser diodes at its fab in Oxford, MA.

its diode manufacturing volumes in the future.

IPG is in the process of constructing extra fab cleanroom capacity at its headquarters and indicated to *Compound Semiconductor* that it plans to significantly increase its production of GaAs-based lasers, which emit at 980 nm.

Having manufactured an estimated aggregate of 1 MW in total laser chip output power in 2005, the company is hoping to double that figure this year and then to reach 6 MW in 2008. Each IPG chip typically emits 8 W, although the firm is also working on increasing that figure.



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RFICs

Carolina's big guns board the GaN train

With some major developments at **Cree**, **RF Micro Devices** and **Nitronex**, there's no doubting where the push to commercialize GaN-based RF devices is coming from.



Cree, RFMD and Nitronex are all located in North Carolina. While Cree and Nitronex were both spawned from the research group headed by Bob Davis at North Carolina State University, RFMD gained its wide-bandgap expertise through the acquisition of Cornell University spin-out RF Nitro Communications in 2001.

Much hope, and indeed hype, has long accompanied the prospects for wide-bandgap RF technology based on GaN and SiC transistors. This now seems set to become a commercial reality. Not only have industry big guns RF Micro Devices (RFMD) and Cree both launched a wide range of high-power GaN-based transistors, but their North Carolina neighbor Nitronex has cornered another \$22 million in equity finance.

With all three now set to plow greater effort and cash into pushing the technology at customers in the broad-band wireless access and infrastructure sector, 2006 looks likely to go down in history as the turning point for GaN microelectronics.

That's largely because Cree and RFMD are such key players in the compounds business, and have been central to the success of GaAs and SiC-based electronics. The success or otherwise of their GaN offerings may well determine the fate of the overall sector.

RFMD's involvement is arguably the most significant development. The Greensboro-based device maker is the world's major GaAs wafer producer and not a company that launches a range of new products based on a new material platform without a great deal of forethought. "RFMD is fairly conservative," admits Jeff Shealy, head of RFMD's wireless infrastructure unit, lending weight to the theory that GaN's time has now come. He says that while the market opportunity for GaN has been there all along, only now has the reliability of products reached a point where customers are serious about deploying it. Coupled with this is the widespread availability of 3 inch SiC substrates on which to manufacture GaN devices.

Proving reliability is perhaps the most critical problem that GaN has faced. Armed with a substantial data set from a long run of GaN-on-SiC wafers, Shealy is in the process of educating potential customers in the base-station business who want, unsurprisingly, to see watertight stats before they commit to a new line of products. Shealy believes that they are now finally waking up to the advantages that the wide-bandgap technology can bring, and that the cellular industry in particular is committed to backing GaN technology for applications in wideband-CDMA base stations.

Shealy says that RFMD is looking to compete in the high-end cellular sector for final-stage, linearized amplifiers. Already sampling to the top-tier vendors of cellular base-station equipment, its new family of GaN HEMT transistors features nine different products. Transistors for cellular applications include four HEMTs, the most powerful being a 120 W device. On the WiMAX front, RFMD launched new 50 W products for both the 2.5 and 3.5 GHz frequency bands.

Of the three North Carolina companies, RFMD looks to have the best chance of success within the cellular business. Crucially, it is in a position to exploit its experience in high-volume GaAs manufacturing to give it the edge over a relative upstart such as Nitronex. And although Cree also has plenty of volume-manufacturing expertise

thanks to its great success with GaN-based LEDs, it is not nearly so well established in cellular infrastructure. "RFMD has great customer relationships and a qualified high-volume facility," said Shealy. Although its GaN process will need individual qualification, which is set to begin in September, cellular customers are already convinced that RFMD can deliver as a company.

Having now converted much of its 4 inch GaAs capacity to 6 inch, RFMD has been able to apply its smaller manufacturing line for back-end processes such as metalization and lithography to 3 inch GaN-on-SiC without the need for costly redevelopment. "We plan on competing [for this market] in the context of our GaAs fab," said Shealy. "It means that GaN looks no different to any other wafer."

A key difference is at the epitaxy stage, where RFMD uses MOCVD for GaN deposition rather than MBE. The latter is its standard method for GaAs wafer epitaxy. The company uses both internal and external sources of GaN epitaxial material and has two MOCVD machines of its own. Durham-based Cree is also targeting WiMAX and cellular applications with its own family of 2.4–3.9 GHz HEMTs. At the MTT-S exhibition in mid-June, Cree released higher-power versions, including a 120 W device.

Head-to-head

Meeting as competitors for the first time, one side issue that Cree and RFMD might need to resolve is the supply of SiC substrates. Despite the locality of the two companies and its dominance of the SiC market, Cree is not currently RFMD's primary supplier of wide-bandgap material. Even though the two will compete directly for the first time with their GaN products, the market for these new devices is at such an early stage that for Cree to supply RFMD with material should be viewed as a minor conflict of interest.

Nitronex, based just down the road from Cree in Raleigh, is the young pretender that stands against the two established chip makers. The key difference is its technology, GaN-on-silicon. The thinking here is that silicon wafers can already be scaled much larger than SiC, and ultimately provide a more economic materials solution with tougher thermal problems dealt with through innovative packaging solutions. Having recently sealed an additional \$22 million in venture capital, Nitronex is poised to move into a new state-of-the-art facility in early 2007, in preparation for device production.

While acknowledging the potential threat posed by its near neighbors, Nitronex CTO Kevin Linthicum is happy to see their involvement: "Commercial customers like Nokia and Siemens will want more than one supplier," he said. "The GaN train is leaving the station and Cree and RFMD don't want to be left behind."

Of course, the relative merits of the North Carolina trio will be rendered irrelevant if silicon LDMOS continues to dominate the infrastructure scene. As always for III-V developers, silicon will pose the biggest threat of all.

Optical integration move

Photonic integration was one of the hot new ideas that emerged during the telecoms boom, but it was subsequently shelved by cash-strapped component vendors. Now, as **Roy Rubenstein** reports, the technology could be set to make a big revival.

Today, the development of monolithically integrated InP circuits featuring several different optical components is being driven by high-speed transmission, in particular the move towards 40 Gbit/s and the new 100 Gbit/s standards. Indeed, the most widely deployed InP photonic integrated circuit (PIC) to date is an electro-absorption modulated laser (EML) that combines a laser and modulator, while there is also a smaller market for tunable lasers that integrate several functions in a single InP chip. "Tunable lasers are selling in reasonable volumes – several tens of thousands a year – while EMLs are in the hundreds of thousands," says Vladimir Kozlov, founder of transceiver market analyst company Lightcounting.

US firm Apogee Photonics is targeting this market with its 10 Gbit/s lasers. The company has its origins in two InP start-ups: ASIP and ThreeFive Photonics, the latter having brought to market such monolithic devices as a multi-wavelength receiver and an optical performance monitor. Now, Apogee's focus is to exploit its selective-area growth and asymmetric twin-waveguide technologies to optimize the optical functions in its products. "We connect functions using tapers, and with precise control of the composition and structure we can determine the performance of the laser and modulator," says Milind Gokhale, Apogee's CTO.

One example is Apogee's uncooled EML, which operates over a wide temperature range. "It is fair to say that we are using one of the best integration platforms to make more down-to-earth products that the market needs in large quantities," says Erik Pennings, Apogee's director for product marketing.

Pennsylvania-headquartered InP-chip specialist Cyoptics is also making EMLs, as well as tunable lasers under contract for other firms. Like Apogee, its staff have made some exotic PICs in the past. "We made a distributed Bragg grating with phase control, a power detector, and a modulator for a tunable laser over the C-band [1530–1565 nm]," says Robert Hartman, Cyoptics' vice-president for device design and development. "We even had a version with a semiconductor optical amplifier that was finished in development." But the market wasn't ready for such devices, he says, and didn't want to pay any more than a 10% premium for single-wavelength (untuned) devices.

Now, however, Cyoptics is seeing renewed interest



Do it all: InP is already the material of choice for active optical devices, and its ability to

in PICs. "Regarding photonic integration, some of the meetings I had [at OFC/NFOEC 2006] were the best in five years," says Stefan Rochus, director for marketing and business development, who added that particular interest is being shown in the emerging 100 Gbit/s Ethernet standard.

In fact, optical chips operating at these transmission rates are already being built and deployed by Infinera, a US-based vertically-integrated company that manufactures InP chips at its Californian fab and uses them to build systems. The company has even detailed a lab demonstration of a 1.6 Tbit/s optical chip comprising 40 channels operating at 40 Gbit/s. "The reasoning [for such a device] is purely economic," explains Jagdeep Singh, CEO of the US systems vendor. "It is the lowest cost way to deliver bandwidth."

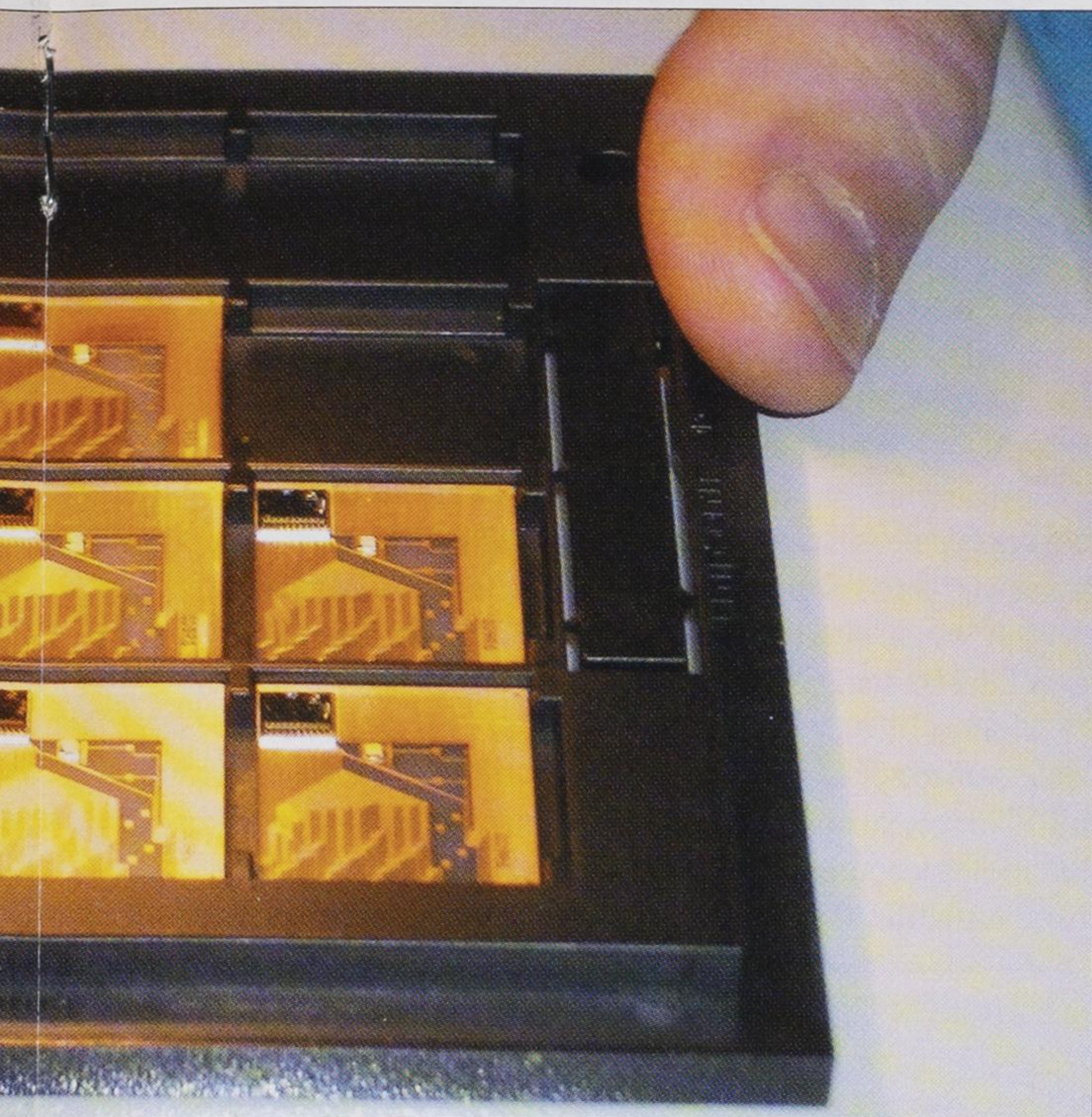
Even though this 1.6 Tbit/s device will not be deployed for several years, it highlights the performance hike that can be achieved. More significantly, Infinera's PIC strategy could signal a forked path in the optical networking industry. Indeed, Infinera's PICs are the optical industry's sole example to date of Moore's Law-style progress.

For now, though, carriers – and by implication system vendors – want to maintain flexibility by using only a fraction of a system's capacity. More channels are lit, or a channel is upgraded from 2.5 to 10 Gbit/s,

"A highly integrated device is not necessarily the best solution."

Emmanuel Desurvire
Alcatel

es back onto the agenda



ility to support passive waveguides makes it the ideal platform for monolithic integration.

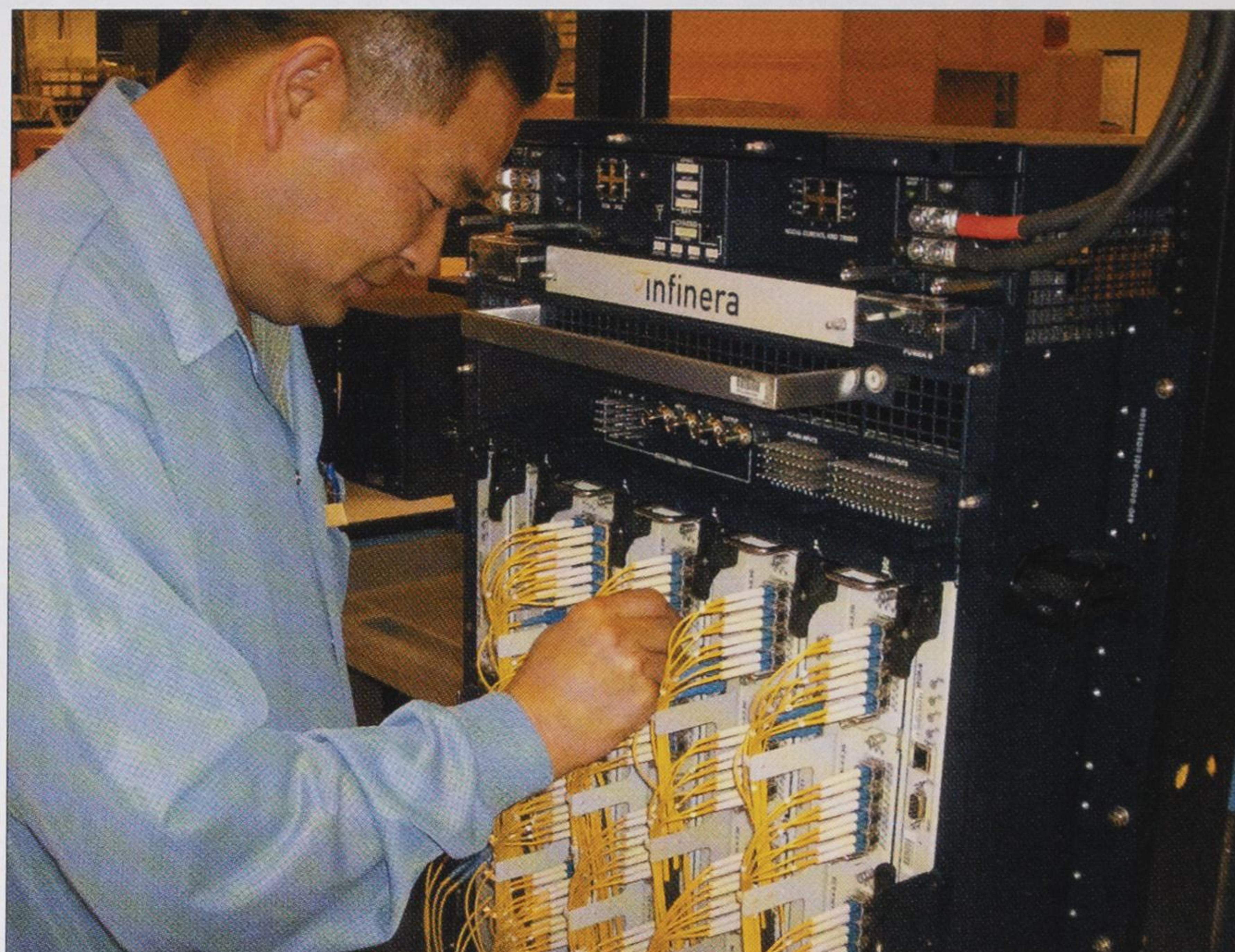
only when the need arises. “For any WDM system, our philosophy is pay-as-you-grow,” says Emmanuel Desurvire, senior director for photonic technologies in Alcatel’s photonic-network product group.

When designing a new system, vendors such as Nortel Networks look at the platform specification in terms of the interfaces – and the density of interfaces wanted by the carrier – and the reach. “We look at what new technologies can be brought to bear,” says Maurice O’Sullivan, manager of physical layer and optical design at Nortel. Depending on the maturity of the integration process, Nortel will consider the technology if it delivers power, size and, in some cases, improvements in system performance.

The cost of integration

Alcatel stresses that adequate trade-offs between different performance criteria must be made when considering integrated products. Adopting an integrated device will probably require the line card to be redesigned, and that adds cost. “The technology also has to be mature and proven – we don’t take chances in the field,” says Desurvire. “A highly integrated device is not necessarily the best solution. Throwing away what you have can have an impact across the [network] architecture.”

