

# COMPOUND SEMICONDUCTOR

January/February 2006 Volume 12 Number 1

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

## TRANSISTORS

**Cree's GaN HEMTs target US Navy radar**

## OPINION

**JDSU's Toby Strite on a strategic shift in laser diodes p13**

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### Switched on

LEDs and GaN lasers make a splash at the Consumer Electronics Show in Vegas. **p5**

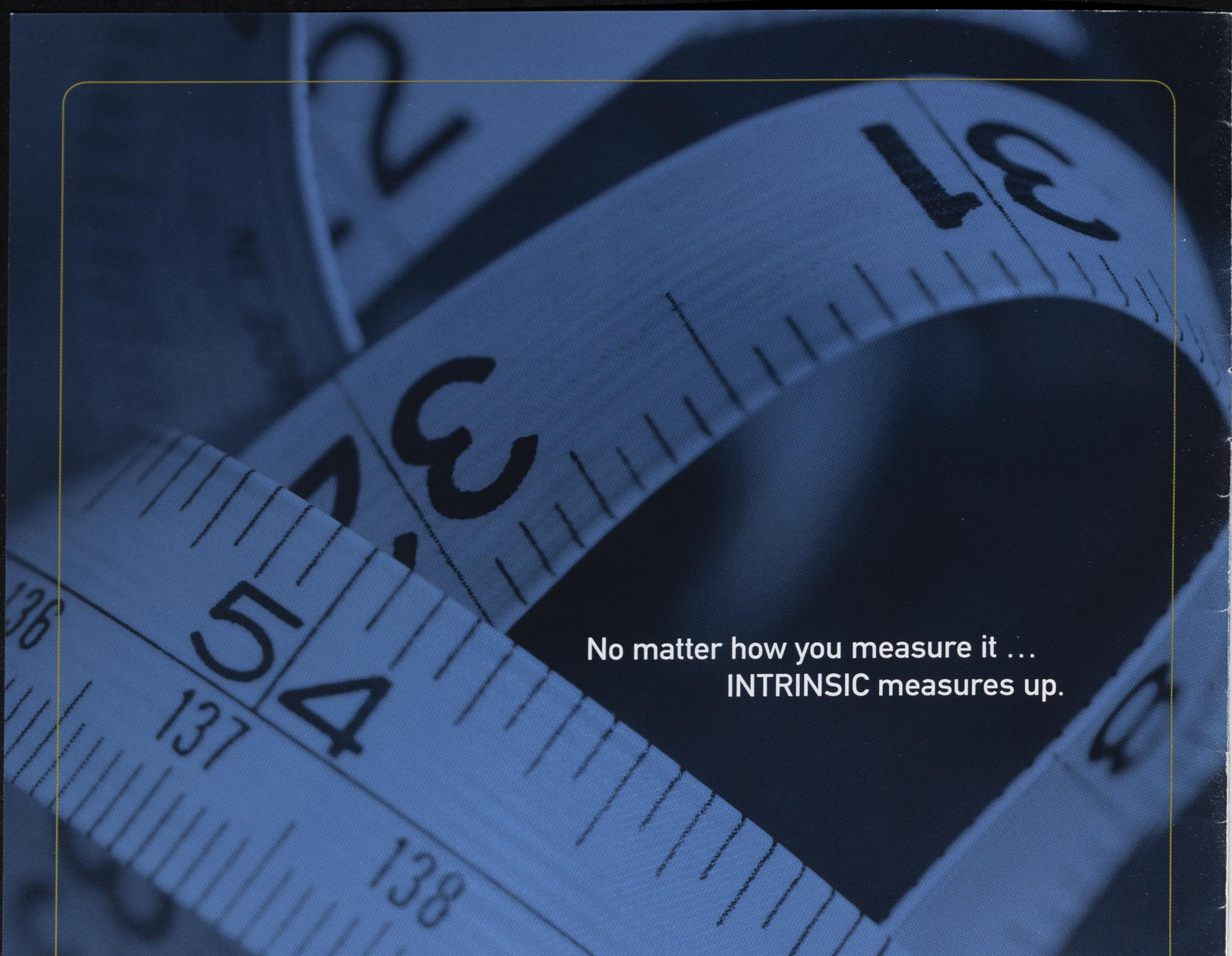
## TECHNOLOGY



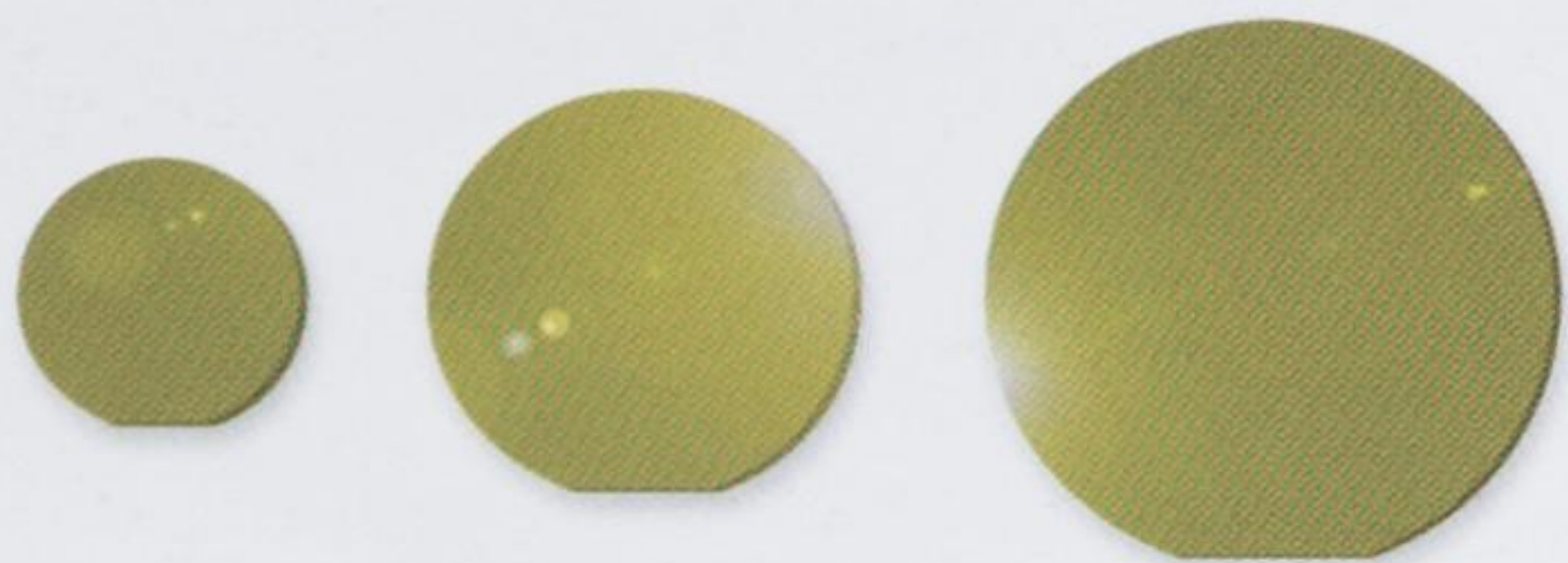
### Crowded house

Will the wealth of suppliers force down SiC substrate prices? **p16**





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## INDUSTRY

- 5** **Headline News:** Blu-ray and HD DVD blitz Vegas show...Foundry fraudster begins 14 year jail sentence for embezzlement...Connecting the compound semiconductor community.

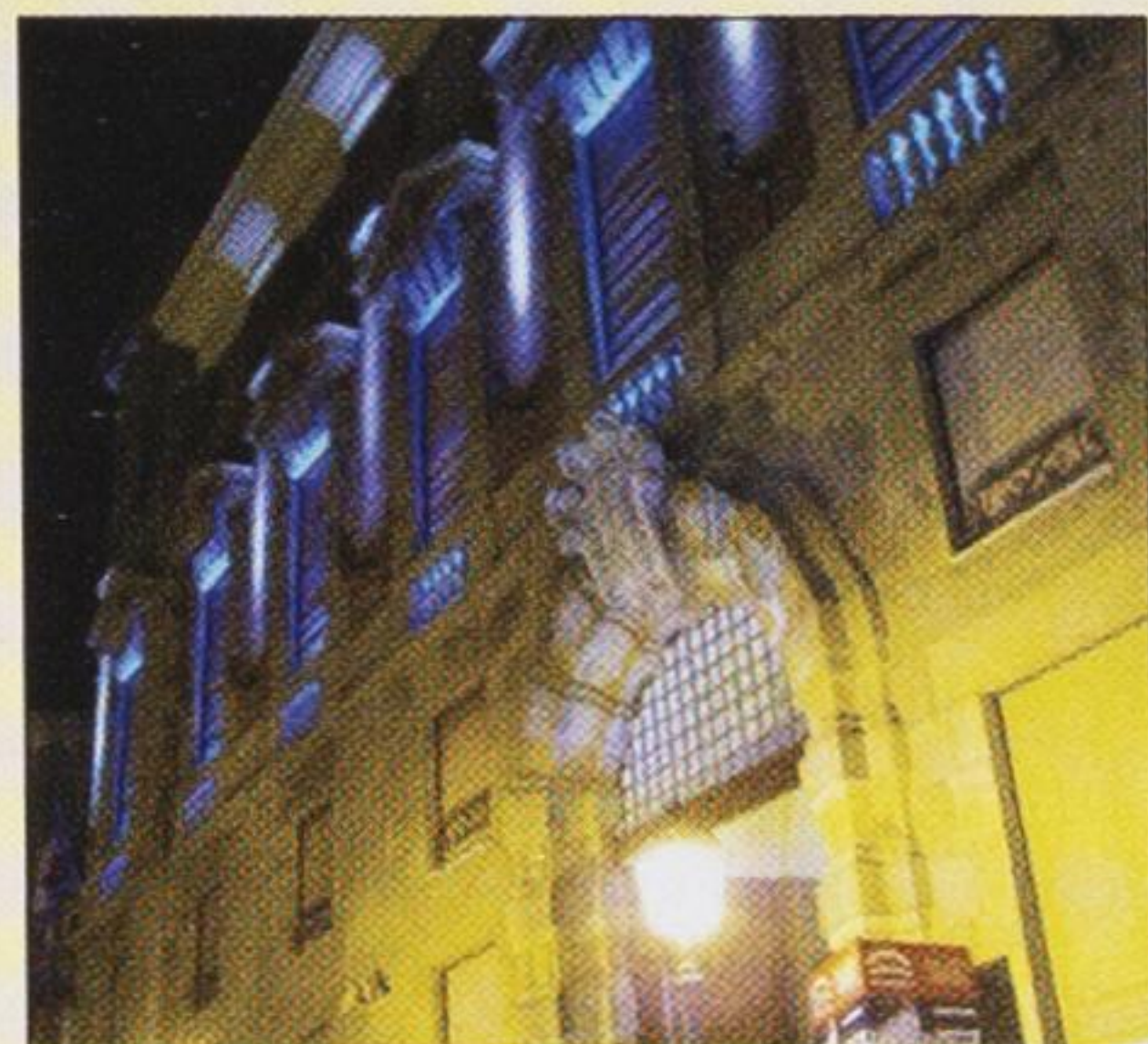


### The next generation

The Consumer Electronics Show in Las Vegas showcased next-generation DVD players, which will feature GaN-based laser diodes. **p5**

- 6** **The Month in RFICs:** Kopin ramps dilute-nitride production for phone PAs...RFMD expands Beijing plant to meet demand...Picogiga sales rocket as Soitec grows fast...Mobile WiMAX gets IEEE seal of approval...Freescale and Skyworks launch silicon technology to rival GaAs.

- 8** **The Month in HB-LEDs:** Samsung's new televisions use LED-based backlights...Cree and Space Cannon to light up Olympics...Trade Commission investigates Lumileds' allegations of violation...Novel concept for lighting homes and offices.



### Faster, stronger, brighter

Cree's power LED lamps will be used by high-profile lighting designer Space Cannon at the Turin Winter Olympics in February. **p8**

- 10** **The Month in Optoelectronics:** Bookham secures Nortel order worth \$72 million...Boeing wins contract for satellites powered by triple-junction cells...Analyst tips solar cells for terrestrial success...Association bemoans company strategies.

- 13** **Opinion: Laser manufacturers get industrious** In the first of a two-part series, Toby Strite explains why leading makers of semiconductor laser diodes are switching development dollars away from telecom.

- 14** **Market Report: Ethernet evolution to drive VCSEL ramp** The 10 Gigabit Ethernet fiber-optic datacom standard will give makers of optoelectronic chips access to a mass market, reports Michael Hatcher.

## TECHNOLOGY

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- 21** **High-power GaN HEMTs battle for vacuum-tube territory:** The vacuum tubes used in today's millimeter-wave transmitters face an increasing threat from GaN HEMTs. Cree's Yifeng Wu and Primit Parikh are leading the GaN charge with designs that incorporate field plates, iron-doped buffer layers and a thin AlN interlayer to deliver a record power at 30 GHz.

- 25** **IEDM showcases power HFETs:** III-V device highlights at the 2005 International Electron Devices Meeting held in Washington, DC, included high-power GaN HEMTs with both single and dual field plates, and metal-insulator-semiconductor structures producing very low leakage currents. Richard Stevenson rounds up.



### Capital performance

December's IEDM in Washington, DC, included some hot research topics. **p25**

- 27** **Shallow etch could power dilute-nitride VCSEL breakthrough:** Alight Technologies is tackling the need for powerful long-wavelength, single-mode VCSELs by marrying its photonic-bandgap technology with Infineon's dilute-nitride platform. Dan Birkedal and Dirk Jessen detail the hybrid design and reveal why it will benefit datacom and telecom networks.

- 30** **Product Showcase:** II-VI Incorporated...Engis...Leighton Electronics.

- 31** **Equipment Update: Reflectance sensor eases the strain** A new reflectance sensor from LayTec aids LED development and manufacturing by providing *in situ* strain measurements of the epilayers. Richard Stevenson learns how German start-up Azzurro Semiconductors is using the sensor for GaN-on-silicon growth.

- 32** **Research Review:** UIUC researchers break speed record with 710 GHz pseudomorphic HBT...Extra quantum well boosts bandwidth and temperature stability...InP channel delivers reliability at 94 GHz.

**Main cover image:** Vacuum tubes are used in many radar systems, but the US military has pumped millions of dollars into the development of solid-state GaN devices, which will be smaller, cheaper, more reliable and quicker to build.



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# The last war



You know when Bill Gates gets up on stage to promote a new technology there's a pretty good chance that the *ubergeek* might just be on to something. In early January, Gates used his keynote presentation at the Consumer Electronics Show in Las Vegas to show off the delights of high-definition DVD, the Toshiba-backed optical storage format that relies on GaN-based blue lasers.

The message was clear enough – HD DVD is here. As well as high-profile next-generation DVD hardware releases from all the major consumer electronics suppliers, this year will also see Microsoft's Xbox 360 games console feature a new HD DVD option, while Sony's PlayStation 3 will rely on a Blu-ray Disc. So, at long last, the commercial era of the GaN laser has arrived. The challenge now is to ensure that supply meets demand. Just how great that demand will be remains to be seen.

Bill's enthusiasm is no bad thing, but to stimulate a real ramp-up in GaN laser manufacturing, we need consumers to go out and buy the technology in their millions. Will they go for it? Having coughed up hard-earned cash to buy DVD players and recorders relatively recently, it is much too early to say whether the appeal of Blu-ray and HD DVD is enough to extend beyond the early adopters.

Even if consumers do buy into it, Blu-ray versus HD DVD will likely prove to be the last format war over optical data storage. The emergence of Web-based content delivery and the incredible improvements in capacity made by developers of much smaller hard-disk and flash-based data storage could soon make such skirmishes a commercial irrelevance.

## New year – new look

This first issue of 2006 features our updated magazine design. As well as bringing in a fresher overall look, the new layout is intended to make the various parts of the magazine more distinctive. Our front-end covers industry news, market developments, opinion and analysis, with the back-end focused on technological innovation in compound semiconductor devices, materials and equipment. Your feedback – both positive and negative – is appreciated.

**Michael Hatcher** *Editor*

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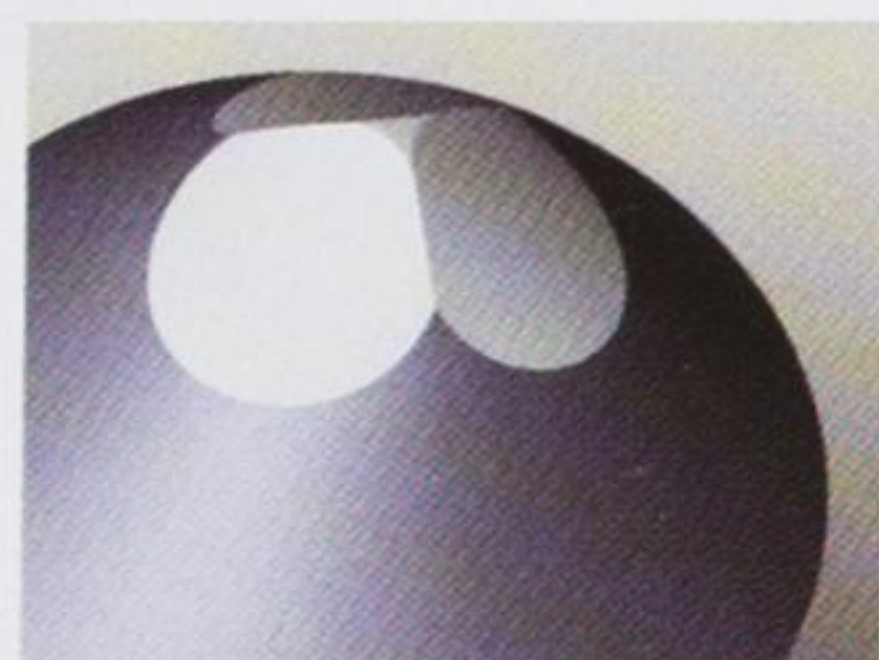
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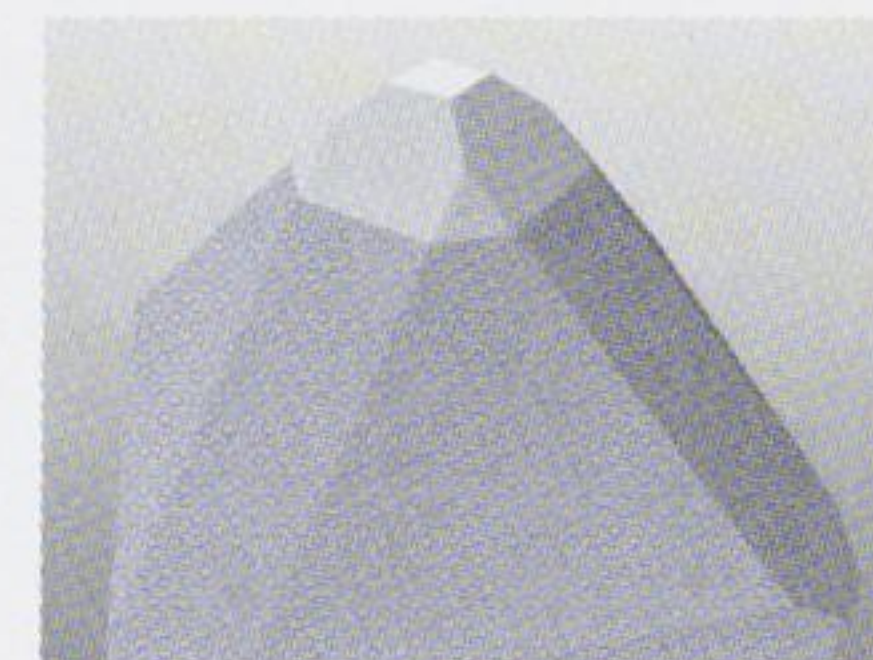
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## LASERS

# Blu-ray and HD DVD blitz Vegas show

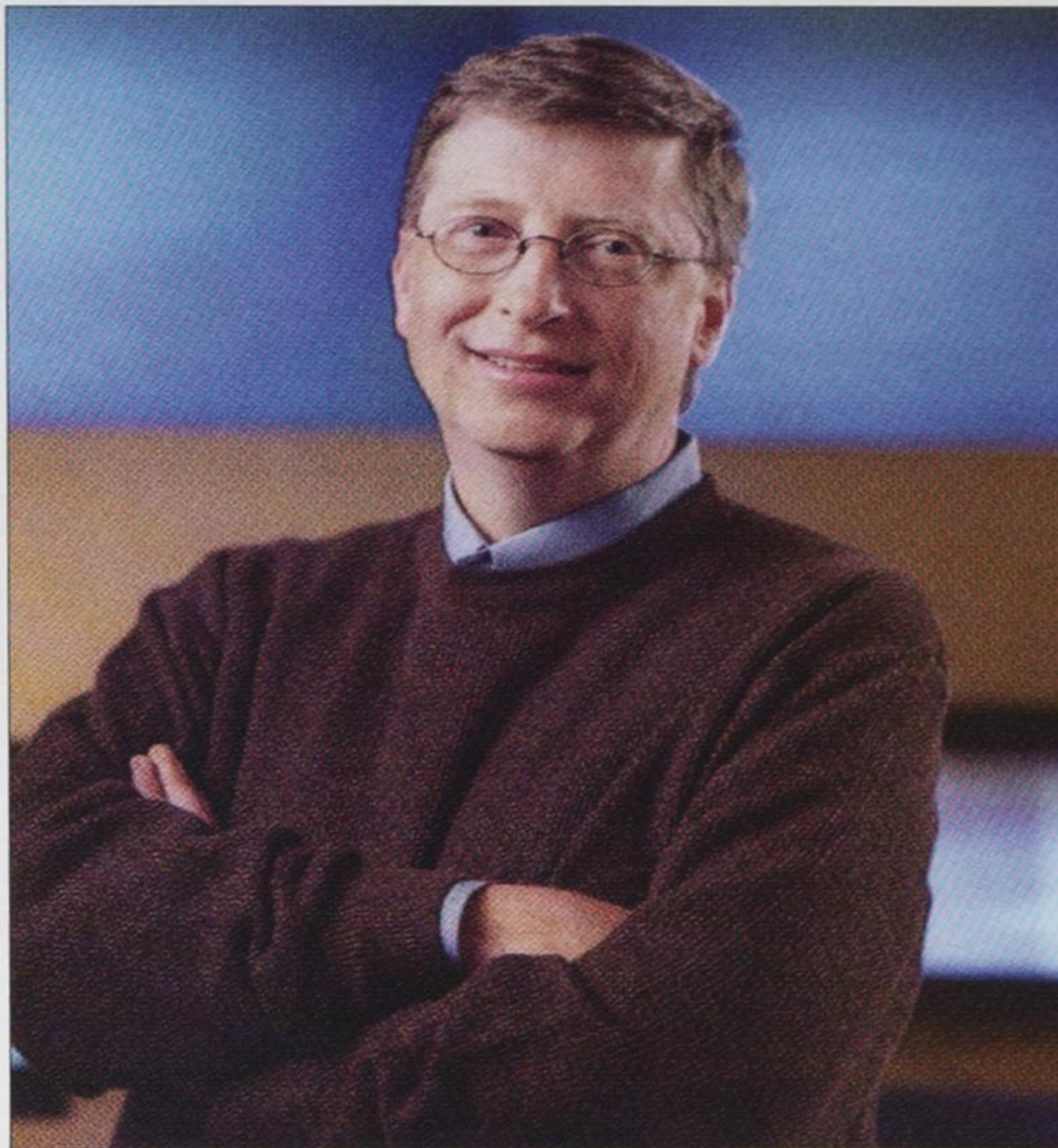
At long last, leading manufacturers have detailed the launch plans for their next-generation DVD hardware, and GaN-based blue laser diodes now finally appear set to enter volume production.

At the Consumer Electronics Show (CES) held in Las Vegas, Sony said that its first Blu-ray Disc home player, the BDP-S1, will be launched in the US in "early summer". Samsung plans a similar launch in "early spring", while Pioneer is aiming for June and Philips the second half of the year.

Sony's PlayStation 3 game system, which is set to use Blu-ray technology, will also launch in 2006, although the console is now expected to debut at the end of the year rather than spring as originally intended. Sony's Vaio computers will also feature the new drive format.

The US launch of both Blu-ray and the rival high-definition (HD) DVD hardware was originally slated for late 2005, but a variety of problems, including very poor yields from the semiconductor wafers on which the blue lasers are manufactured, appeared to delay that schedule.

Toshiba, Sony's key rival from the HD DVD camp, also unveiled its first players for the US market at CES. With a March launch date, and a sale price of \$499, Toshiba should



January's annual consumer electronics jamboree in Las Vegas saw Toshiba, Sony, Samsung, Philips, Pioneer and other manufacturers detail the release of their next-generation DVD players, all of which will feature GaN-based laser diodes. Keynote speaker Bill Gates (left) also revealed Microsoft's plans to offer an HD DVD drive for its new Xbox 360 videogames console.

beat Sony to market and undercut it on price.

Toshiba's date is expected to tie in with the release of around 50 movie titles in HD format from Hollywood studios, although Blu-ray proponents claim that copy protection and licensing issues will cancel out any time-to-market advantage that HD DVD might initially appear to have gained.

If Toshiba's low pricing strategy attracts

large numbers of US consumers then GaN laser fabs will need to ramp up wafer production and solve yield issues to meet demand.

The software giant Microsoft could add significantly to this demand with plans to offer an external HD DVD drive for its popular new games console, the Xbox 360, later in the year. Chairman Bill Gates opened CES with a keynote presentation.

## PROCOMP SCANDAL

## Foundry fraudster begins 14 year jail sentence for embezzlement

Sophie Yeh, the disgraced former chairwoman of Procomp Informatics, has been handed a 14 year jail sentence for embezzlement and violation of Taiwanese securities law.

Yeh, who established the Hsinchu Science Park GaAs foundry in 1991, has already spent several months behind bars following the financial scandal that engulfed Procomp in June 2004.

According to the local *Taipei Times* newspaper, 27 other executives of the company, which housed both MBE and MOCVD fabrication techniques, were also convicted at the Shihlin District Court.

On top of the jail sentence, it is reported that Yeh received a fine of NT\$180 million (\$5.4 million), although this pales into insignificance compared with the alleged scale of the fraud, which involved "missing" liquid assets of up to NT\$6.3 billion.

The fraud is now thought to have begun in

1994, although it was only uncovered a decade later when Procomp defaulted on a NT\$3 billion bond payment. According to prosecutors, reported *eTaiwan News*, that was because Yeh managed to cover up the illegal operation by first ordering Procomp employees to falsify shipment records, and then persuading them not to reveal the scam with large cash handouts.

Last year, *Compound Semiconductor* learned from a senior source in Taiwan that Procomp had shipped products to its own branch companies in the US with false invoices. "In other words, they did not have real sales and did not ship the products at all," revealed the source.

Yeh reportedly avoided most of the questions that were aimed at her during the prosecution by pleading that she was suffering from depression or could not remember what had happened.

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Be part of your community

As no doubt our more eagle-eyed readers will have already noticed, this issue of *Compound Semiconductor* looks a little different. We've updated our design to give the different sections of the magazine a more distinctive appearance, and we hope you like it.

In this and subsequent issues, you will also see some new sections, including regular opinion and interview pages, updates on specific innovations in equipment and materials technology, and industry analysis.

The idea behind these changes is to better serve you, the compound semiconductor community. As part of that drive, we want you to tell us about your opinions, company strategies, and innovations that will drive the industry forward. The ultimate aim is for this magazine, our *compoundsemiconductor.net* website and our events to be the focal point of the community. To be part of it, e-mail [michael.hatcher@iop.org](mailto:michael.hatcher@iop.org).



## EPIWAFERS

# Kopin ramps dilute-nitride production for phone PAs

Key HBT epiwafer supplier Kopin says that it has begun volume production of GaAsInN (GAIN) material destined to be used in cell-phone handset power amplifiers (PAs).

The company, which has worked on the development of the advanced technology with PA supplier Skyworks Solutions, expects “tens of millions” of faster PAs to be manufactured using the GAIN-HBT epiwafers with just the initial design-ins. It is forecasting weekly wafer shipments in the “low hundreds” throughout 2006, and has already dispatched circuits featuring this technology.

“The addition of indium and nitrogen reduces the bandgap energy for low-voltage operation, and the gradually varying composition creates an internal electric field for higher-speed operation,” explained Roger Welser, who has led the development of the new material. The key GAIN base epilayer is 50 nm thick, and InGaP and GaAs layers are used for the emitter and collector, respectively.

In addition, says Welser, the greater bandgap

difference between the GAIN-HBT emitter and base layer (compared with conventional InGaP HBTs) improves PA reliability.

Other advantages over InGaP include a base layer that allows good PA performance across a wider temperature range, and “potentially higher power efficiency”.

Matthew Micci, Kopin’s vice-president of sales, GaAs products, told *Compound Semiconductor* that the various improvements will enable handset makers to produce cheaper phones containing fewer parts that are more robust and less affected by temperature change.

Thanks to the close collaboration with Skyworks, the GAIN material, which is grown on both 4 inch and 6 inch substrates, can simply be dropped into the processing line in place of the InGaP wafers previously used.

Kopin revealed the start of volume production at the IEEE Topical Workshop in Power Amplifiers for Wireless Communication, which took place in San Diego, CA, on January 15–20.

## ASSEMBLY

## RFMD expands Beijing plant to meet demand

RF Micro Devices’ (RFMD’s) board of directors has approved the expansion of the company’s assembly operations, which are located in Beijing, China.

The expansion, which is expected to be up and running during the June quarter of 2006, should increase RFMD’s internal-assembly capacity by 50%. It will also enable the Greensboro, NC, company to meet a quarter of its assembly requirements in-house.

“Expanding assembly capacity is consistent with our overall goal of improving profitability,” said company CFO Dean Priddy.

“Our in-house assembly products have lower manufacturing costs, allowing improved gross margin versus components assembled by third parties,” he continued.

## FINANCE

## Picogiga sales rocket as Soitec grows fast

Picogiga, the French company that specializes in GaN-on-silicon and silicon-on-polycrystalline-SiC material, is on track to double its annual sales.

According to its parent company Soitec, which supplies silicon-on-insulator (SOI) wafers, in the nine months of the current fiscal year Picogiga’s sales have grown by 76.5%.

Already spectacular, that growth should increase over the next quarter, says Soitec, with the full-year Picogiga revenue for 2005–2006 set to double the 2004–2005 figure.

