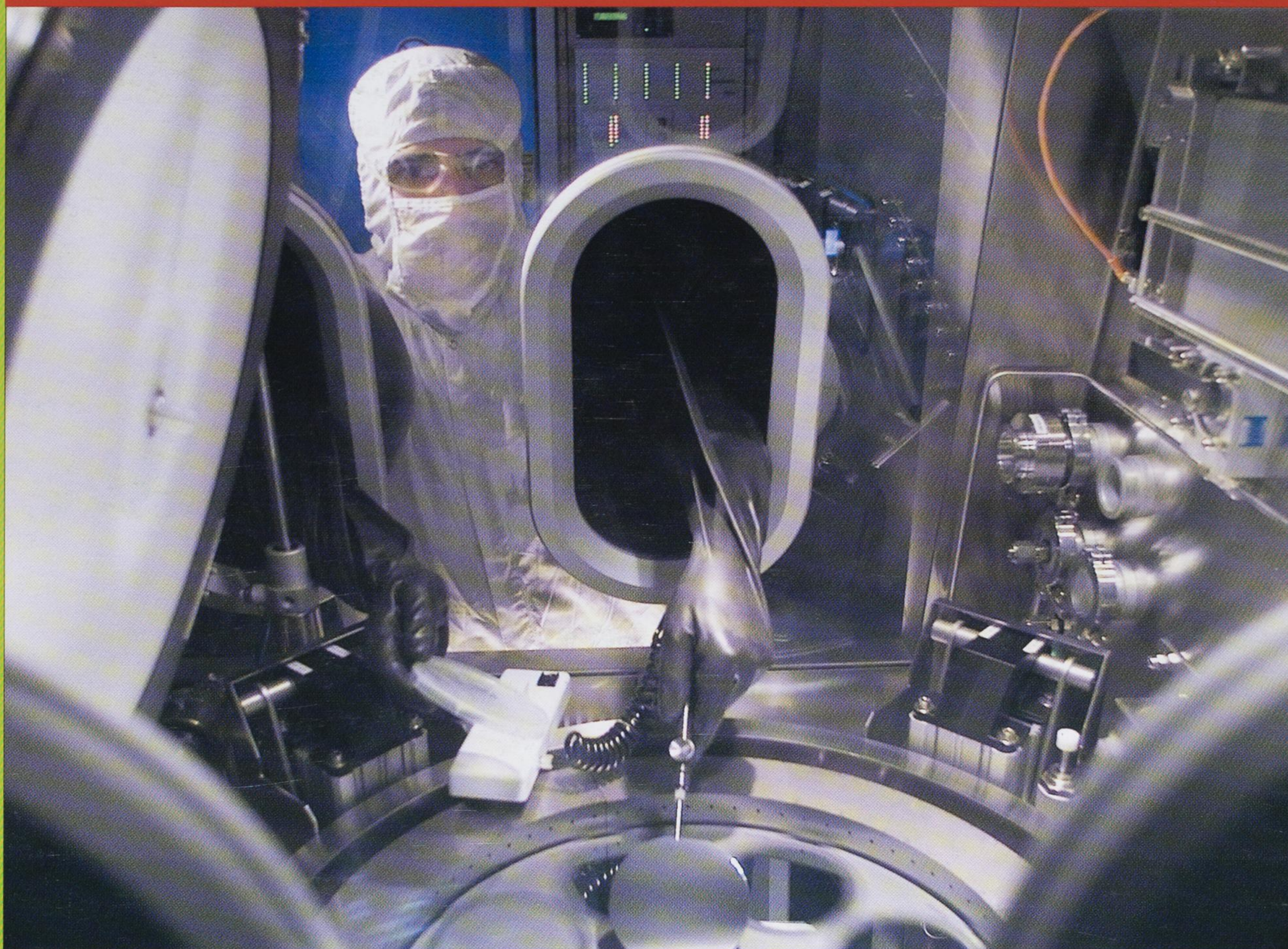


COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

April 2005 Volume 11 Number 3



WAFER CHARACTERIZATION
Automated techniques
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deep-UV LEDs**

**DARPA splashes
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On the cover: Automated techniques to measure epiwafer doping concentration and to characterize different types of defects promise to aid the development of GaN-based devices (image courtesy of Kopin Corporation/Beaupre & Co).

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Editorial

GaN primed to come of age under DARPA's guidance



Whenever somebody touts a new technology as “the next big thing”, you can be sure to find a wag nearby who’ll quip: “And it always will be.” And, so often, that is the case.