With Nortel and Alcatel selling their optical-component divisions, it has also become more com-



Look inside: Infinera’s DTN (digital transport network) is the first transport platform to be based on large-scale InP photonic integrated circuits. Its features include protection switching, grooming, signal regeneration, bandwidth management and digital performance monitoring.

plicated to explore how integration can benefit system design. “It is difficult to predict what optical component players are doing and for them to second-guess systems performance,” says Michel Belanger, senior technical advisor in Nortel’s next-generation optical network group.

Indeed, Infinera’s decision to make systems allows the company to put its PIC technology at the heart of its design. “If you don’t have control of the optical technology, you can’t have a differentiated product,” says Dave Welch, Infinera’s chief strategy officer.

Infinera’s digital transport network (DTN) platform addresses the cost issue of optical–electrical–optical conversions by integrating discrete transponder functionality into its transmit and receive PICs. Infinera will not detail the resulting cost savings, but one carrier suggests that its DTN platform is 30% cheaper than equivalent dense wavelength-division multiplexing (DWDM) systems. Since every wavelength is converted into the electrical domain, whether it is dropped or passed, several other key benefits result. The signal’s condition can be monitored, switching and grooming can be performed, and the signal can be properly regenerated – unlike in the optical domain where both signal and noise are only amplified.

Welch claims that Infinera’s InP manufacturing process is robust enough to achieve high yield. “We

make distributed-feedback lasers in a similar fashion to everyone else, as we do our modulators," he says. What is different is that Infinera gets its engineers to design around the process. "We design what the process can manufacture."

Infinera's design also trades off optics and electronics. Forward-error correction and electronic dispersion-compensation techniques are used to relax the optical specifications, placing more of the link-budget burden on the electronics. Nortel makes a similar point about the importance of integrated components – not just optical, but also analog and digital silicon chips.

"Infinera can basically do what others thought impossible because they expanded the domain over which they did their design trade-offs to span systems to processing," says Karen Liu, research director for components at Ovum-RHK.

And while the industry is focused on a pay-as-you-grow approach, Infinera's strategy is to deliver wavelength blocks – in chunks of 10×10 Gbit/s – cheaply enough, whether or not they are all needed. Welch argues that a line card costs roughly the same, regardless of what is on it, and the company's PIC shifts the industry from 10 to 100 Gbit/s on a line card. Infinera's prototype 40×40 Gbit/s PIC will also deliver a further 10-fold hike in three to four years' time.

But Ovum-RHK's vice-president for communications components Daryl Inniss is less optimistic. "A

tier-one carrier will not wholly replace its network with Infinera equipment in the next 5 or 10 years," he says. "It's a good idea, a radical idea, but the path they offer is way ahead of incumbent systems."

Baby steps

As to whether the pace of monolithic integration will hasten in the next five years, most believe not. But that doesn't mean there won't be exciting developments. "Infinera's 10×10 Gbit/s is all-in-one-go, but there will be some baby steps by the industry towards its solution," says Inniss.

Perhaps the most exciting is the placing of a tunable laser within an XFP package that supports line-side transmission distances of 80 km and greater. Agility (recently bought by JDSU) has an InP monolithically integrated tunable laser that is sufficiently small to fit within an XFP package.

This development indicates that a variety of transceiver types will converge to one form factor, with one laser and one receiver, says Inniss. Unit volumes will go up, while the price of such a tunable, pluggable DWDM interface will dip below \$1000.

Meanwhile, Infinera believes it is only a matter of time before someone breaks away from the pack to make a PIC triplexer. At the same time, advances in hybrid technology continue to reduce packaging costs, and only time will tell which integration method will win. ●

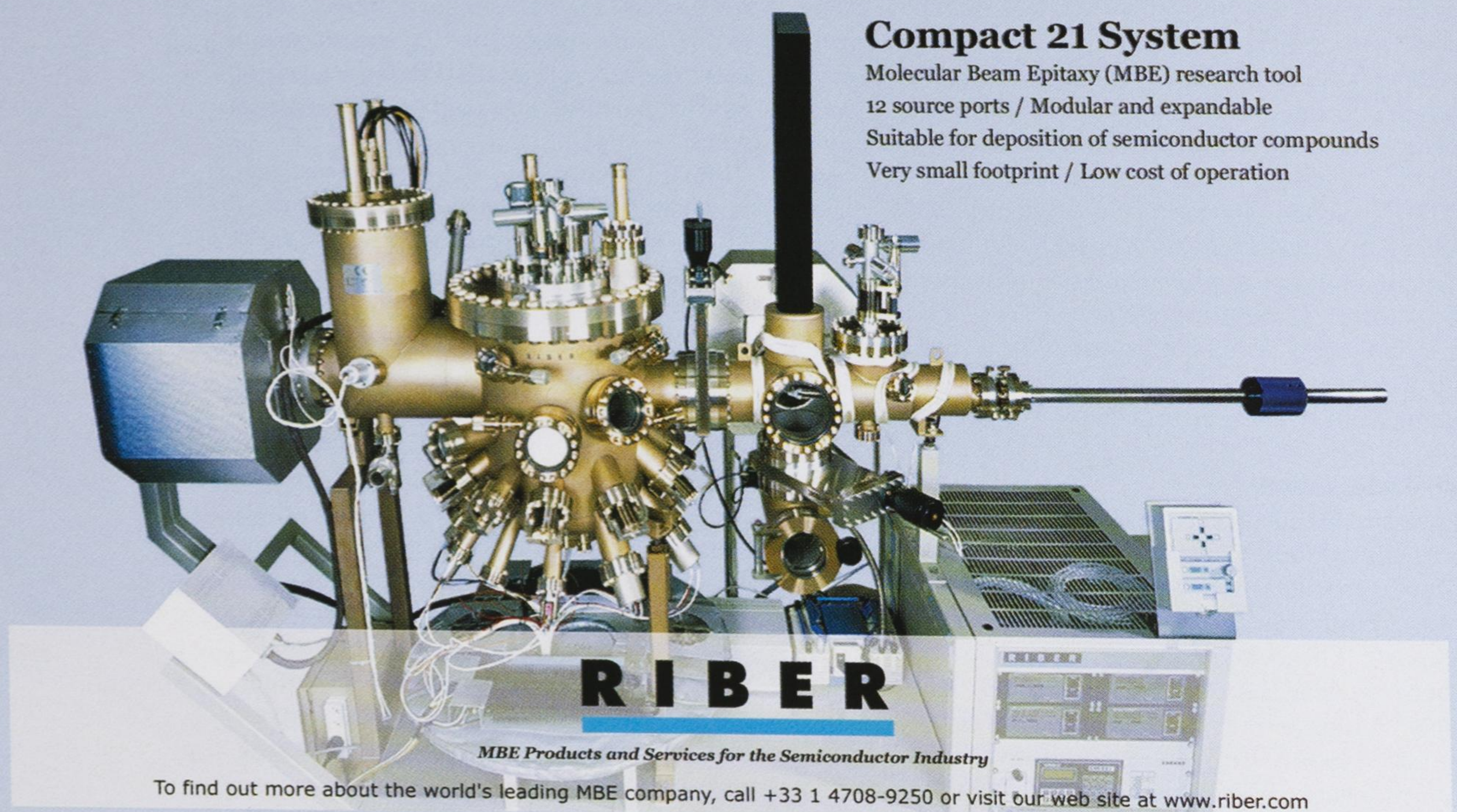
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Simulations provide additional insights into GaN HFET reliability

GaN HFET reliability can be improved by adding field plates to the structures. This is believed to reduce carrier trapping at the surface, but simulations by **Ric Borges, Nelson Braga, Bo Wu** and **Vidas Mickevicius** of Synopsys show that it also decreases the electron temperature and bulk trapping throughout the device.

GaN HFETs are attracting considerable attention as high-power and high-frequency devices for radar, avionics and wireless base-station transmitters, thanks to the unique material properties of III-N material. However, the commercialization of these devices has been hampered by reliability issues that have been attributed to carrier trapping in either the bulk or surface of the device. These problems are being addressed by experimental studies that can produce epitaxy- and processing-related improvements, and simulations that can optimize device design.

Simulations provide key insights into device operation and the degradation mechanisms that affect reliability. They can contain structural details such as layer thicknesses, doping profiles and trap concentrations. The software-based approach can also aid the tailoring of a structure to specific market applications requiring particular performance characteristics, and can be an effective tool for selecting and optimizing the design.

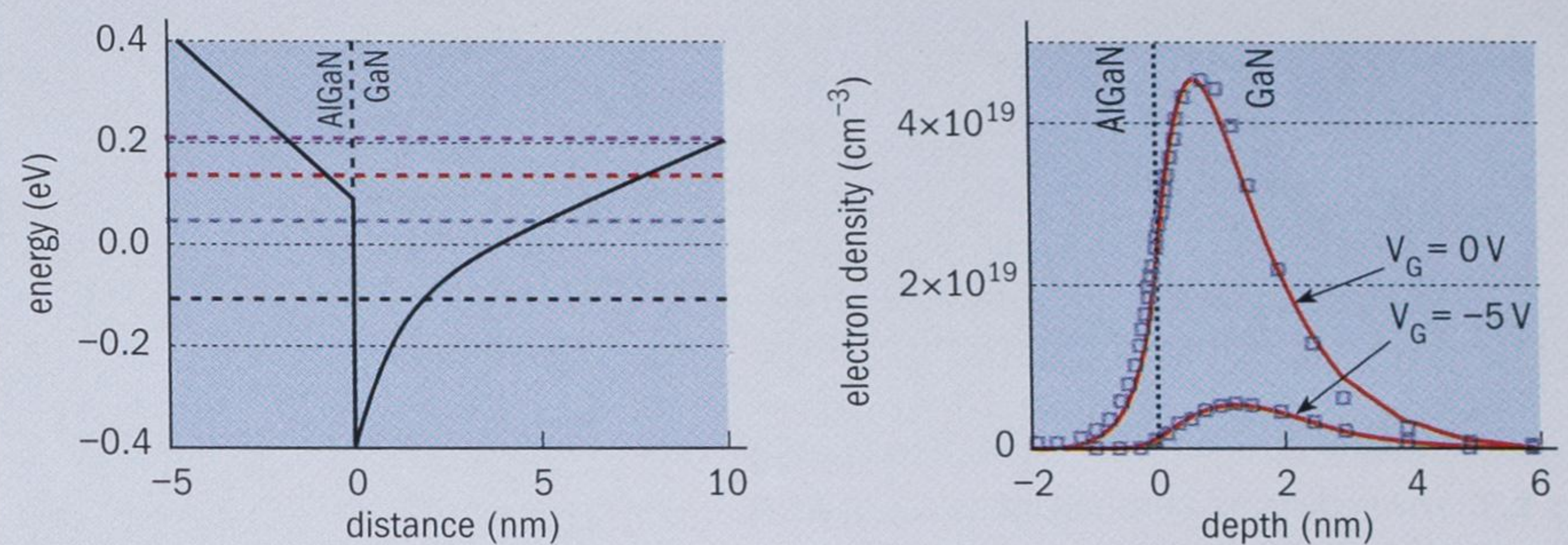
In the silicon industry, process and device simulation – referred to as technology computer-aided design – is widely used to develop and optimize various technologies ranging from highly scaled CMOS to power management, non-volatile memory and image sensors. Over the past decade this approach has also been increasingly used for III-V technologies, and recent advances to III-N devices has promoted the use of simulation for improving GaN HFETs.

Investigating current collapse

At Synopsys we have built the simulator software Senterius Device (see “Simulation software” box, opposite, for details) to explore a physical mechanism that is referred to as either current collapse or dispersion, and is defined as the drain current (I_D) degradation under operational or stress conditions. This mechanism limits GaN HFET reliability and is consequently inhibiting device commercialization. However, its origin is still under debate despite the various models that have been proposed, such as electron trapping in the GaN buffer and AlGaIn barrier layers, and at the surface (Binari *et al.* 2002, Vetury *et al.* 2001).

Our simulations can help to understand the nature of current collapse, provide a detailed insight into

Simulation software



The interface between the GaN and AlGaIn layers can confine electrons in the conduction band in four different energy states (see left figure). Although calculations using Schrödinger's equation can be used to simulate the electron density in the channel at $V_G = 0$ V and $V_G = -5$ V (see right figure, solid line), time savings can be made using the density-gradient approach, which involves a quantum-mechanical correction to the continuity equation (see right figure, square markers).

The simulation of GaN HFETs presents several challenges and needs to cater for the polarized wurtzite crystal structures of AlGaIn, InGaIn and GaN, which have dipoles across the crystal in the [0001] direction. These dipoles can cause spontaneous (pyroelectric) polarization, while pseudomorphic heterostructures fabricated from these III-Ns also have strain-induced (piezoelectric) polarization.

At Synopsys, our software, which can be run on either PCs or workstations, provides a rigorous calculation of the polarization fields from the stress in the structure – including local stress sources such as the gate metal and dielectric passivation – and leads to in-plane polarization vector components. The resulting polarization-induced charges are included in our calculation.

Quantization effects at the AlGaIn/(In)GaN heterointerface create a two-dimensional electron gas channel. A quantum-mechanical solution is needed to properly account for the electron spatial distribution in this channel. Our model uses a quantum potential correction to the continuity equation, known as density gradient. This closely matches the solution to the full Schrödinger equation (see figure, above right), while improving the simulation's robustness and providing a five-to-ten fold cut in computational time. Our simulation also accommodates hot-carrier effects and dynamic trapping/detrapping, which is needed to simulate the physical mechanisms behind device degradation.

device operation, and point towards mitigation strategies to avoid current collapse. However, they cannot predict the formation of non-ideal device properties such as traps.

The software has simulated a GaN HFET (see figure 1, p18) with a room-temperature Hall mobility of

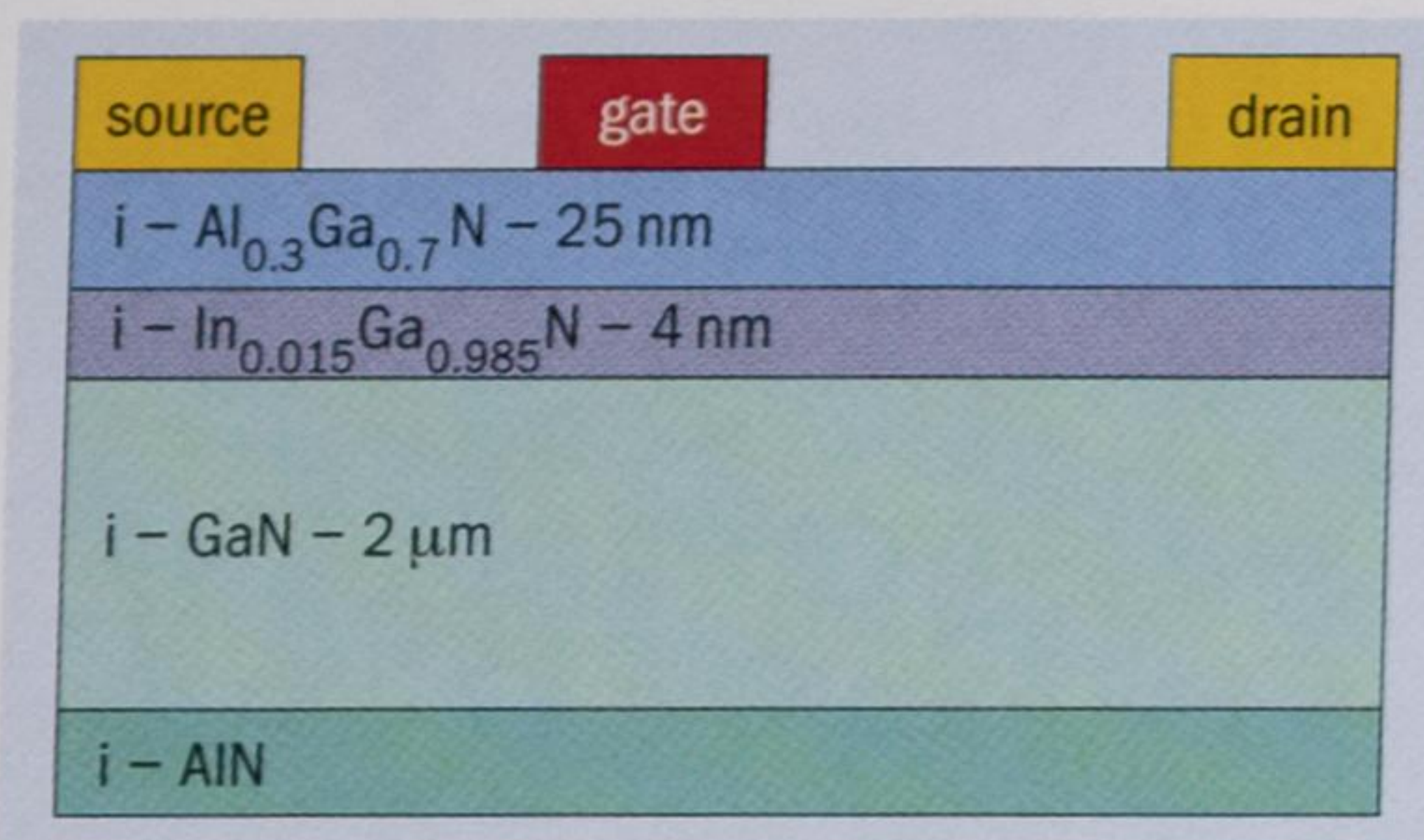


Fig. 1. Our simulations model intrinsically (i)-doped AlGaIn/InGaIn HEMTs with a $5 \times 10^{17} \text{ cm}^{-3}$ trapping density and $\sigma_{Tn} = 1 \times 10^{-15} \text{ cm}^{-2}$ capture cross-section.