In the most recent quarter Picogiga’s sales surged to €2.6 million (\$3.1 million).

Meanwhile, the parent company is enjoying similar success, saying that the “era of the SOI wafer has arrived”. That appears to be the case: in a red-hot market, Soitec has increased its financial guidance on three occasions in the last year. Thanks largely to AMD’s success with SOI-based processors, total sales at Soitec more than doubled from last year to reach €70.9 million in the most recent quarter, prompting the third guidance notice.

AMD has now signed a whopping \$150 million contract with Soitec for calendar 2006. The two companies agreed a long-term deal in 2005 under which Soitec is supplying both 200 mm and 300 mm wafers manufactured using the so-called “Smart Cut” process.

Picogiga has also developed this process for GaN material, while Soitec is working on strained-silicon epiwafers and germanium-on-insulator technology.



### From our Web pages...

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#### ...two-stage power amplifier

W J Communications has expanded its portfolio of InGaP HBT intermediate power amplifiers with the release of its AH212 device. The component is a 1 W, high dynamic range, two-stage driver amplifier optimized for a range of next-generation wireless technologies including GPRS, GSM, CDMA and W-CDMA.

#### ...MBE reactor sales

Epitaxy equipment supplier Veeco Instruments has received orders for GEN2000 MBE systems from two leading suppliers of RFICs used in mobile applications. The customers will use the 7 × 6 inch multi-wafer systems for the manufacture of GaAs-based ICs used in power amplifiers (PAs) and deployed in handsets and wireless LANs (WLANs).

#### ...wireless modules

Anadigics has unveiled two integrated circuits for wireless LAN (WLAN) and multiple input multiple output (MIMO) applications that combine the power amplifier, low-noise

amplifier, and RF antenna switch on a single die. “Unlike other RF front-end solutions, Anadigics’ AWL6254 and AWL6255 are offered in an ultra-low-profile plastic package meeting the latest height requirements for use in consumer electronics, such as mobile phones, cameras, PDAs, and game controllers,” said Ron Michels, general manager of broadband products at Anadigics.

#### ...executive changes

Fabless manufacturer of RF devices Hittite Microwave has promoted Brian Jablonski from director of operations to vice-president of operations. In his new role he will oversee the company’s supply-chain management and manufacturing operations.

#### ...GaN HEMTs

Hitachi Cable has qualified Aixtron’s Close-Coupled Showerhead (CCS) system for the growth of GaN HEMT structures suitable for base-station and mobile telecommunication applications.



## REGULATIONS

## Mobile WiMAX gets IEEE seal of approval

In a move that should help the development of broadband wireless access (BWA) systems across the globe, the IEEE has approved the 802.16e "WiMAX" standard.

RF chipmakers will welcome the move, which extends the existing 802.16 standard that addressed wireless metropolitan-area networks (WMANs) for broadband access but previously supported only fixed, or stationary, terminals. The new standard covers fixed and mobile BWA subscriber stations moving at speeds typical of car travel. Mobile WiMAX will operate in licensed bands below 6 GHz.

A number of compound semiconductor chip companies, such as Nitronex, Cree, Eudyna Devices and TriQuint Semiconductor, are targeting WiMAX already, with components based on GaAs, SiC or GaN transistors.

Semiconductor suppliers have been heavily involved in the development of the standard in the past three years, said Roger Marks, the chair of the IEEE 802.16 working group on BWA. "The foundation for a global industry is now in place," he added.

Acknowledging that the road to development had been both long and difficult, Brian Kiernan, who led the IEEE mobile WiMAX task group, said: "The [new] standard gives service operators the ability to provide a wide range of revolutionary high-speed, mobile wireless applications and services that will greatly improve people's way of life."

The precise application areas where mobile WiMAX will end up deployed are not yet fixed, since the protocol faces stiff competition from other broadband services such as third-generation cellular technology.

One theory is that mobile WiMAX could prosper in more remote locations where cellular coverage is patchy or non-existent. However, to win this business it will have to battle against the satellite-phone technology that is also targeting this particular market.

Unsurprisingly, WiMAX Forum president Ron Resnick welcomed the approval of the standard. "The WiMAX Forum and its members can now move forward with confidence as we collaborate to ensure that certified products arrive by late this year or early 2007," Resnick said. "We have already achieved accelerated progress by developing system profiles based on the 802.16e specification and identifying conformance test tools and methods," he added.

Compound semiconductor firms in the WiMAX Forum include TriQuint, M/A-COM, Skyworks Solutions and Filtronic.

## COMPONENTS

## Freescal and Skyworks launch silicon technology to rival GaAs

RF chipmakers Freescale and Skyworks are launching silicon-based amplifiers and switches to complement their GaAs products.

Freescale has developed a power amplifier for 3.5 GHz WiMAX applications that is based on silicon LDMOS technology. The company's power transistor, which it says is the first LDMOS device to meet the stringent requirements for WiMAX base stations, could prove to be a tough competitor to GaAs- and GaN-based alternatives in the 3.5 GHz band.

The DMOS transistor is available for sampling and can deliver an output of 16 W, while two similar devices will be released soon.

However, Freescale is also continuing to develop its high-voltage GaAs PHEMTs operating up to 6 GHz for use in more demanding WiMAX systems and other applications.

Meanwhile, Skyworks is ramping production of two of its CMOS switches for satellite receiver applications. The Woburn-based com-

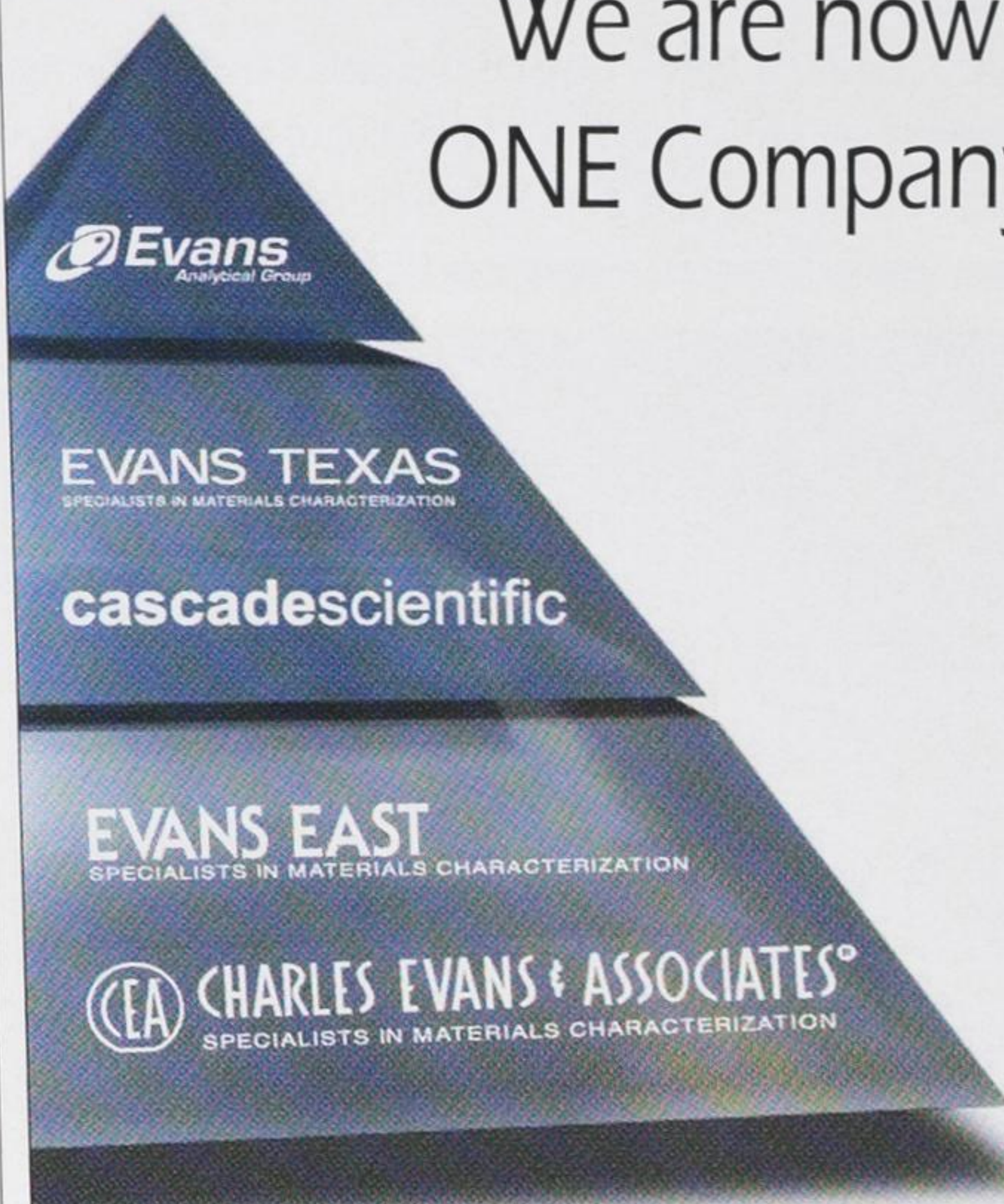
pany says that its switches (SKY13264-360LF and SKY13264-340LF) are cheaper, easier to implement, and provide greater integration than those using either GaAs or discrete silicon technologies.

The switches can be used in equipment that can receive signals from multiple satellites and access hundreds of different channels with just one dish. "We are capturing substantial market share just six months after the introduction of our RF CMOS solution," said Stan Swearingen, Skyworks' general manager of linear products.

• Another silicon-based RF switch technology, silicon-on-sapphire, is being offered by Peregrine Semiconductor. The company says that its PE42671 switch, which rivals GaAs PHEMTs and is suitable for WCDMA and GSM networks, can reduce the overall part count in an antennae switch module by as many as six devices and thirteen wire bonds.



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### SIMS Technology Advances at EAG

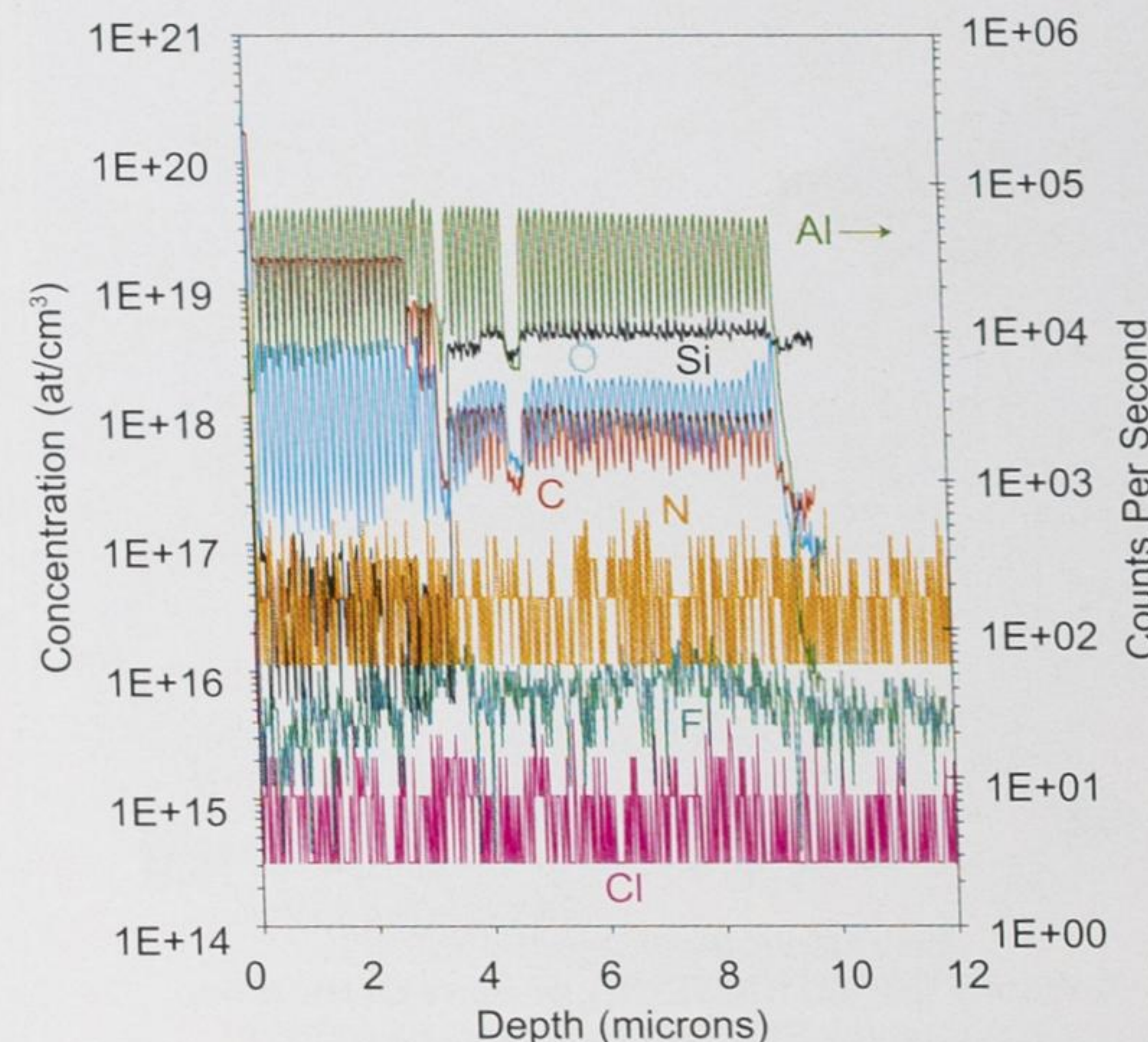
Most Accurate SIMS Characterization of

- Shallow Boron, Arsenic, Phosphorus Implants
- SiGe and devices
- Ultra thin (1nm) SiON
- Very small area (10 x 10µm) devices
- Dopants and Impurities of SOI films
- SiC and GaN

Characterization of Multi-Compositional III-V epitaxial Films

- AlGaAs, InGaP, GaInAsN, InGaAsSb, InP: HBT, FET
- AlGaAs/InGaAs, AlGaAs/InGaP: HEMT
- AlGaAs/InGaAlP/InGaP: VCSEL
- AlGaAs/InGaAs: Laser
- InGaAlP, GaN/InGaN: LED, HEMT

Small (50µm dia.) Area Analysis on a VCSEL Device





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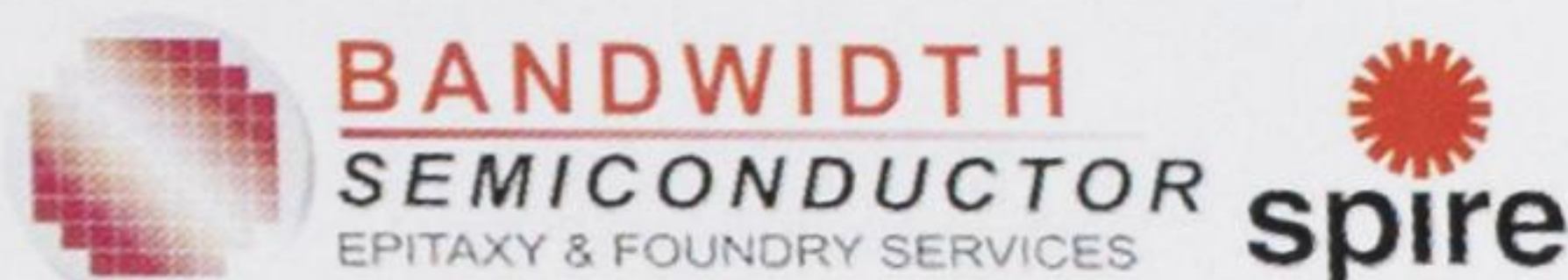
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## APPLICATIONS

# Samsung's new televisions use LED-based backlights

The Korean consumer electronics giant Samsung has unveiled some high-end televisions that feature LED-based backlights.

LED manufacturers are pinning their hopes on backlighting of large-area displays as a key new market for their devices as growth is slowing in today's biggest application area – illumination of cell-phone keypads and screens.

While the company's rival Sony has already released some top-of-the-range televisions featuring LED backlights, Samsung says that its 82 inch LCD is the largest commercial model to feature the technology.

Using LEDs means that the colors produced by the television are more "true to life" than in conventional sets that use a fluorescent backlight, particularly the color red. That's because the three-color LED backlights have a greater red component than the fluorescent tubes used in conventional flat-screen television designs, leading to what television makers call an "increased color gamut".

Samsung has also released a 56 inch rear-projection television that is said to be the first such screen to utilize LED backlights. The "LumiLit" backlight features red, green and blue LEDs.

The LED-lit televisions do not come cheap, however, with the 56 inch rear-projection screen set to sell for \$4199 when it is released



**This 56 inch television** from Samsung is the first rear-projection screen to feature LED backlights.

commercially in April. LED chip manufacturers will be hoping that the new backlight technology soon filters down to regular televisions and becomes a mass-market application.

The US chip manufacturers Cree and LumiLeds have both developed backlight "engines" for large LCD televisions and monitors. And last year German firm Osram demonstrated an 82 inch television backlight.



**The Winter Olympics** in Turin will be lit up by Cree's high-brightness LED XLamps, after the Durham, NC, company signed a \$5.4 million deal with the Italian lighting design company Space Cannon.

The lighting firm specializes in high-profile architectural lighting installations, and previous projects have included the Towers of Light to commemorate the World Trade Center Towers in New York, the 101 Building in Taiwan and the Palazzo Asperia building in Alessandria, Italy (pictured).

Space Cannon added that it plans to use Cree's power LEDs in all of its future solid-state lighting installations. "Cree has demonstrated superior products and technical support, which is why we are switching exclusively to XLamp power LEDs," said Space Cannon founder Bruno Baiardi.

Norbert Hiller, the VP of solid-state lighting at Cree, commented that he was "thrilled" with Space Cannon's switch to using the XLamp range of products.



## PATENT DISPUTE

# Trade Commission investigates Lumileds' allegations of violation

The US International Trade Commission (USITC) is to follow up the recent complaint of patent violation filed by Lumileds Lighting against two of its major competitors.

The technologies under dispute include Epistar's omnidirectional mirror adhesion (OMA) LED products and UEC's metal-bond and glue-bond LEDs. The USITC will investigate whether or not the two Taiwanese firms, which have since merged, are in violation of the US Tariff Act of 1930 by either importing the disputed products into the US, selling them for subsequent importation into the US, or selling

them directly into the US market.

Lumileds submitted evidence including an LED-based flashlight believed to feature a glue-bond UEC chip, and a beacon light said to contain an Epistar OMA device, to the USITC. If it finds in favor of Lumileds, the Washington, DC, body could stop US imports of Epistar and UEC products seen as violating patent law.

Lumileds has also taken its complaint to a district court in northern California, where it is looking for substantial damages for willful infringement by the companies.



**This novel concept** for lighting homes and offices from the Lighting Research Center in Troy, NY, integrates LED technology with building materials and systems to create electronic walls and ceilings. The design includes interchangeable, modular panels with LED lighting fixtures that "snap" in and out of an electrical grid. Occupants can change the location of light fittings or introduce new fixtures on a whim to satisfy their needs or their mood, says the LRC. The panels can be rearranged simply and rapidly to cater to changes in room layouts or personal preference.



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### ...Audi's daytime lights

The German car manufacturer Audi has revealed that a second vehicle in its high-end range will feature LED-based daytime running lights (DRLs). The Audi S6, scheduled for release in the spring of this year, has a strip of white emitters along its front bumper. Two years ago, the company's A8 6.0 became the first production vehicle fitted with LED-based DRLs, which were supplied by Lumileds.

### ...Cree licenses Kingbright

Cree has licensed its white LED patent to one of its chip customers, Taiwan-based manufacturer of LED-based lamps and displays Kingbright Electronic. Kingbright's license of US patent 6,600,175 will allow the company to add a color-converting phosphor to Cree's blue chips, and incorporate these white-light emitters into its products. According to the US chip maker, Kingbright will be using Cree's LED chips exclusively in its white LED products.

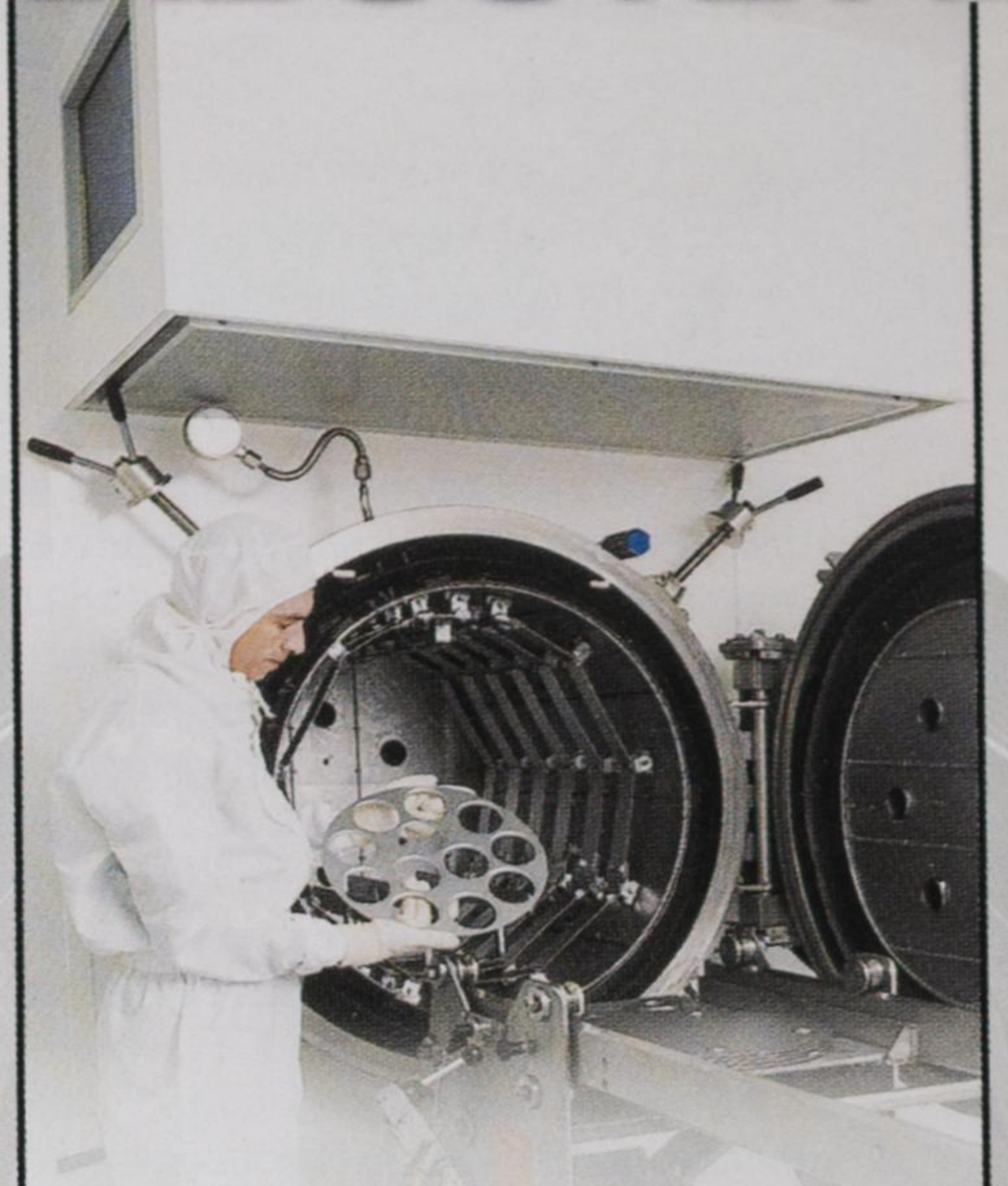
### ...Aixtron over the Rainbow

The Chinese LED manufacturer Rainbow Optoelectronics Material Shanghai has ordered a new Thomas Swan MOCVD reactor to increase its GaN device output. The new 19 x 2 inch Close Coupled Showerhead (CCS) system will complement Rainbow's earlier purchases such as the AIX 2600G3HT in a 24 x 2 inch configuration, and will also be used for the production of high-brightness (HB) blue LEDs. The MOCVD reactor will mean that Rainbow's facility has one of the largest GaN LED capacities in China.

### ...Everlight grows

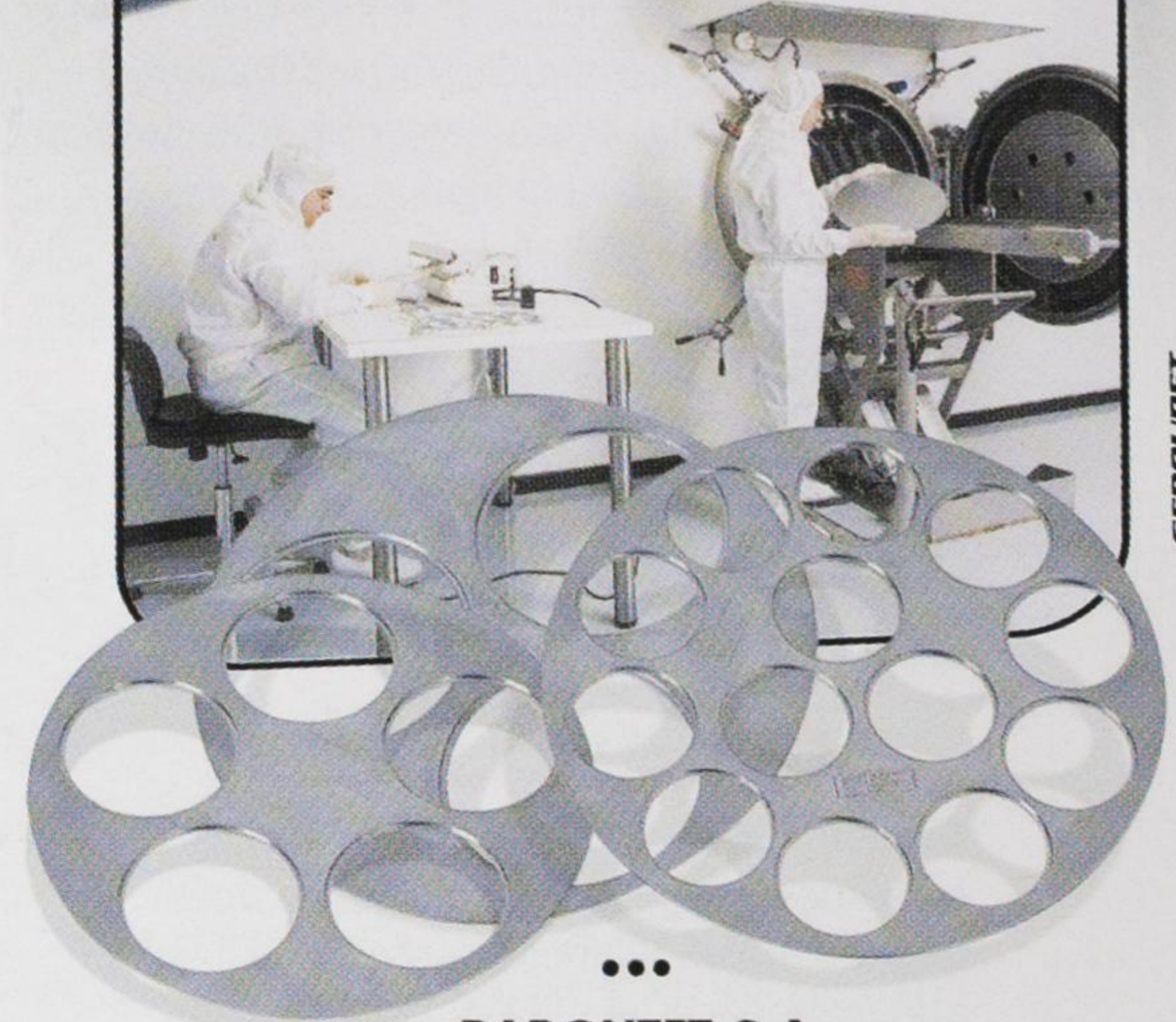
The US subsidiary of Taiwan-based chip maker Everlight Electronics has acquired the LED and LED display product lines belonging to the giant US firm Fairchild Semiconductor. The companies previously worked together on LEDs. Financial details of the deal, which should close this quarter, were not disclosed.

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**...Avanex shortfall**

Avanex saw a substantial shortfall in revenue for its latest financial quarter because of a contract manufacturing problem that delayed product shipments. As *Compound Semiconductor* went to press, Avanex estimated sales of \$35 million–\$37 million for the three months ending on December 31, 2005, much less than the \$41 million–\$45 million originally forecast. Paul Negus, the company's vice-president of operations, resigned in early January.

**...European research**

Europe has a new body championing the cause of photonics research thanks to the creation of "Photonics 21". More than 200 experts from 16 European member states and 120 companies celebrated the launch event in Brussels, Belgium, last December.

The group was set up by the European Photonics Industry Consortium (EPIC). Its members include key MOCVD equipment supplier Aixtron, sapphire substrate maker CrystalQ, GaN specialist Picogiga and epiwafer foundry IQE. Also involved are a host of chip manufacturers including Bookham, Osram Opto Semiconductors and Jenoptik, as well as end-users of optoelectronic technology such as Audi and Philips Lighting.

**...Army likes InGaAs**

Goodrich Corporation's optical and space systems team, formerly known as Sensors Unlimited, has won a \$750 000 development contract from the US Army to improve InGaAs device manufacturing. The army wants the Princeton, NJ, firm to deliver a detector array for night vision that can record high-definition images in the infrared range while simultaneously capturing visible-range imagery. The proposed 1920 × 1080 pixel cameras should also show an improvement in sensitivity, and detect light in an unspecified "new" wavelength band.

Martin Ettenberg's Goodrich team will focus on improving the design of the chips used within the camera. "These improvements will result in higher device yields, which will lower the cost per unit and provide much higher sensitivity in dark or low-light conditions," added the company.

**...Firecomms expansion**

Firecomms, the Ireland-based developer of high-speed semiconductor light sources, has opened regional offices to provide sales and application support in Houston, US, and Yokohama, Japan.

**FINANCE**

# Bookham secures Nortel order worth \$72 million

Optical component and module vendor Bookham has secured a supply agreement with Nortel Networks that will guarantee it at least \$72 million in sales this year.

The Canadian network equipment supplier has long been Bookham's key customer, particularly since the acquisition of Nortel's optical components business back in 2002.

The latest deal replaces the agreement that Bookham and Nortel reached last year, and which was scheduled to expire in late April. In recent quarters, Nortel has been responsible for around half of Bookham's overall sales.