One of the perennial next big things in the compound semiconductor business is wide-bandgap microelectronics, specifically ICs based on GaN and SiC. But with the US military in the guise of the Defense Advanced Research Projects Agency (DARPA) ploughing what may eventually amount to around \$100 million to transfer GaN out of the R&D laboratory and into military systems, there is a great chance that the material will avoid becoming the butt of cheap jokes.

The DARPA projects are highly reminiscent of the agency’s efforts to develop GaAs MMICs in the early 1990s, which paved the way toward cheap power-amplifier technology and the global modern phenomenon that is the cell-phone industry.

The big winners in the GaN project to develop advanced millimeter-wave and microwave ICs include Raytheon – which is aligned with Cree on a \$27 million project – as well as Northrop Grumman (receiving funding of up to \$53 million), TriQuint (receiving up to \$32 million) and their various collaborators. The notable absentees this time round appear to be HRL Laboratories and Rockwell.

At the end of the projects, which should be around 2010–2011, US war planes fitted with the new technology ought to be able to use their power more efficiently and effectively in the form of better RF sensors, communication links and the like.

But the true measure of success for the wider industry will come later, if and when GaN technology finds a way into commercial applications in the same way that GaAs MMICs found a niche in the cell-phone market. And that will be the time when we can truly say that GaN has come of age.