The properties of III-Ns

	GaN	InN	AlN
Dielectric constant	9.5	15.3	8.5
Energy gap (eV)	3.47	0.8	6.2
Electron affinity (eV)	3.4	5.8	1.9
Electron mobility ($\text{cm}^2/\text{V-s}$)	1100	2400	300
Electron saturation velocity (cm/s)	1.2×10^7	2.6×10^7	1.5×10^7
Effective conduction band density of states (cm^{-3})	2.65×10^{18}	1.3×10^{18}	4.1×10^{18}
Energy relaxation time (ps)	0.1	0.1	0.1

Table 1. The Synopsys simulations use the room-temperature values for III-Ns that are shown in the table. The values are taken from the work by M E Levinshtein and colleagues (M E Levinshtein *et al.* 2001 *Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN and SiGe*, Wiley, New York).

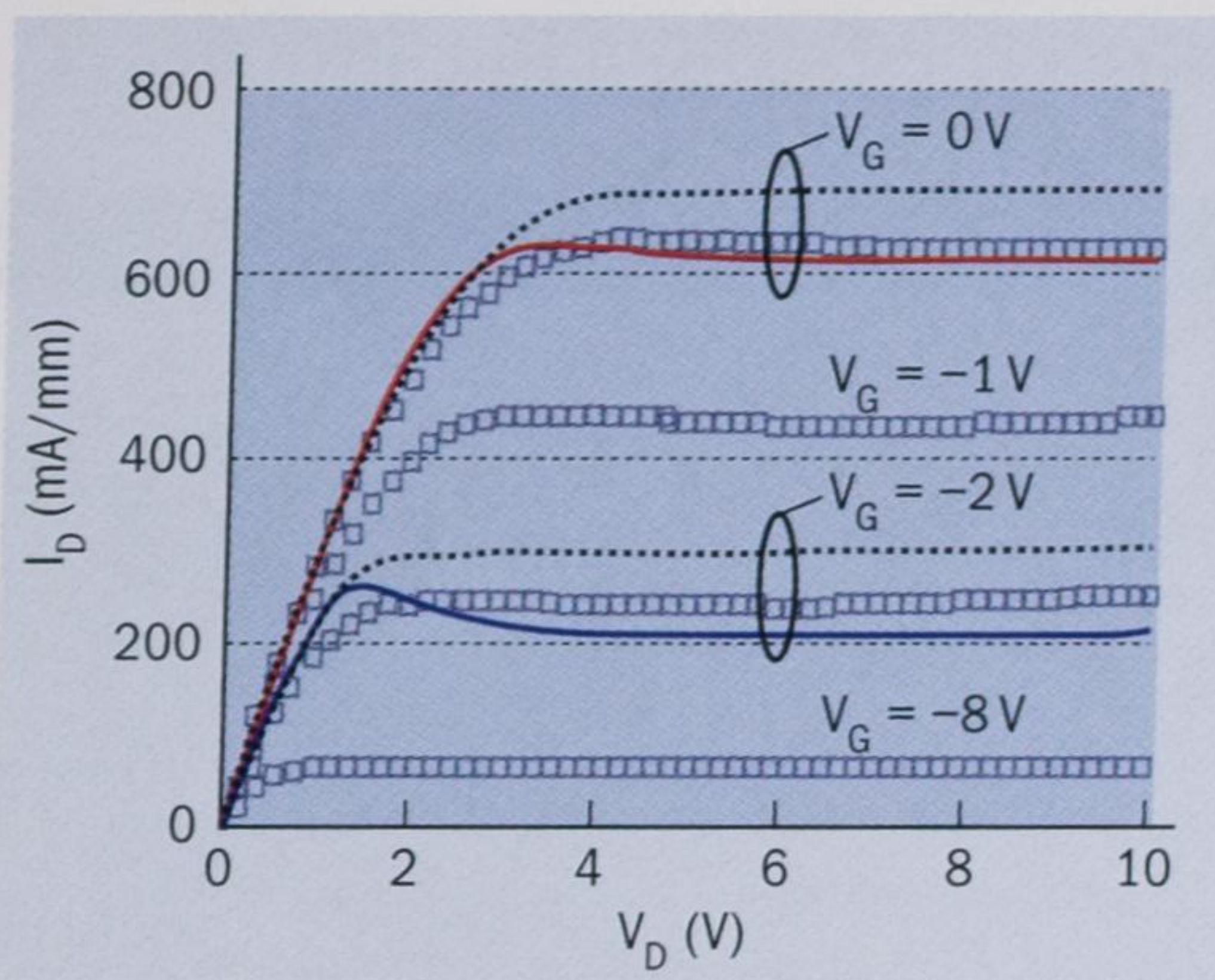


Fig. 2. The hydrodynamic transport model (solid lines) that includes hot-electron effects is a better fit to the experimental data (squares) than the drift-diffusion model (dotted lines). Simulations have only been performed for $V_G = 0$ and -2 V .

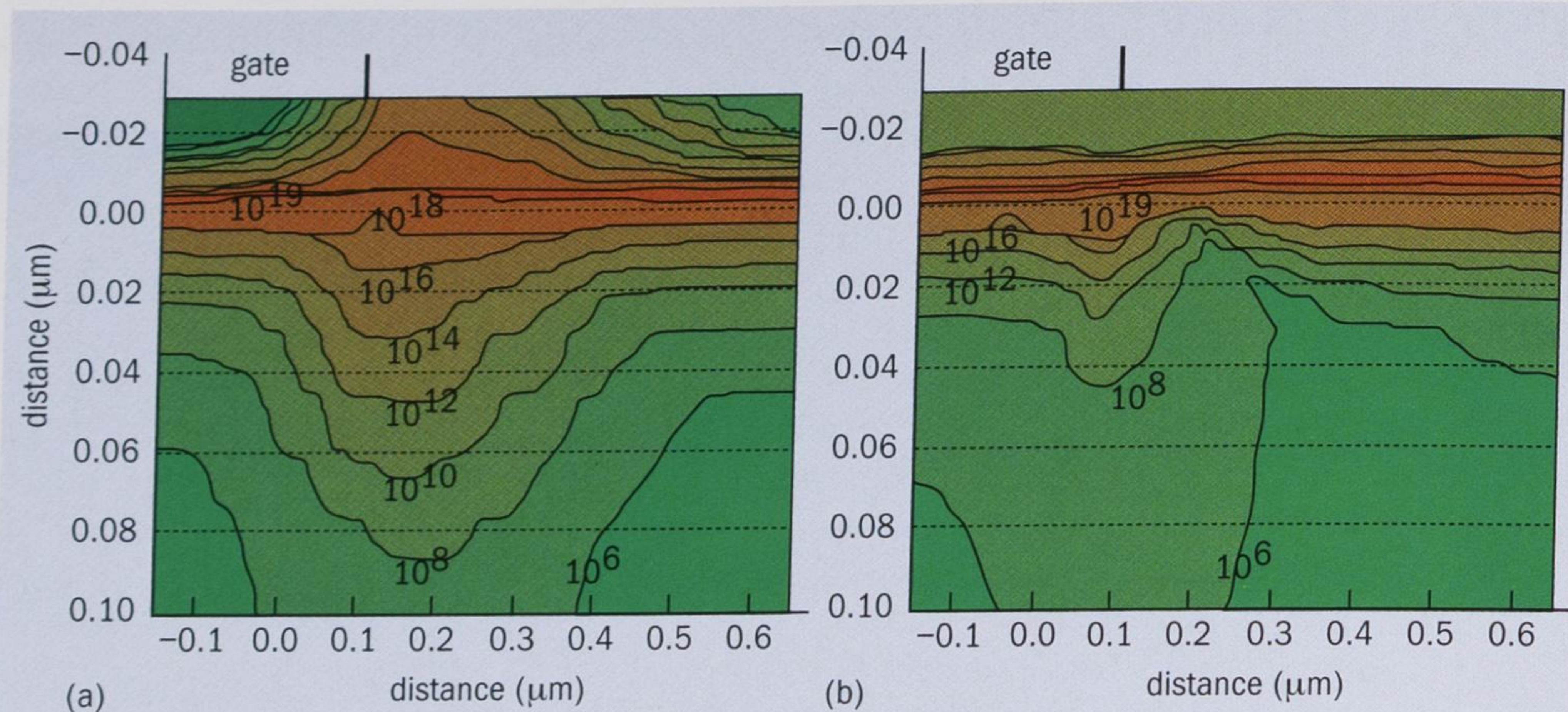


Fig. 3. The simulated electron density map of the cross-section of the AlGaIn/InGaIn HEMT generated using the hydrodynamic model shows that the electrons spread over the AlGaIn barrier into the GaN bulk (a). The simple drift-diffusion model simulation, which does not consider hot-electron effects, confines the electrons to the channel (b).

$1100\text{--}1200 \text{ cm}^2/\text{V-s}$ and sheet carrier concentration of $8\text{--}9 \times 10^{12} \text{ cm}^{-2}$ (Braga *et al.* 2004). The calculations used values for the band structure, carrier mobility and saturation velocity of GaN, InN and AlN that are shown in table 1. Interpolation of the corresponding binary parameters provided values for AlGaIn and InGaIn.

Trapping behavior

To investigate trapping behavior and gain insight into the current-collapse mechanisms, we inserted a background of acceptor/electron bulk traps with a density of $N_T = 5 \times 10^{17} \text{ cm}^{-3}$ into our model of this particular device. Since the motivation behind this study is to obtain a qualitative insight, the traps were defined with a single energy level 1 eV above mid-band. However, our simulation software can accommodate multiple trap levels that are commonly ascribed to GaN epitaxial material (see Binari *et al.* 2002) in either the bulk or at the surface.

Using these conditions we could match our simulations of direct-current (DC) I-V characteristics with measured data if we used an interface charge of $1.15 \times 10^{13} \text{ cm}^{-2}$ and an electron saturation velocity that is 40% of the theoretical bulk value. The value used for the interface charge, which equates to a partially relaxed AlGaIn layer, is lower than that associated with theoretically-ideal strain conditions, which would have a value of $1.5\text{--}1.7 \times 10^{13} \text{ cm}^{-2}$. However,

this value is consistent with observations from several experimental groups who have seen a reduction of the piezoelectric component. A reduction in saturation velocity has already been proposed, due to modified scattering of the two-dimensional electron gas (2DEG) at the heterointerface.

We also compared the experimentally-measured DC $I_D\text{--}V_D$ output characteristics with simulations that both ignore and include hot-electron effects (see figure 2). Our drift-diffusion (DD) model assumes that the carriers are in thermal equilibrium with the lattice, while the hydrodynamic hot-electron compatible (HD) model accounts for carrier heating and non-local electric field effects. The measured and simulated curves created with the hydrodynamic model have a decline in their I_D value after the peak – known as a negative differential conductance – that is absent in the curve produced with the DD model. We believe that this feature is not attributable to self-heating (Deng *et al.* 1999), but is in fact evidence for hot-electron capture at bulk traps under sufficiently high drain bias.

The HD model also shows that at large drain biases electrons in the channel are significantly heated and can exit the AlGaIn barrier and then spread toward the GaN bulk – an effect that is not predicted with the DD model (see figure 3). At these high drain biases electrons occupy more traps. This increases the energy of the conduction band under the gate edge located

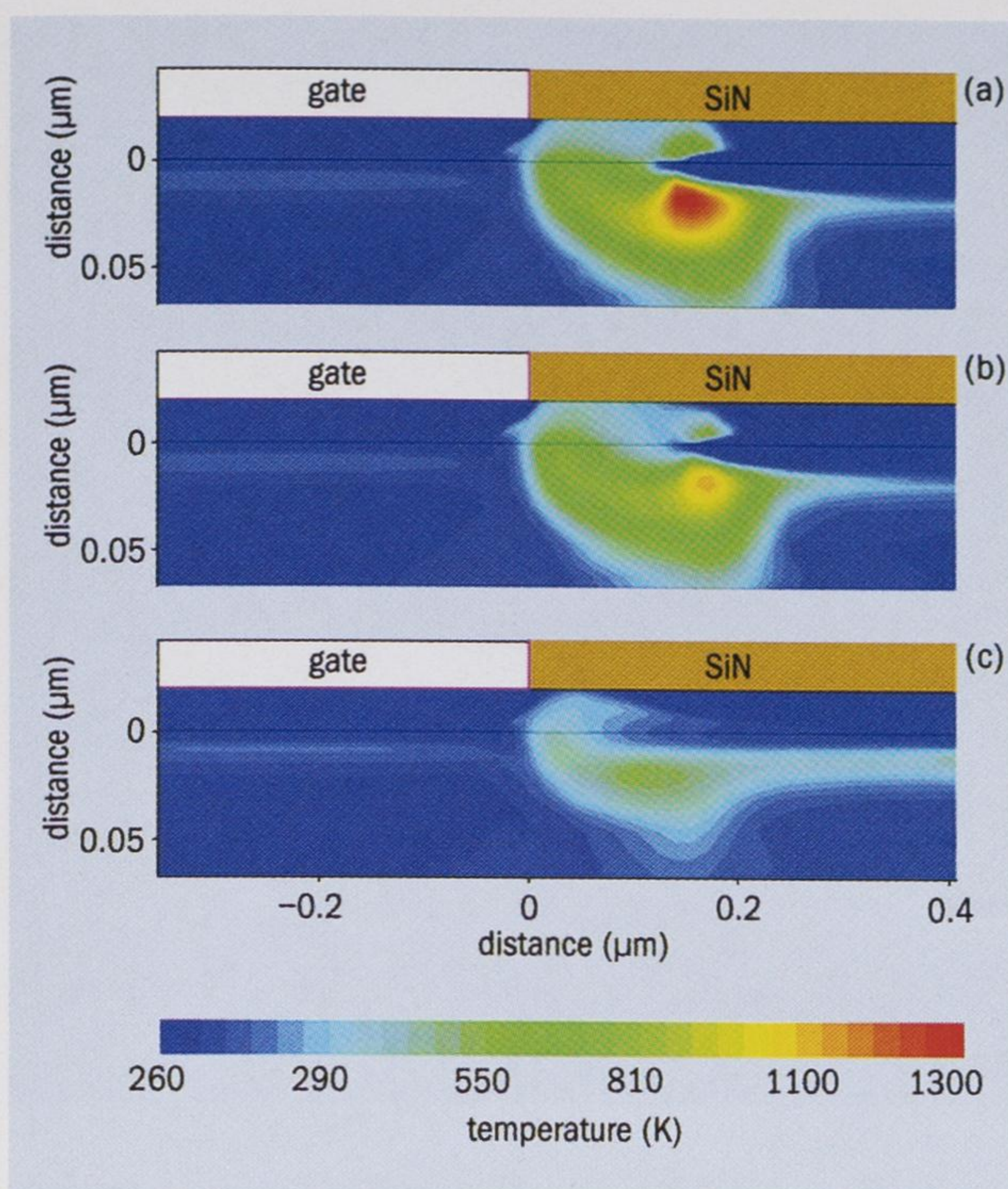


Fig. 4. GaN HEMTs with gate field plates (c) and source field plates (b) have lower electron temperatures near the drain-edge of the gate than comparable devices without a field plate (a). Note that the field plates are not shown in the plots.

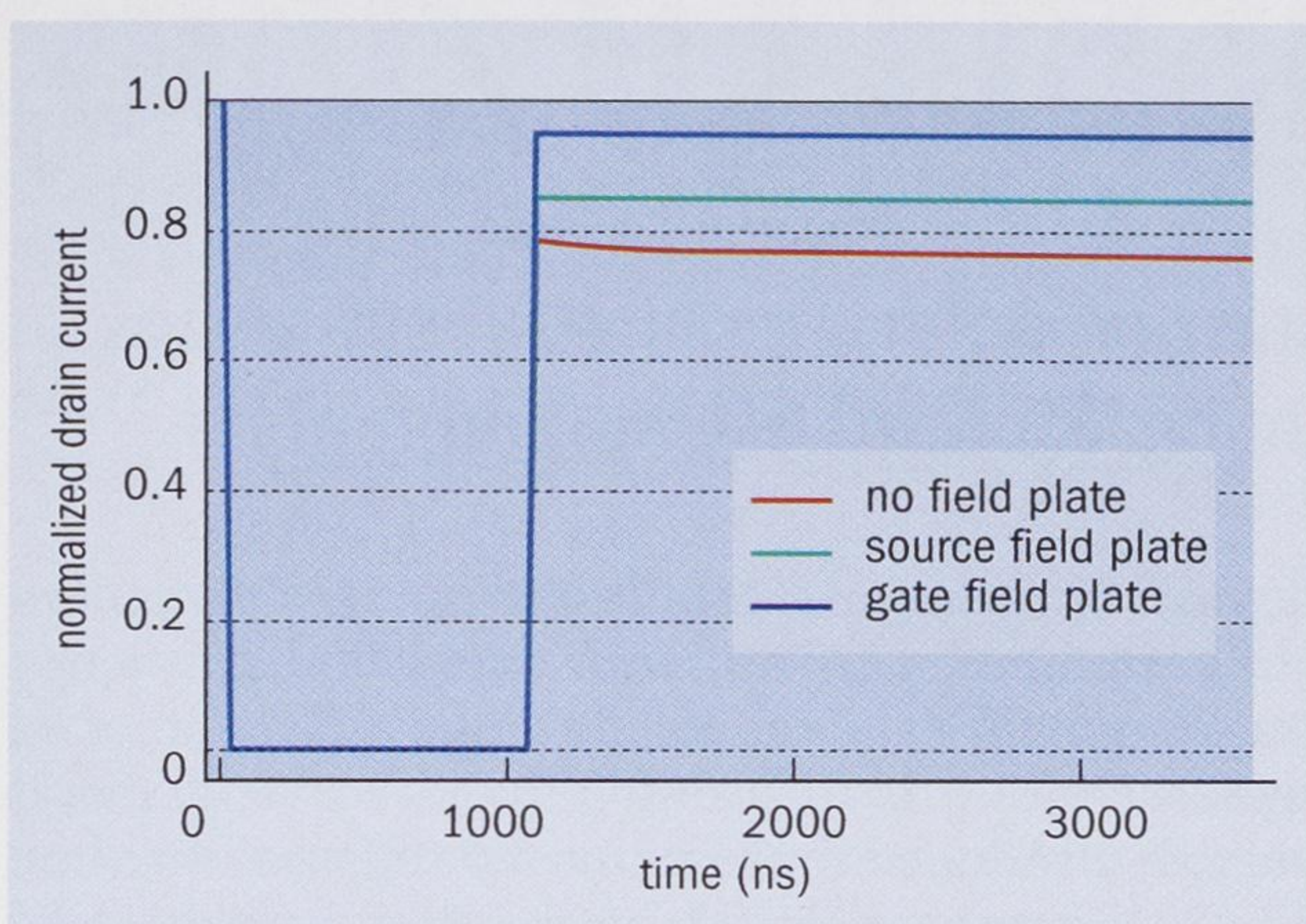


Fig. 5. Transient gate-lag simulations show that the source and gate field-plate structures both aid the recovery of the drain current, and will consequently improve device reliability.

toward the drain, and creates a potential barrier to electron flow.