Bookham, which manufactures InP-based optoelectronic chips at its facility in Caswell, UK, has also paid off around \$65 million of its long-term debt, including a Nortel loan.

The total included a cash payment of \$20 million plus interest to Nortel, as well as the issue of more than 10 million new shares and warrants to buy more stock to institutional investors who will take on some of Bookham's debt. The share warrants have an exercise price of \$7 and can be used over the next five years.

In a third transaction, \$19.4 million of outstanding debentures were converted in a stock-and-cash deal. Bookham now plans to eliminate its remaining \$6.1 million of debenture-related debt in a similar move that will require shareholder approval.

While Bookham's share price dipped by almost 10% on news of the refinancing, the amount of extra stock issued meant that the company's market valuation increased.

**PHOTOVOLTAICS**

# Boeing wins contract for satellites powered by triple-junction cells

Boeing is to build three huge communications satellites, all of which will be powered by triple-junction GaAs solar cells. Expected to launch around 2009, the satellites have been ordered by the US communications company Mobile Satellite Ventures (MSV).

Boeing is likely to award the lucrative contract for the solar cells for the satellites to its Californian chip-making subsidiary Spectrolab, its rival Emcore, or both companies.

Construction of the first satellite will take an estimated 44 months, with the second and third payloads following a few months later. Boeing said that the MSV deal represented its biggest single contract for a satellite system since 1997.

After launch, the three satellites will form the backbone of an advanced network covering North and South America that will deliver voice and data communications using a combination of satellite and cellular technologies.

According to MSV, the satellites will work in tandem with ground stations to provide high-speed links in remote areas, and extra capacity in cities where satellite signals are frequently blocked by buildings.

The result should guarantee regular cell-phone users the benefits of a satellite-phone service. In the past, similar networks such as



**Boeing subsidiary Spectrolab** and rival Emcore will be vying for a contract to deliver the GaAs-based solar cells needed for Boeing's three-satellite deal with MSV.

Iridium have demanded much larger phones to detect the relatively weak satellite signal.

MSV adds that the service should also benefit emergency-response teams by ensuring that cell-phone networks stay connected via the satellites even if ground stations are destroyed, as happened when Hurricane Katrina struck the Gulf Coast last year.

The network will have a high power demand, so Boeing will use the triple-junction cells to supply 11 kW through five-panel arrays on each satellite.



## EMCORE

# Analyst tips solar cells for terrestrial success

Chip manufacturer Emcore will start to see revenue from sales of solar cells into terrestrial power applications this year, according to John Lau, an analyst with Jeffries and Company.

Compound semiconductor-based solar cells are much more efficient than silicon-based cells, but are generally regarded as being much more expensive. However, Lau says that Emcore believes it can now compete on cost with silicon because GaAs-based solar cells can be designed into "concentrator" systems, where a lens is used to focus sunlight onto a much smaller area of semiconductor than in conventional systems.

These systems also track the movement of the Sun throughout the day, producing a higher overall electrical power output. While Lau feels these designs do not suit residential use, he does expect to see them deployed commercially.

Lau adds that Emcore will be aided by the current shortage of polysilicon. There is no shortage of GaAs resources, or the germanium substrates on which the triple-junction cells are made. He believes that systems using Emcore's

cells will operate at a cost of \$3/W output, similar to the figure for silicon cells. As a result, he expects the Somerset, NJ, company to see a positive impact on revenue generation in the second half of 2006.

Emcore also has a potentially lucrative contract to supply solar cells to an unspecified satellite manufacturer that could generate up to \$20.6 million in revenue.

- Emcore's Ortel division has acquired the fabless laser developer K2 Optronics. Emcore was already an investor in the Sunnyvale, CA, company, and bought the remaining portion in a stock deal valued at \$4.8 million.

K2 specializes in directly modulated external-cavity lasers (ECLs), which Emcore believes could revolutionize cable television (CATV) and fiber-to-the-premises (FTTP) applications. "We expect to see our CATV and FTTP customers insist on the performance and cost advantages that directly modulated lasers [based on K2's ECL technology] can offer over traditional laser technology," said Hong Hou,

who leads Emcore's Ortel division. Following a six-month transition period, K2's design and engineering teams will be integrated with Emcore's Santa Clara, CA, design center.

K2 attracted around \$45 million in venture funding before Emcore's initial investment in the company in February 2005. Fellow chip maker JDSU had also invested in prior funding rounds, while K2 boasted that it was the first company to mass-produce packaged ECLs through its Thailand-based contract manufacturing partner Fabrinet.

Emcore expects combined sales of K2's existing products and its own directly modulated transmitters featuring K2's lasers to generate about \$7 million this year. The Somerset, NJ, company is then anticipating strong growth, leading to sales of \$14 million in 2007.

The K2 acquisition is Emcore's latest move in a bid to increase its presence across the communications industry. In the past year it has acquired JDSU's cable TV component business, the optical module supplier Phasebridge and the video broadcast company Force.

## R&amp;D

## Association bemoans company strategies

The US-based Optoelectronics Industry Development Association (OIDA) says that the sector faces a difficult future because of a lack of investment in research.

"Unfortunately, the level of research and development across the industry seems to be lower than that needed to support the communications roadmaps [we have] developed," said OIDA executive director Michael Lebby. Last year, Lebby called for the implementation of an optical foundry industry model, echoing the findings of a similar study carried out by the Massachusetts Institute of Technology.

Lebby added that without this investment, the optoelectronics market would be unable to thrive over the next decade.

According to the OIDA, one major problem is the current mindset of chip manufacturers such as Bookham and Mitsubishi, which believe that success lies in vertical integration and high-value, non-standard devices—rather than the development of standard platforms that would lower product costs.

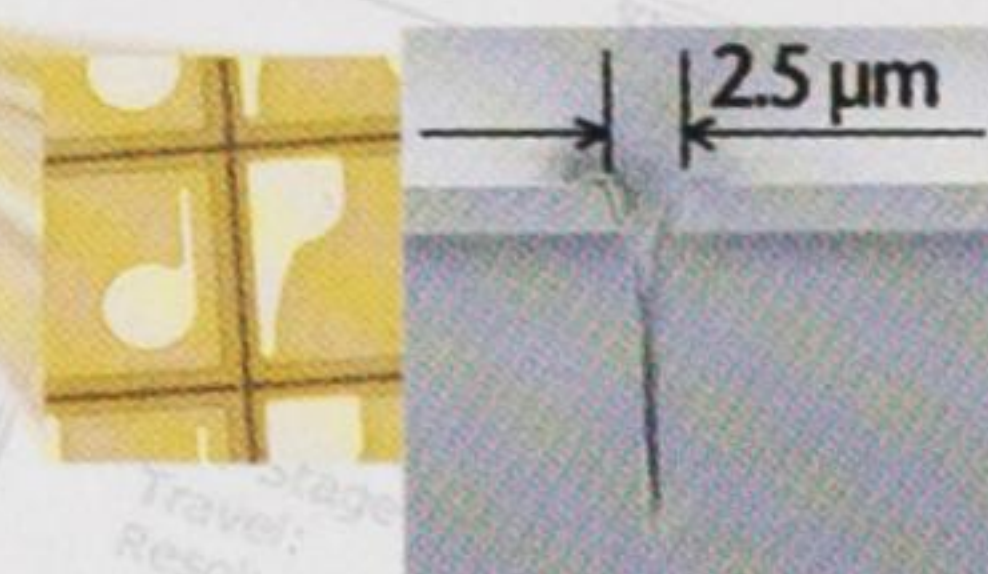
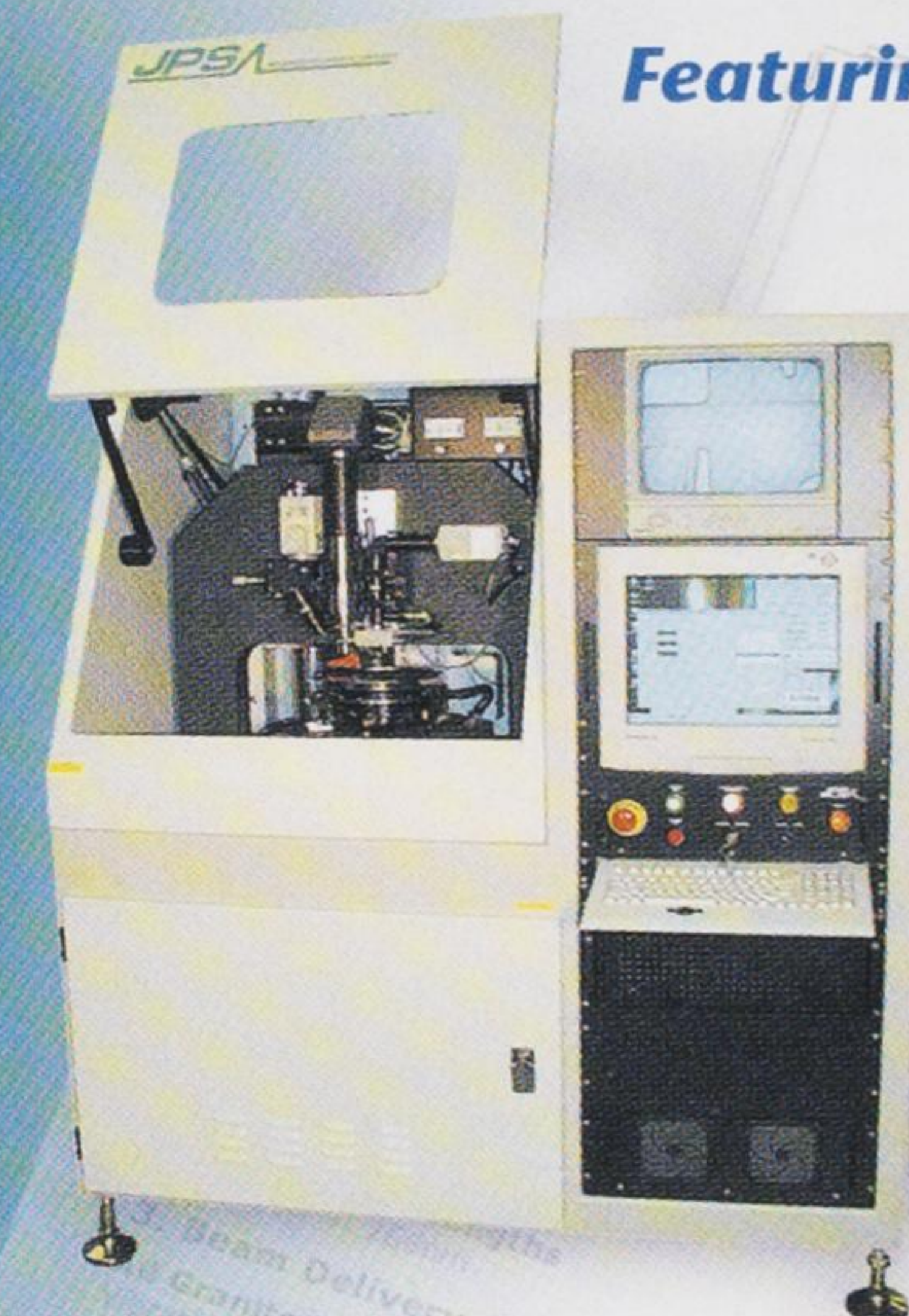
"Because there is no commonality, there are limited economies in manufacturing, and this has led to high cost structures," bemoaned Lebby.

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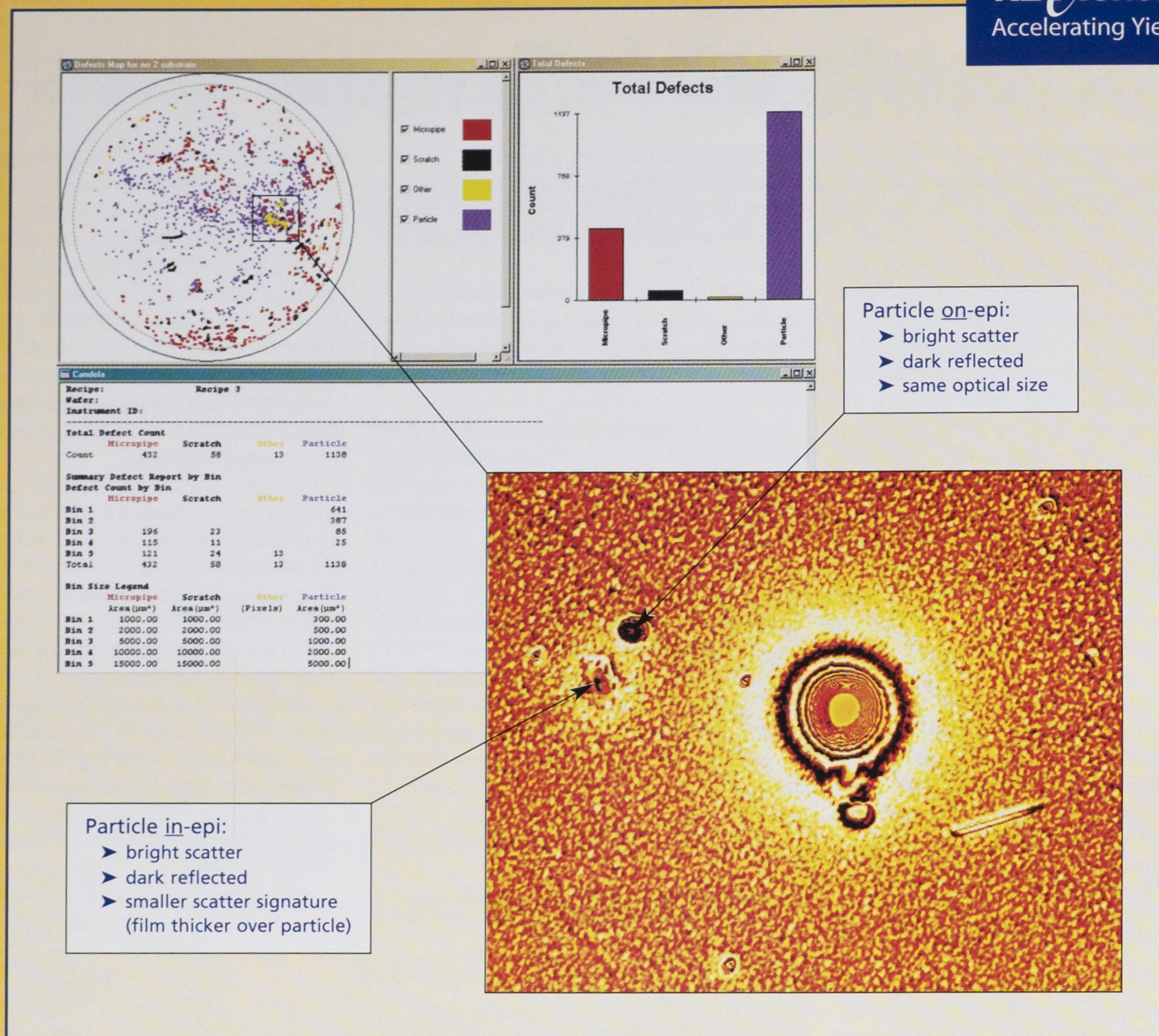
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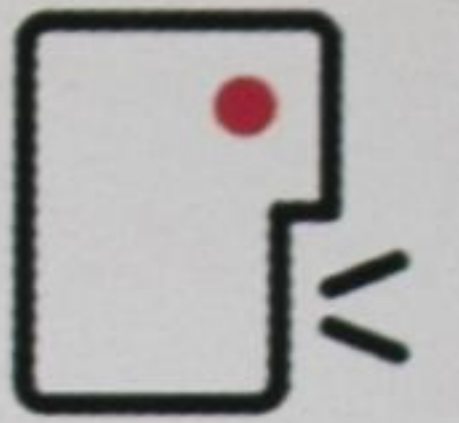


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## OPTOELECTRONICS

# Laser manufacturers get industrious

In the first of a two-part series, **Toby Strite** explains why leading makers of semiconductor laser diodes are switching development dollars away from telecom.



Toby Strite is marketing manager for JDSU's High-Power Lasers group in San Jose, CA. E-mail [toby.strite@jdsu.com](mailto:toby.strite@jdsu.com).

During the go-go 1990s, telecom ambitions dominated the thoughts of the world's most capable laser-diode manufacturers. The handful of firms able to manufacture reliable 980 nm diode lasers supplied up to \$500 million per year of pump-laser modules to the erbium-doped fiber amplifier (EDFA) market. Even leading lights of the industrial lasers arena like Coherent and Spectra-Physics scrambled to upgrade their capabilities to join the telecom gold rush because their traditional markets were puny in comparison.

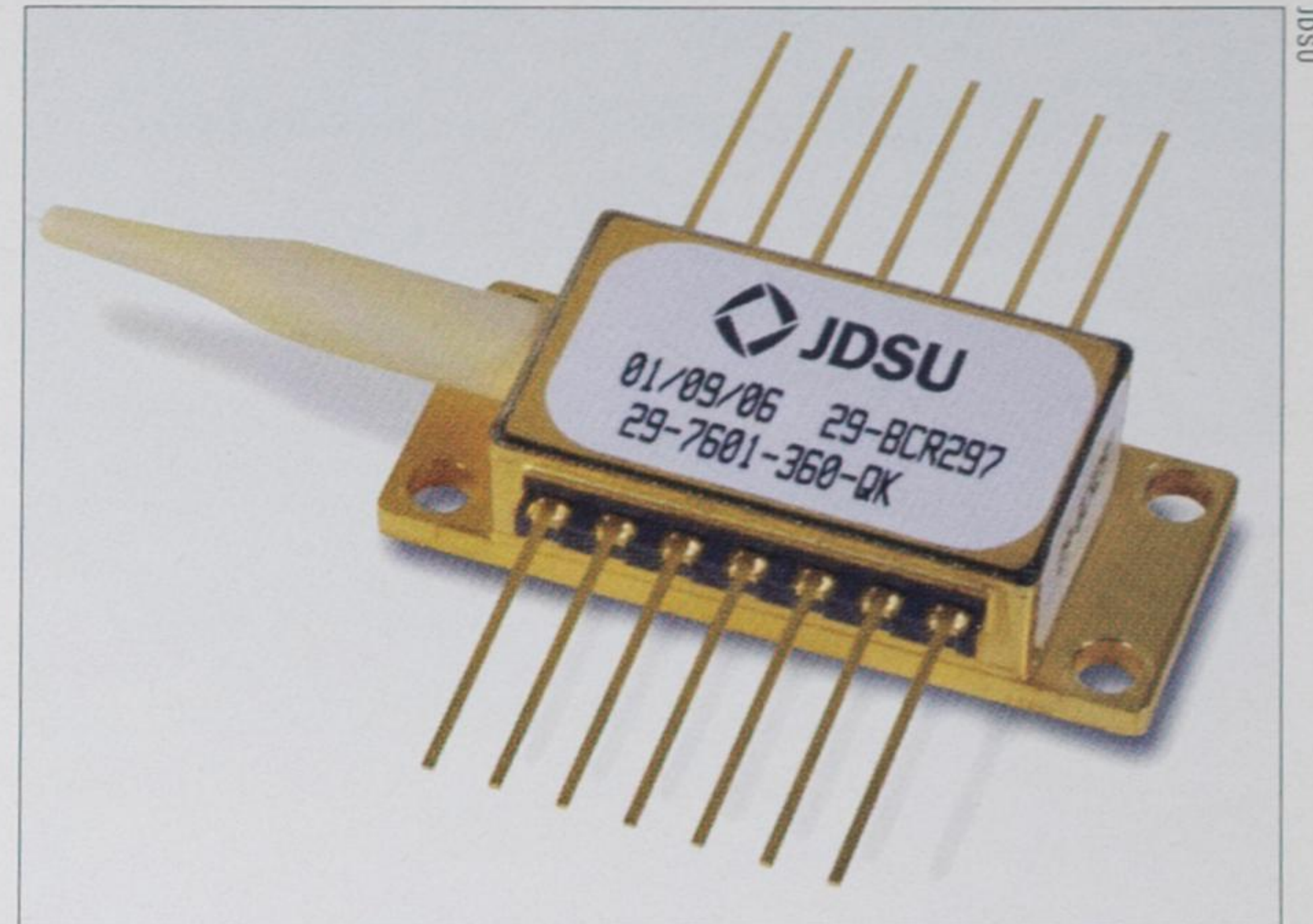
The telecom boom resulted from huge, unsustainable over-investment. Perhaps less remembered is the disruptive effect of the EDFA, which attracted all that capital. The EDFA represents the difference between a single wavelength traveling 80 km over fiber between expensive optical-electrical-optical regenerators, and 160 wavelengths traveling 600 km at a radically lower transmission cost per bit.

As optical networks expanded from 4 to 16 to 160 wavelengths, the amount of optical pump power needed to fuel an EDFA grew proportionately. In a decade of whirlwind productivity, telecom-grade, single spatial-mode 980 nm diode laser power increased at a rate of 25% every year. Production efficiencies simultaneously enabled falling selling prices. A 90 mW, 980 nm pump module that sold for \$7000 in 1994 now fetches less than \$400, representing a 22% annualized price erosion. A 500 mW pump now sells below \$1000, representing a more than 26% year-on-year decline in dollars per mW over that same period.

Such gaudy figures represent high tech as it should be. In an environment of rapid productivity improvement, the entire value chain shares the wealth and thrives. However, despite a newly buoyant telecom market, pump lasers are at an inflection point. Now that a single 500 mW pump laser services an entire EDFA gain stage, the previously unquenchable thirst for 980 nm power in a single fiber is largely sated. To continue to feed the EDFA value chain, pump-laser suppliers must either innovate along in a new, as yet undefined, technological direction, or face commoditization.

This conundrum resembles that recently faced by Intel. For years its technical roadmap focused on speeding the microprocessor clock rate – eventually saturating the PC market. But if your Dell has a 2 GHz processor does that leave you pining for 4 GHz? For Intel, the need for speed has diminished and been replaced by more useful things – wireless capability, reduced power consumption for extended laptop battery life, and a microprocessor core with more functionality. We've barely heard a peep from marketeers about microprocessor GHz since.

For telecom pump lasers, a value-added lateral innovation like Intel's has not yet been identified. If a single diode could service multiple gain stages, demand would be rekindled for yet higher power devices delivering lower overall dollars per mW. However, EDFAs increas-



**Like PC microprocessors**, 980 nm pump lasers for telecom face commoditization. For future growth, better prospects lie in industrial laser applications such as welding and cutting.

ingly provide mid-stage wavelength add/drop agility, which decouples the amplification power needed in each stage. Independent and dynamic control of the amount of pump power reaching separate EDFA stages is lacking, and there is no foreseeable solution. Many have concluded the fundamental value metric of telecom pumps is destined to move from dollars per mW towards strictly dollars per laser, which smacks of commoditization. As a result, diode-laser research dollars are increasingly being redirected towards industrial markets that sustain long-term growth rates in excess of telecom's 6–8%.

Let's quickly recap the telecom-driven diode-laser era. Sleepy research teams that once nestled within large, corporate R&D labs landed at aggressive, medium-sized companies who provided them with unprecedented investment. The result was telecommunication-grade 980 nm pumps sustaining facet powers exceeding 50 MW/cm<sup>2</sup>, representing perhaps the highest man-made energy density short of a nuclear explosion. The companies transferred their diode-laser assembly to Pacific Rim factories as a matter of survival, but are yet to earn sustainable returns.

Today, the few players capable of state-of-the-art volume diode-laser manufacture are lean, scalable and eager to unleash their highly refined technology into new growth markets. The market of choice is solid-state laser pumping for industrial applications. For a second consecutive decade, disruptive diode-laser advances will yield explosive consequences.

• In our next issue, Toby Strite describes how semiconductor laser-diode manufacturers will transform the industrial laser market.

**“Despite a newly buoyant telecom market, pump lasers are at an inflection point.”**

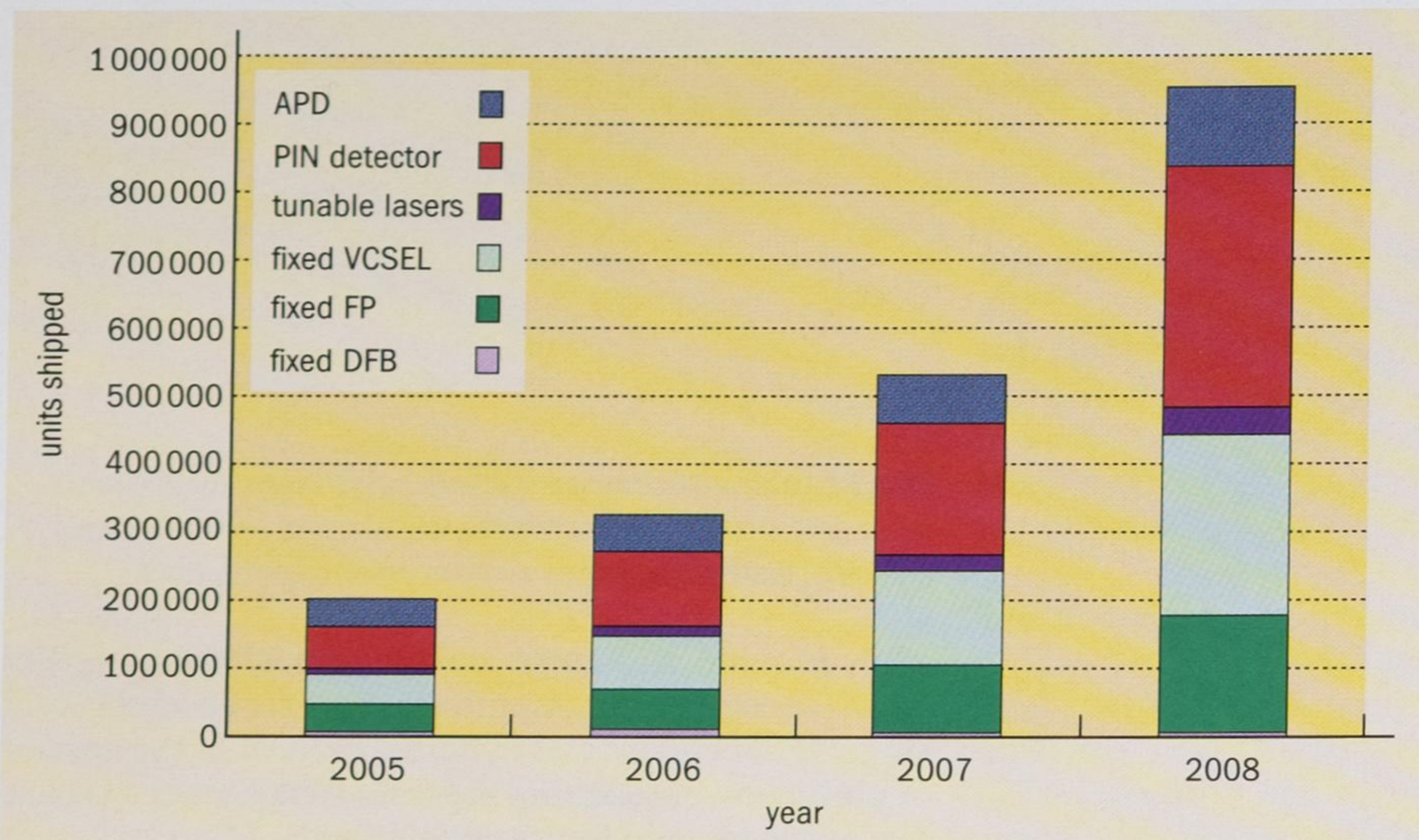




FIBER-OPTIC COMPONENTS

# Ethernet evolution to drive VCSEL ramp

The 10 Gigabit Ethernet fiber-optic datacom standard will give makers of optoelectronic chips access to a mass market, reports **Michael Hatcher**.



While Communications Industry Researchers (CIR) expects to see a lot more shipments of VCSELs and PIN detectors as the 10 Gbit/s fiber-optic communication becomes a volume application, the deployment of fixed-wavelength distributed feedback (DFB) lasers looks set to recede after this year.

**“Around late 2006 or early 2007, 1310 nm VCSELs will ship on a large scale.”**

CIR

With capital expenditure by service providers growing, manufacturers of fiber-optic equipment, modules and components now have less reason to whine than in recent years. And according to the market analyst company Communications Industry Researchers (CIR), the growing popularity of the latest Ethernet data communications standard should soon add some vigor to that recovery process.

Having observed the relatively dormant 10 Gbit/s Ethernet (10G) market over the past five years, CIR now believes that this protocol is showing signs of becoming the general-purpose successor to the widely deployed Gigabit Ethernet (1 Gbit/s operation) standard.

Unlike the copper-based Gigabit Ethernet generation, 10G is inherently a fiber-optic standard, so it could offer optical equipment manufacturers, module suppliers and component vendors access to the mass market that the industry has long craved.

## Opportunities for 10G

“10G interfaces, which just a few years ago would have appeared only in a telecom environment, or occasionally on the largest Ethernet switches, are now becoming common on servers and on modular Ethernet switches,” says CIR. Although 10G is far from ubiquitous – and unlikely to feature on a standard PC for several years – CIR says that there is now a genuine opportunity for makers of 10G components, who can expect to sell large volumes of semiconductor chips that

emit and detect rapidly modulating laser light.

The type of compound semiconductor components affected by this expected surge in demand are those found in the 10G modules sold through a variety of multi-source agreements (MSAs). These include both fixed-wavelength and tunable edge-emitting lasers, VCSELs, PIN diodes and avalanche photodetectors. In the short term, the major beneficiaries should be major VCSEL suppliers such as Emcore, Avago Technologies and Finisar (through its Advanced Optical Components division), with CIR predicting a rapid increase in unit shipments of VCSELs over the next three years (see figure).

## Good news for VCSEL manufacturers

Makers of long-wavelength VCSELs, including dilute nitride structures for operation at 1310 nm and beyond, should also start to find some traction for these cutting-edge products, whose longer wavelengths enable longer-reach communications. The US company Picolight, as well as the Danish outfit Alight Technologies (which acquired the dilute nitride VCSEL technology belonging to Infineon Technologies recently), could start to see a big pick-up in demand around the end of this year, when CIR expects volume commercial shipments of 1310 nm VCSELs. Unfortunately, Optical Communication Products (OCP) recently decided to cease its development of these devices, despite the added advantage of backing from the Japanese electronics giant Furukawa Electric, and major customers in Alcatel and Cisco.

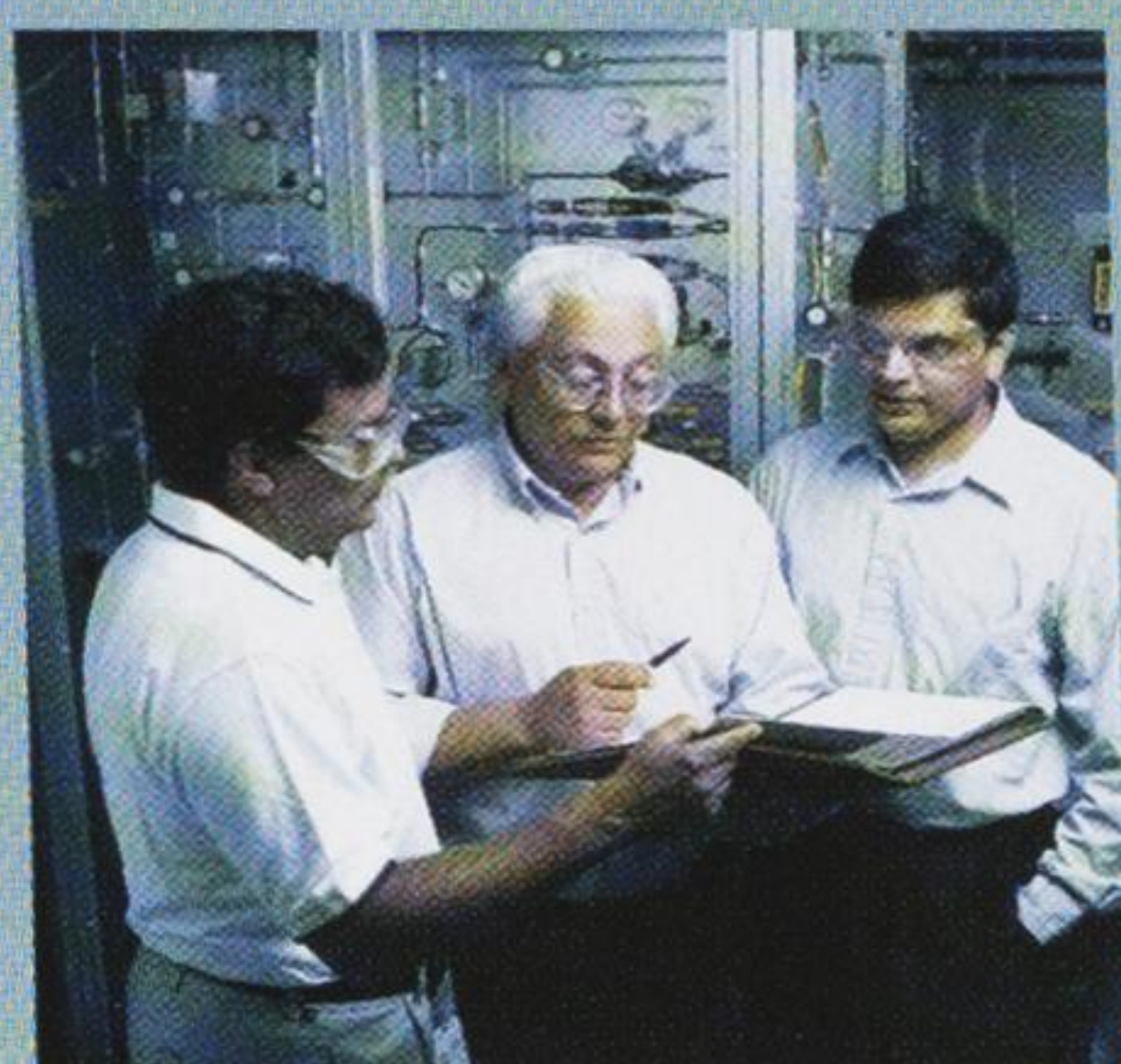
Unlike most of its peers in the fiber-optic component and module businesses, OCP has already got its finances on a relatively even keel, and posted both operating and net profits in its most recent financial quarter.

The surge in the 10G business expected by CIR may come too late to save all of the remaining component vendors, as it seems inevitable that at least some of those with dwindling cash resources will go out of business without an injection of new funding. For those that do survive, there could be rich pickings. Of all the various MSA module types, CIR expects XFP (10G small-form-factor pluggable) to yield the biggest opportunity.

While the 10G business is rapidly becoming commoditized, with margins shrinking fast, the same can certainly not be said for the next level in high-speed optical communications – 40G. While there have been recent signs of life in the 40G sector (see *Compound Semiconductor* November 2005 p15), CIR is not expecting it to become anything more than a niche business, albeit one that will offer very high profit margins for a handful of vendors. “The [40G] business is too small, and will involve too much up-front capital to make it a solution to the module industry’s wobbliness,” reflected CIR.

• *CIR’s report The Market for 10G and 40G Modules and Components: 2006–2013 is available at [www.cir-inc.com](http://www.cir-inc.com).*





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# SiC suppliers shoot for er

There is increased competition among the suppliers of SiC substrates, but does that mean lower prices for customers? Not necessarily, discovers **Yvonne Carts-Powell**.

Users of SiC substrates, which are currently available in 2 inch and 3 inch diameters, will soon have a choice of vendors for 4 inch – or more precisely 100 mm – material. During September's International Conference on SiC and Related Materials (ICSCRM), Cree announced that it was providing sample quantities of 100 mm SiC substrates to customers and planned to launch commercial production in 2006. However, although Cree is the market leader in the industry, with about a 75% share of the SiC wafer market, the company does not have a clear field. Intrinsic Semiconductor, II-VI, Caracal, Norstel and Dow Corning all intend to offer 100 mm wafers, and some have plans for ramping up to production quantities within the year.

"The key application driver for 4 inch SiC is RF transistors," explained market analyst Richard Dixon of Germany-based Wicht Technologie Consulting, who co-authored a market report on SiC last summer. Because these transistors have a relatively large footprint, larger wafers are better suited to manufacture as they produce less wasted edge-space and greater economies of scale. Smaller but already commercialized devices such as GaN LEDs and Schottky barrier diodes will benefit as well.

However, production costs, which are strongly influenced by yield, are crucial for these devices because they compete with silicon – which has inferior technical specifications but is entrenched and inexpensive. For large-area devices such as RF and power transistors, defect density is a critical factor. But, as Cree's Adrian Powell pointed out at ICSCRM, even if larger wafer sizes have a slightly higher defect density, they can still deliver a higher yield due to more efficient use of the substrate area.

## Vertical integration: pros and cons

Cree – and most of its competitors – produces SiC from powders using some variation of physical vapor transport (PVT), with growth at 2100–2500 °C. Cree's major advantage is that as well as manufacturing most of the SiC wafers sold today, it uses a huge number of these wafers internally for its highly profitable LED chip production. "Our biggest advantage is really the volume that we run," explained Cree's director of advanced materials John Palmour. Dixon agrees: "Cree benefits from being vertically integrated, which allows the company preferential access to high-quality wafers,



**Chemicals giant Dow Corning** has recently won a \$3.6 million contract from the US

and to feed device performance data directly back to its materials development program."

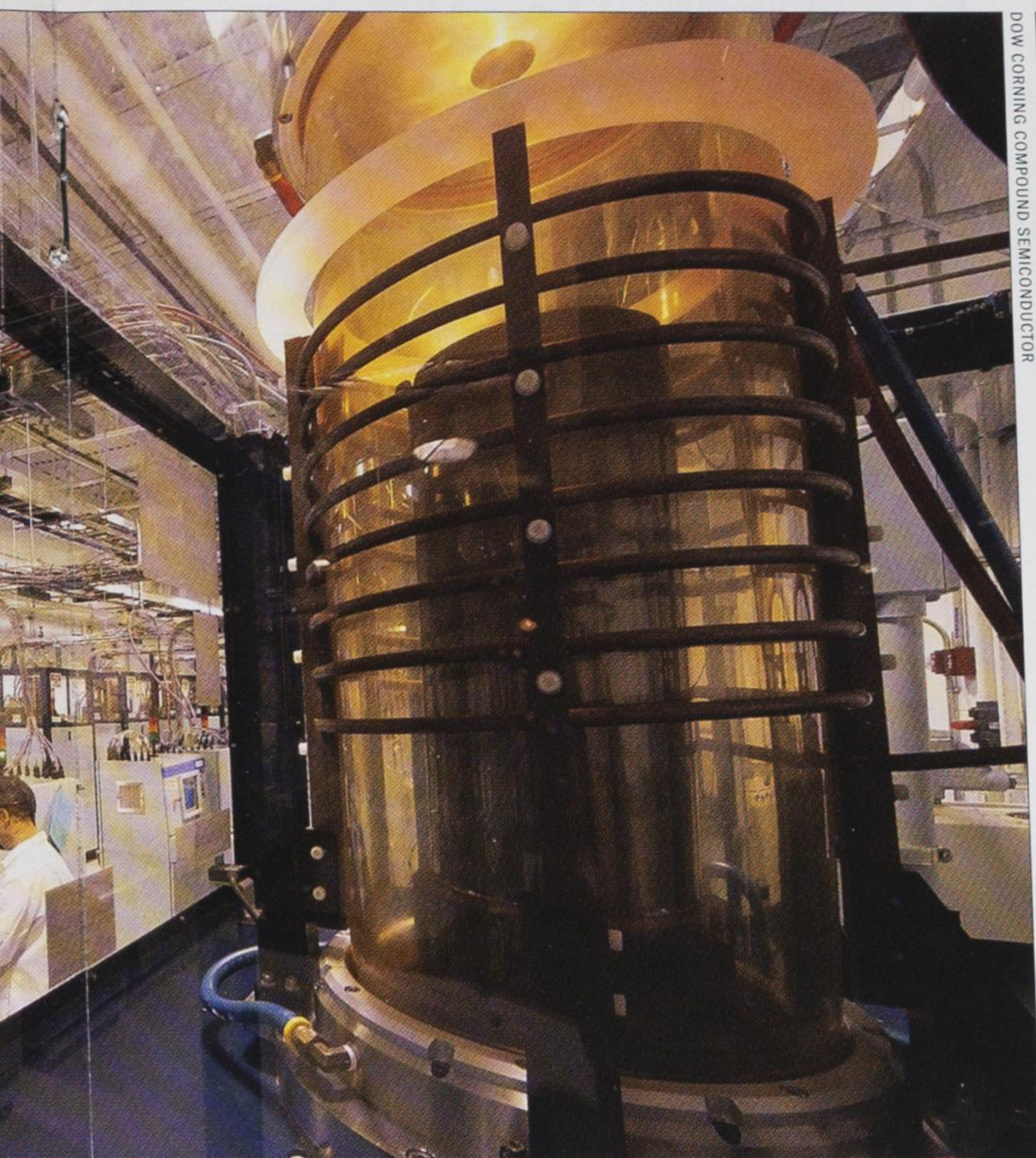
US-based Intrinsic Semiconductor, like Cree, is vertically integrated and can fabricate prototype devices for customers. The company has already started sampling 100 mm substrates and plans to offer production material in the current quarter. It is aiming for full production in the latter half of the year. The company's current claim to fame, however, is producing substrates with a very low micropipe density.

A few years ago micropipes were the major defect worrying device manufacturers, but efforts to reduce their incidence have resulted in lower densities across the board. In late 2005 Intrinsic announced that it had produced 3 inch wafers completely free of any micropipes. Other defects are also important, however. Dixon points out that basal plane dislocations (which are critical for PIN diodes), as well as inclusions of different SiC polytypes, and chips and scratches accrued during the dicing process, can all degrade device performance.

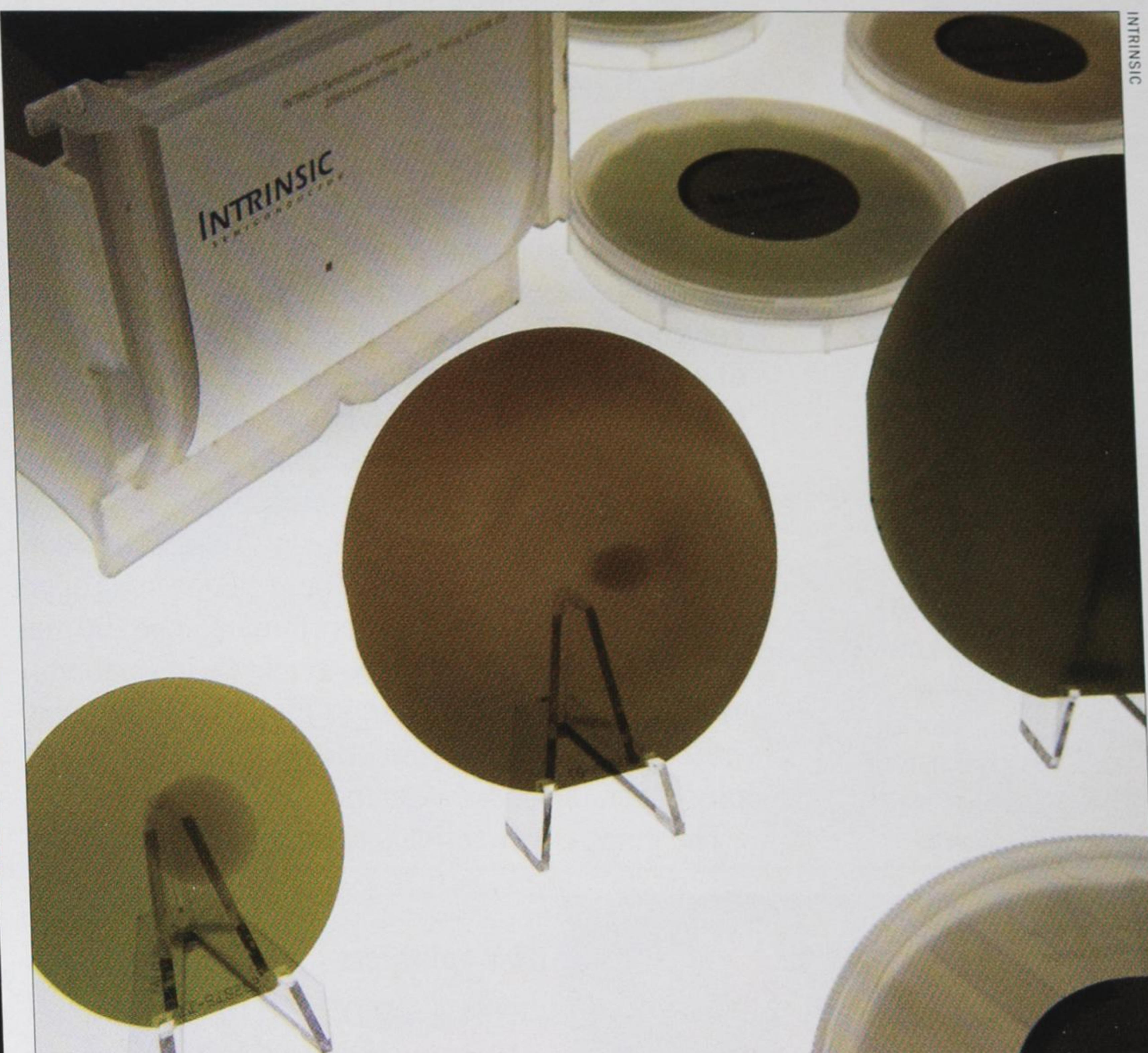
Intrinsic CEO Cengiz Balkas says that his company is focused on providing high-quality materials, with an intense effort on reducing basal plane dislocations. He agrees that controlling polytype uniformity is also important. Because power electronic devices require



# emerging 100 mm market



DOW CORNING COMPOUND SEMICONDUCTOR



INTRINSIC

from the US Navy to develop device-quality SiC substrates up to 100 mm in diameter.

**Intrinsic Semiconductor** is already sampling its 100 mm SiC substrates, and expects to ramp up the manufacture of this material through 2006, aiming for full production in the latter half of the year.

the 4H form of SiC almost exclusively, the inclusion of 6H material is a problem. Intrinsic has demonstrated both types of material and can produce 4H 100 mm wafers with micropipe densities of  $1/\text{cm}^2$ .

Intrinsic now also has the capacity to deposit epitaxial layers on 100 mm substrates, after working with a tool maker to build a reactor that is capable of accommodating the larger wafers. The company has increased its customer base by half in the past quarter, with the majority ordering 2 and 3 inch SiC epiwafers for power electronics.

Like Cree, Intrinsic uses PVT to produce its substrates. According to Balkas this method is mature and inexpensive. "What makes it very expensive for others," he says, "is if you're only getting a few usable wafers out of a batch."

US-based II-VI, which has SiC production facilities in Pine Brook, NJ, and Saxonburg, PA, differs from Cree and Intrinsic, claiming that it has an advantage because it is not vertically integrated and so doesn't have to compete with its customers. The company produces only substrates and intends to offer sample quantities of 100 mm material by mid-2006. II-VI is currently increasing its production capacity in New Jersey and has plans to expand in a new facility in Mississippi, near

to SiC epiwafer supplier Semisouth Laboratories.

Andrew Souzis, II-VI's manager of technology and programs, says that micropipes are no longer the issue they were five years ago. According to him, micropipe densities are now simply a yield-loss issue rather than a show-stopper. He is more concerned about dislocations that may not be immediately obvious but can affect device reliability. He added that the issue of device reliability is being addressed in the three DARPA programs related to GaN that were announced in early 2005. As part of this funding, II-VI received a \$7.5 million contract to scale up its growth method (advanced PVT, a variant of sublimation) to 100 mm sizes.

## Gases versus powders

In contrast to Cree, Intrinsic and II-VI, start-ups Caracal and Norstel are using gas-based methods to grow SiC. US-based Caracal is aiming to introduce 4 inch wafers

**"We count 15 actual and potential companies on the open market."**

**Richard Dixon**

Wicht Technologie Consulting



to the market in 2006. The company is focusing on the production of 4H conducting material for the power electronics market, but it can also grow 6H and semi-insulating wafers.

Jerry Connelly, Caracal's chief marketing officer, claims that methods like seeded sublimation face challenges with respect to quality and growth rate, which result in the high cost of today's wafers. "The advantages of gas-based growth include the inherent purity of the gases, greater control over the sublimation process, and the ability to cover pre-existing cracks in material, leading to higher-quality wafers," he explained. Similarly, Norstel CEO Asko Vehanen claims that his company's process has advantages over seed sublimation. These improvements include better control of purity, a more stable chemical composition of gases at the crystalline interface, a more stable temperature distribution and a better control of growth geometry during the single-crystal growth process.

Norstel uses a high-temperature CVD growth method developed at Linköping University in Sweden. In 2006 its new plant in Norrköping will become operational, producing 3 inch wafers initially. The 100 mm wafers, says Vehanen, will be available in small volumes during 2007, and in large volumes the following year. The company produces both substrates and epitaxial wafers for customers worldwide.

The giant US chemicals company Dow Corning

recently won a \$3.6 million contract from the US Navy to develop SiC, saying that it would use this funding to develop a manufacturing capability for producing device-quality SiC substrates up to 100 mm in diameter. Dow's global director of new business development programs Robert Johns declined to specify when it might enter the 100 mm market, but claimed that Dow's infrastructure and its ability to provide both epiwafers and substrates gives it a competitive advantage.

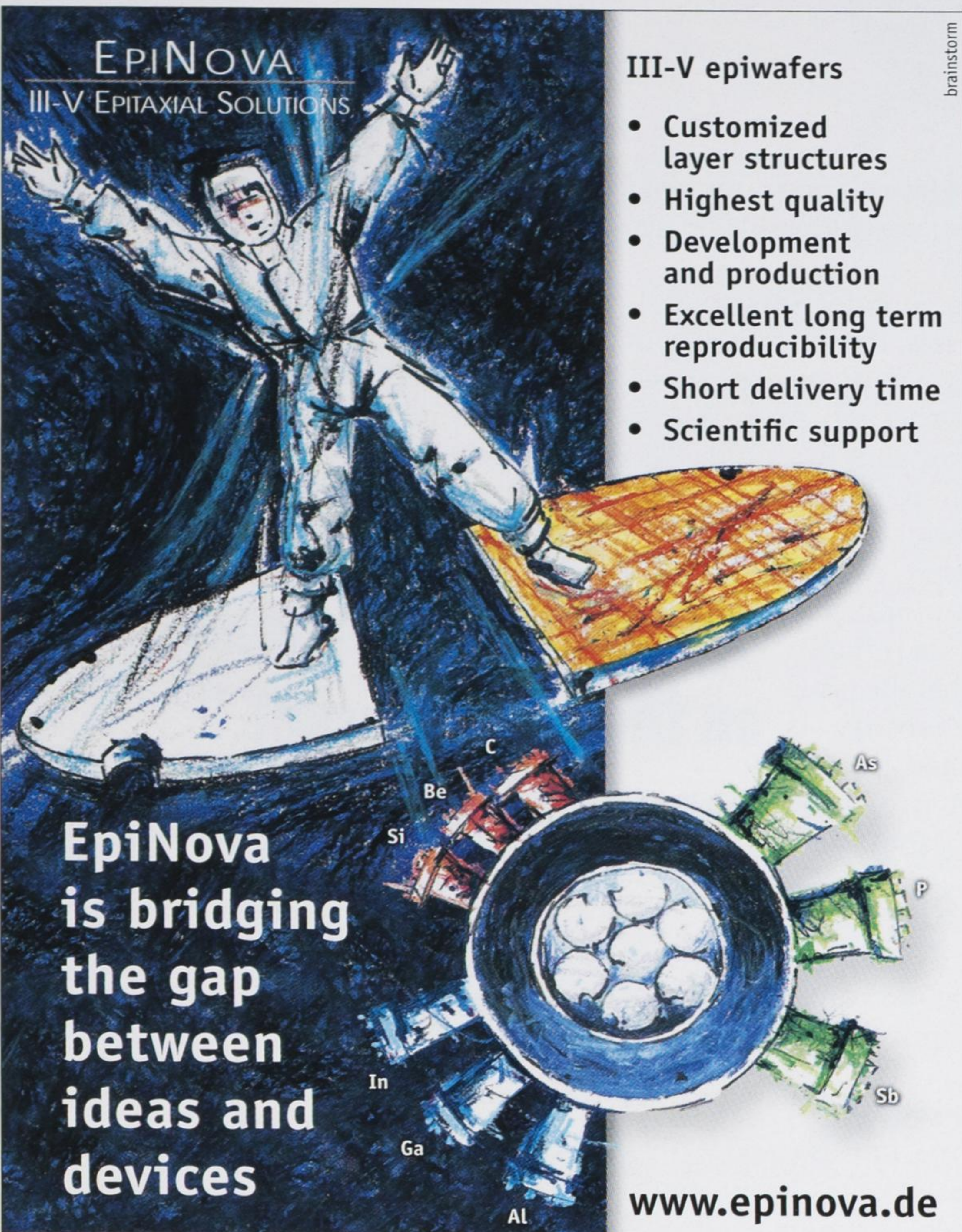
#### An unsustainable supply base

Given the size of the market, there is currently an unsustainable number of SiC suppliers. In the US the government is providing contracts and support to Cree, Dow Corning, II-VI and Intrinsic, which improves their chances of success, while Norstel also enjoys support from the Swedish government, but in all these cases the funding will not continue for ever.

"We count 15 actual and potential companies on the open market, and others such as Toshiba that have implemented their own production lines for captive use," said Dixon. However, many of these companies are not capable of producing substrates in sizes as large as 3 inches or 100 mm. Dixon added: "Although we expect that increased competition will contribute to a lowering of wafer prices, in the current absence of a process to cost-effectively manufacture large SiC wafers, this [reduction in costs] would be marginal."

#### About the author

**Yvonne Carls-Powell** is a freelance science writer based in Belmont, MA, who specializes in photonics, imaging, microtechnology and nanotechnology. E-mail [yvonne@nasw.org](mailto:yvonne@nasw.org).



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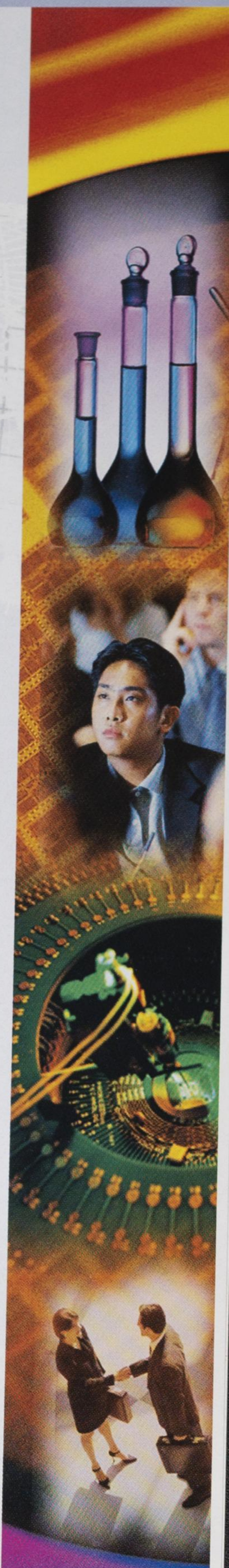
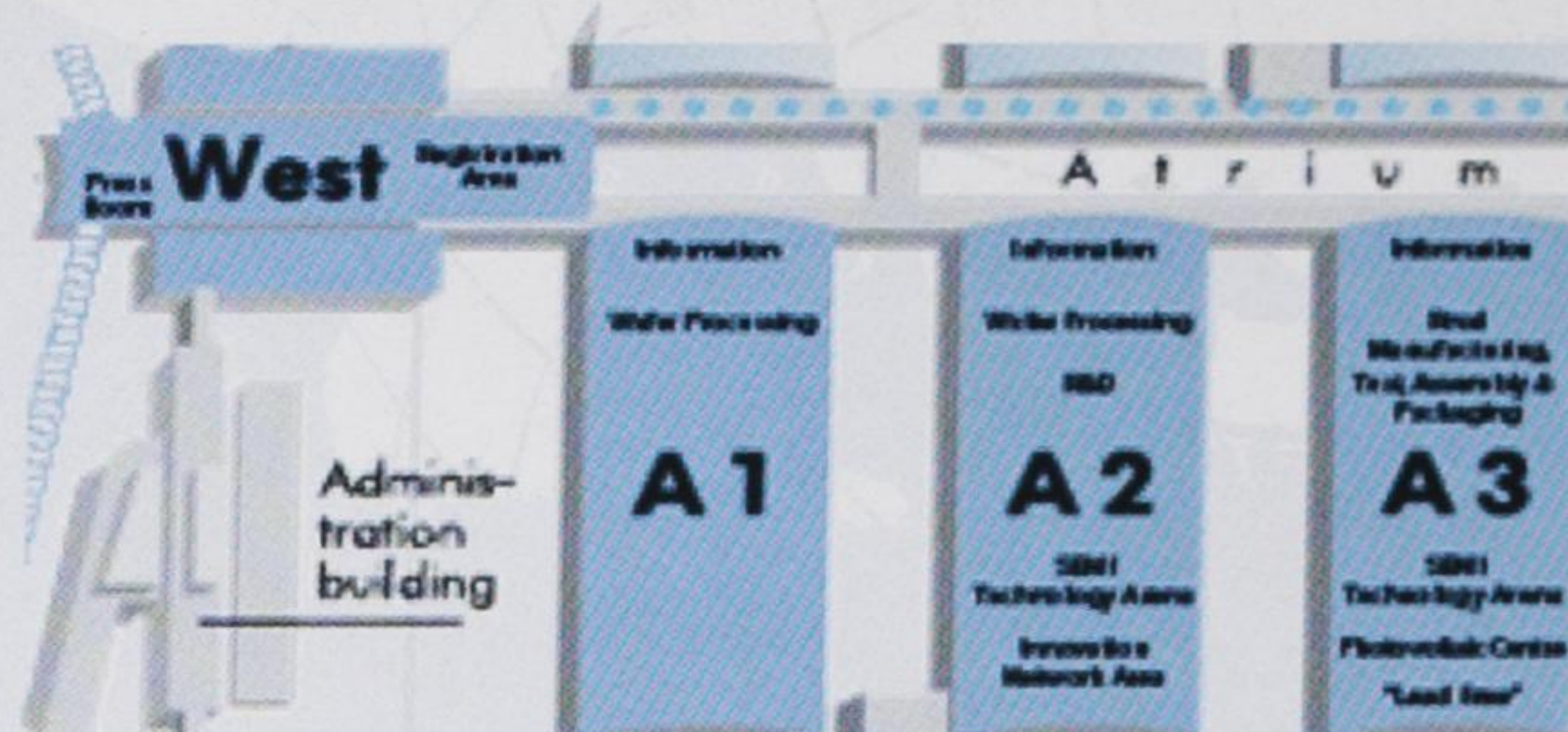
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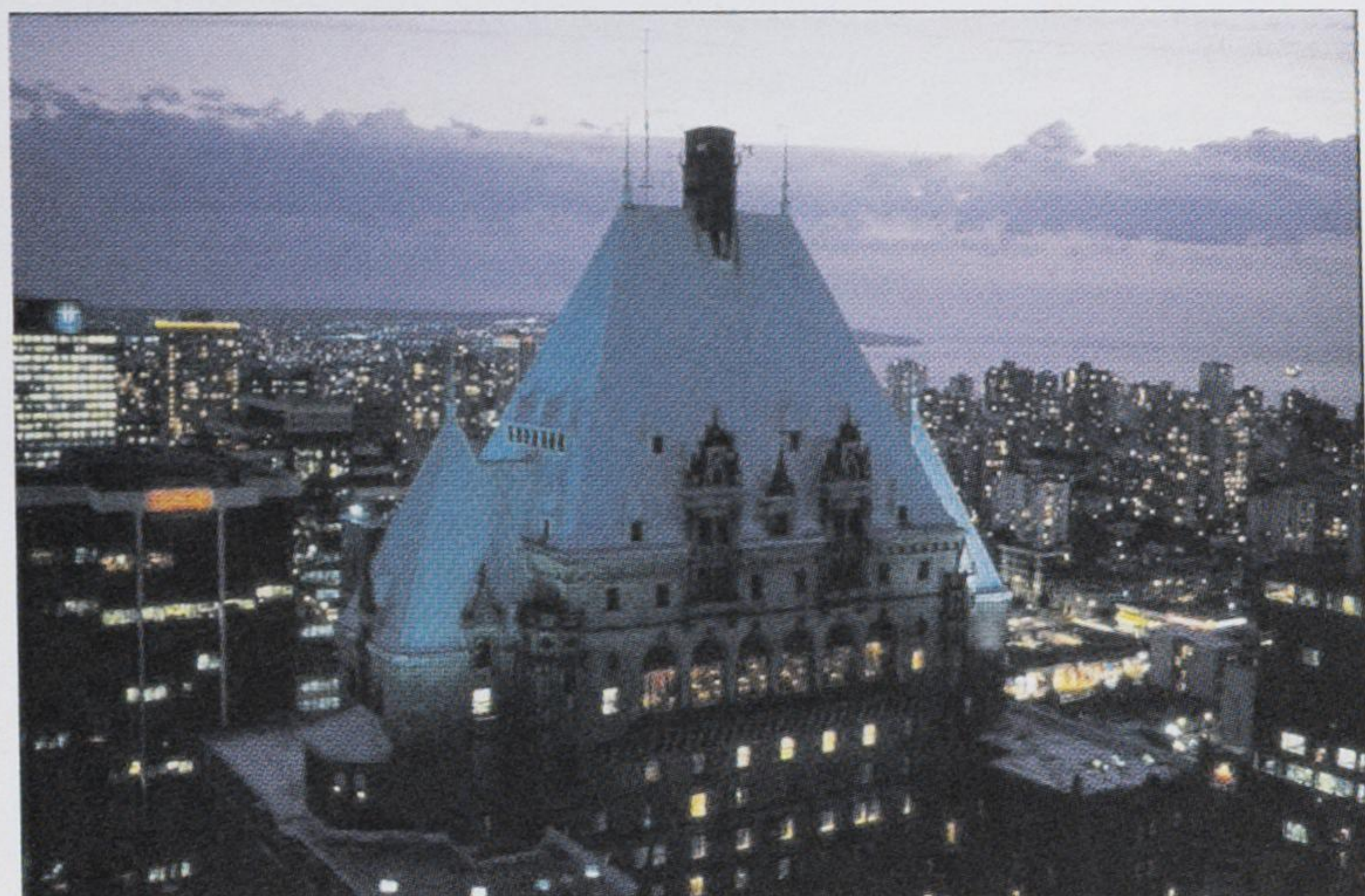
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# High-power GaN HEMTs battle for vacuum-tube territory

The vacuum tubes used in today's millimeter-wave transmitters face an increasing threat from GaN HEMTs.