The loss of electrons from the drain channel, which leads to current collapse, can be prevented by improving the electron confinement in this region. In fact this improvement has already been observed in a AlGaIn/InGaIn/GaN double heterojunction FET structure that features a potential barrier between the InGaIn channel and the underlying GaN layer (Simin *et al.* 2001).

We simulated the effect of the potential barrier on current collapse by carrying out transient simulations at differing indium concentrations that are akin to gate-lag measurements. These HD simulations involve setting the drain voltage to 0.1 V and giving the gate a

1 μ s gate pulse from 0 to -5 V, which is then restored back to 0 V. These simulations confirm the improvement in current collapse resulting from the use of InGaIn layers to provide superior channel confinement of the 2DEG.

Field-plate enhancements

One of the most compelling attributes of GaN HFETs is their high-voltage operation, which produces a higher output impedance and wideband impedance matching. Recent work suggests that field-plate structures are effective at reducing current collapse at high voltages (see, for example, *Compound Semiconductor* January/February 2006, p25). This is because field plates reduce the electric field at the drain-edge of the gate, which leads to a lower electron temperature.

We investigated the electron temperature in GaN HFETs with no field plate, a source field plate and a gate field plate. When the device is built without a field plate, hot electrons diffuse into the bulk and are trapped, but when a gate field plate is used, the electron temperature is reduced (see figure 4).

The impact of field plates on current collapse can be assessed with transient simulations. Using conditions identical to those for the transient simulation already described, but with the exception of an increase in the drain voltage to 6 V, revealed that the gate field-plate structure yields an almost complete recovery of the drain current, indicating very small gate lag (see figure 5). This analysis is consistent with reduced hot-electron diffusion and trapping, and shows that the addition of field plates will improve device reliability.

Our hot-electron-based model of current collapse suggests a different mechanism from the “virtual gate” model, which argues that high electric fields at the drain-edge of the gate cause electrons to be injected from the gate into surface traps (Vetury *et al.* 2001). However, since surface trapping of electrons is well known in compound semiconductors, it is plausible that both models play a role in current collapse.

We believe our simulations, which show that field plates and double heterostructures can suppress the hot-electron effects in the bulk region of a transistor, can accurately model device behavior, and are an invaluable tool for optimizing this promising technology toward its eventual commercialization. ●

Acknowledgments

We would like to thank Michael Shur of the Rensselaer Polytechnic Institute, Remis Gaska of Sensor Electronic Technology, and Grigory Simin and Asif Khan of the University of South Carolina for guidance and experimental support.

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Nelson Braga (top right) is Synopsys' manager of corporate applications engineering, and was previously an associate professor at the University of Sao Paulo, Brazil.

Bo Wu (bottom left) is corporate applications engineer at Synopsys, focusing on heterostructure device simulation.

Vidas Mickevicius (bottom right) is senior manager of corporate applications engineering at Synopsys, and has more than 20 years of semiconductor experience.



MONTPELLIER TOURIST BOARD

Researchers seek material solutions to GaN deficiencies at ISBLLED 2006

Researchers are turning to alternative capping layers and GaN and non-polar sapphire substrates to push the output power of LEDs to levels suitable for everyday lighting. **Richard Stevenson** reports.



ISBLLED 2006 was held on May 15–19 in the city of Montpellier, France, and attracted 228 delegates.

At many of today's conferences you will often see a presentation by a major LED manufacturer outlining a roadmap that begins with the indicator lights of the 1970s and points towards the future growth of solid-state lighting. This map gives the impression that performance improvements are inevitable and it is easy to avoid thinking about the technological breakthroughs that are required to maintain progress.

However, the message was a little different at the recent International Conference on Blue Lasers and LEDs (ISBLLED). At the Montpellier meeting Werner Goetz, director of epitaxial technology at Philips Lumileds, didn't speak in vague terms about the need to improve the output of phosphor-converted blue and green LEDs to 150 lm/W to win business in general lighting, LCD backlighting, automotive and projection applications – he actually detailed the improvements in various LED characteristics that are needed to hit this target.

In his opinion, to produce 150 lm/W green LEDs for red-green-blue light sources will require an increase in extraction efficiency from 65 to 85% and a hike in internal quantum efficiency (IQE) from 20 to 40%. These gains will have to be delivered in high-power

devices operating at typically 350 mA. For phosphor-converted blue LEDs similar extraction efficiency improvements are required, but the IQE must be increased from 50% to almost 100% – a value that is already produced in GaAs-based red and infra-red LEDs. Goetz says that there are already laboratory results at Philips Lumileds and other claims within the industry of 85% extraction efficiency in GaN-based LEDs. "We now have to focus on increasing the IQE through improvements in material quality."

Material issues...

Goetz believes that all of the material quality improvements must be compatible with uniform, reproducible and high-throughput manufacturing, and he says that today's issues can be sub-divided into problems associated with either the n-type, active or p-type regions of GaN LEDs. The low p-type doping efficiency, low solubility of the magnesium dopant and high levels of impurities such as oxygen and carbon are all associated with the GaN/AlGaIn p-type region that provides hole injection and electron confinement. Meanwhile, the performance of the active region is hindered by low efficiencies at higher currents, difficulties associated

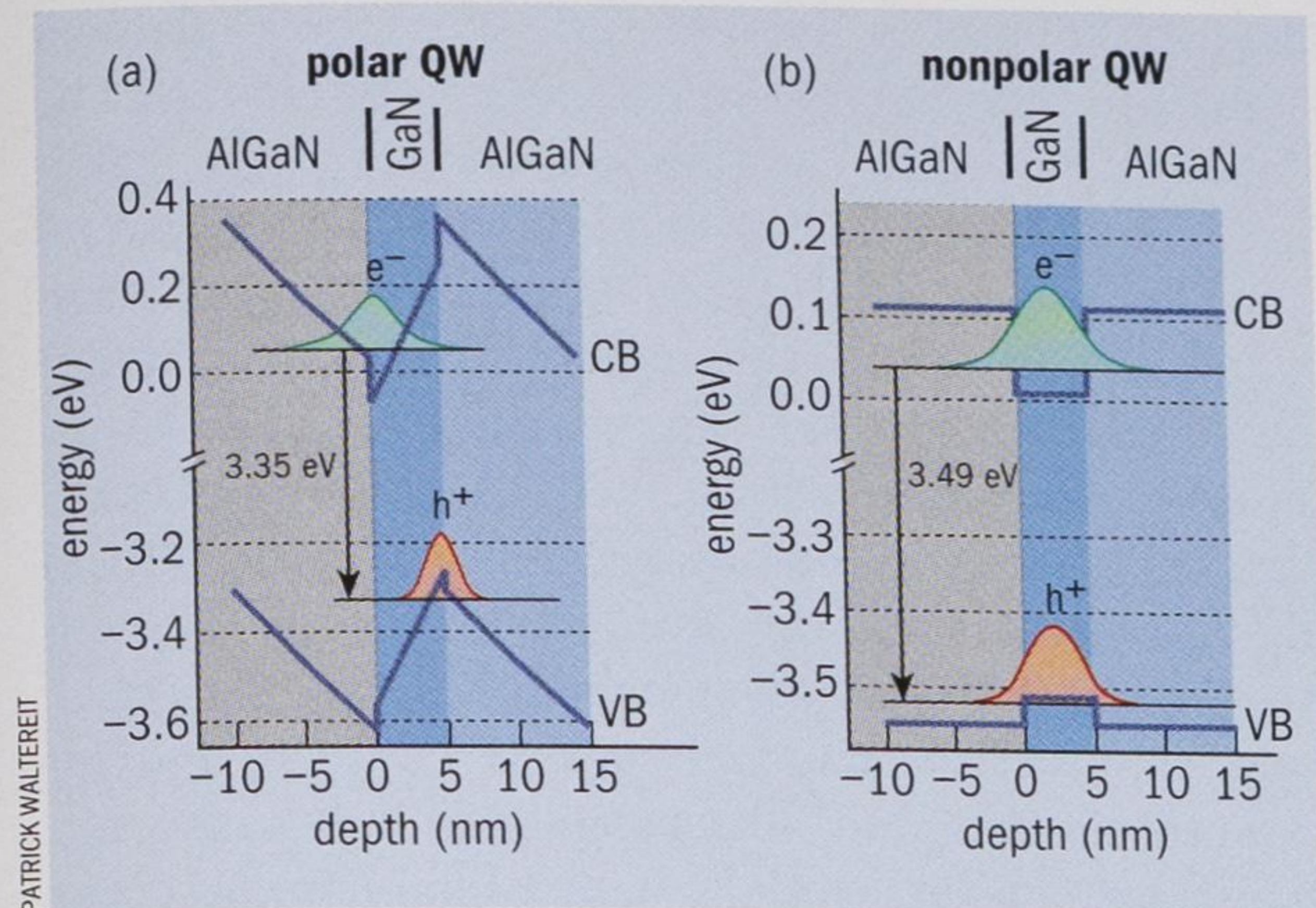


Fig. 1. The quantum-confined Stark effect, which occurs in quantum wells (QWs) grown on conventional polar substrates, involves the separation of electrons and holes with a built-in electric field (a). This effect reduces the internal quantum efficiency. Researchers are looking to avoid this condition by using non-polar substrates that allow the growth of devices that do not suffer from the Stark effect (b).

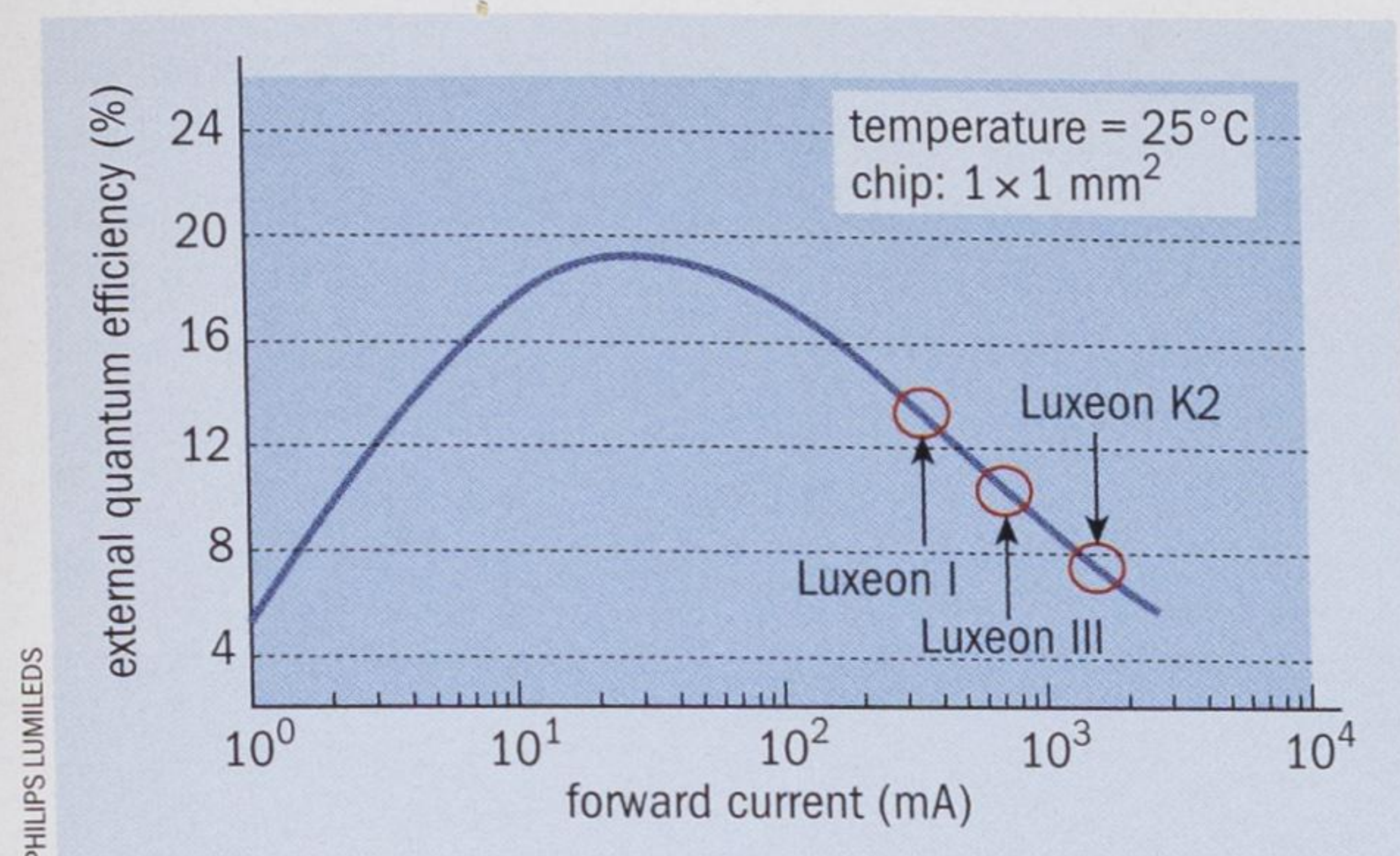


Fig. 2. Commercial high-brightness LEDs, such as the Philips Luxeon range of 1×1 mm chips targeting the solid state-lighting market, operate well-outside the external quantum efficiency “sweet spot”.

with growing high-quality InGaN material at longer wavelengths and polarization effects. The latter could be improved through the use of non-polar substrates. Goetz says that the typically silicon-doped n-type region suffers from tensile strain and growth-related issues that are linked to the difficulties associated with deposition on a sapphire substrate.

According to Goetz, there are also several reasons why it is particularly difficult to grow highly efficient green LEDs. Firstly, the additional indium content increases the piezoelectric strain between the InGaN and GaN layers, which leads to increased carrier leakage and a reduced IQE due to the quantum-confined Stark effect (see figure 1). Higher-indium-content layers also require growth at lower temperatures, but under these conditions adatoms are less mobile, the impurity incorporation and the density of “V”-shaped defects increases and it is more difficult to crack ammonia – the standard nitrogen source.

Goetz notes that another problem with today’s devices is reduced external quantum efficiency at high currents (see figure 2). According to him, all commercial InGaN-based LEDs, regardless of color, have peak efficiency at a current density of $1\text{--}10\text{ A/cm}^2$. Goetz

said that improvements can be made through device design to reduce current density, but also added that the origin of the IQE reduction is not fully understood.

... and solutions

Many of the challenges outlined by Goetz are already being addressed by several research groups who presented at the conference. Russell Dupuis from Georgia Institute of Technology described an increase in green LED output produced by switching from a p-doped GaN layer to a p-doped InGaN layer.

Dupuis explained that the conventional fabrication of green LEDs structures involves high-temperature growth of a p-doped GaN layer, which degrades the active region by increasing indium compositional fluctuations in the InGaN quantum well. His research group has tried to reduce this effect with lower temperature growth of a magnesium-doped $\text{In}_{0.04}\text{Ga}_{0.96}\text{N}$ layer that increases hole concentration and conductivity.

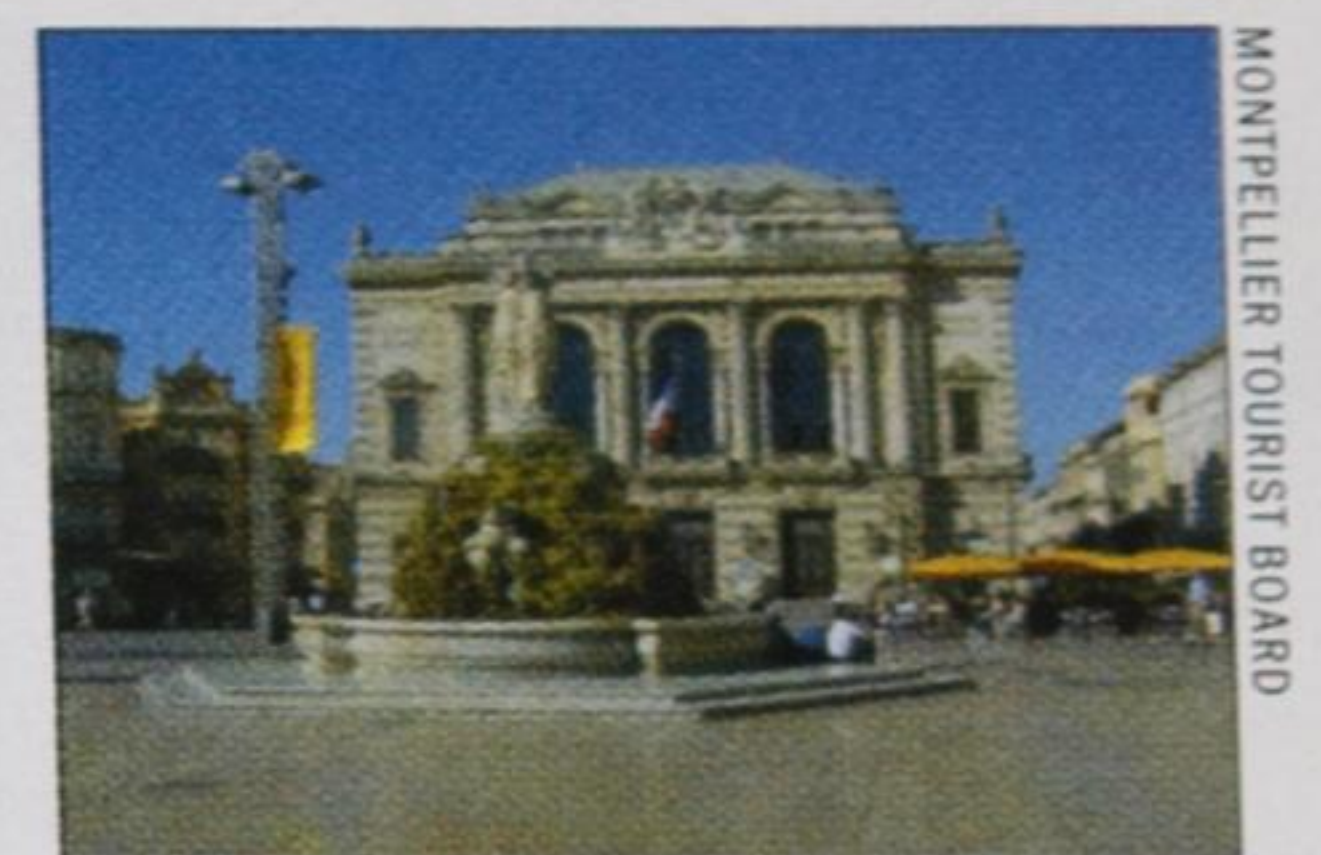
The team compared MOCVD-grown LEDs made with a magnesium-doped GaN layer deposited at 930°C and a magnesium-doped $\text{In}_{0.04}\text{Ga}_{0.96}\text{N}$ layer grown at 840°C . In both cases the quantum wells were grown at 740°C , and an inductively coupled plasma etch with a silicon-dioxide mask defined $230 \times 230\text{ }\mu\text{m}$ mesa devices that were given Ti/Al/Ti/Au and Ni/Au n-type and p-type ohmic contacts, respectively.