Cree's **Yifeng Wu** and **Primit Parikh** are leading the GaN charge with designs that incorporate field plates, iron-doped buffer layers and a thin AlN interlayer to deliver a record power at 30 GHz.

The market for millimeter-wave power amplifiers includes applications in military, commercial and consumer sectors. The armed forces use the devices in transmitters for the detection of small targets and target imaging, in radar equipment, communications and smart weapons systems. In the commercial sector the amplifiers are widely used in high-data-rate communication systems such as digital radio links, SATCOM and wireless LAN, while the consumer market is expected to turn to millimeter-wave systems for applications such as automotive radar.

Vacuum tubes are used in the vast majority of high-power amplifiers operating at millimeter-wave frequencies. However, this incumbent technology is under threat from solid-state power amplifiers (SSPAs) that are smaller, cheaper, more reliable and quicker to build.

Although these SSPAs could be constructed from GaAs and InP HEMTs, these devices can only operate at low voltages and low powers. These limitations mean that multiple amplifiers or MMICs must be combined in order to deliver the output powers required, which leads to highly complex systems operating at relatively low efficiencies. GaN HEMTs can deliver high powers at higher voltages, and promise simple, efficient millimeter-wave power amplifiers.

## Traps and other obstacles

GaN HEMTs are clearly excellent devices on paper. However, in practice they can suffer from high trap densities, and at millimeter-wave frequencies their performance can be adversely affected by insufficiently low channel resistance and poor pinch-off characteristics (a relatively large gate voltage is required to extinguish the drain current).

High trap densities are exacerbated by the large strain and high polarization charges in the AlGaIn/GaN structures. The trapping effect severely reduces AC



current under large-signal operation, and subsequently deteriorates the output power and efficiency.

At the relatively high millimeter-wave frequencies, to maintain an acceptable power output it is essential to achieve a low channel resistance while maintaining good pinch-off characteristics as the device gate length shrinks. Low channel resistance results from a high value for the product of the charge density and mobility. However, if the charge density of the 2DEG is increased by raising the aluminum content in the AlGaIn layer, alloy scattering also increases, which degrades the mobility and consequently compromises the charge-mobility product.

**Vacuum tubes** are currently used in many radar systems, but the US military has pumped millions of dollars of research money into the development of solid-state GaN devices, which will be smaller, cheaper, more reliable and quicker to build.



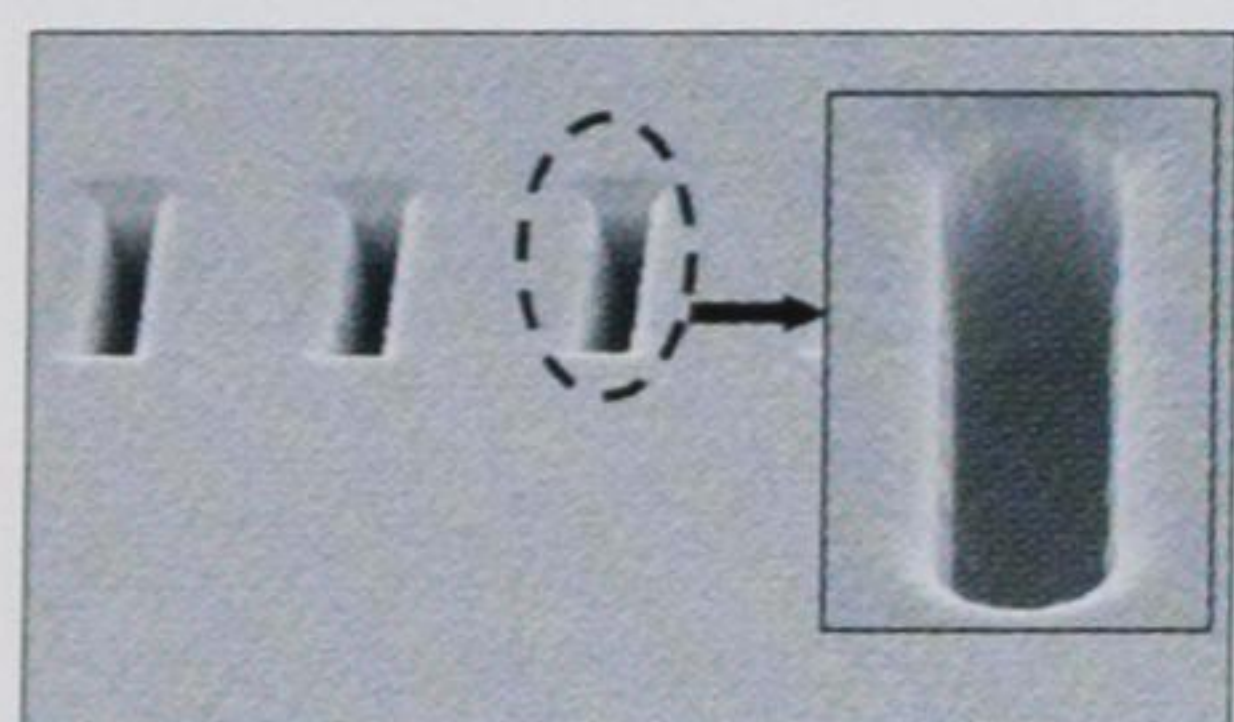
## The advantages of GaN

GaN's wide bandgap increases the breakdown field by five times and the power density by a factor of 10 to 20, compared with GaAs-based devices. The GaN components are therefore smaller and have a lower capacitance for the same operating power, which means that amplifiers can operate over a wider bandwidth while exhibiting good input and output matching.

GaN devices are also highly efficient because they can operate at higher voltages (24–35 V, compared with 5–8 V for GaAs-based devices at millimeter-wave frequencies), as well as having a lower on-resistance that results from the properties

of the two-dimensional electron gas (2DEG) in the AlGaIn/GaN system. The high voltage also reduces the bus current, which improves the power supply efficiency, while the 2DEG produces a high electron velocity, ensuring good signal gain at K, Q and even W band frequencies.

In addition, GaN devices built on SiC substrates have a thermal conductivity 10 times higher than those fabricated from GaAs, which means that these wide-bandgap devices can operate at higher power densities. GaN HEMTs can also work at higher temperatures, which reduces the need for cooling and allows for a more compact module design.



**Cree** offers both epiwafers and device/MMIC foundry services for Ka- and Q-band applications. Through these services, Cree's customers can gain access to the company's field-plated, electron-beam lithography GaN MMIC technology. An individual source via process (shown above) has recently been applied to SiC substrates, enabling microstrip MMICs delivering even higher total power, gain and efficiency than those of the devices described in this article.

The pinch-off characteristics are related to the energy of the Fermi level of the GaN buffer layer below the active channel. Although this Fermi level can be increased by adding p-type dopants or other impurities, this action also creates unwanted drain lags that are attributed to buffer traps.

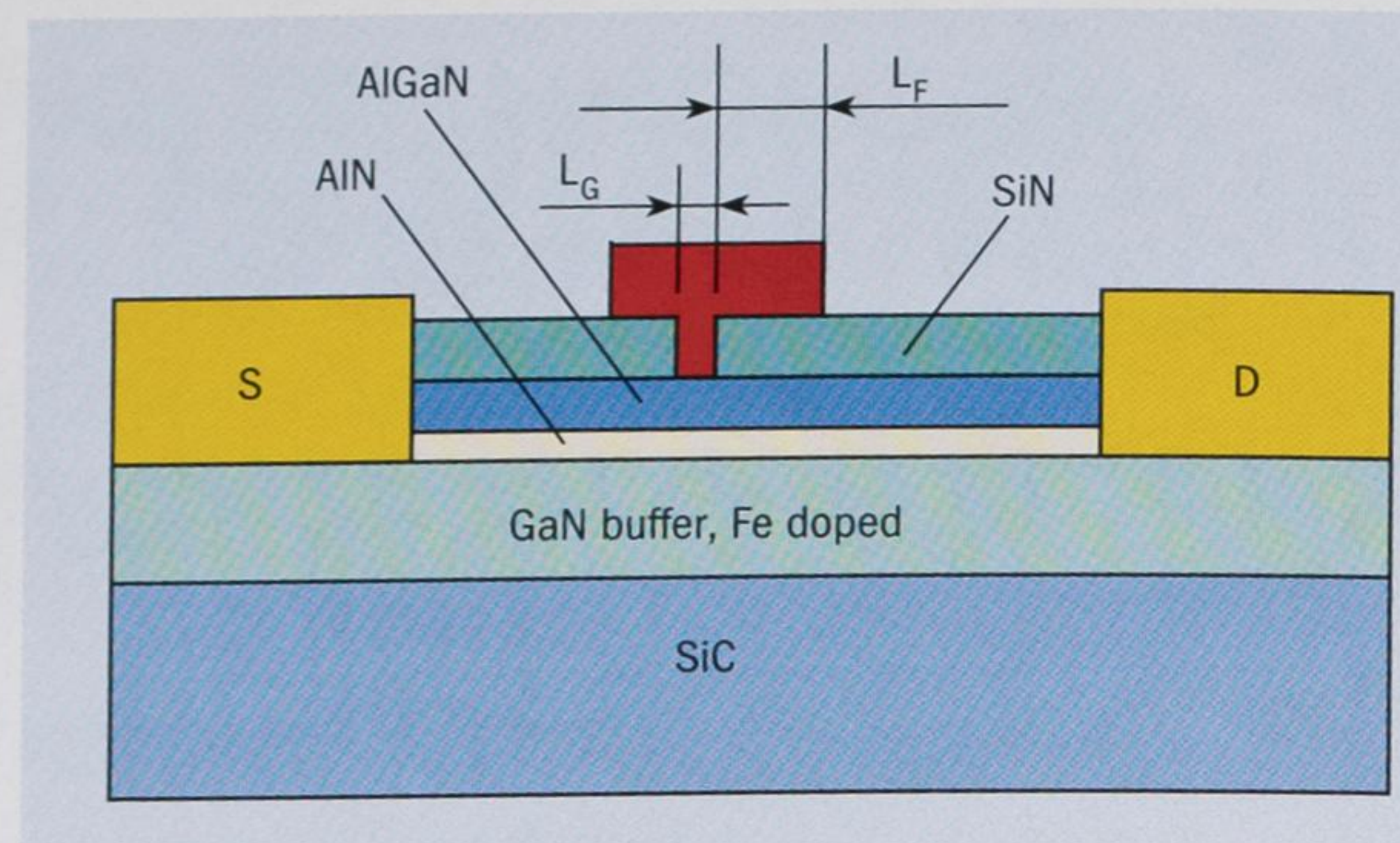
### Designed for power

At Cree we have designed and built a GaN HEMT that overcomes all the issues that we have highlighted by incorporating a field plate, an AlN interlayer and an iron-doped buffer layer into the device (see figure 1).

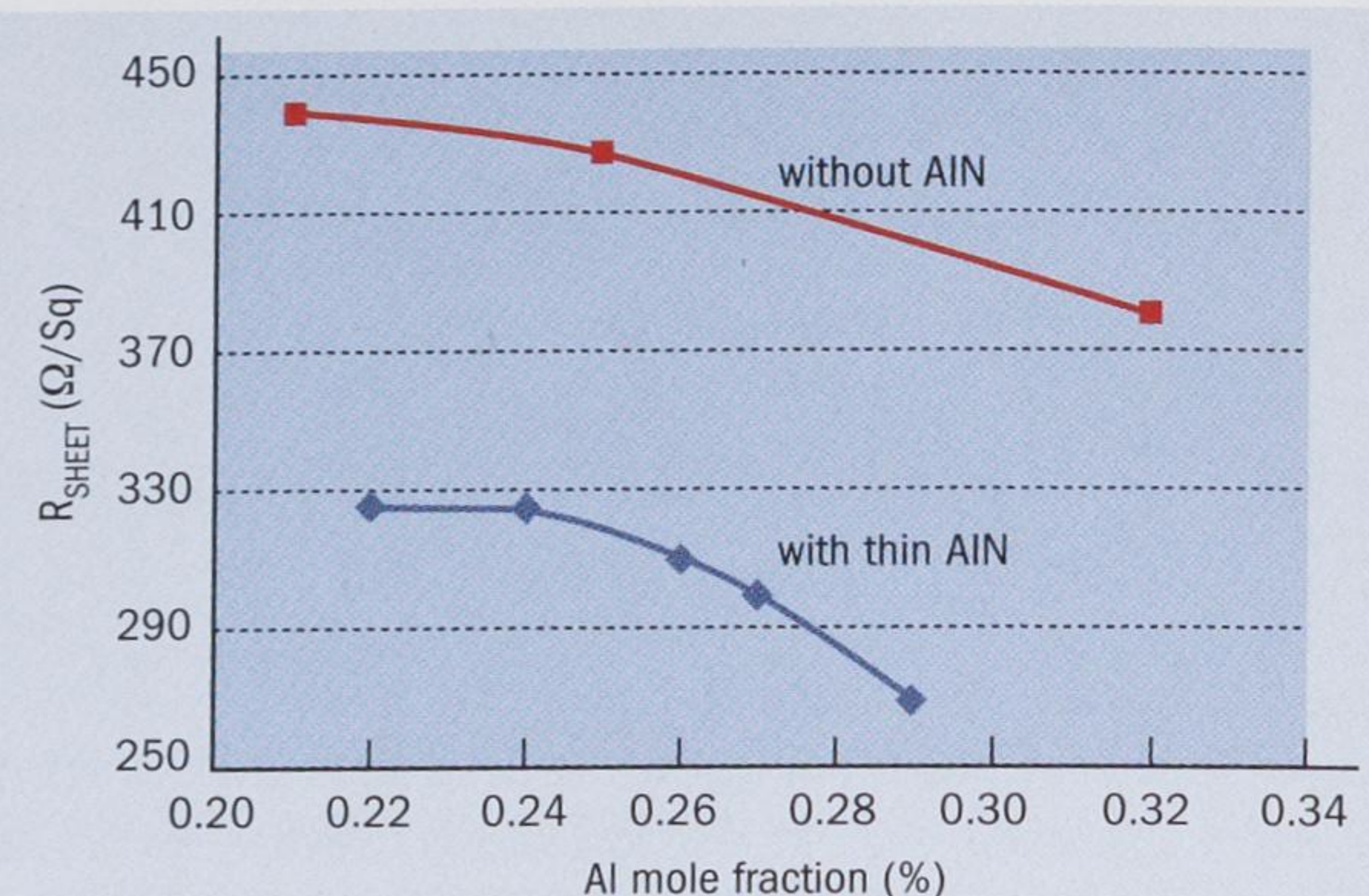
The T-shaped structure built into the SiN layer is an integrated field plate. Traditionally, field plates were introduced to reduce peak electric fields in silicon LDMOS devices and GaAs FETs, which increased their breakdown voltages. In GaN HEMTs, however, the onset of electron trapping only occurs at high fields, so the field plate can reduce or even eliminate trapping effects. We achieved extremely high power densities of greater than 30 W/mm with good efficiencies at 4–8 GHz using this scheme. The drawback of a field plate is the addition of gate-to-drain capacitance, which acts as a path of negative feedback, reducing power gain.

If GaN HEMTs are to operate at millimeter-wave frequencies, the gate and field-plate dimensions must be scaled down accordingly. In our design the lengths of the gate ( $L_G$ ) and field plate ( $L_F$ ) are 0.15–0.18  $\mu\text{m}$  and 0.3  $\mu\text{m}$ , respectively, giving typical current-gain and power-gain cutoff frequencies ( $f_t$  and  $f_{\text{max}}$ ) of 60 and 120 GHz. Although this  $f_t$  is lower than that of non-field-plated devices of similar gate length (65–70 GHz), we believe that the improved large-signal characteristics more than compensate for this.

In our devices a thin AlN layer at the AlGaIn/GaN interface significantly reduces alloy scattering in AlGaIn, and this decreases the transistor's channel resistance. The insertion of this layer has delivered a substantial reduction in the sheet resistance throughout the aluminum content range that was investigated (see figure 2).



**Fig. 1.** Cree's GaN HEMTs were grown by MOCVD on a semi-insulating SiC substrate. An AlN nucleation layer was deposited first, followed by a 2–4  $\mu\text{m}$  thick iron-doped GaN buffer, a strained thin AlN layer and a 22 nm thick AlGaIn barrier. Ohmic contacts were produced by annealing a Ti/Al/Ni/Au alloy at 880 °C. A Ni/Au contact formed the Schottky gate, after the dimensions were defined by electron-beam lithography and subsequent dry etch through a SiN layer.



**Fig. 2.** Inserting an AlN interlayer reduces the channel resistance and improves GaN HEMT operation at higher frequencies.

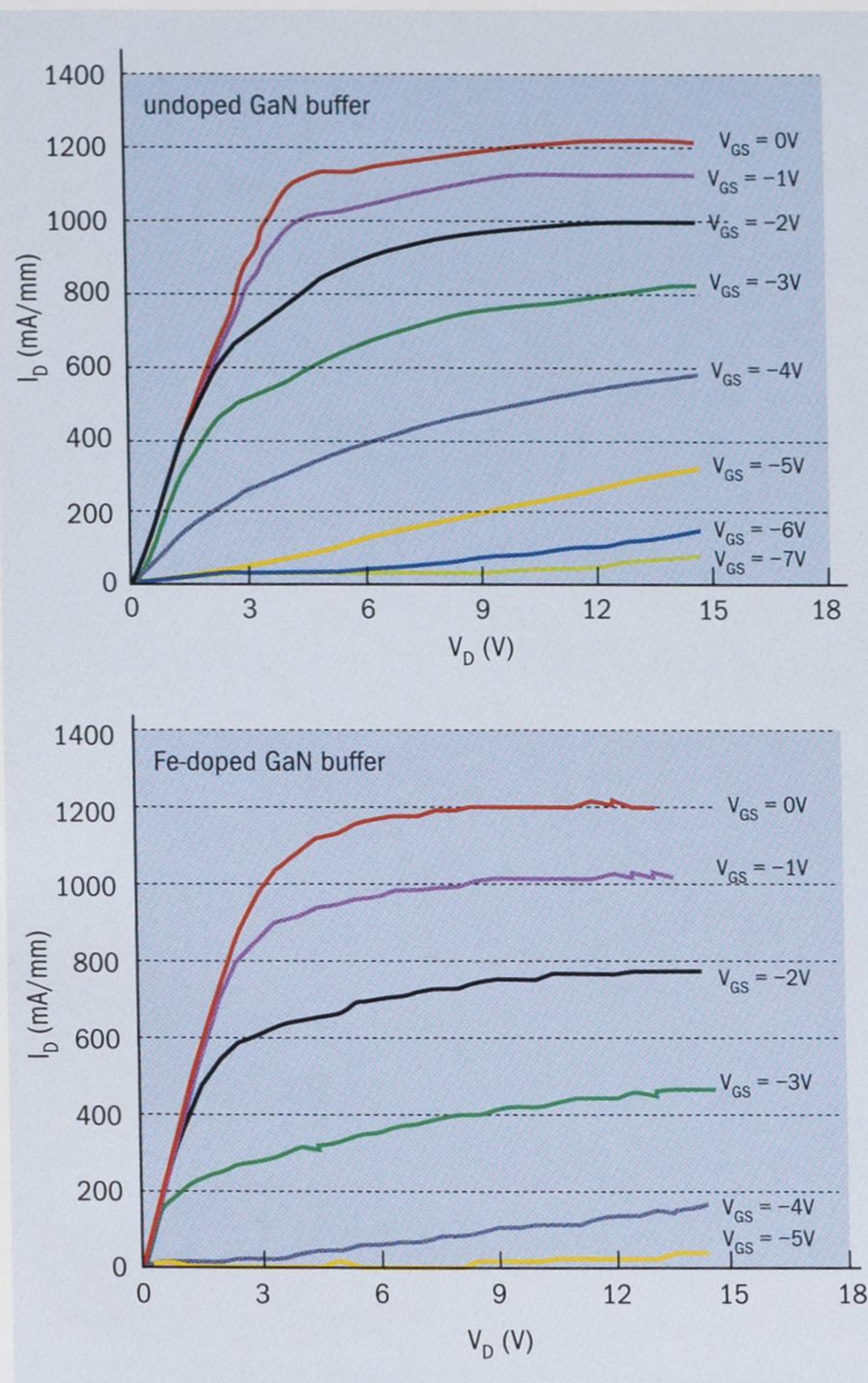
Adding an iron-doped GaN buffer layer addresses short-channel effects that can cause poor pinch-off characteristics (see figure 3). The iron dopant drastically cuts the transistor's buffer conductivity without degrading its large-signal performance.

Power measurements of unit cell devices clearly demonstrate the performance improvements resulting from our design (see figure 4). The 100  $\mu\text{m}$  wide device generates 0.86 W of output power, or 8.6 W/mm, at 40 GHz. Linear gain is 6 dB, while associated power gain and power-added efficiency (PAE) at peak power are 4.1 dB and 34%, respectively. This is a significant step up from previous values of 3–4 W/mm and 20–30% PAE, which were produced using generic electron-beam-gate GaN HEMT structures.

### Scaling up

We have also scaled up the device periphery using an oversized air-bridge structure to produce the output powers required for transmit power-amplifier applications. This structure provides minimum grounding resistance and inductance without the need for via-hole etching in applications where co-planar waveguide transmission line systems are preferred. The scaling was suitable for 1.5 and 1 mm peripheries for devices



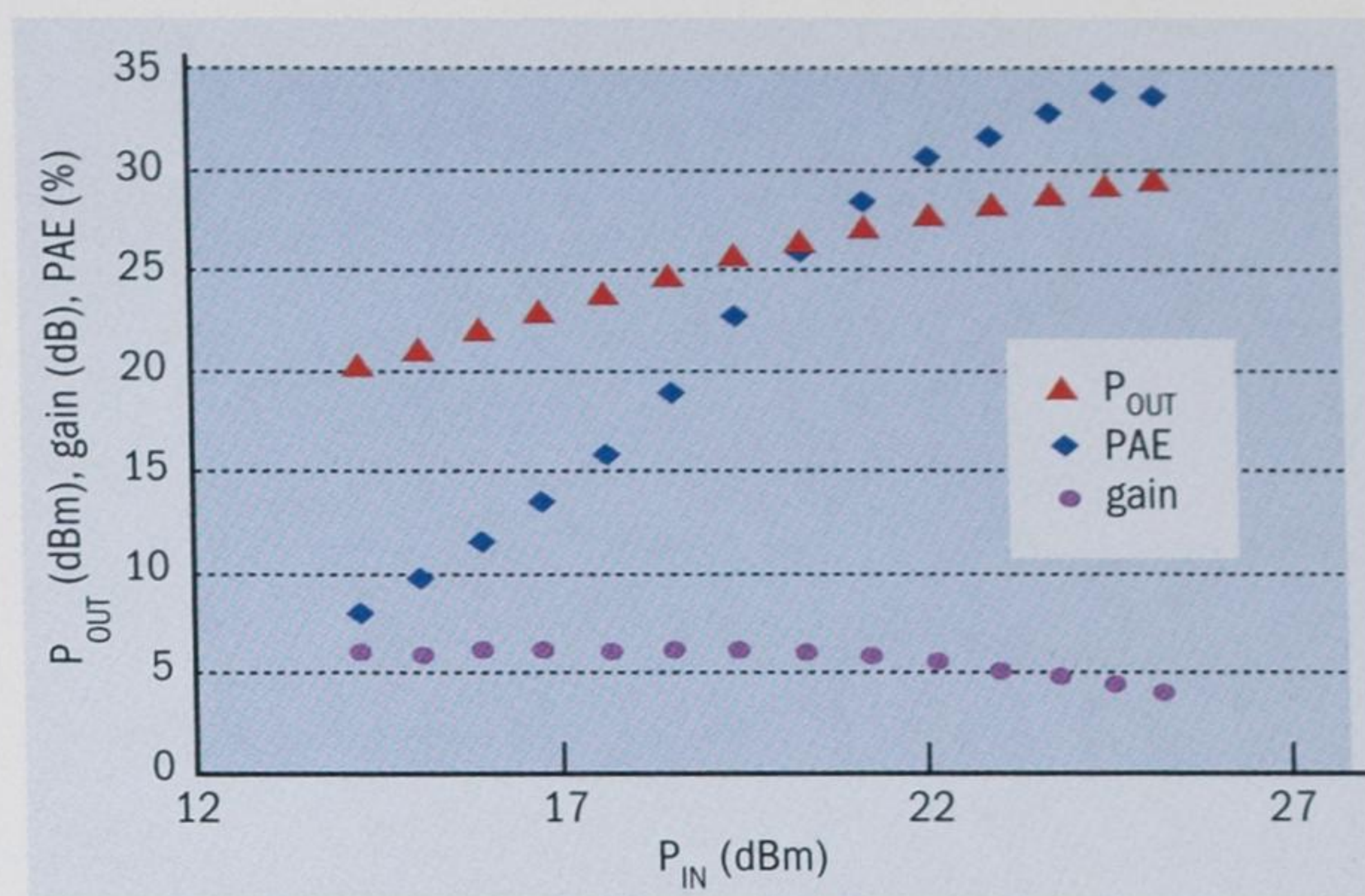


**Fig. 3.** Switching from an undoped to an iron-doped buffer improves the HEMTs' pinch-off characteristics (a smaller gate voltage is required to extinguish the drain current), and consequently increases the device's output power and efficiency.

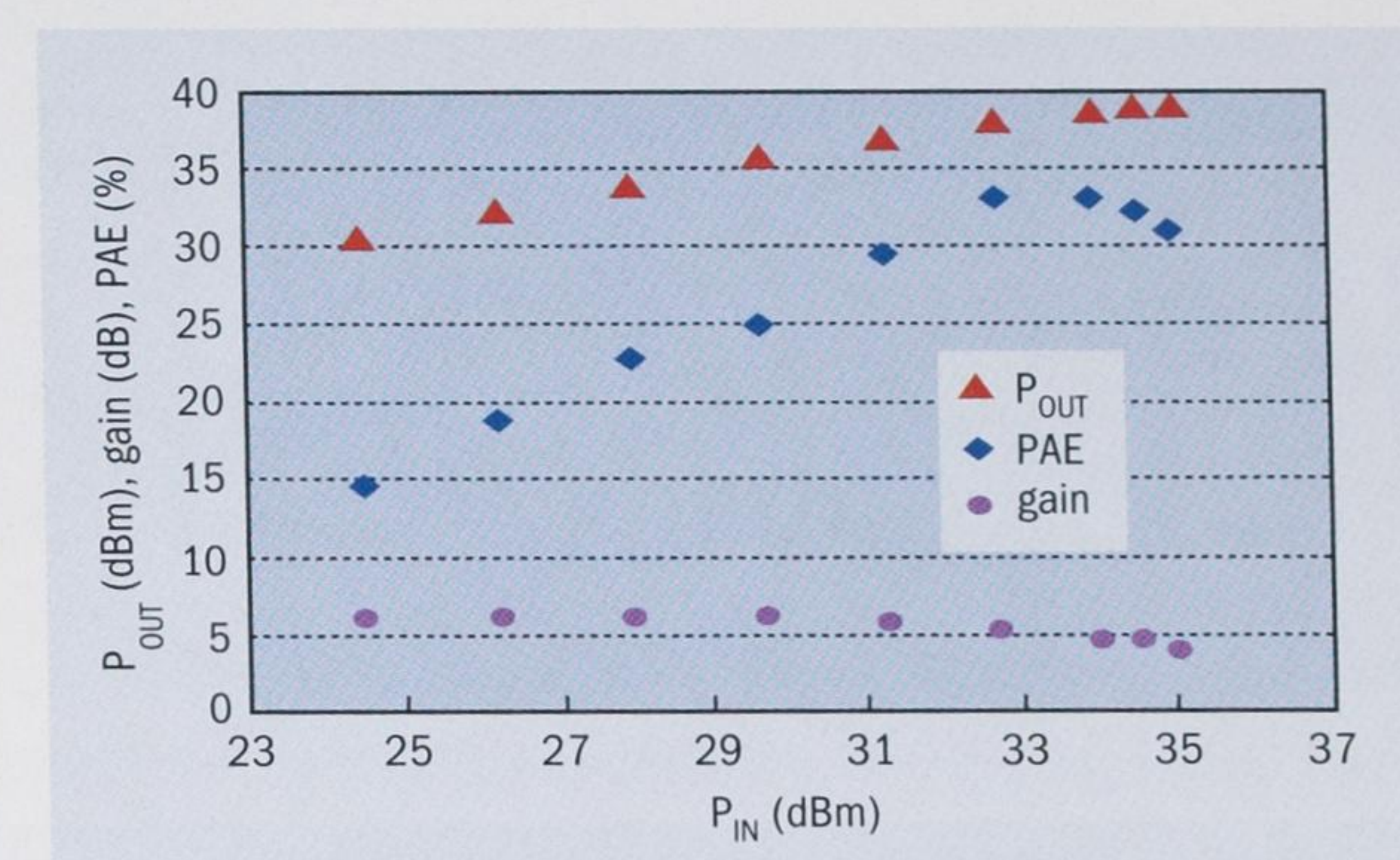
operating at 30 and 40 GHz, respectively.

Two single-stage amplifiers were designed using 1.05 mm wide devices with on-wafer pre-matching circuits operating at 30 and 35 GHz. On the millimeter-wave test bench the 30 GHz amplifier generated 5.4 W at a 36% PAE, while the 35 GHz amplifier produced 5.2 W and a 31% PAE. The associated gains were 6 and 5 dB at the respective frequencies (the pre-matching loss was allocated to the devices and not included in the calibration). This result is a substantial improvement over previous values of 3.5–3.6 W and 22–26% PAE obtained from non-field-plated devices of the same size at the same frequencies, and confirms the advantages of our design.

To determine the maximum scalability of a single-cell GaN HEMT, we have also built a single-stage amplifier with a 1.5 mm wide device. The pre-matched GaN HEMT delivered 8.05 W of output power at 30 GHz with a 31% PAE and 4.1 dB associated gain (see figure 5). We believe that this is the highest power generated by a GaN transistor operating at millimeter-wave frequencies. The output is equivalent to that of a GaAs-based MMIC with a 14.7 mm wide output device, but delivered by a component with a periphery just one-tenth of that size. The higher operating



**Fig. 4.** Cree's latest 100  $\mu\text{m}$  wide devices can deliver 8.6 W/mm at 40 GHz with a power-added efficiency (PAE) of 34%. This is a significant improvement over the performance of generic GaN HEMTs produced using electron-beam lithography, which generate 3–4 W/mm at PAEs of 20–30%.



**Fig. 5.** GaN HEMTs can slash the footprint of the power amplifier. This GaN-based pre-matched 1.5 mm wide device generates a record 8.05 W at 30 GHz. To produce the same power with GaAs MMIC requires a device 10 times wider.

voltage for the GaN HEMT of 28 V, compared with 5 V for the GaAs MMIC, also reduces the bus current requirements and improves the conversion efficiency of the power supply.

Although significant progress has been made, in terms of power output and efficiency, the reliability of millimeter-wave GaN HEMTs remains a challenge. However, we expect that additional innovations to the design will not just improve the reliability of these devices, but also signal gain and manufacturability. These advancements will lead to the emergence of next-generation HEMTs that will benefit many aspects of military and commercial communication systems.

Although GaN HEMTs will initially be a replacement technology vying to take market share from established products, their compact size, lower cost and high performance will eventually increase system efficiency and reduce costs. Cost savings will be transferred to customers, and this will drive increased sales that will eventually lead to the growth of new markets for these devices.

#### Further reading

Y-Fu Wu *et al.* 2005 *IEEE IEDM Digest* 193  
Y-Fu Wu *et al.* 2003 *IEEE IEDM Digest* 579.



#### About the authors

**Yifeng Wu** (left) has been a lead research scientist on GaN power devices and amplifiers for eight years, working first at Widegap Technology LLC, before moving to Nitres and then Cree. **Primit Parikh** (right) is currently managing the GaN electronics effort at Cree Santa Barbara Technology Center.

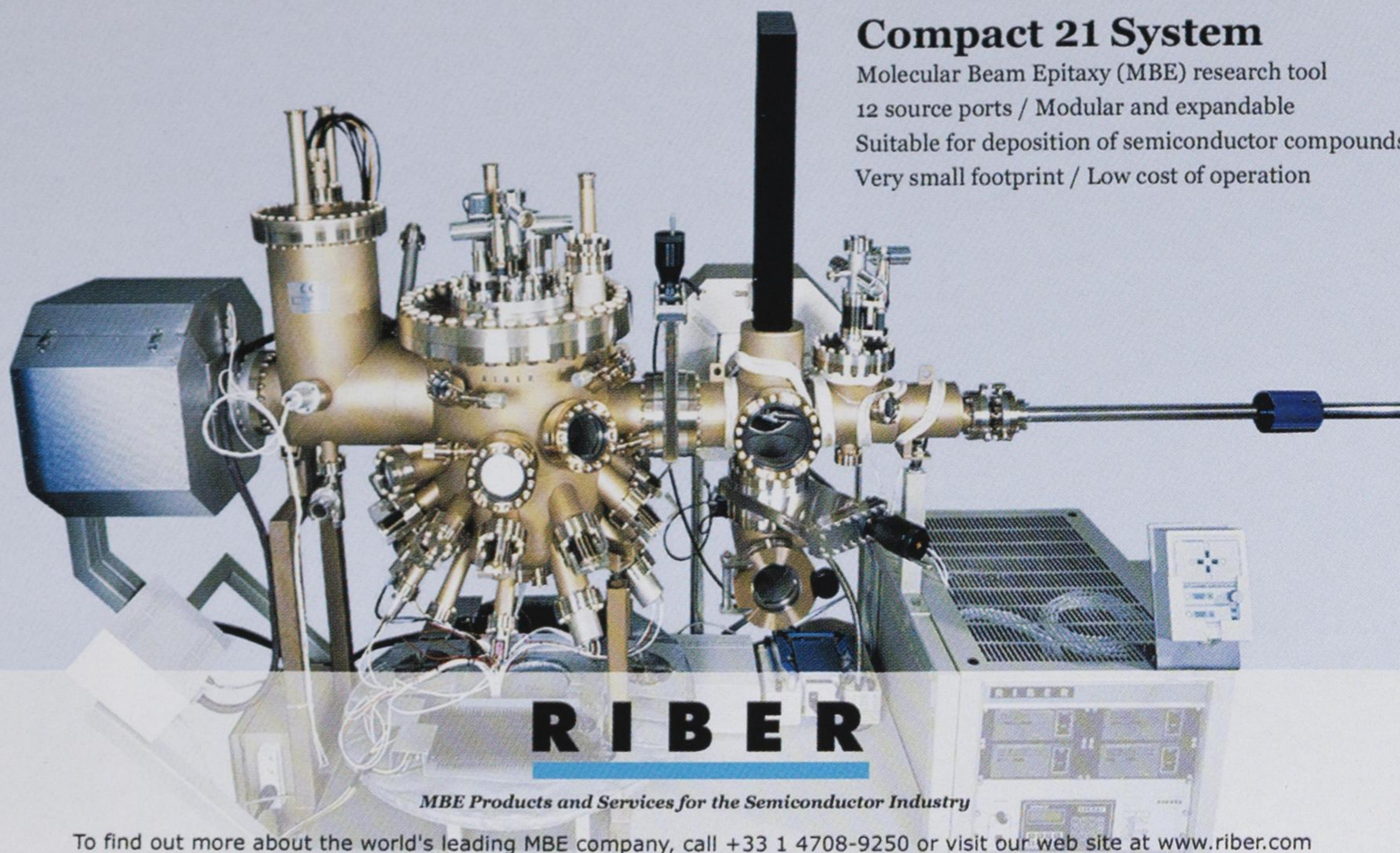
The mm-wave device and circuit development work was funded by ONR. Materials development was funded by DARPA and ONR, and monitored by **Harry Dietrich** at ONR.



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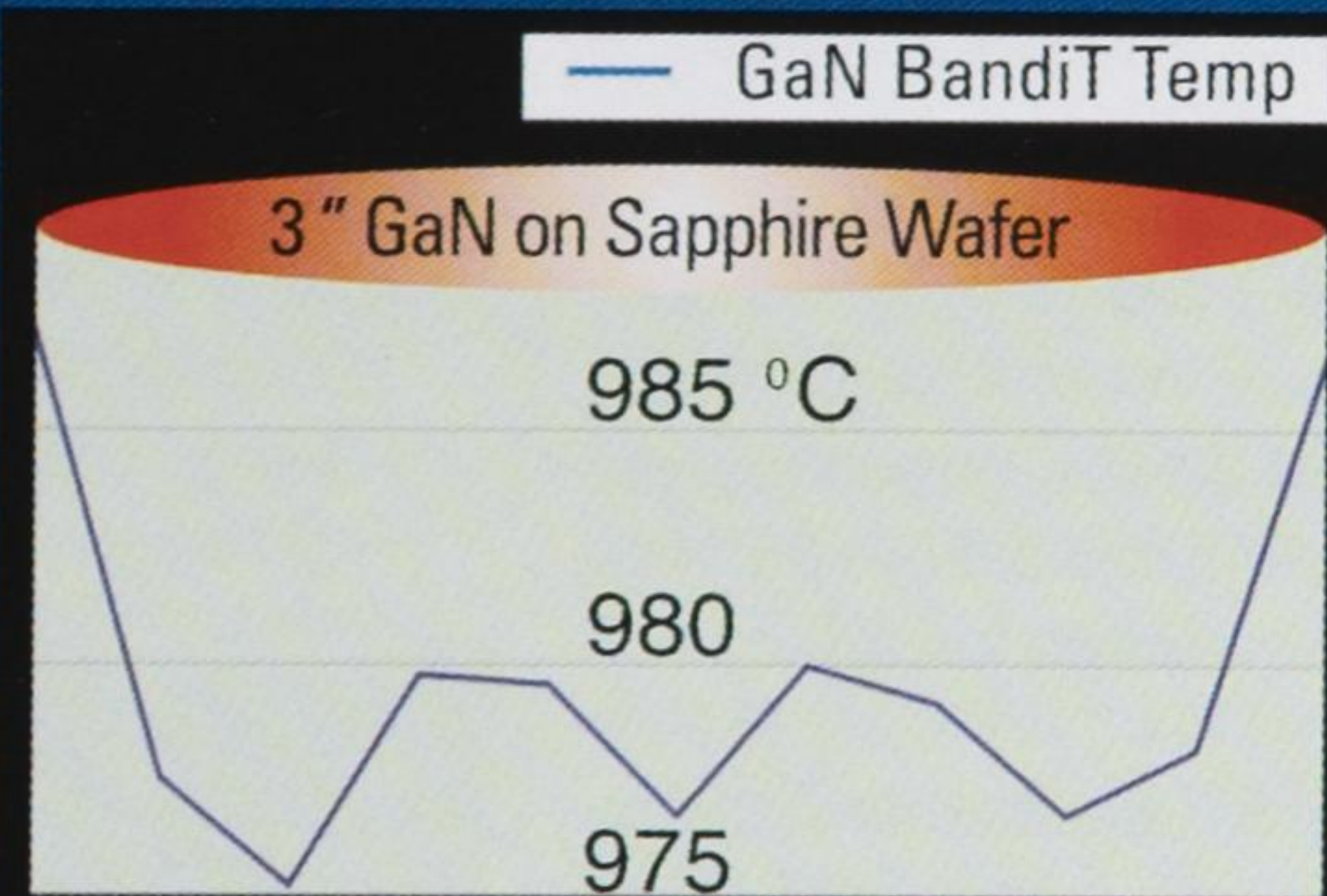
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# IEDM showcases power HFETs

III-V device highlights at the 2005 International Electron Devices Meeting held in Washington, DC, included high-power GaN HEMTs with both single and dual field plates, and metal-insulator-semiconductor structures producing very low leakage currents. **Richard Stevenson** rounds up.

The IEEE's International Electron Devices Meeting (IEDM) is always dominated by silicon devices, and this year's conference proved no exception. However, the organizing committee also chose to squeeze in a session on one of the hottest research topics in compound semiconductors – GaN high-power transistors for RF and microwave applications.

The session began with Nitronex detailing the development of 368 W GaN-on-silicon HFETs that feature a field plate (FP) connected to the transistor's source electrode and extending to the center of the gate-drain region. The addition of this source field plate (SFP) is thought to be a critical development, enabling high output power and drain efficiency at high drain voltages.

Nitronex CTO Kevin Linthicum and a team of engineers compared the performance of GaN HFETs with and without an FP. Both types of device were fabricated on high-resistance silicon (111) substrates with gate lengths of 0.7  $\mu\text{m}$ , and gate-to-source and gate-to-drain spacings of 1 and 3  $\mu\text{m}$ , respectively. The single-chip transistors, which have a 36 mm gate periphery, were then packaged using a gold-silicon eutectic die attach in industry-standard RF packages with a two-stage input match and no output match.

Pulsed RF power measurements at 2.14 GHz using a 1% duty cycle and a 300  $\mu\text{s}$  pulse width showed that the SFP device delivered 368 W with a maximum drain

efficiency of 70% and 17.5 dB of small signal gain at a 60 V drain bias. The device without the SFP produced just 225 W at a lower drain voltage, with a drain efficiency of just 33%.

## Adding field plates

NEC engineers have taken the idea of improving transistor performance by adding FPs one stage further, by fabricating an AlGaIn/GaN dual FP FET on a semi-insulating SiC substrate (see figure 1, p26). The first FP forms part of the gate and improves the transistor's breakdown characteristics while suppressing current collapse. The second FP, formed on the SiN film at the gate edge, is connected to the source. This shields the electric field between the first FP and the drain, eliminating the high gate-drain capacitance seen in single FP structures.

Comparing the performance of single and dual FP FETs, the NEC team found that at a 40 V drain bias the dual FP transistor delivered an extra 3 dB of stable gain compared with the single FP device. On-wafer load-pull measurements revealed that the dual FP FET had wider stable load impedance, allowing easy tuning at maximum power.

The dual FP FET also showed greater linearity, with a 5 dB improvement in adjacent channel leakage power ratio over the single-plate versions. The researchers

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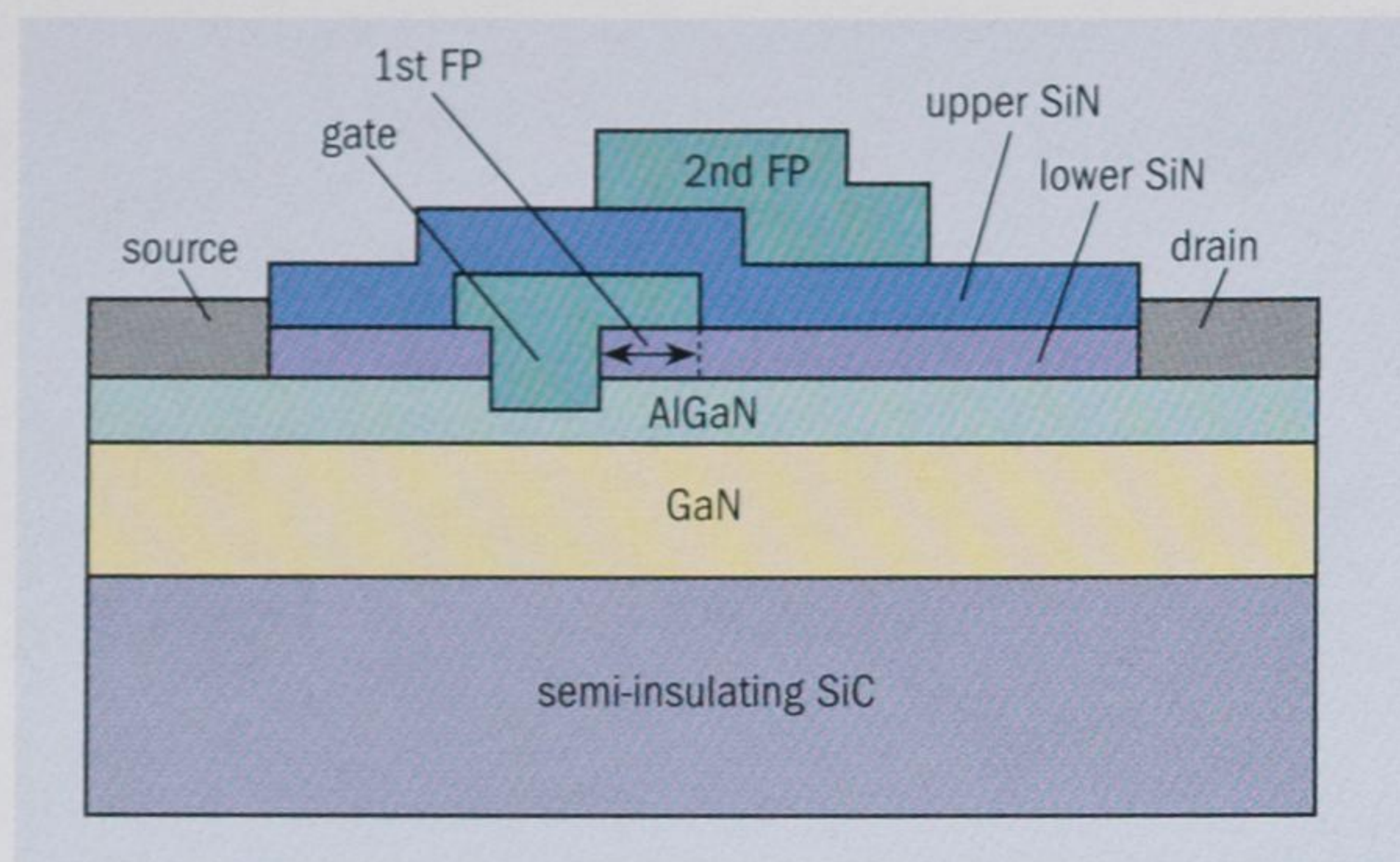
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**Fig. 1.** NEC researchers made dual field plate (FP) FETs delivering 160 W output with a 0.5  $\mu\text{m}$  gate length. The first gate FP also measures 0.5  $\mu\text{m}$ , while the second FP on the SiN film is 1.5  $\mu\text{m}$  long.



claim that the dual-plate device produces a state-of-the-art combination of 160 W output and 17.5 dB linear gain at 2.15 GHz, with wideband code division multiple access (W-CDMA) modulation and a 45 V drain bias.

#### Uncovering the traps

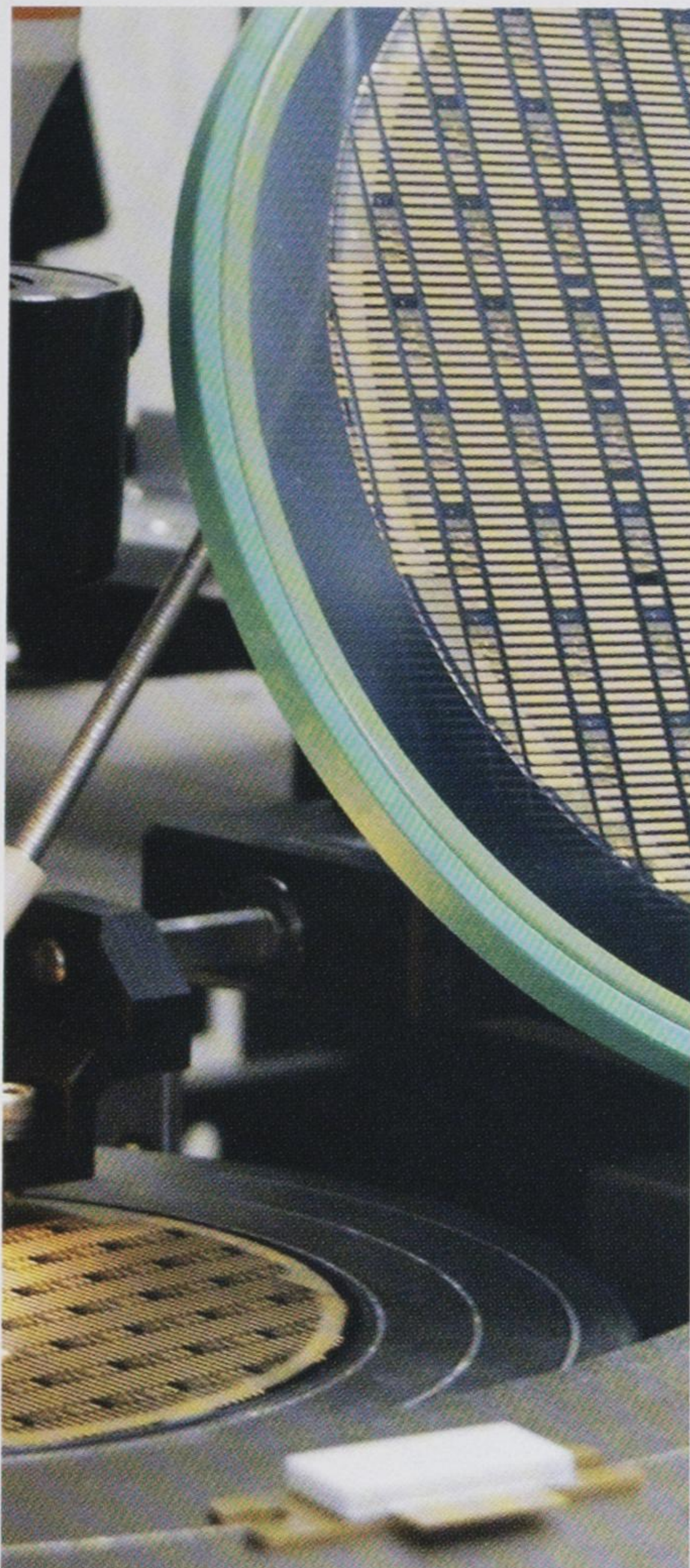
Meanwhile, the Alcatel-Thales III-V laboratory outlined its evidence for trapping phenomena and trap creation in GaN-based HEMTs on SiC, thanks to a collaboration that included the universities of Padova and Bordeaux and France's Institute of Electronics, Microelectronics and Nanotechnology. The work, which should help the community improve its understanding of failure mechanisms in GaN transistors, is claimed to be one of the longest tests published for this type of device.

The 3000 hour transistor test involved a 25 V drain voltage, with the gate voltage adjusted to maintain 6 W/mm of dissipated power to define the on-state, and drain and gate voltages of 46 V and -6 V, respectively, for the off-state. Channel temperatures were 260 °C and 130 °C for the on- and off-states.

The on-state produced the most detrimental effect on drain current. Since the transistor's metal contacts were stable, the researchers concluded that degradation was probably caused by hot electrons in the active area during on-state stress.

Later in the session, a Fujitsu Laboratories team detailed GaN-based metal-insulator-semiconductor (MIS) HEMTs delivering 110 W and 13 dB of linear gain at 2.14 GHz. Toshihide Kikkawa and colleagues say that GaN HEMTs tend to suffer from high gate leakage currents under large RF input signals that degrade device performance and reliability. However, Fujitsu's AlGaIn/GaN MIS-HEMTs showed only small leakage currents under high-voltage and high-power operation.

Analysis of the MOCVD-grown MIS-HEMTs revealed that the reverse and forward gate leakage currents were two and six orders of magnitude lower, respectively, than a Schottky gate HEMT operating under identical conditions. The MIS-HEMT also delivered a breakdown voltage in excess of 400 V, which the Fujitsu researchers claim is the highest ever reported for this type of device.



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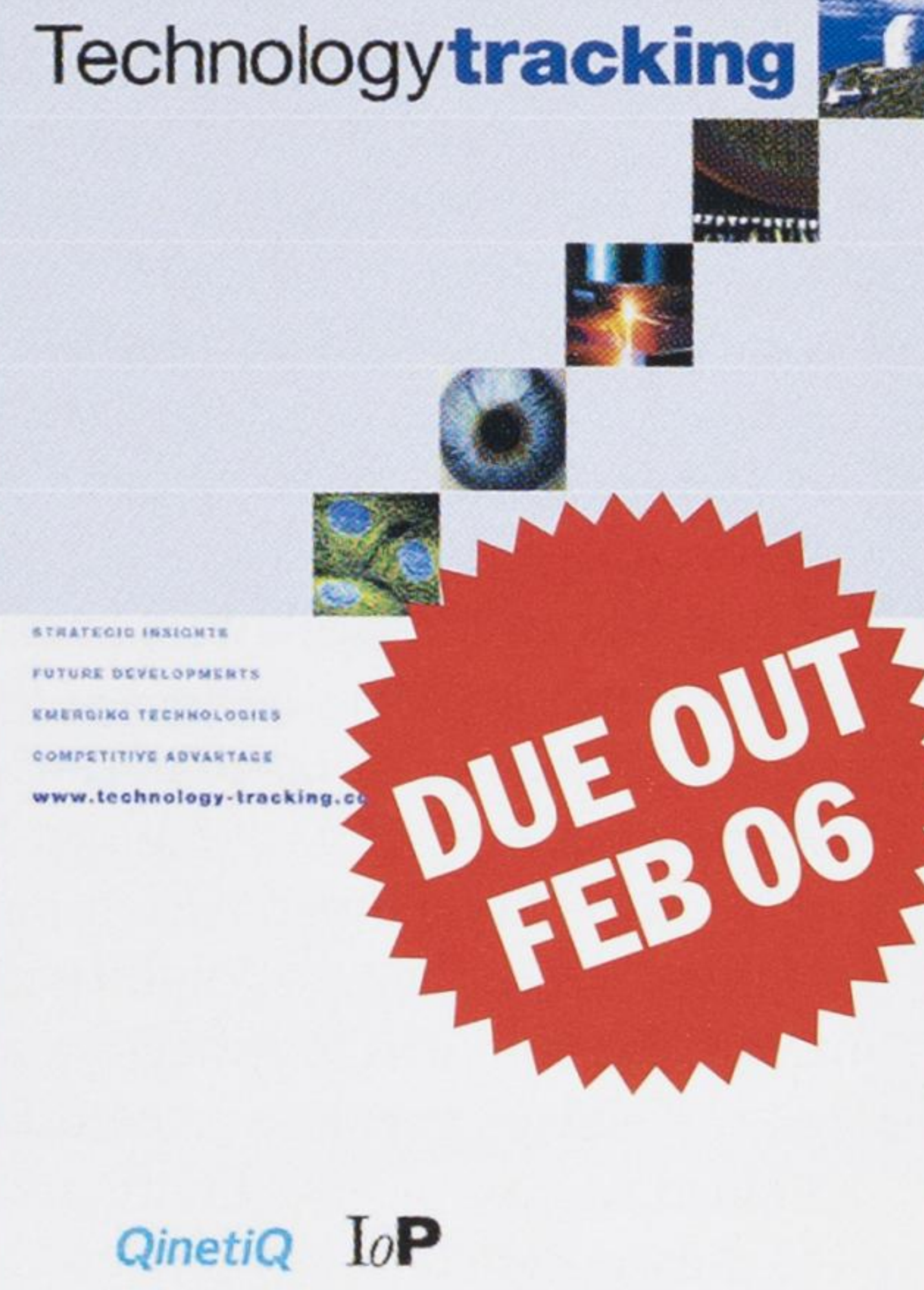
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# Shallow etch could power dilute-nitride VCSEL breakthrough

Alight Technologies is tackling the need for powerful long-wavelength, single-mode VCSELs by marrying its photonic-bandgap technology with Infineon's dilute-nitride platform. **Dan Birkedal** and **Dirk Jessen** detail the hybrid design and reveal why it will benefit datacom and telecom networks.

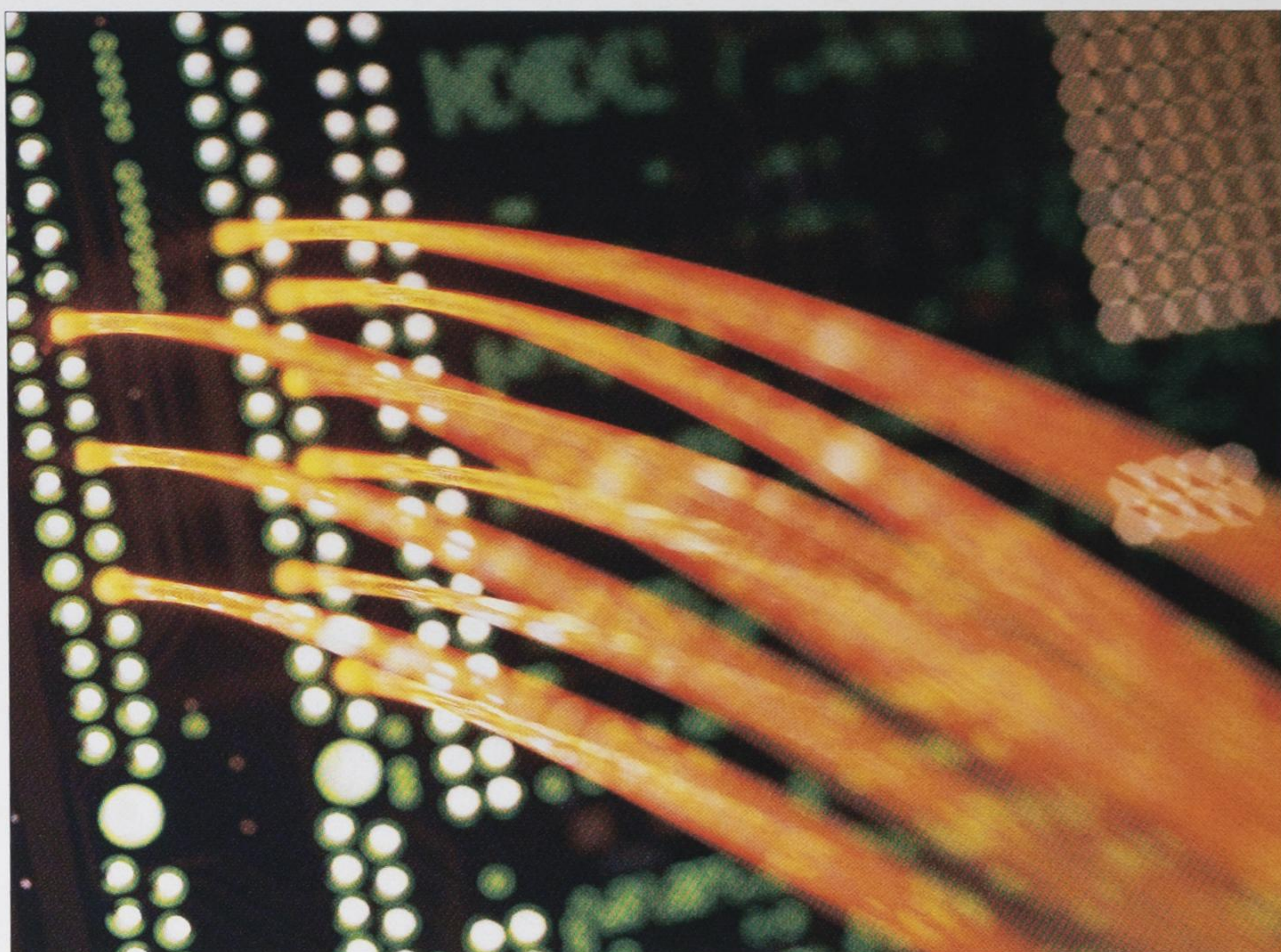
Multimode VCSELs operating at 850 nm are the dominant source for today's short-range datacom applications. However, despite advantages such as on-chip testing and straightforward fiber coupling, these surface-emitting devices are still to impact the longer range and higher speed datacom and telecom applications.