At a drive current of 100 mA the device with the InGaN p-doped layer had an electroluminescence peak almost three times higher than the standard structure, and at lower currents this difference was even more pronounced. The new structure’s only downside is a small increase in the forward voltage from 3.1 to 3.2 V, which Dupuis attributes to the abrupt heterojunction between the p-type InGaN layer and the upper GaN quantum-well barrier. However, he thinks that the magnesium-doped InGaN layer could improve current spreading and reduce diode series resistance, and that the forward-voltage value is still less than most of the latest devices.

One of Goetz’s other suggestions to improve GaN LED output – the use of “non polar” substrates that have a different crystalline orientation – was a hot topic among the delegates, including GaN LED and laser pioneer Shuji Nakamura. Unfortunately, his first results using these substrates showed that the device output powers were significantly lower than those of standard LEDs. The best blue devices made by the University of California, Santa Barbara professor’s team had an output of 1 mW at 20 mA drive current, while the best green LEDs produced 0.26 mW at 250 mA.

Nakamura believes that these low output powers are due to either stacking faults or point defects. Although the output powers may be lower than expected, the novel devices are showing some of the other benefits that Nakamura had predicted. For example, the emission wavelength of the non-polar LEDs does not change with different drive current, which means that their color is extremely stable.

These devices also have a lower series resistance and the carrier concentration in the p-doped layer is an order of magnitude higher than for standard devices.



Held in the heart of the historic city of Montpellier (above), ISBLED featured a concert for delegates on the first night of the event (below).



“The only problem [with non-polar LEDs] is output power.”

Shuji Nakamura

EQE values for LEDs on sapphire and GaN with different thickness quantum wells

	20 mA (%)	200 mA (%)
LED on sapphire, 3 nm quantum wells	8.8	5.6
LED on sapphire, 5 nm quantum wells	3.1	4.4
LED on GaN, 3 nm quantum wells	8.3	4.9
LED on GaN, 5 nm quantum wells	7.9	6.6

Their polarized emission makes them suitable for direct backlighting of LCD displays, which normally require a polarizing light filter to operate with conventional LED backlights. "The only problem is output power," concluded Nakamura.

Improving the device platform

The materials-related problems in the n-type region of the LED that Goetz described can be addressed by switching from sapphire to GaN substrates. It is an approach that has been pursued by Sumitomo Electric Industries' Katsushi Akita, who explained: "Our motivation is to produce GaN with lower threading dislocation densities that could lead to high extraction efficiencies at high current densities."

Sumitomo's engineers compared the performance of MOCVD-grown LEDs with identical active layers that are built on either c-plane sapphire or HVPE-grown GaN that had a threading dislocation density of less than $1 \times 10^6 \text{ cm}^{-2}$. They grew two types of LED

on each substrate: one featured a 3 nm thick quantum well and the other a 5 nm thick quantum well. The results of external quantum efficiency (EQE) measurements performed with a pulsed injection current (10 kHz duty cycle, duty = 5%) are shown in the table.

Akita believes that the decrease in EQE at higher currents in both of the 3 nm quantum-well devices is due to carrier localization and that the devices fabricated on GaN contain non-radiative centers (NRCs) that are unrelated to threading dislocations. The density of these NRCs is lower in the LEDs with 5 nm thick quantum wells because these devices have a lower indium concentration (10% rather than 14%), said Akita, before backing up this claim with cathodoluminescence images of the structures that showed fewer defects.

All the chips were then mounted p-side down to improve thermal management and increase light extraction, but this only benefited the LED with 5 nm thick quantum wells that was grown on GaN. For this device a 20 mA drive current produced 17 mW at 30% EQE, while a 200 mA current produced 148 mW at 26% EQE.

Other presentations focused on the use of low-polarity GaN epitaxial layer overgrowth to eliminate stacking faults and the benefits of selective-area growth by HVPE. The need to generate substantial improvements in external quantum efficiency is critical to the future success of solid-state lighting, and the discussions at ISBLLED should go some way to ensuring that LED manufacturers' device roadmaps can be trusted. ●

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Fujitsu proves reliability of GaN HEMTs

Fujitsu's GaN program has led to proven device reliability, a fabrication process using low-cost conducting 3 inch SiC substrates, and record output power from MIS-HEMTs, says **Toshihide Kikkawa**.

Wireless mobile networks will continue to evolve, and from 2010 we can expect to see the roll-out of 4G services offering transmission speeds of more than 100 Mbit/s. These next-generation networks will require faster, more powerful transmission amplifiers that will consume more energy and take up more space. This could lead to larger base stations operating with higher running costs if the incumbent and relatively inefficient silicon LDMOS is deployed, and so efforts are being directed at developing alternative technologies, such as GaN HEMTs, for future networks.

These GaN HEMTs are efficient, can produce high output powers from relatively small chips sizes, and have higher breakdown voltages and cut-off frequencies than transistors based on other semiconductor materials. At Fujitsu we have already demonstrated highly efficient push-pull amplifiers based on this material delivering 250 W wideband code division multiple access (W-CDMA) signals. However, if these GaN transistors are to fulfill their promise and provide a viable alternative to silicon LDMOS, then improvements have to be made in terms of reliability, distortion, cost and gate leakage at high output powers.

At Fujitsu Laboratories in Kanagawa, Japan, we addressed all these issues by investigating the performance and refining the design of our GaN HEMTs. Our standard structure was used to study device reliability (see figure 1a), while modifications to the substrates and top structures provided reductions in cost and improvements in output power (see figure 1, b and c).

Addressing failure mechanisms

Our reliability tests were carried out with the GaN HEMT mounted on a conventional metal/ceramic package. We addressed the mechanisms limiting reliability – transconductance dispersion and large-signal drain-current degradation, which is commonly known as current collapse – with a fabrication process that controls the polarization-induced surface charges with a moderately-doped n-type cap layer. This approach differs from that of many researchers, who use an AlGaN cap, or dope the GaN cap either more heavily or not at all. Our moderately-doped GaN cap is fully depleted, and can suppress the strength of the electric field under the gate and screen the trapping effect.

We found that device degradation, which is the biggest obstacle to GaN HEMT commercialization, can occur on three different time scales: either just a few seconds, over one to two hours, or after several hours. The most rapid degradation produces an expo-

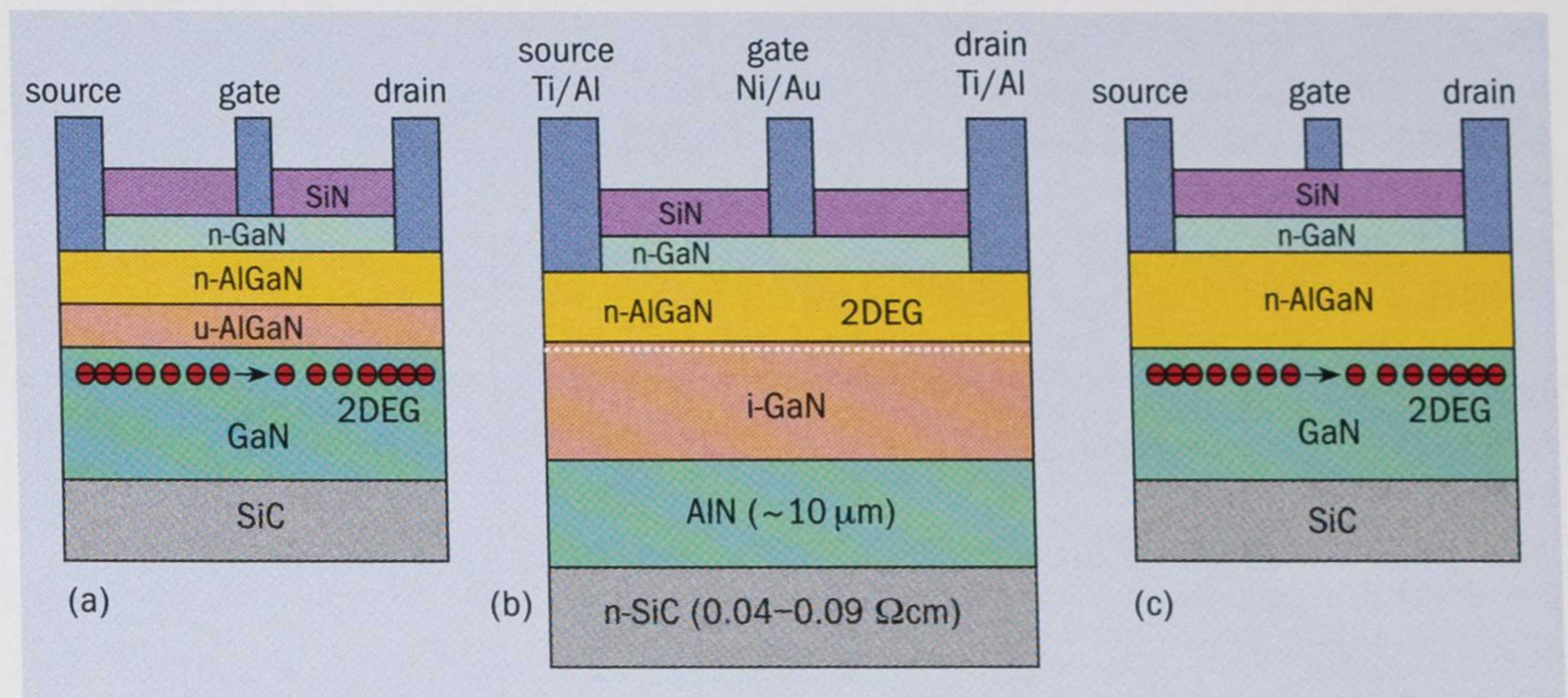


Fig. 1. At Fujitsu, we investigated reliability and yield issues with our standard structure, which is made on semi-insulating SiC substrates (a). The devices are reliable, but costly, and savings can be made by switching to cheaper conducting SiC substrates and inserting an AlN buffer layer into the structure (b). At higher output powers gate leakage current from the GaN HEMTs can impede performance, but this effect can be eliminated by using GaN MIS-HEMTs that have the gate contacted to the SiN layer instead of the n-doped GaN cap (c). n-doped, undoped and intrinsically doped layers are designated by n, u and i.

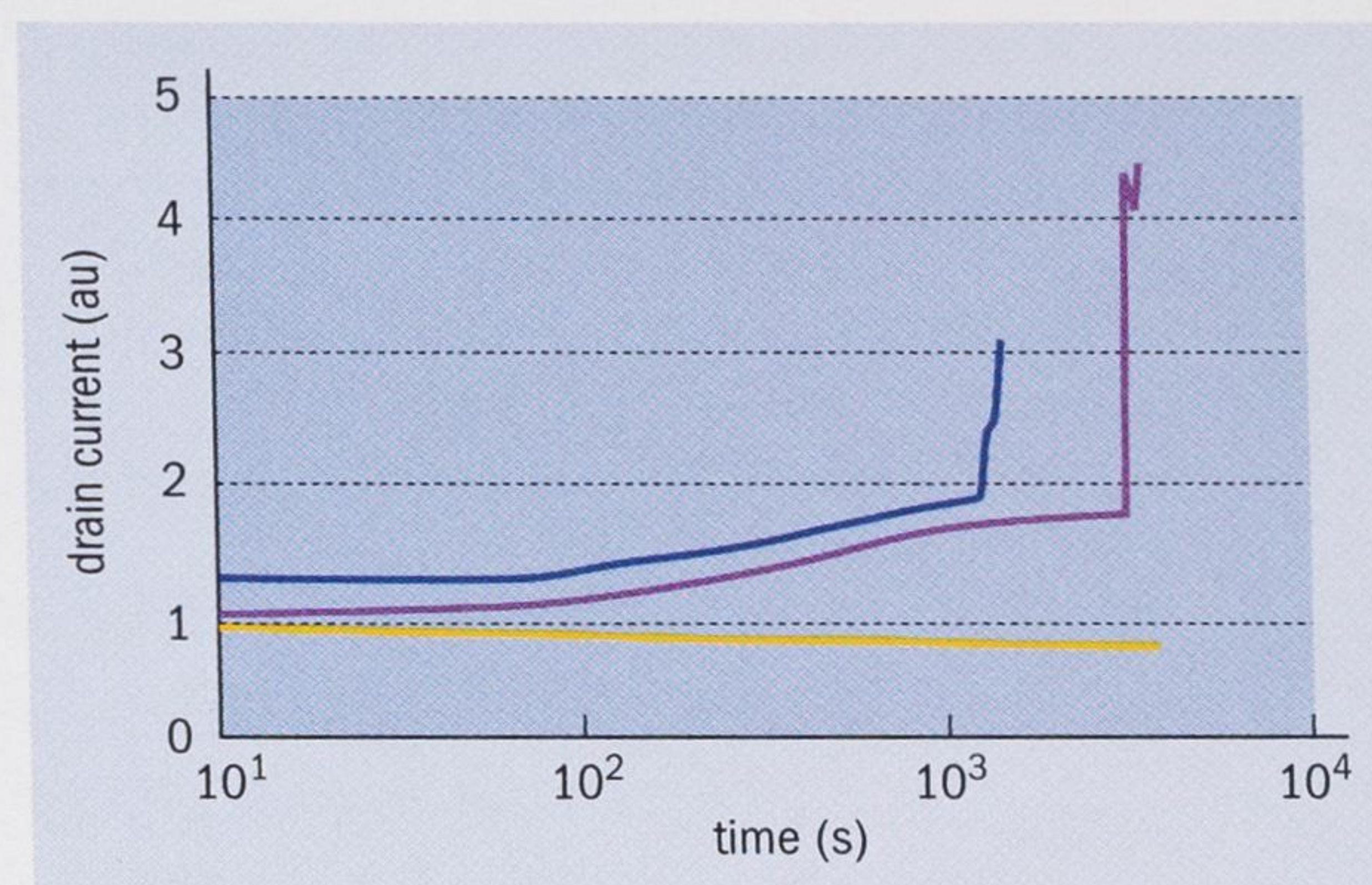


Fig. 2. The sudden increase in drain current after several hours of operation appears to be linked to device processing and epitaxial layer quality. This test was conducted at 150 °C and at a gate-source voltage of -3 V.

ponential increase in the gate leakage current and can be eliminated by improving the interface stability between the gate electrode and the GaN surface.

Sudden device failure can also occur after one to two hours of a high-temperature direct-current stress test and appears as a drain current spike (see figure 2). The likelihood of failure depends on the quality of the epitaxial layers and the processing steps. The transistor can still operate after it has degraded, and room-temperature leakage current measurements at low gate-source voltages cannot identify the damaged devices (see figure 3, p24). However, if the test is repeated at 150 °C the defective device is exposed by a leakage current increase of two to three orders of magnitude.

We also witnessed a gradual degradation in the HEMT output power of less than 0.5 dB during a room-



This report is based on Toshihide Kikkawa's paper "Recent progress of highly-reliable GaN HEMTs for mass production" that won the best paper award at this year's CS Mantech show. The other authors on the paper were Kenji Imanishi, Masahito Kanamura and Kazukiyo Joshin.

Fig. 3. (left) Room-temperature tests of the gate leakage current at gate-source voltages (V_{GS}) close to 0 V cannot distinguish between degraded and undamaged devices. At 150 °C, however, the degraded devices have a much higher leakage current at all V_{GS} values.

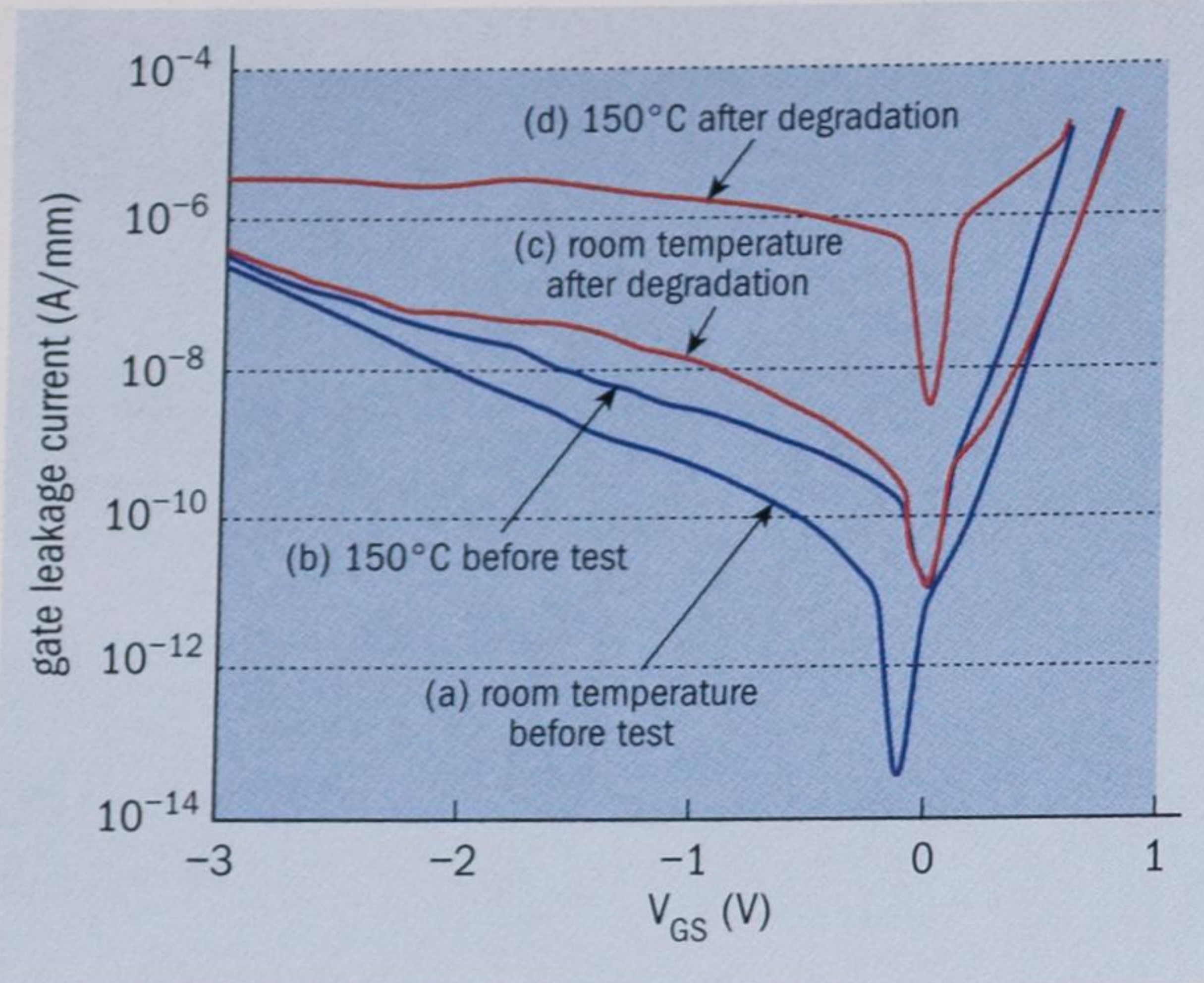


Fig. 4. (right) The small changes in output (ΔP_{out}) and drain-source current (I_{DS}) when the device is operated at a drain-source voltage of 60 V prove the reliability of these GaN HEMTs.

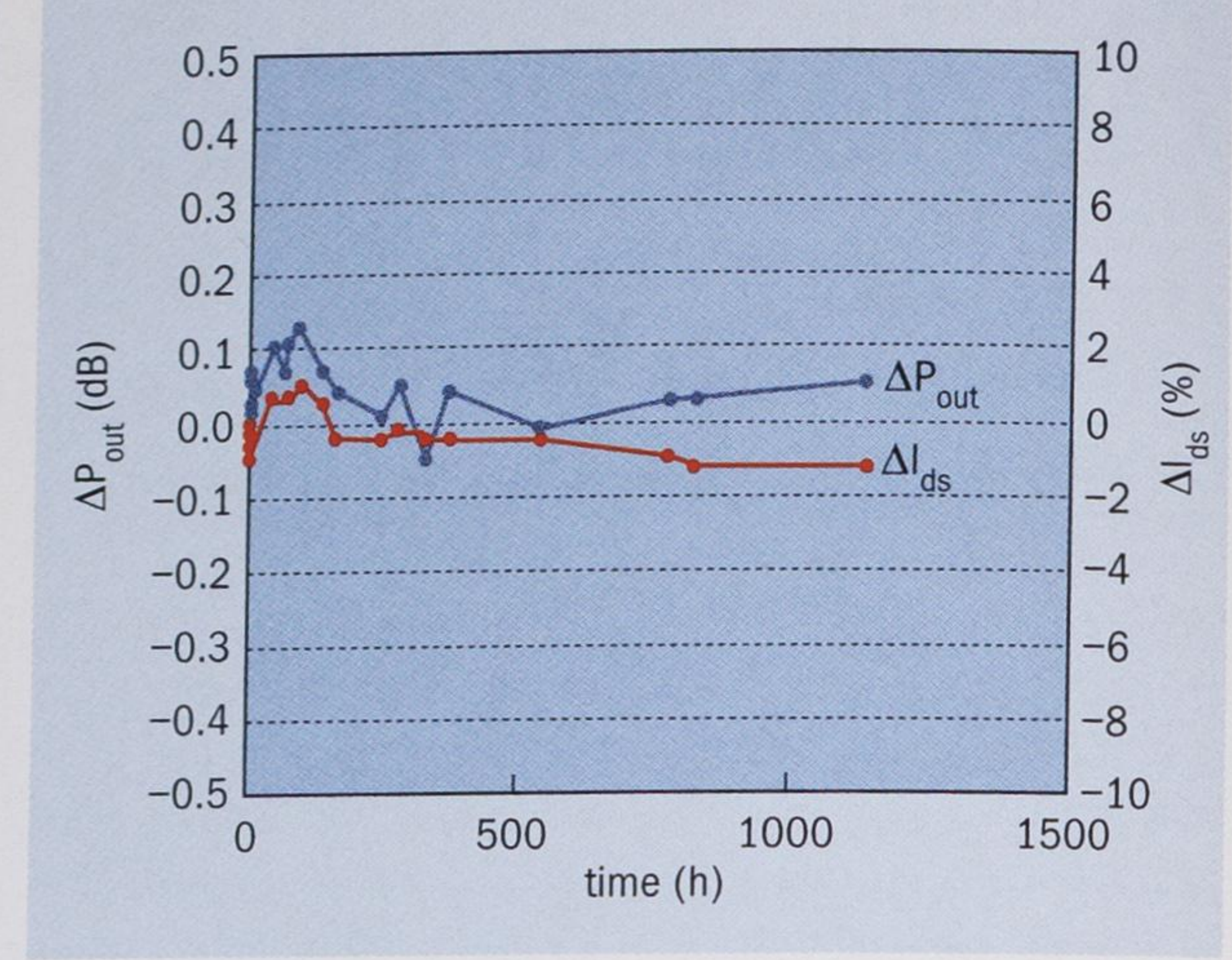


Table 1. The AlN buffer-layer quality strongly influences device performance. Device A, which has a lower surface roughness than device B, has superior RF and DC characteristics that are comparable with devices grown on semi-insulating (SI) substrates.

The effect of AlN quality on GaN HEMTs			
	SI	Device A	Device B
P_{out} (W/mm)	5.2	5.2	3.1
PAE (%)	63	56	51
Current collapse	small	small	large
AlN FWHM (ω scan) (arcsec)	—	280	970
AlN FWHM ($\omega-2\theta$) (arcsec)	—	25	76
GaN FWHM ($\omega-2\theta$) (arcsec)	31	39	42
RMS @1 μm^2 (nm)	0.16	0.27	0.41
RMS @25 μm^2 (nm)	0.22	0.48	1.95
Mobility ($cm^2/V/s$)	1750	1670	1610

temperature P3dB-RF stress test (this compression test compares RF input and output signals, and determines the point at which gain falls by 3 dB from the linear gain that occurs at low input powers). This degradation depends on the process conditions of the surface layer and the quality of the buffer layer. We addressed these concerns by optimizing the transistor's pulsed I-V characteristics with fabrication process improvements, and produced devices with suppressed efficiency degradation (see figure 4). By preventing any device degradation on this, and the two far shorter time scales, we proved the reliability of the GaN HEMTs.

Cutting manufacturing costs

GaN HEMT prices will strongly depend on yield and consequently substrate quality. Today, many SiC substrates have pits that can reduce device efficiency – due to an increase in the source-drain current – if electrodes are deposited on top of these defects (see figure 5, p26). This is not a significant issue for relatively low-power transistors that have gate electrodes of typically 1 mm, since the yield for these devices is only weakly dependent on pit density. However, hexagonal pit densities of less than 1 cm^{-2} are needed for the large-periphery gate die used for transistors delivering higher outputs, such as 100 W.

GaN HEMTs also need to have a low memory effect – a small value for the hysteresis between the input and output powers. This effect can be examined by looking at a third-order intermodulated signal that is

produced from two signals and results from the non-linearity of the amplifier. The memory effect of this third-order signal is relatively weak over a wide frequency range, which is due to SiC's good thermal conductivity and high load impedance.

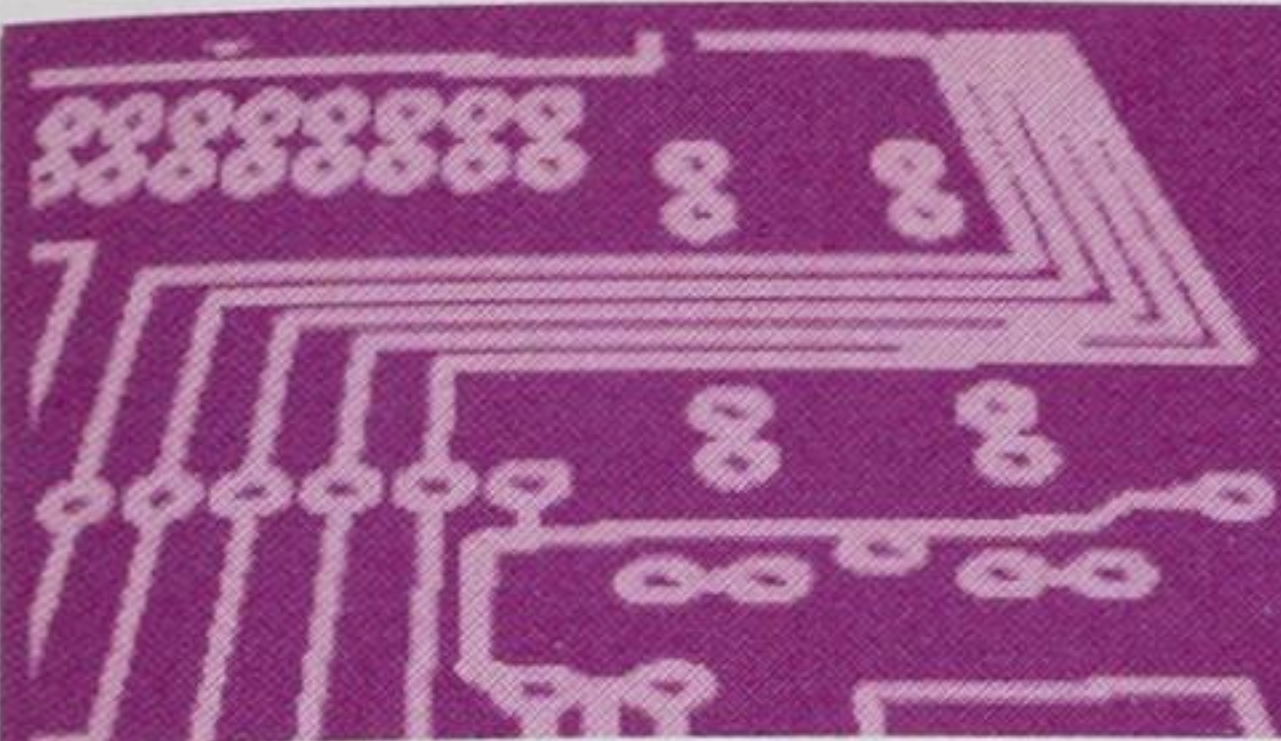
We also built GaN HEMTs on n-doped SiC, which could cut production costs by between two-thirds and one-half. These lower cost substrates offer a good mix of price and performance, because although they are not as cheap as silicon or sapphire, they produce the same thermal memory effect as semi-insulating SiC.

These substrates do have the problems that are associated with any conductive substrate, such as parasitic capacitance and isolation leakage, but we addressed these issues by inserting a 10 μm thick HVPE-grown AlN buffer between the transistor and a 3 inch SiC substrate (see figure 1b). The quality of the oxidized AlN layer strongly influences the GaN layers' roughness and device performance (see table 1). The root-mean-square (RMS) value for surface roughness increased with scan area, and we found it was easier to discriminate between the different surfaces with these wider scans.

Scaling it up

Two years ago, we reported that we could produce 100 W GaN HEMTs on 2 inch conductive SiC substrates, and now we are developing the transistors on 3 inch material because this will deliver lower manufacturing costs. However, large substrates bring their own problems, such as bowing, and MOVPE growth of the GaN HEMT structure produced an epiwafer bow of 8.7 μm . This level of deformation did not prevent the deposition of high-quality 0.8 μm long gates, and we were able to make 1 mm-gate-periphery GaN HEMT chips from the entire wafer. The transistors were operated at 60 V and delivered a continuous-wave output power density of 7.0 W/mm, and a power-added efficiency (PAE) of 70% at the 3G base-station transmission frequency of 2.14 GHz. Standard deviations for the power density, linear gain and PAE at 50 V across a whole wafer were 0.42 W/mm, 0.2 dB and 3%, respectively.