Infineon Technologies, Picolight and Optical Communication Products have all developed 1.3  $\mu\text{m}$  VCSELs, but their single-mode output powers are limited, and this has hindered market penetration in more demanding applications. Instead, current networks are served with edge-emitting sources – either Fabry–Pérot lasers that are limited in range by modal dispersion at higher modulation frequencies, or distributed-feedback lasers that usually require an additional optical isolator.

However, recent efforts at our company, Alight Technologies, have revealed that a VCSEL's single-mode output power can be increased to fulfill the requirements of communications applications through the addition of a photonic-bandgap (PBG) structure. Our team, which is based in Copenhagen, Denmark, has made the breakthrough by combining this photonic technology with Infineon's 1.3  $\mu\text{m}$  dilute-nitride VCSEL design, which we acquired late last year.

The single-mode output of a conventional VCSEL is primarily limited by the oxide aperture that confines the electrical current and the optical modes. This aperture has to be quite small ( $<7 \mu\text{m}$ ) to ensure fundamental-mode operation, but this restriction limits the output power. It also degrades the laser's lifetime and reliability, while the large electrical resistance causes local heating and hinders high-speed operation.

However, our colleague Svend Bischoff, who is a senior staff engineer at Alight, has reported that it is pos-



sible to produce high-speed, high-power single-mode VCSELs by combining a PBG structure for lateral optical confinement with a large oxide aperture providing current confinement. The PBG is formed by etching an array of holes in the VCSEL's top mirror. The modified structure produces a wavelength shift in the cavity resonance that leads to an effective refractive-index change, and this produces the lateral optical mode confinement that ensures single-mode operation.

## Etching effects

The shift in cavity resonance wavelength is very small for shallow etch depths of a few hundred nanometers into the VCSEL's top-mirror surface, so the VCSELs fabricated up until now – at the University of Ulm in Germany and Korea's Advanced Institute of Science and Technology – have featured holes with a depth of 10–20 mirror periods. The holes deliver the required shift in cavity resonance wavelength, but also increase the optical losses and reduce the photon lifetime (the average time that photons spend in the cavity). This means that these lasers have low output powers and a small modal volume because the lateral mode confinement is determined by both the photon lifetime and the shift in cavity resonance wavelength.

**Incorporating** a photonic bandgap structure into a dilute nitride VCSEL increases its single-mode output power and enables it to compete with the Fabry–Pérot and distributed-feedback lasers that are serving today's networks.



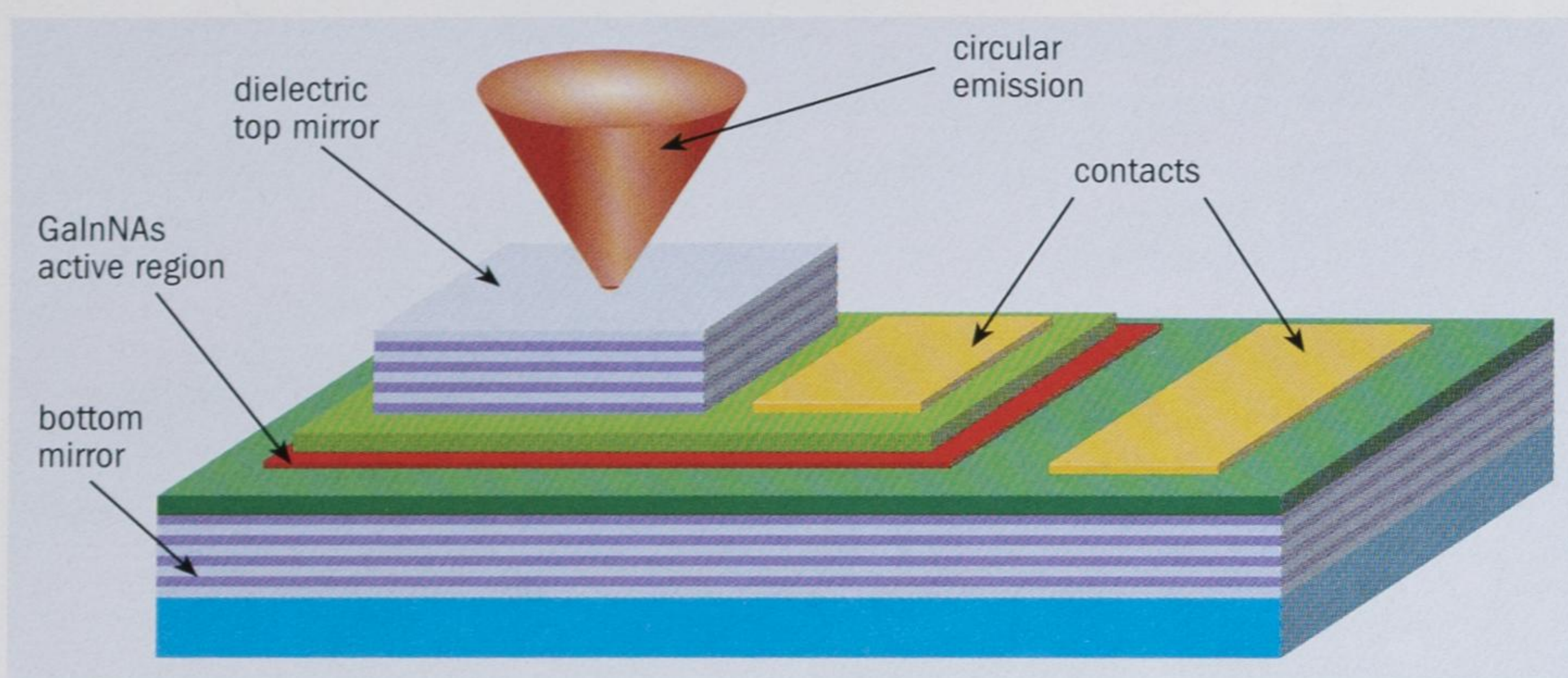
## Manufacturing photonic-bandgap VCSELs

Alight Technologies' laser-manufacturing processes are similar to those used for conventional VCSELs. However, a few specialized processes common to other parts of the optoelectronics industry are needed, including a high-resolution lithography step to define the photonic-bandgap array.

Electron-beam lithography is used for prototyping and low-volume production, since it combines flexibility with control. However, the feature sizes used are large enough to be conveniently fabricated with a conventional high-resolution stepper,

and in the long run we are considering using novel imprint technologies for high-volume, low-cost production.

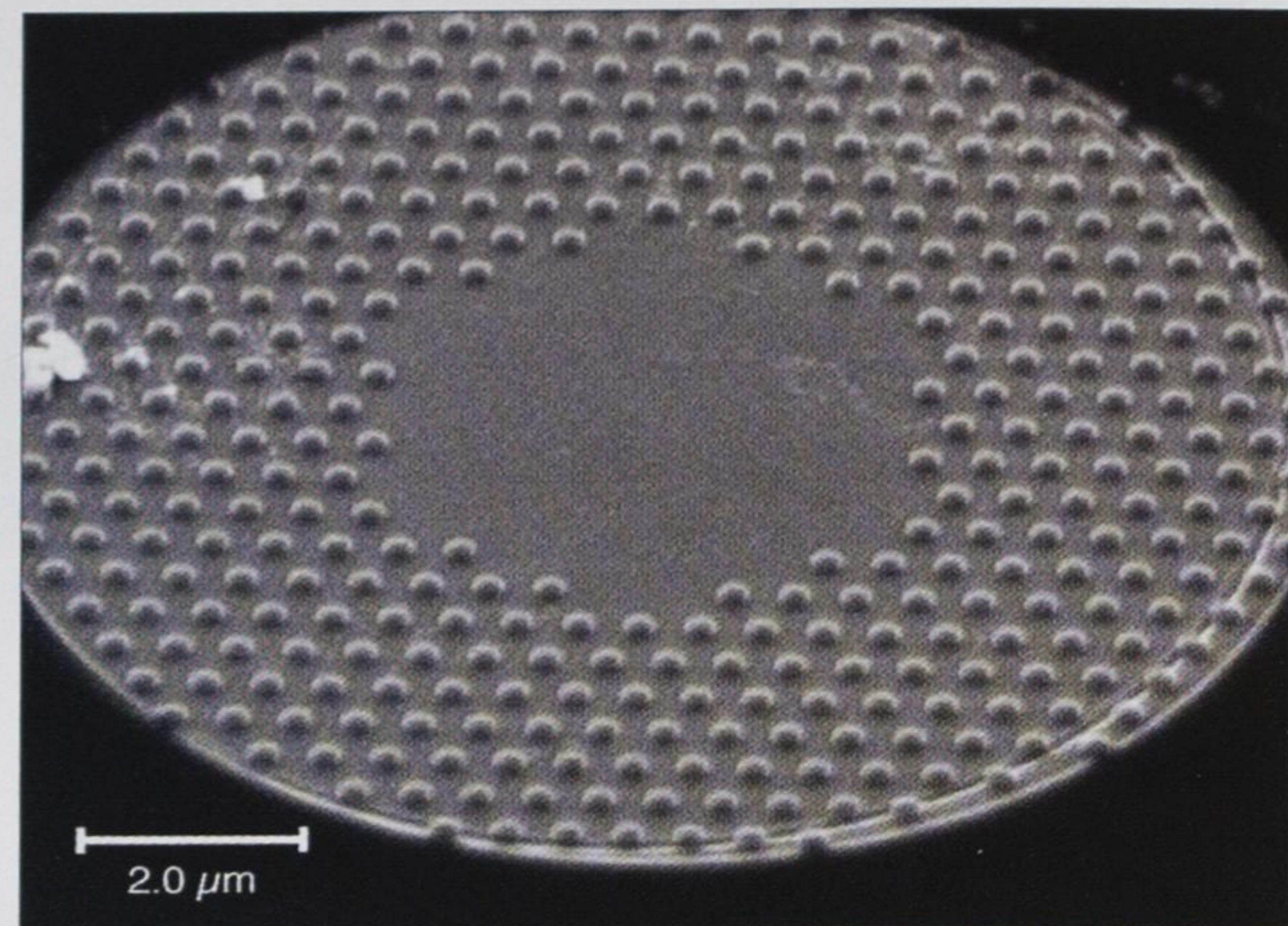
Lithography is followed by dry etching into the semiconductor, with an emphasis on high etch-depth control and good uniformity. Maintaining a smooth surface morphology that cuts scattering losses in a processed device is also essential. Finally, the dielectric top mirror is deposited. The mirror's quality is determined by low stress and good adhesion to the semiconductor surface, and a low optical loss.



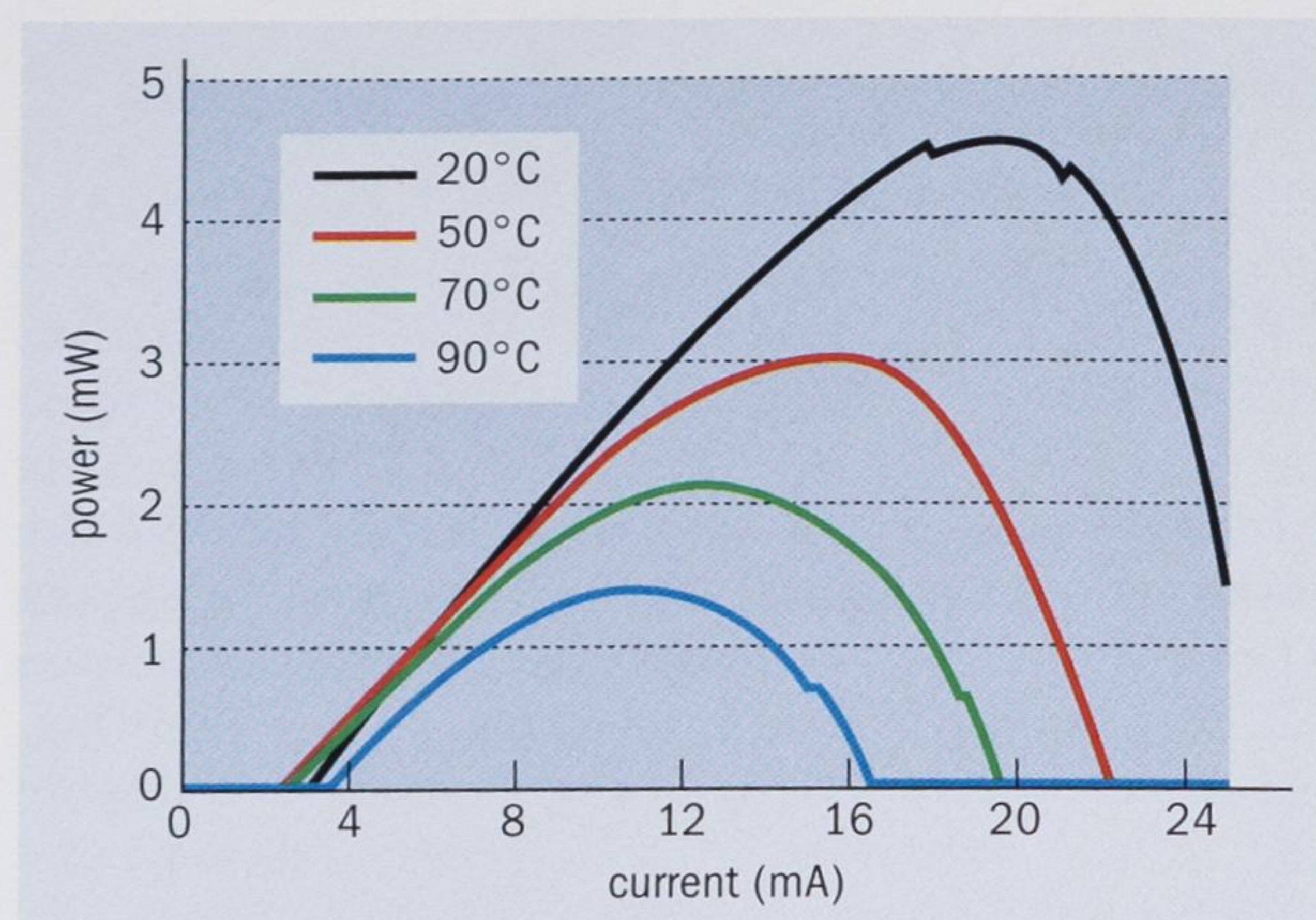
**Fig. 1.** Alight's VCSELs combine Infineon's dilute-nitride surface-emitting laser structure with its own photonic-bandgap technology. The photonic bandgap, which is used to produce lateral optical mode confinement, is formed by etching an array of holes into the active region.

At Alight we have circumvented this problem by shallow etching into a layer close to the active region, before depositing a dielectric top mirror. This approach produces very large cavity resonance wavelength shifts ( $>10$  nm) for etch depths of only a few tens of nanometers. We have already produced 850 nm VCSELs and are now extending the method to 1.3  $\mu\text{m}$  GaInNAs VCSELs (see figure 1). These lasers are produced by shallow etching a tri-diagonal array of rods into the semiconductor surface, just below the dielectric top mirror. The PBG lasing defect is formed by omitting several rods in the center of this lattice (see figure 2).

As well as increasing the cavity wavelength's sensitivity to the etch depth, our design has additional advantages resulting from the close proximity of the PBG layer to the active region. In particular, the number of DBR mirror pairs is constant over the entire structure, which means that reflectivity is high and unmodulated. Consequently, the VCSELs' lateral guiding mechanisms are determined solely by local variations in wavelength or effective index, and not by loss/gain guiding. Loss guiding would increase the internal optical losses, which is highly undesirable due to the low saturated gain of the active material. Gain guiding is negligible since the index guide of the PBG is much stronger, and completely governs the cavity's



**Fig. 2.** Alight forms the photonic-bandgap lasing defect by omitting several rods in the central region of the tri-diagonal lattice.



**Fig. 3.** Initial results from Alight's VCSELs show a 1.4 mW single-mode output over the entire temperature range, between 20 and 90 °C.

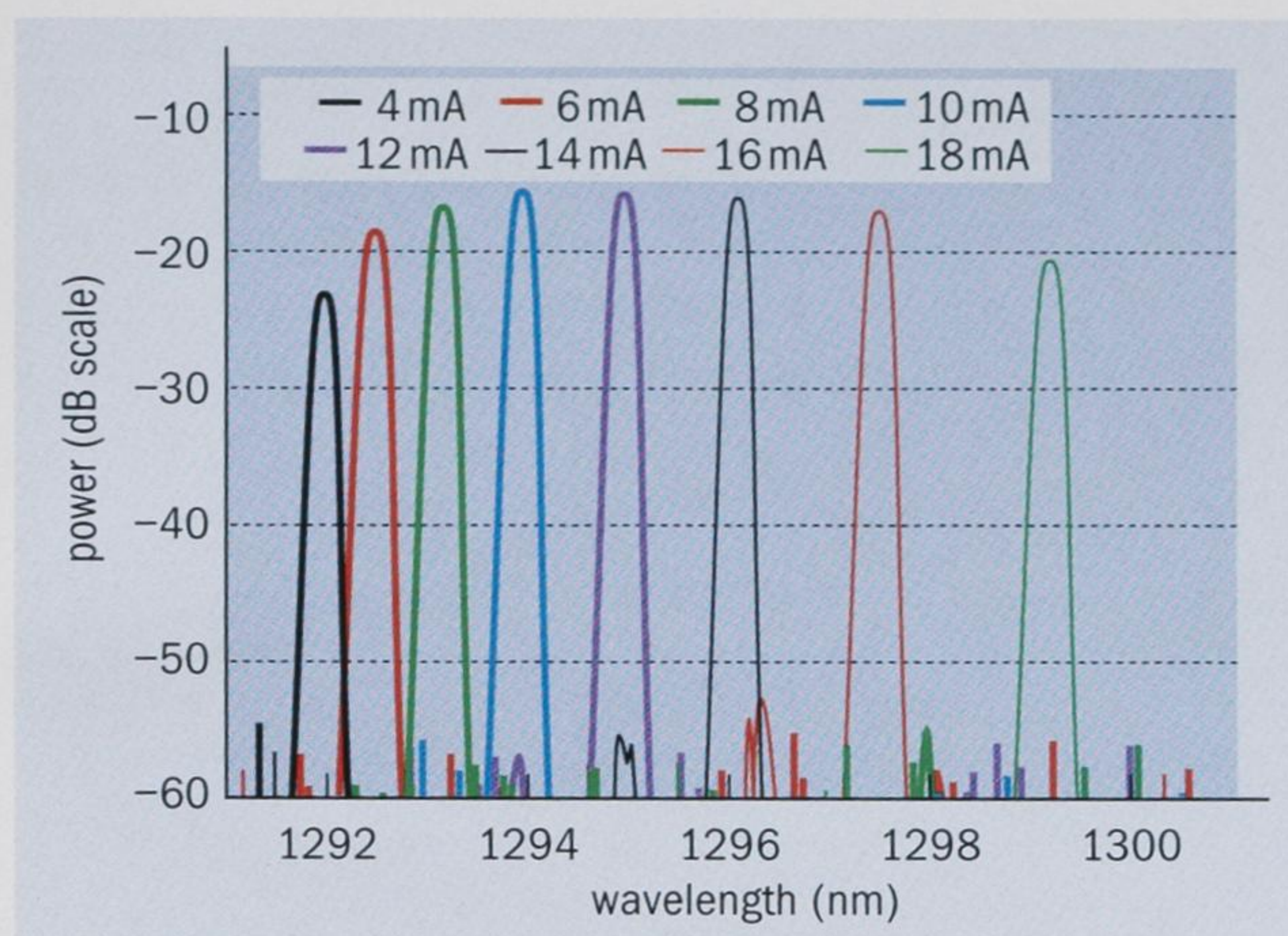
optical mode. In addition, our shallow etch avoids exposure of the aluminum-rich layers to the ambient environment during processing, which simplifies manufacturing.

Our VCSELs use the dielectric top-mirror structure that featured in Infineon's highly reliable, qualified lasers produced by Steinle and colleagues. The dielectric mirrors deliver lower optical losses than DBRs due to the absence of free-carrier absorption, which improves VCSEL performance.

The VCSEL development started with the fabrication of 850 nm lasers. This work was never completed, because of a customer-driven switch to longer wavelengths, but single-mode VCSELs were produced, delivering 3–5 mW. Power levels were limited by ohmic heating, due to a non-optimized contact process, but research showed that it would be possible to construct 10 mW single-mode VCSELs.

Switching to longer wavelength VCSELs required a redesign of the PBG structure, with emphasis on low scattering losses. Initial results of the lasing characteristics for a range of temperatures are shown in figure 3. The devices exhibit single-mode behavior up to 3 mW at 20 °C, can deliver 1.4 mW single-mode power at 90 °C, and produce side-mode suppression ratios exceeding 30 dB (see figure 4).





**Fig. 4.** At a temperature of 70 °C, Alight's VCSELs can deliver side-mode suppression ratios exceeding 30 dB.

### A foundry approach

We believe that it is essential to minimize the VCSELs' time to market, so Alight is working with a foundry, and in close co-operation with a customer, to decrease the time taken from producing a prototype to manufacturing a qualified laser. The company understands that it is essential to establish a credible and reliable supply chain. Although prototyping is performed in a class 10 cleanroom facility in Copenhagen, parallel work at foundry partners validates our volume pro-

duction processes at an early stage.

Based on the promising results that have been obtained so far, we are planning to release 2.5 Gbit/s 1.3  $\mu\text{m}$  VCSELs later this year, targeting datacom and telecom access applications. However, we believe that the transition to higher speed datacom applications in local storage-area networks and optical interconnects, as well as an increased focus on fiber in telecom access networks, will drive the company's future product portfolio.

The PBG technology is generic, which means that it can be applied to VCSELs operating at various wavelengths serving many different applications. For example, high single-mode power is also attractive for sensing applications, printing, passive optical fiber networks and consumer electronics. Our company's strategy is to pursue these opportunities outside of the telecom and datacom markets through partnerships, which will further enhance the penetration of its proprietary technology.