Next-generation networks will need to operate at



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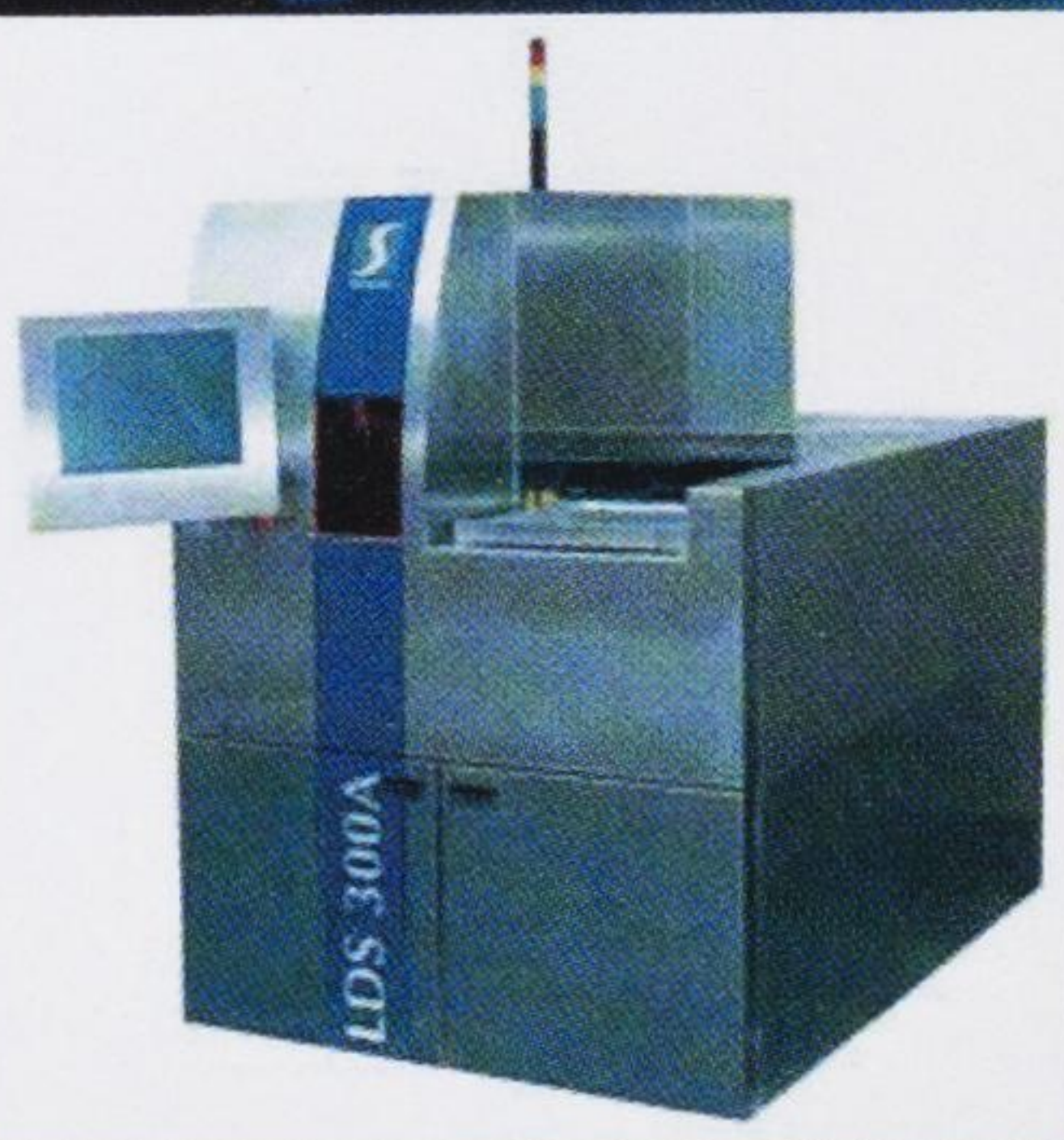
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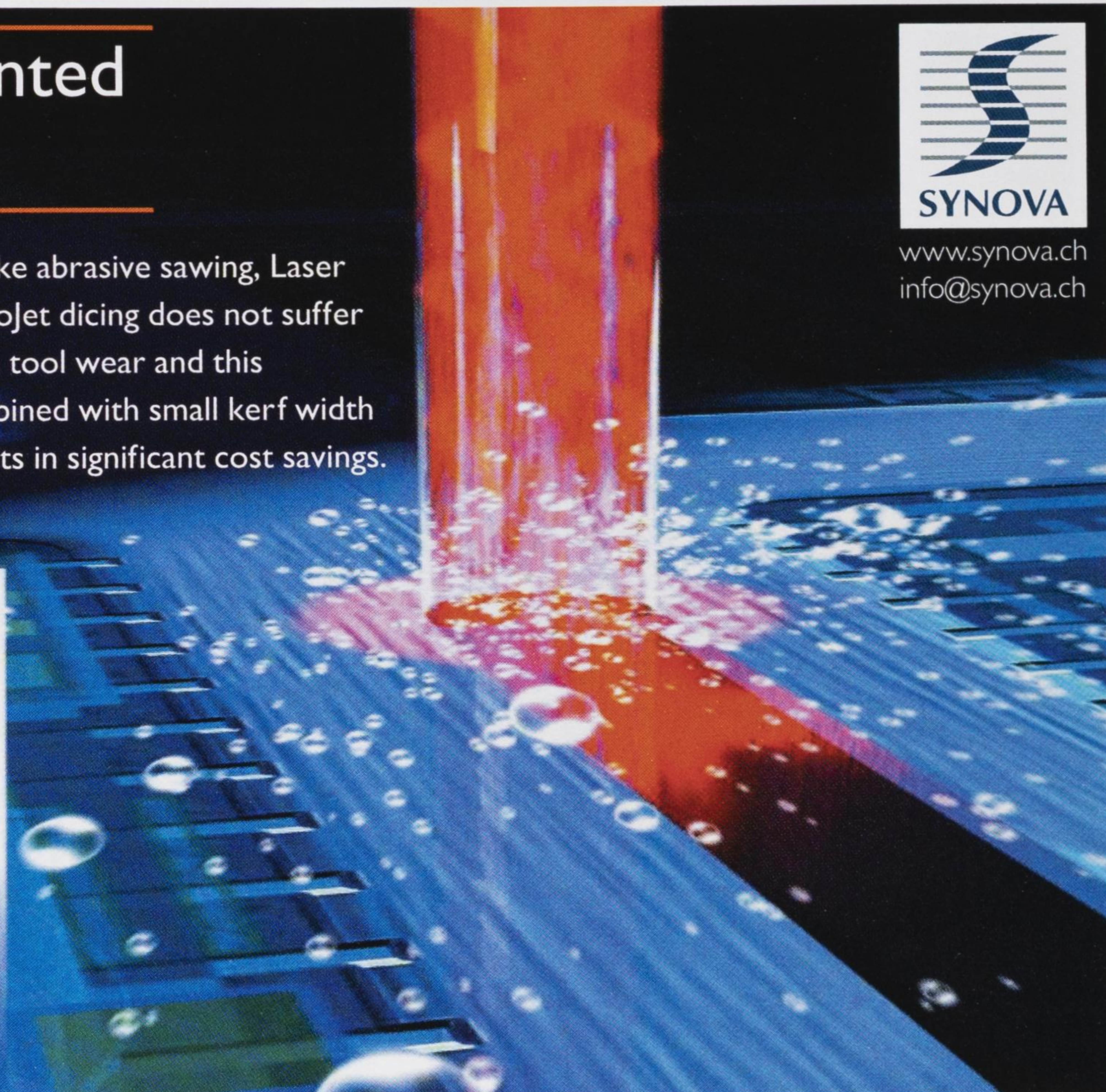
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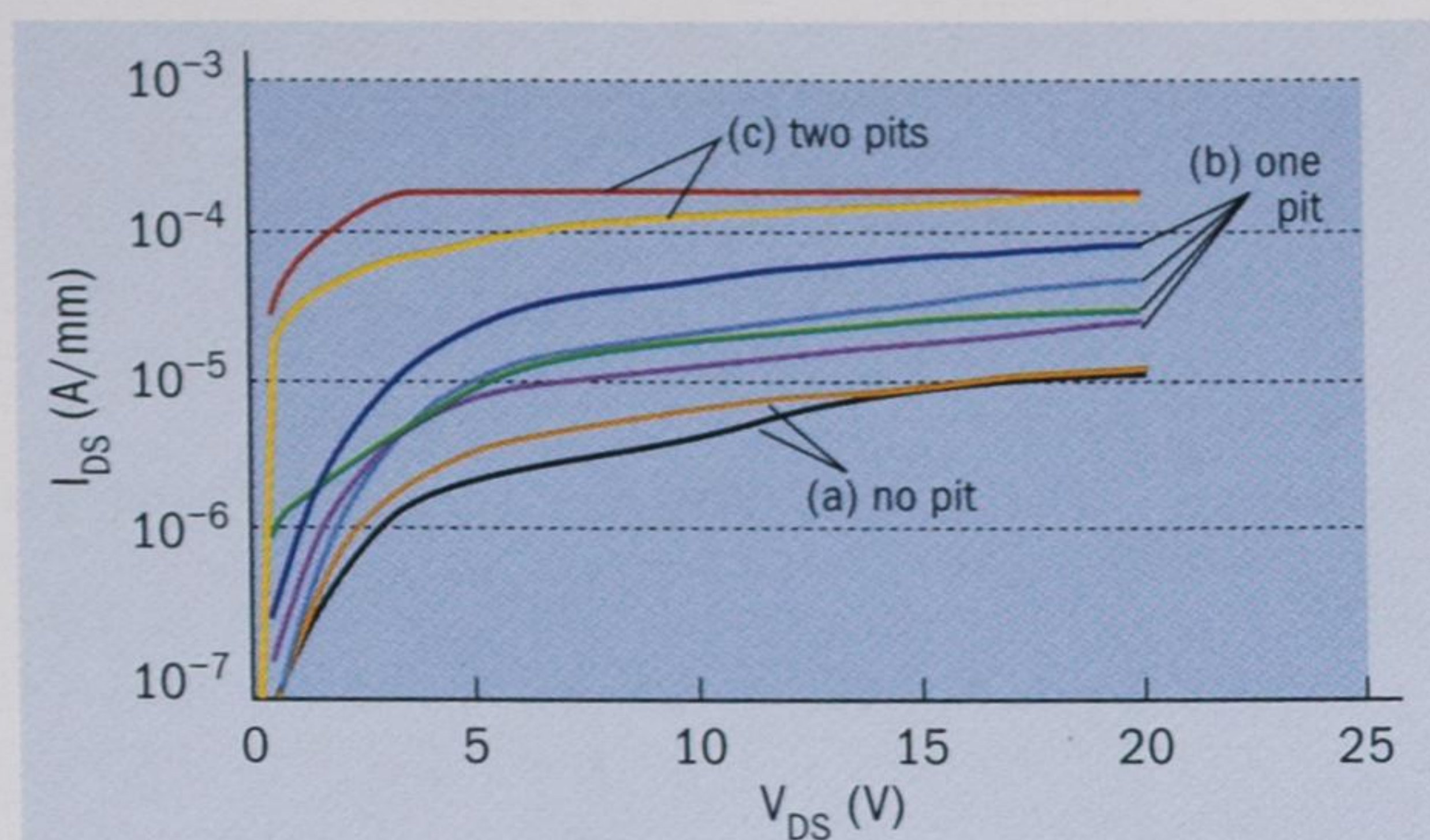


Fig. 5. SiC substrates with a high density of hexagonal pits can reduce device yield, particularly for large-sized devices. If the gate electrode touches a pit then the device's source-drain current (I_{DS}) rises and its efficiency falls.

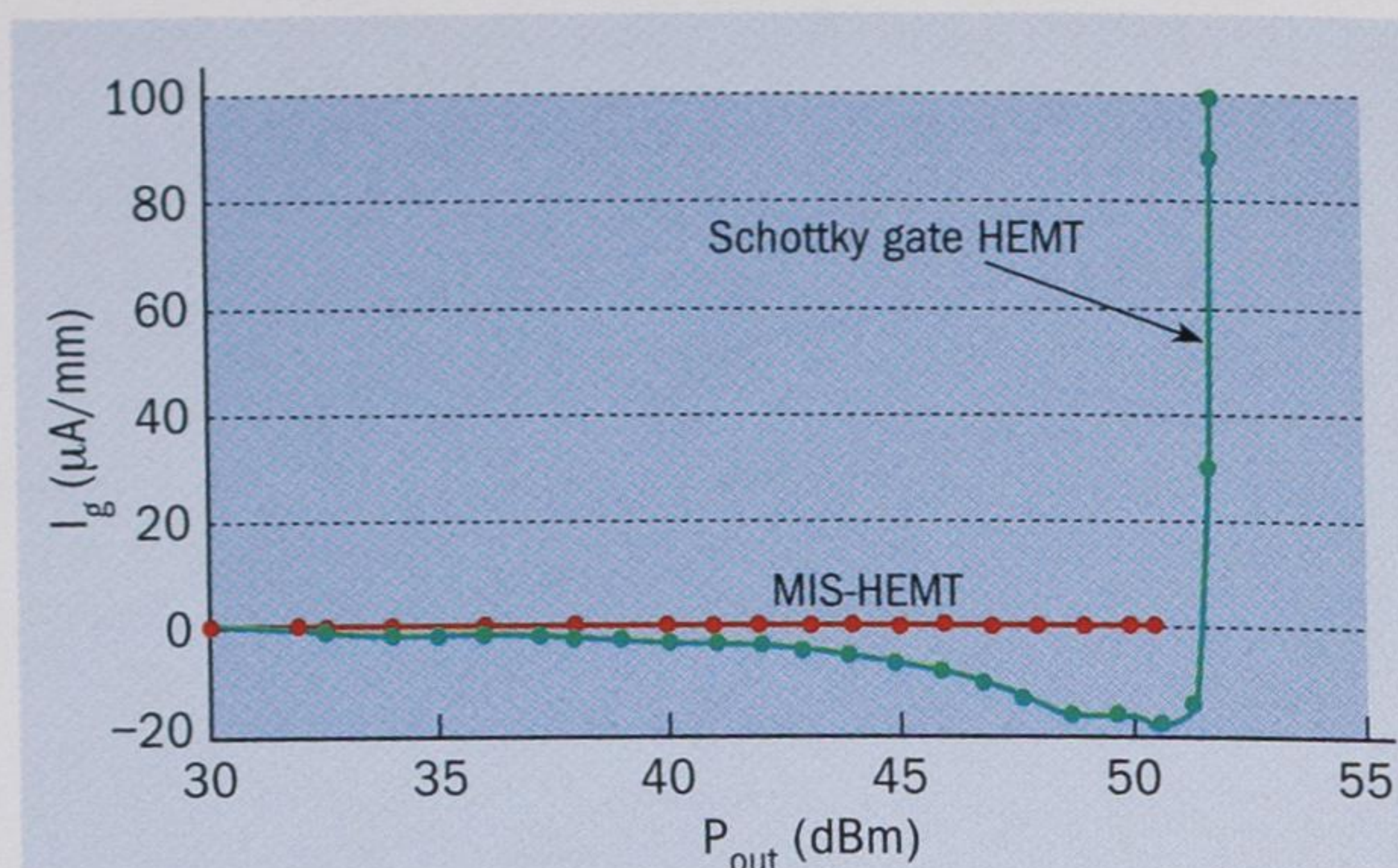
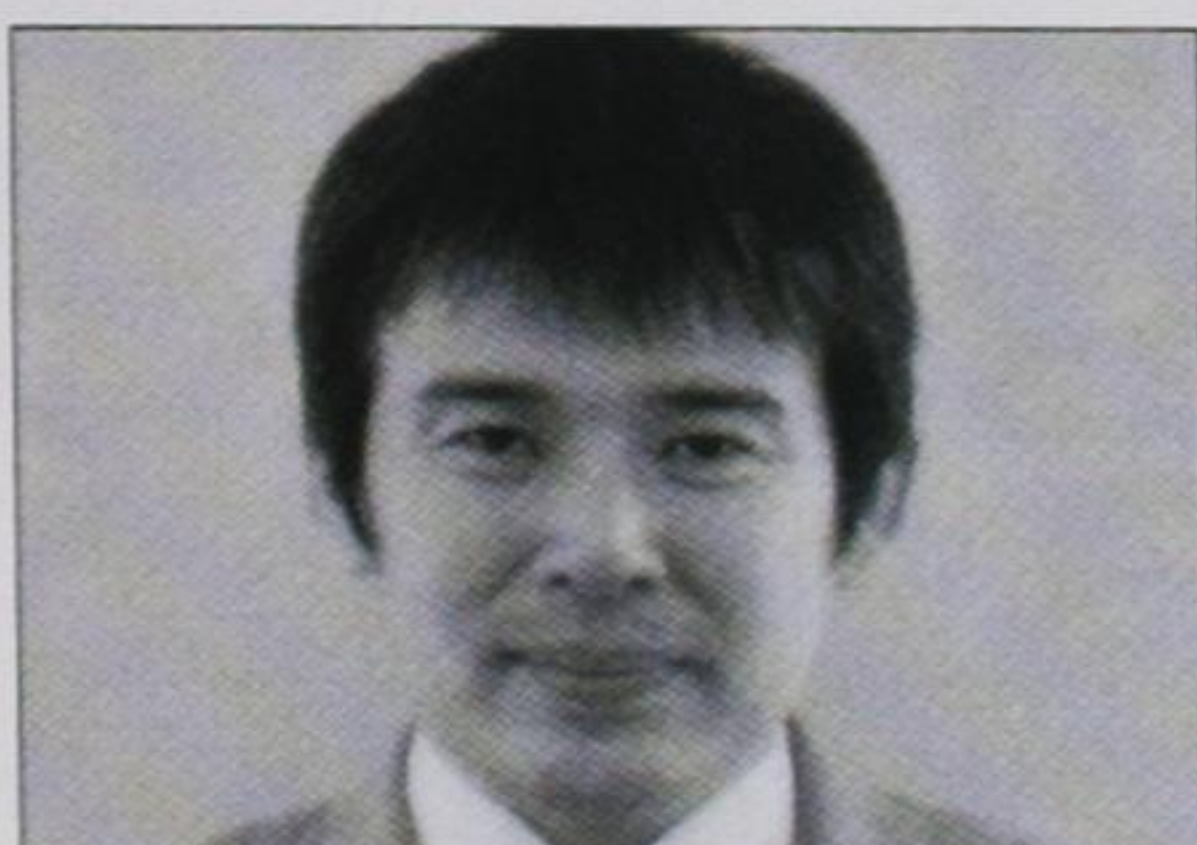


Fig. 6. The insulated-gate MIS-HEMTs have no significant gate current leakage (I_g) even at high output powers, making them strong candidates for amplifiers in next-generation wireless networks.



About the author

Toshihide Kikkawa is a senior researcher at Fujitsu, and is responsible for the fabrication processes to produce GaN chips that can be used in high-power amplifiers for RF infrastructure applications.

higher efficiencies in order to reduce power consumption. This means that the GaN HEMTs will have to operate much closer to their saturation point, but this leads to very high gate-leakage currents that degrade the device's reliability and amplification characteristics. To address this issue we developed GaN metal-insulator-semiconductor (MIS) HEMTs (see figure 1c) that deliver 110 W output with no forward gate leakage (see figure 6). These devices avoid having a semiconductor surface in contact with an AlGaN insulating layer that can easily oxidize and degrade performance,

and are the first insulated gate transistors that produce greater than 100 W. Initial reliability tests show that they have a stable leakage current over several hours.