### Further reading

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### About the authors

**Dan Birkedal** (left) is chief technology officer and founder of Alight Technologies.

**Dirk Jessen** (right) is Alight's vice-president of business development.

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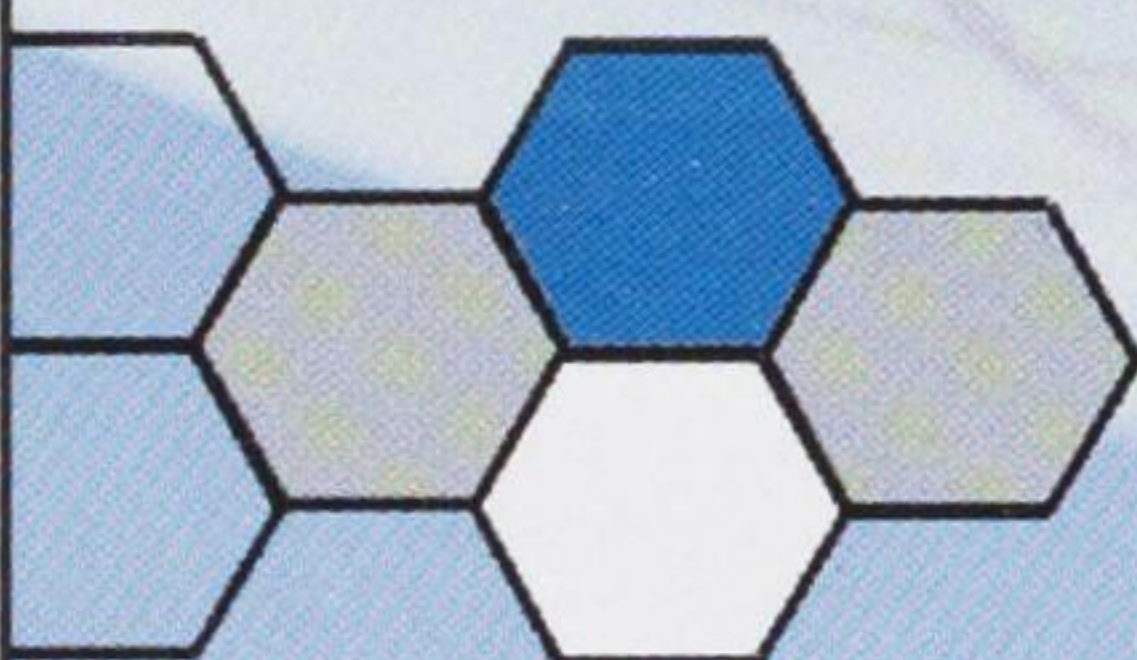
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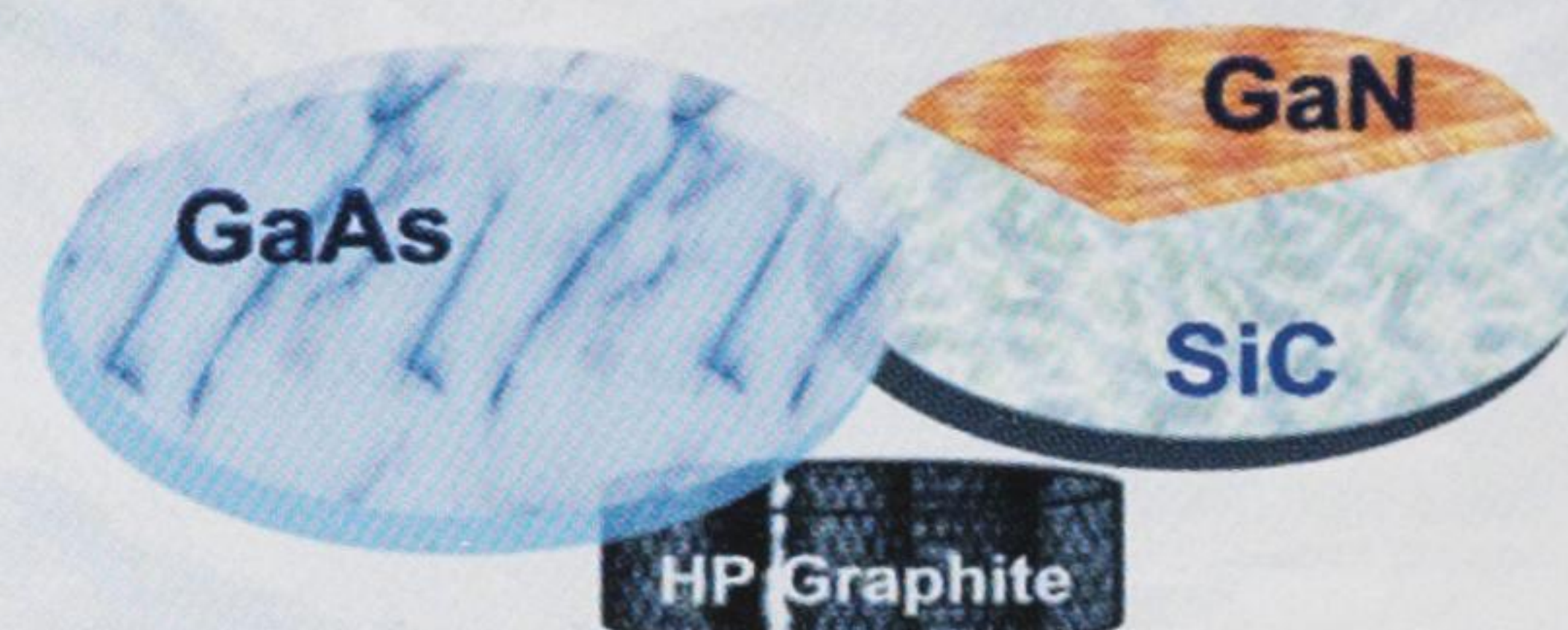
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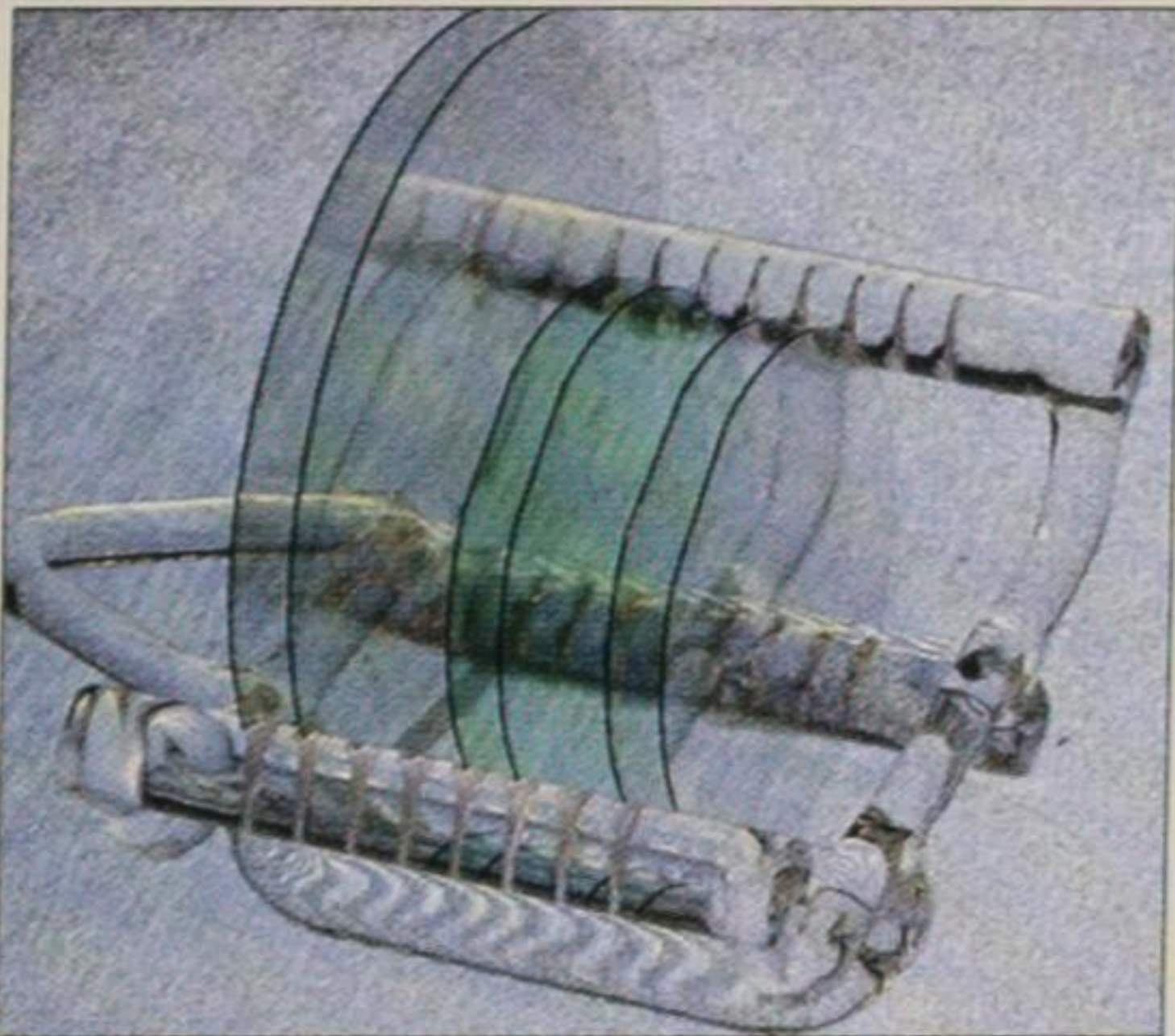
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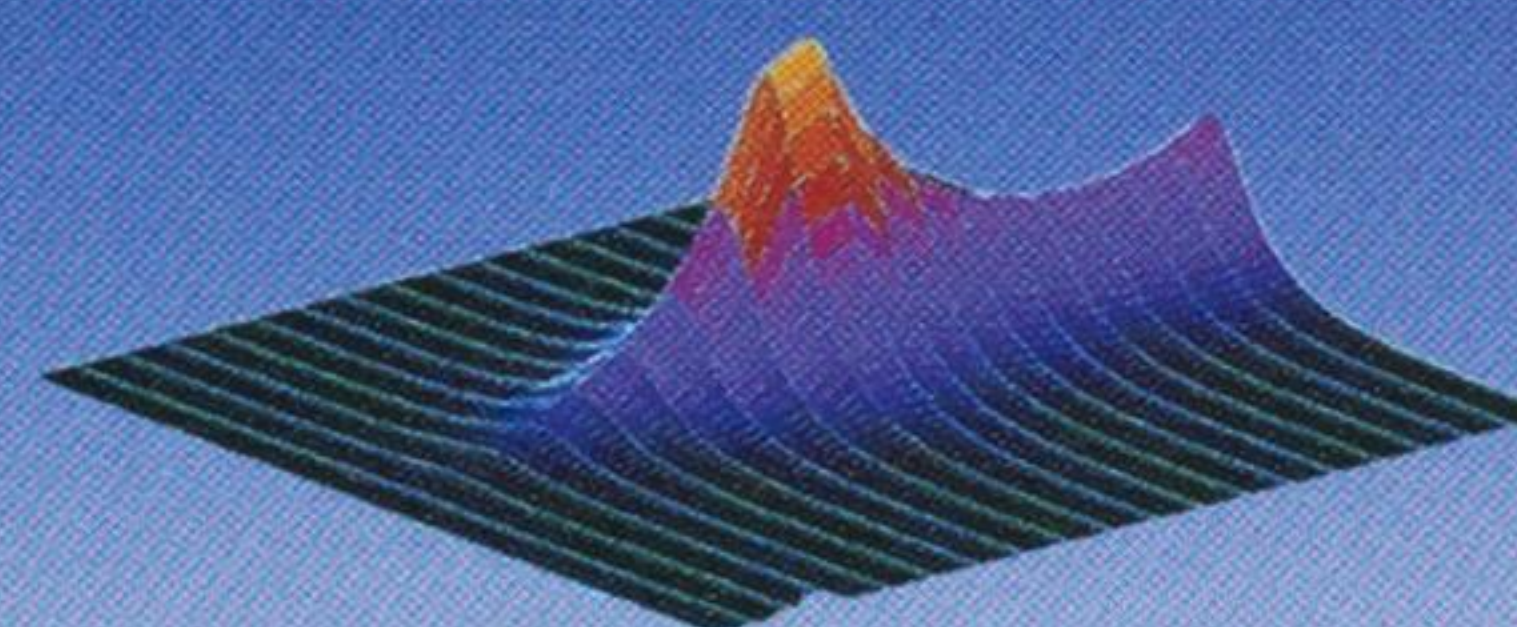
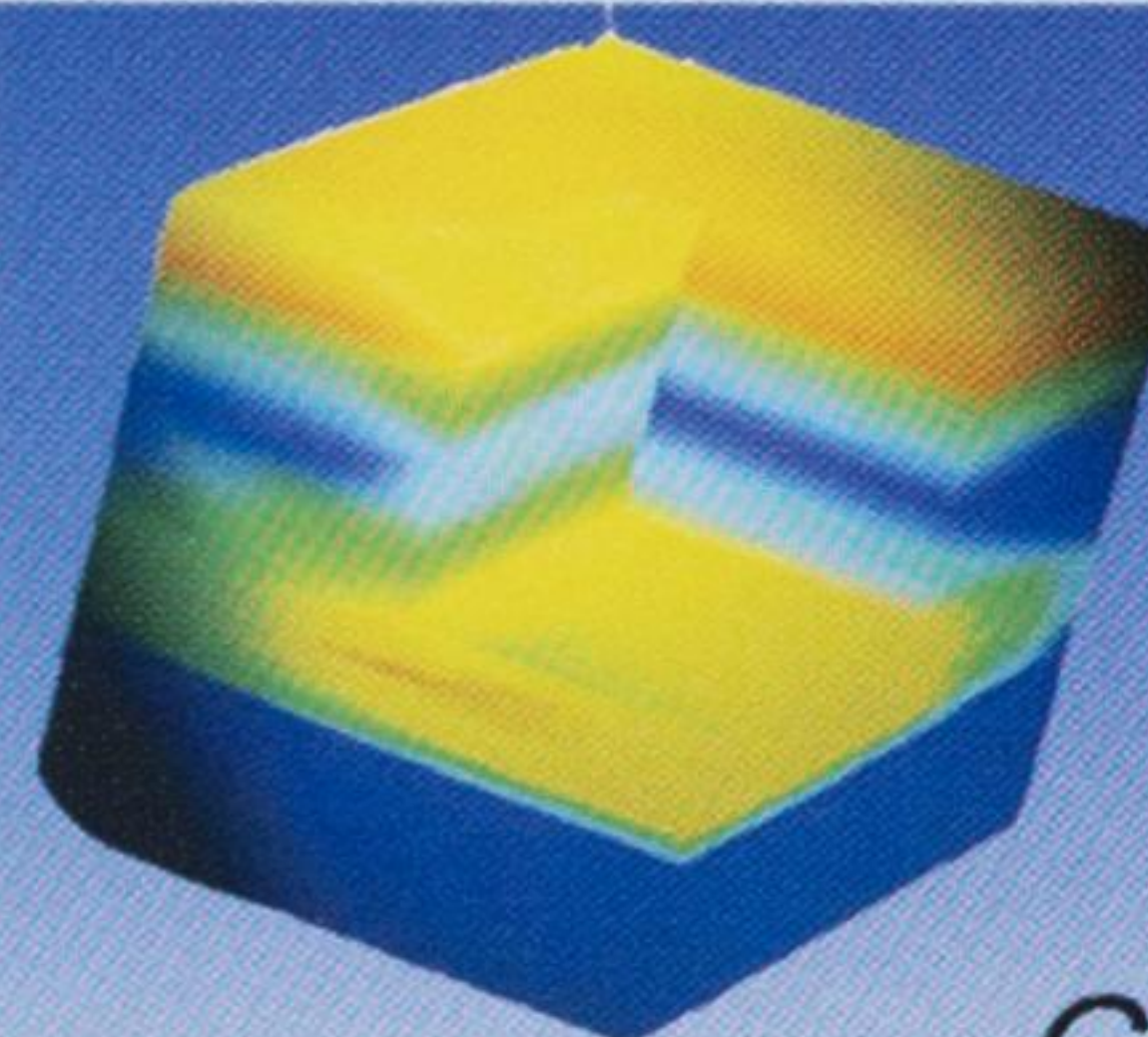
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## MOCVD MONITOR

# Reflectance sensor eases the strain

A new reflectance sensor from LayTec aids LED development and manufacturing by providing *in situ* strain measurements of the epilayers.

**Richard Stevenson** learns how German start-up Azzurro Semiconductors is using the sensor for GaN-on-silicon growth.

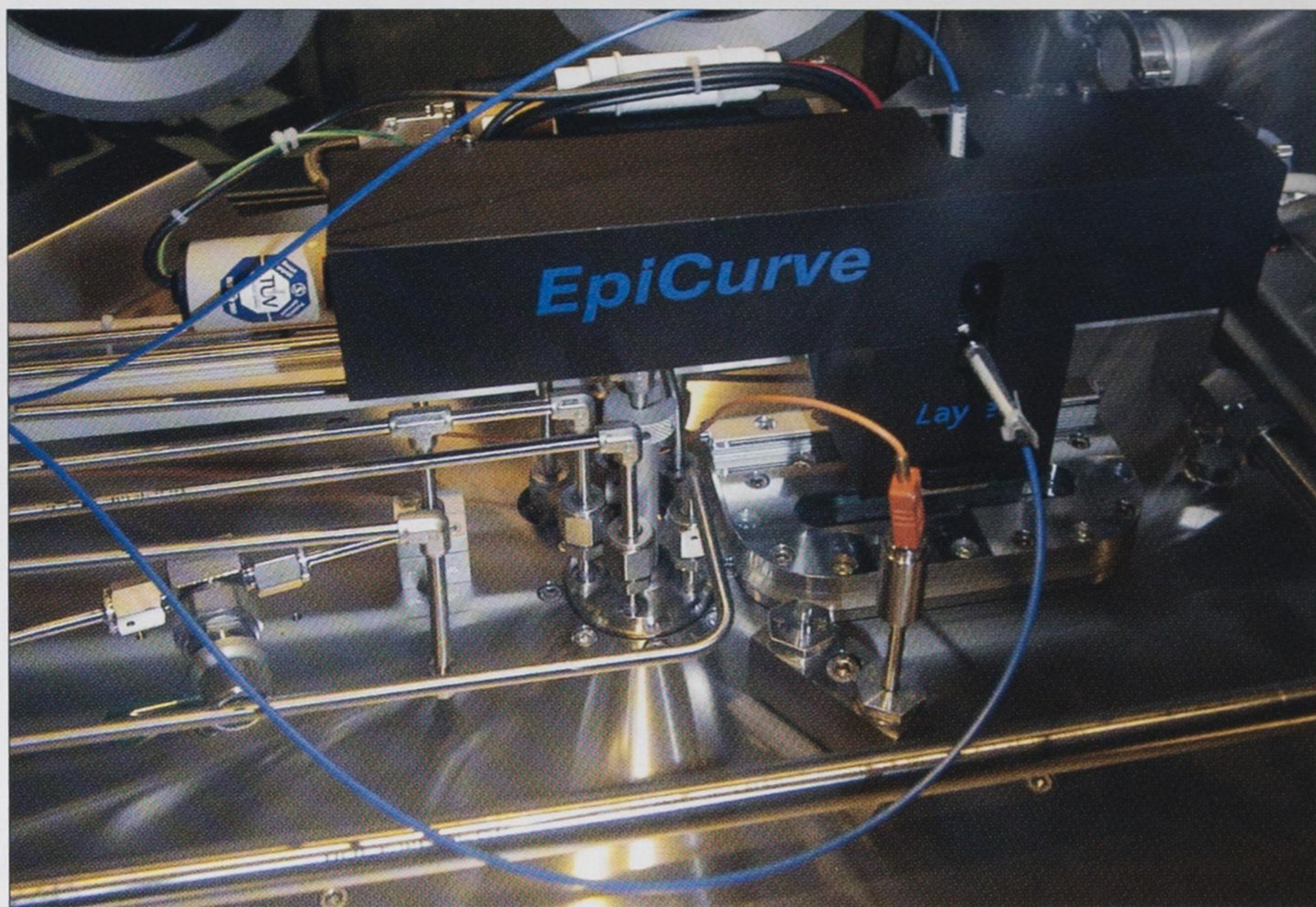
If the high-brightness LED is ever going to replace the light bulb then its price-per-lumen will have to fall substantially. Large savings could result if GaN LED chip makers, which mainly grow their devices on 2 inch sapphire substrates, switch to 4 inch material. However, growth on a foreign substrate causes strain in the GaN epilayers, and managing this strain is a real challenge with larger wafers. Yields suffer if the strain causes the wafer to bend, as any deformation produces a temperature variation across the substrate that leads to inhomogeneities in epilayer composition.

Although it is possible to produce LED epiwafers on large substrates, many growth runs are required to optimize the growth parameters that can cause the wafers to bend. This approach is both time-consuming and expensive, which is why Germany-based LayTec has recently released a sensor for MOCVD reactors that can monitor the wafer's strain *in situ*. According to the company president Thomas Zettler, the EpiCurve reflectance sensor can slash the time and expense required to perfect a structure: "One customer used 80 runs to modify its recipe for blue LEDs, but for the next generation of devices [developed with an EpiCurve tool] only 20 runs will be necessary." The sensor can also improve production efficiency, as it reveals whether the process stays within the limits required to produce an in-spec epiwafer.

EpiCurve can provide reflectance measurements during most stages of the growth of a typical LED, including deposition of AlGaIn layers that typically have a surface roughness of a few nanometers. These measurements are unaffected by isolated defects on the wafer, as their contribution is filtered out by the software. However, the instrument cannot provide meaningful data during growth of the very rough GaN nucleation layer formed at the sapphire-GaN interface.

The sensor was developed a few years ago by Alois Kroist's research team at the Otto-von-Guericke University, Magdeburg, Germany. It determines the strain by monitoring the changes in the separation of two 633 nm laser beams that are reflected from the epiwafer surface—convex and concave wafers are identified by laser spot separation increasing and decreasing, respectively.

"The critical technological breakthrough was to develop a small optical head that was able to measure this effect through only a few millimeters of viewport," says Zettler, who explained that space is severely limited for monitoring equipment installed in MOCVD reactors. The EpiCurve can be fitted to the majority of



**LayTec's EpiCurve sensor** can be fitted to MOCVD reactors to determine the strain in GaN structures grown on sapphire, SiC and silicon substrates. The sensor helps to streamline product development.

Aixtron's single-wafer and planetary MOCVD machines—while Veeco's reactors have their own brand of *in situ* reflectance sensors that can be fitted to these machines.

Although LayTec's EpiCurve sensor can readily determine the wafer's curvature during nearly all the LED growth stages, it is unable to form part of an active feedback system that could automatically adjust growth parameters in real time and maintain optimized conditions during a run. However, Zettler says that in a few years the thickness of a strain engineering layer could be modified by this kind of feedback control mechanism.

Most reactors used for LED manufacturing already have a port for other forms of *in situ* monitoring, so established growth recipes require no alteration after the addition of an EpiCurve sensor. As the existing ports already use a flow of gas to prevent material growth over this area, the sensor can be used for many uninterrupted runs.

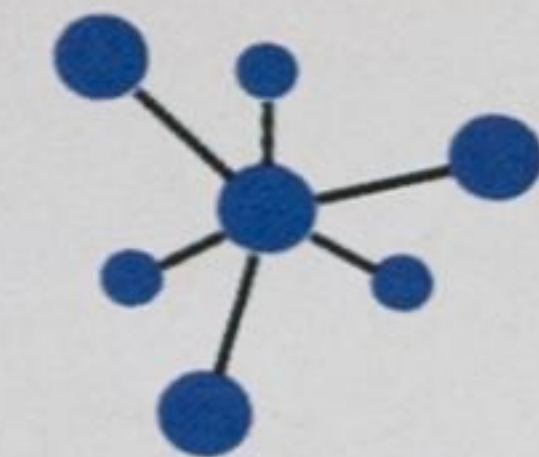
EpiCurve's benefits will probably appeal to many fab managers, but they will have to weigh its advantages against the downtime required to install the sensor onto the reactor. However, Zettler believes that these managers should not be put off by the short delay to production: "For many, many customers the sensor will pay back the effort within a few weeks."

Although the largest target market is GaN LED chip makers, the EpiCurve sensor is also suitable for GaN-on-silicon epitaxy. The prototype EpiCurve sensor built at the Otto-von-Guericke University was actually constructed for this purpose. Today this university's new spin-off, Azzurro Semiconductors, is using the sensor to manufacture crack-free GaN epiwafers of up to 150 mm in diameter, with GaN layers up to 5  $\mu$ m thick.

**"For many, many customers the sensor will pay back the effort within a few weeks."**

**Thomas Zettler**  
LayTec





## InP TRANSISTORS

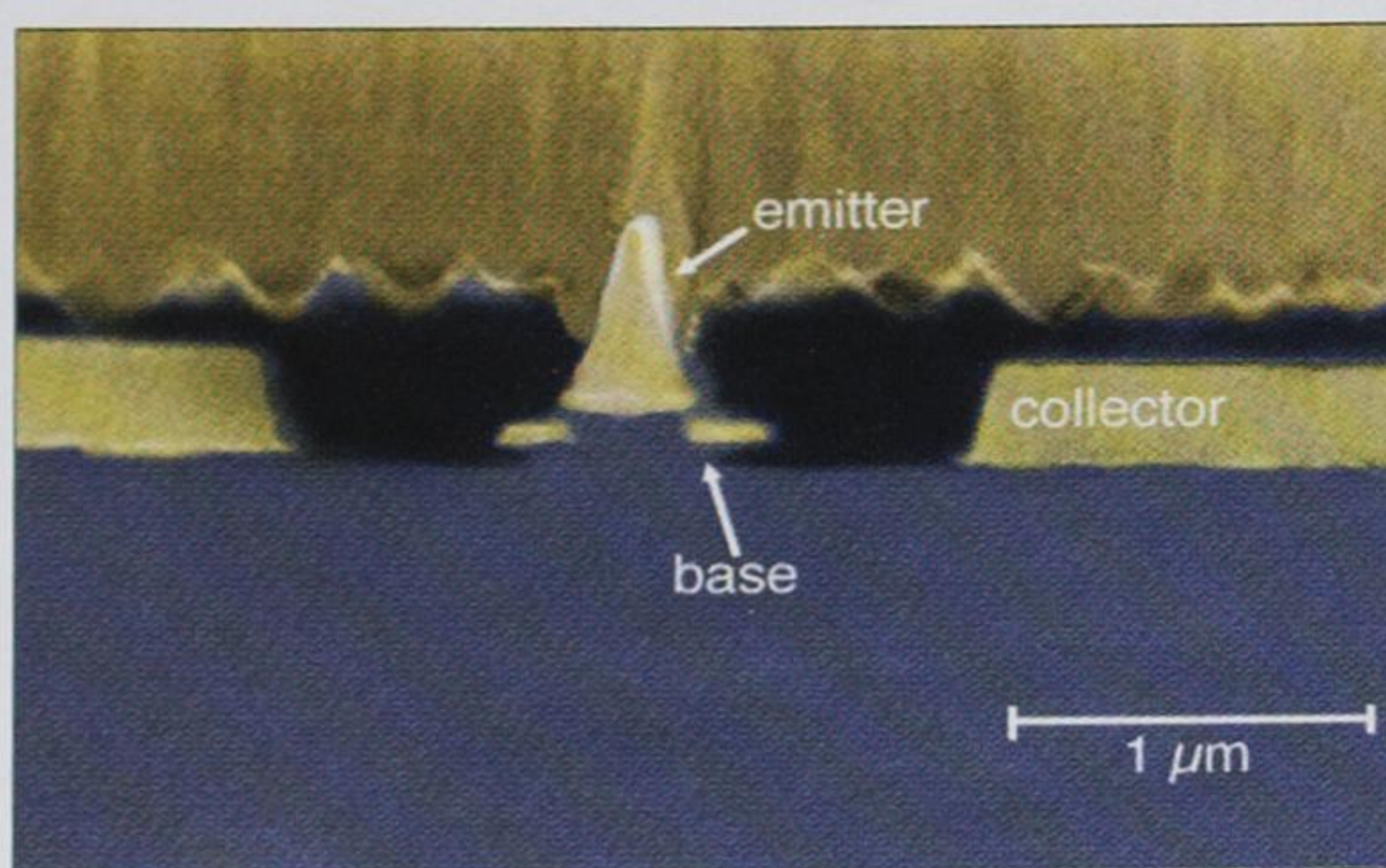
# UIUC researchers break speed record with 710 GHz pseudomorphic HBT

Scientists from the University of Illinois at Urbana-Champaign (UIUC) have again broken the transistor speed record with a pseudomorphic InP HBT operating at 710 GHz.

By cutting the transistor's size and adjusting its composition Milton Feng's team broke its own record (see *Compound Semiconductor* May 2005 p6) by more than 100 GHz. Critical changes included increasing the indium compositional grade from the base to the sub-collector from 16% to 21%, reducing the base layer thickness from 20 nm to 12.5 nm, and shrinking the emitter from  $0.4 \times 6 \mu\text{m}$  to  $0.25 \times 3 \mu\text{m}$ .

The new design delivered an  $f_T$  of 710 GHz and an  $f_{\text{max}}$  of 340 GHz at a collector current density of  $20 \text{ mA}/\mu\text{m}^2$ . Under these conditions the junction temperature increased by  $150^\circ\text{C}$ , and the device dissipated 14 mW.

The record-breaking transistor material was grown by MBE at US-based epiwafer manu-



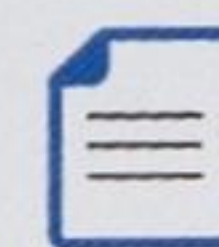
Reducing the transistor's overall size, thinning the base layer thickness, and increasing the indium compositional grade from the base to the sub-collector contributed to a 100 GHz improvement in switching speed.

facturer Intelliepi, and the device was fabricated at UIUC's own Micro and Nanotechnology Laboratory.

The researchers say that their device is the

first high-performance submicrometer HBT in which charging delays dominate the total device delay. Consequently, any attempts at further increasing the transistor's speed will have to focus on reducing its parasitic capacitances and resistances.

UIUC's Walid Hafez says that the team's ultimate goal is to produce a terahertz pseudomorphic HBT operating with current densities as low as  $30 \text{ mA}/\mu\text{m}^2$ , which would aid development of communication systems operating at these frequencies. "HBTs fabricated at the University of Illinois have previously demonstrated the capability of running at current densities of  $30 \text{ mA}/\mu\text{m}^2$ , so we know that this is a feasible target," Hafez pointed out.



## Journal reference

W Hafez et al. 2005 *Appl. Phys. Lett.* **87** 252109.

## LASERS

## Extra quantum well boosts bandwidth and temperature stability

Anders Larsson's group at Chalmers University of Technology in Sweden claims to have built dilute nitride lasers that deliver a record threshold current density, temperature stability and modulation bandwidth.

The  $1.28 \mu\text{m}$  emitters, which could be used one day in fiber-optic communication networks, have a threshold current of  $150 \text{ mA}/\text{cm}^2$  per quantum well, a characteristic temperature ( $T_0$ ) of 180 K for temperatures up to  $70^\circ\text{C}$ , and

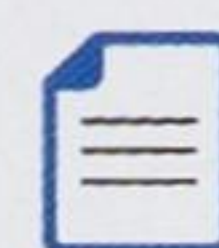
a 14 GHz modulation bandwidth. The lasers have advantages over the InP-based emitters deployed today, because they operate without temperature control, and can be built on cheaper GaAs substrates.

Larsson's MBE-grown lasers contain an active region of two 7 nm thick  $\text{Ga}_{0.613}\text{In}_{0.387}\text{NAs}$  quantum wells separated and surrounded by 20 nm thick GaAs layers. Either side of this active region are 160 nm thick graded AlGaAs layers, followed by  $1 \mu\text{m}$  thick  $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$  cladding regions doped with either silicon or beryllium. A 100 nm thick heavily doped GaAs cap forms the top contact.

The researchers fabricated two types of device:  $100 \mu\text{m}$  wide broad-area (BA) lasers and  $4 \mu\text{m}$  wide ridge waveguide (RW) lasers. The BA lasers, which had a 1 mm cavity, oper-

ated under pulse-mode at room temperature with a threshold current density of  $300 \text{ mA}/\text{cm}^2$ . The  $400 \mu\text{m}$  long RW lasers had a threshold current of 22 mA under continuous-wave operation at room temperature, and a 3 dB modulation bandwidth of 14 GHz.

Larsson told *Compound Semiconductor* that he thinks the threshold current could be reduced even further by optimizing the growth conditions. He also said that improvements to the temperature stability and modulation bandwidth especially at high temperatures are possible through the addition of another quantum well, but he warned that this would also increase the threshold current.



## Journal reference

Y Q Wei et al. 2005 *Electron. Lett.* **41** 1328.

## HEMT DEVELOPMENT

## InP channel delivers reliability at 94 GHz

Farid Medjdoub and co-workers at France's Electronics, Microelectronics and Nanotechnology Institute in Villeneuve D'Ascq have produced an InP channel HEMT with a  $0.1 \mu\text{m}$  gate that has a record cut-off frequency of 94 GHz.

The transistor, which has potential for future radar and satellite communication applications,

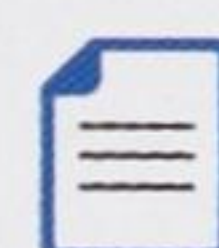
delivers a maximum power output of  $200 \text{ mW}/\text{mm}$ , a 3.8 dB power gain, and a power added efficiency of 13.7% at a drain voltage of 2.5 V.

The researchers are aware that this performance can be matched by other semiconductor devices. However, they point out that GaAs-based devices suffer from a limited cut-off frequency, while InP HEMTs employing an InGaAs channel are affected by impact ionization that reduces the breakdown voltage.

The InP channel HEMT was grown by MBE, and contains an AlInAs buffer layer, followed by a 12 nm thick InP channel, a 3 nm thick AlInAs spacer layer, a silicon doping

plane, 10 nm thick AlInAs and InP layers, and a 20 nm InGaAs cap. The gate was attached to the AlInAs layer, which is claimed to improve frequency performance, power gain and current handling characteristics.

The research team says that if the contact resistances can be improved, and a double doping plane is inserted to improve drain current density, then InP channel HEMTs will become very promising devices for power applications in the W-band (75–110 GHz).



## Journal reference

F Medjdoub et al. 2005 *Electron. Lett.* **41** 1406.





## BREAK AWAY

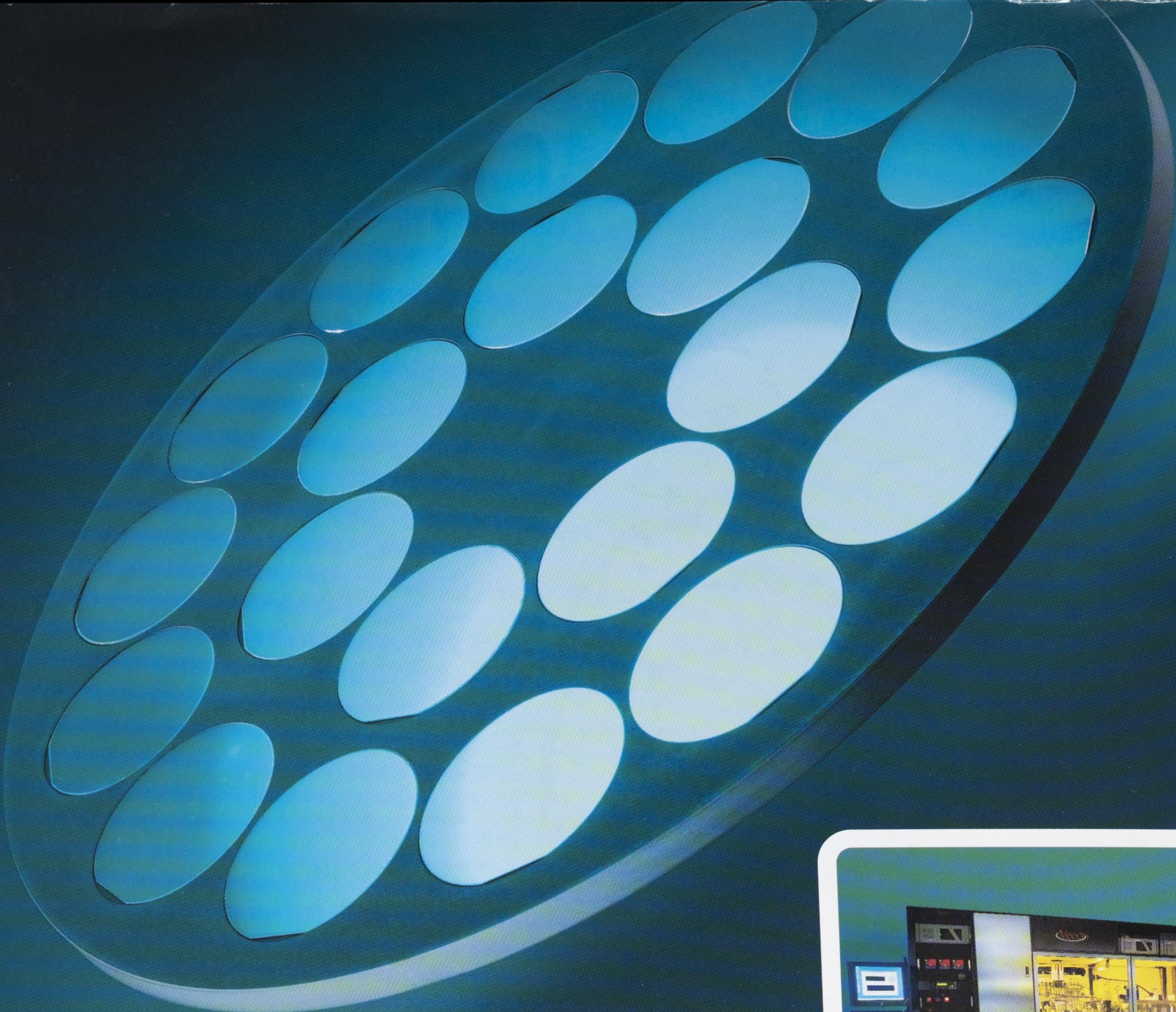
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