Our GaN development program has addressed reliability issues in GaN HEMTs, demonstrated that these devices can successfully operate when grown on lower-cost conducting substrates, and led to the first GaN MIS-HEMTs capable of output powers greater than 100 W. We believe this progress shows that there is a very promising future for GaN transistors in tomorrow's wireless infrastructure market. ●

TRACE ELEMENTAL ANALYSIS

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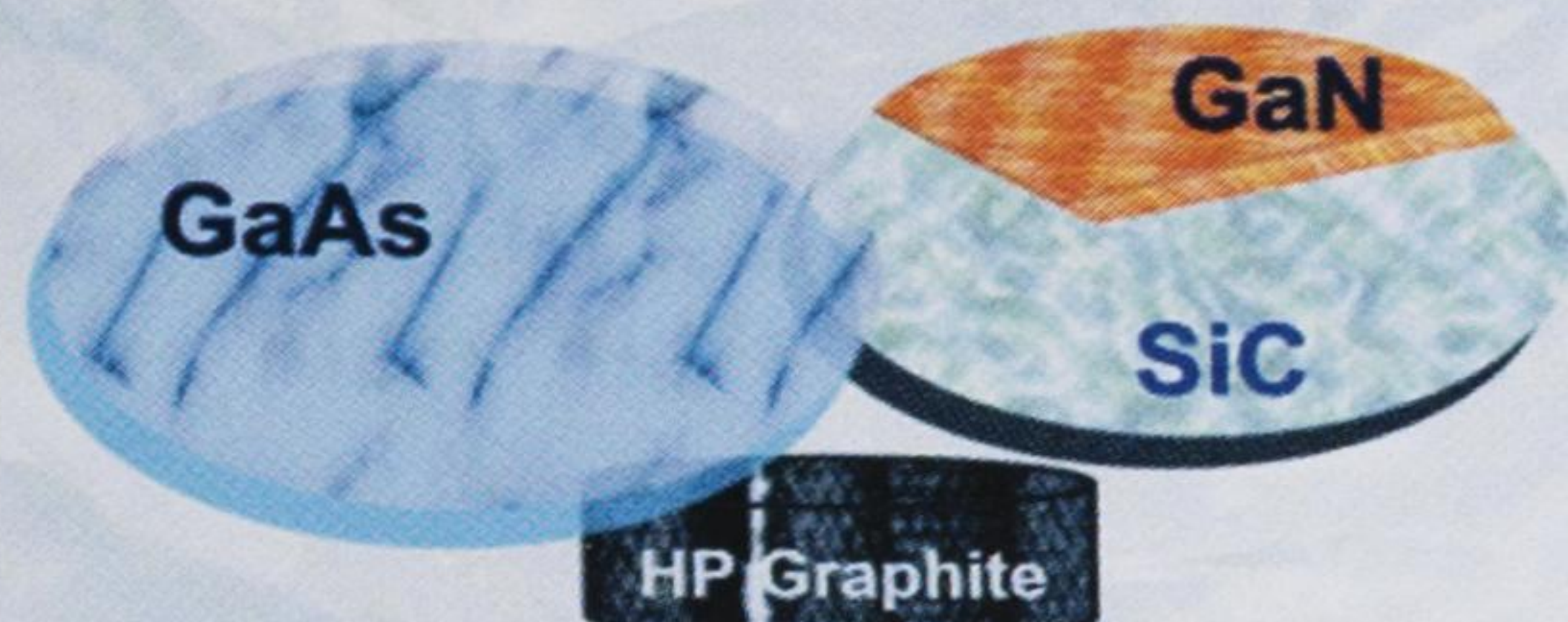
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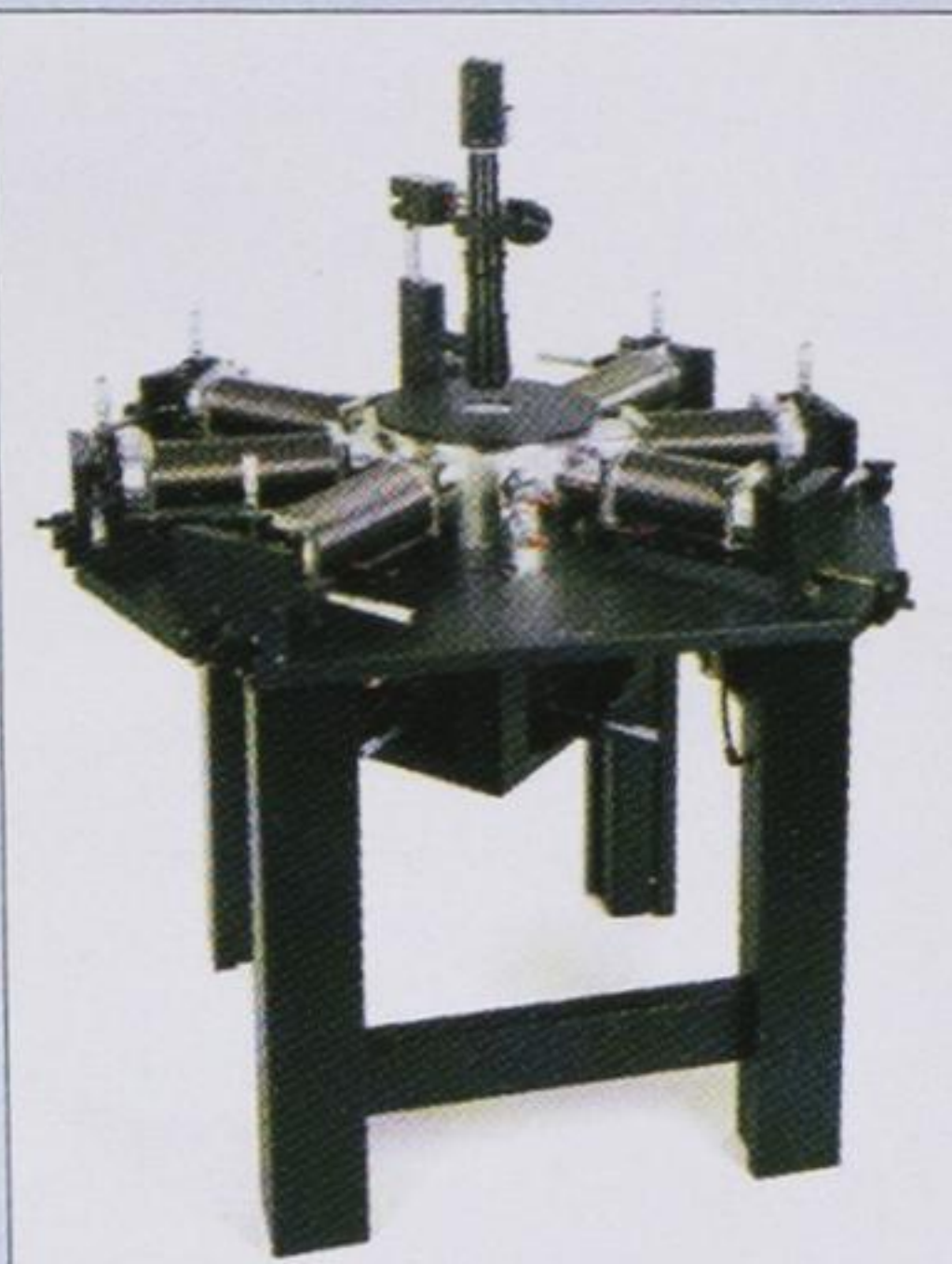
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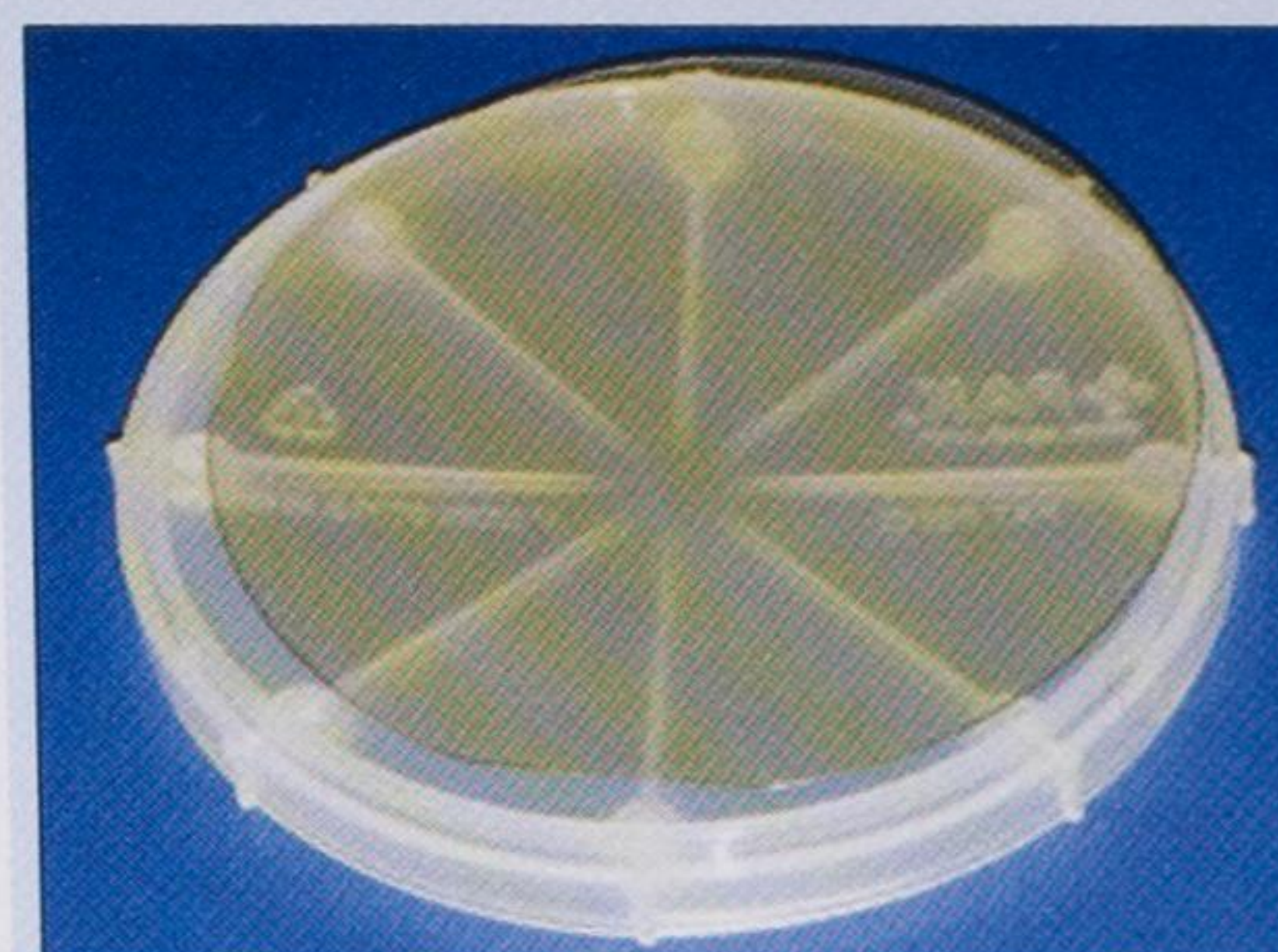
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Emerging Markets for GaN Electronics



Electronic devices based on gallium nitride promise to deliver unrivalled power and thermal performance for RF applications, but widespread adoption of the technology depends on whether manufacturers can produce high-performance devices at low cost.

This new Technology Tracking report, from the publishers of *Compound Semiconductor*, analyses the challenges facing GaN device makers as they seek to develop commercial products that can compete effectively with existing RF technologies.

The report includes critical information in each of the following areas:

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LASERS

German collaboration extends room-temperature VCSEL emission to 2.3 μm

A German team from laser-diode manufacturer Vertilas and the Walter Schottky Institute in Garching has extended the continuous-wave (cw) room-temperature emission wavelength of electrically pumped VCSELs from 2.0 to 2.3 μm .

This means that the multimode monolithic InGaAlAs/InP VCSELs have the potential to operate as sources for tunable-diode laser-absorption spectroscopy at wavelengths beyond 2 μm , where many important gases have absorption peaks. If singlemode versions of these lasers can be built, they could be used to detect CO₂ and CO, which absorb at 2004 and 2332 nm, respectively.

That would enable these lasers to replace the edge-emitting distributed-feedback InP and GaSb lasers that are used today for gas detection. Edge-emitting lasers are inferior because they do not exhibit a wide tuning

range, or offer high-speed measurement.

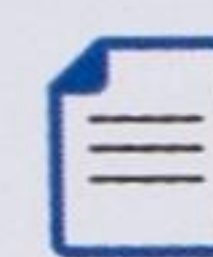
The latest laser is based on Vertilas' buried tunnel junction design (see *Compound Semiconductor* October 2005 p32). Its emission wavelength was extended from 2.0 to 2.3 μm by increasing the indium composition in the center of the InGaAs quantum well, which significantly lowers the transition energy. The center of this quantum well contains a 1 nm thick InAs layer, and the InGaAs composition is varied from this region to the interface with the barrier, where InGaAs is lattice-matched.

The multimode BTJ-VCSEL produces 1.47 mW cw output at 0 °C and 0.74 mW at 20 °C, but ceases to emit in cw mode at 45 °C. At 15 mA drive current the VCSEL emits at 2300.6 nm, while 30 mA produces lasing at 2304.8 nm, giving a maximum room-temperature tuning range of 4.2 nm. Side mode suppression is more than 20 dB at 15 mA, and

more than 10 dB at 30 mA.

The researchers say that the effective threshold current is 5 kA/cm², assuming that the carrier diffusion length is 1.5 μm . This is double the threshold current of shorter-wavelength BTJ VCSELs. However, the higher figure is not surprising because at longer wavelengths the losses from Auger recombination are stronger, as are free-carrier and intervalence band absorption.

Team member Markus Ortsiefer told *Compound Semiconductor* that the collaboration is now developing singlemode versions of the VCSELs for sensing applications. He revealed that these lasers will be implemented into systems for the detection of CO after they have been qualified.



Journal reference

M Ortsiefer et al. 2006 *Electron. Lett.* **42** 640.

LEDs

Cermet makes ZnO LEDs on n-type substrates

by Richard Stevenson in Montpellier, France.

Cermet's Varatharajan Rengarajan told delegates at the recent International Conference on Blue Lasers and LEDs (ISBLLED) that the Atlanta, GA, company has produced electroluminescence from ZnO LEDs fabricated on n-doped ZnO substrates.

ZnO LEDs offer potential advantages over those made from other compounds, such as lower threshold voltages, lower growth temperatures, wet-etch processing techniques and a larger exciton energy. However, progress



Cermet has fabricated ZnO LEDs with a turn-on voltage of 3 V and an emission peak at 384 nm.

has been hampered by problems with the growth of p-doped layers that are needed to form these devices.

Although Cermet can produce its own 50 mm ZnO substrates with an etch pit density of 10⁴ cm⁻², p-doping of these substrates is difficult. However, the company has developed an MOCVD process to produce p-type ZnO layers with a carrier concentration of 3 × 10¹⁷ cm⁻³ and a mobility of 4.6 cm²/Vs.

LEDs with a turn-on voltage of 3 V were fabricated using indium dots and multiple metal layers for the n-type and p-type contacts, respectively. When driven at 140 mA these devices showed strong emission at 384 nm, which Rengarajan believes is due to donor-acceptor pair recombination between shallow donors and nitrogen luminescent centers.

MICROWAVE AMPLIFIERS

InAs HEMT prototype breaks efficiency record

A team of engineers from the Naval Research Laboratory (NRL) in Washington, DC, claim to have broken the record for microwave amplifier efficiency with a new InAs HEMT design. The team's two-stage narrowband amplifier dissipates only 350 μW , while delivering 20 dB of gain at 2.5 GHz.

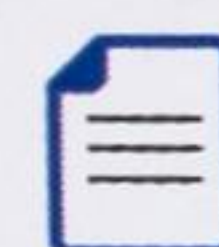
According to the NRL group, the amplifier's low power dissipation could increase the lifetime of battery-powered modules that provide

narrowband gain in the S-band (2–4 GHz) and very low noise.

The InAs HEMTs were grown by MBE on semi-insulating GaAs (001) substrates, and featured an AlGaSb buffer layer to accommodate the 7% mismatch between GaAs and InAs. The design used a 3 μm source-drain spacing and gate lengths and widths of 0.3 μm and 50 μm , respectively. The transistor's channel mobility was 25 000 cm²/Vs.

Using the InAs transistors to form an AC-coupled two-stage amplifier on a 1 × 0.75 inch circuit board produced record low-power dissipation at a bandwidth of 4%.

The prototype amplifier was built in hybrid form for convenience, but the design could easily be adapted for MMIC fabrication.



Journal reference

W Kruppa et al. 2006 *Electron. Lett.* **42** 688.

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Report 1: High-power LEDs

Efforts are still continuing to increase the total lumen output and improve the efficiency of high-power LEDs. This report analyses the technical innovations being made at both the chip and module levels, as well as the measures being taken to make high-power LEDs more price-competitive with traditional light sources.

Report 2: Performance and standards

Sustained growth in the LED industry is being hampered by the confusion that surrounds the performance metrics used to characterize LEDs, as well as the many different packages available from LED manufacturers. This issue will analyse the measures that are being taken, and must be taken in the future, in order for the LED community to achieve greater standardization and continued industry growth.

Report 3: White LEDs

The colour performance of white LEDs continues to be a major concern for lighting-systems developers and LED manufacturers. This report will evaluate current strategies to address such issues as colour variation between LED die; techniques for measuring colour output; colour shift during operation; and methods to produce white light more efficiently and with better spectral properties.

Report 4: Packaging and optics

This edition of *LED Quarterly Insights* will assess which packaging techniques are most likely to yield practical and affordable LED solutions, and will review new and emerging methods for optical design that will help to deliver the most efficient lighting systems.

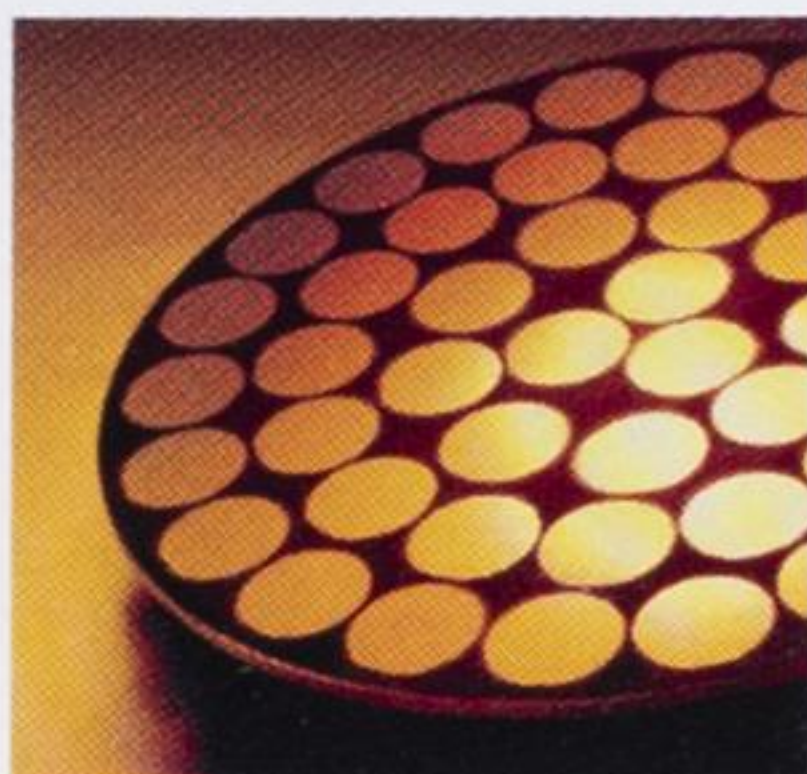
LED Quarterly Insights is a series of four in-depth reports, providing you with incisive analysis of the crucial technology innovations and commercial opportunities in the fast-moving LED industry. *LED Quarterly Insights* is essential reading for equipment and materials suppliers, LED device and module manufacturers, and lighting-systems developers.

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