Michael Hatcher

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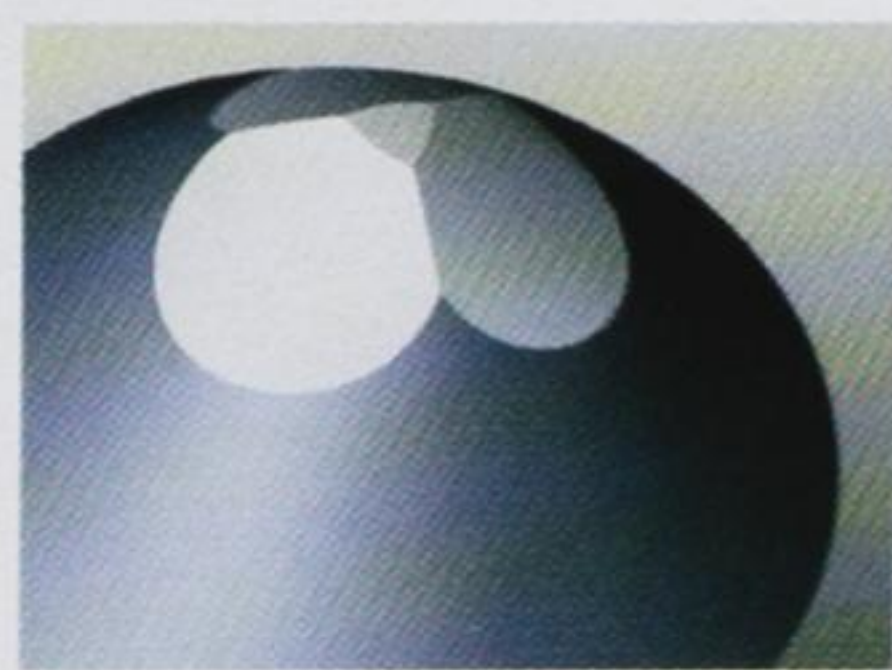
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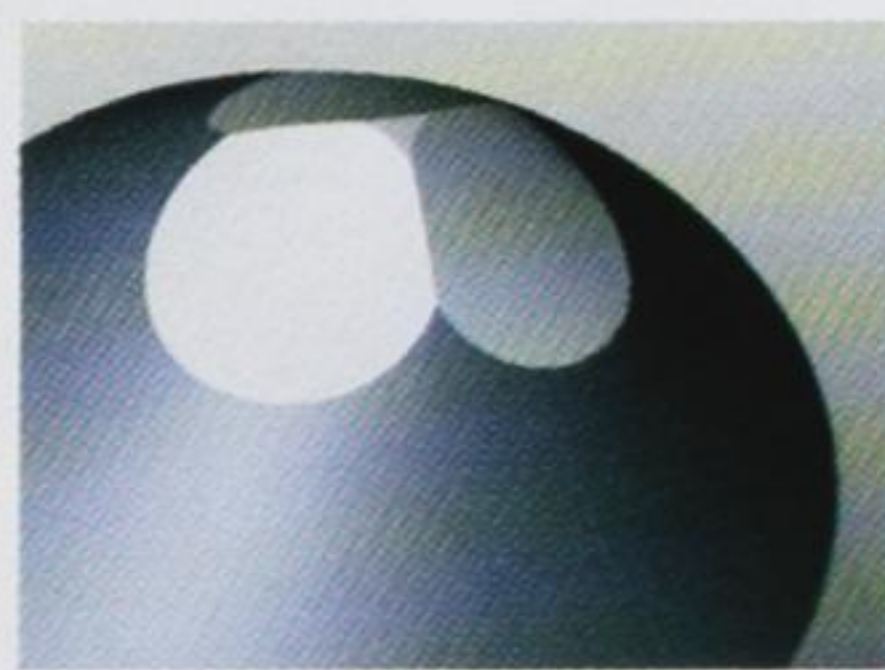
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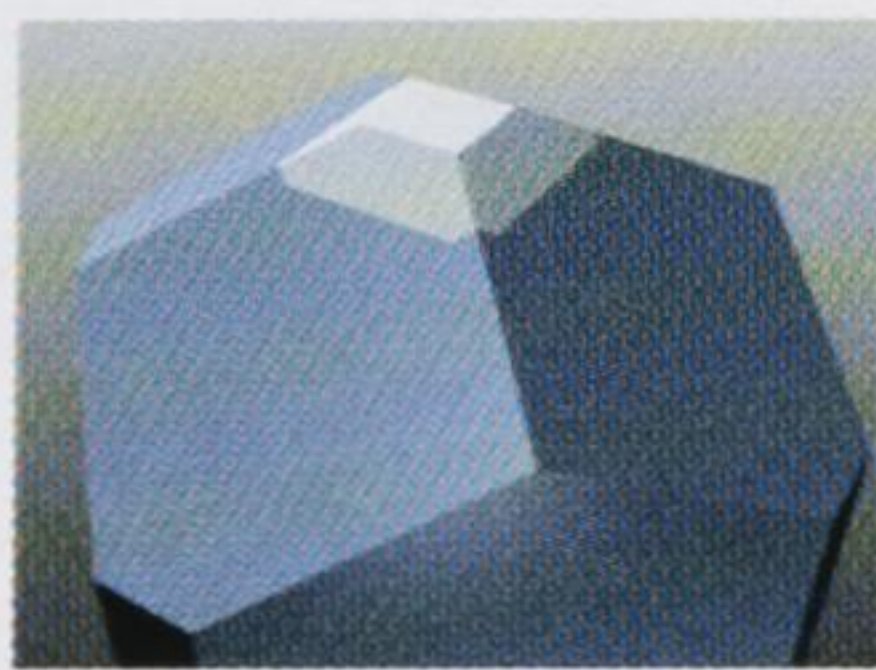
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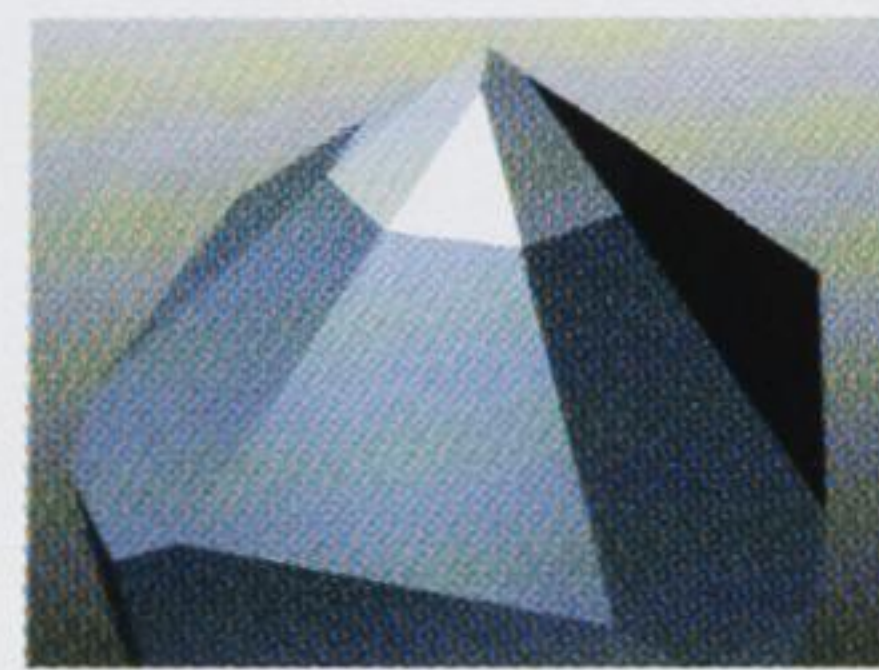
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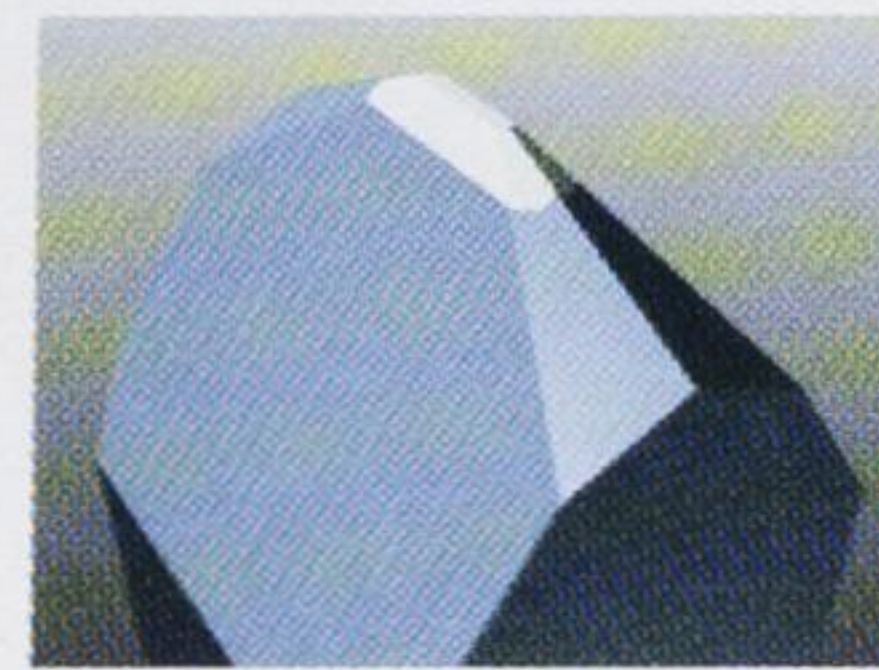
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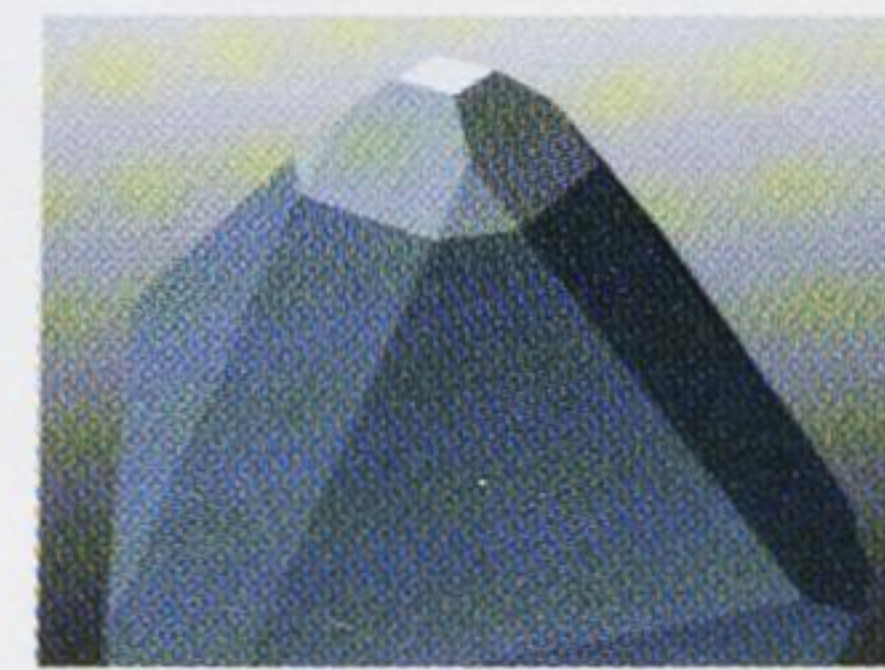
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TECDIA
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DARPA splashes the cash on initiatives to fast-track GaN-IC commercialization

By Michael Hatcher

The US military has moved to increase the speed of development of GaN-based ICs with a series of project awards worth tens of millions of dollars. Three separate initiatives to develop the technology are being supported by the Defense Advanced Research Projects Agency (DARPA).

Northrop Grumman has received an initial \$16.5 million for its three-year effort on millimeter-wave GaN HEMTs, which follows on from a \$5.1 million effort that began in 2002. If all the program options are exercised however, that figure could rise to \$53.4 million.

Meanwhile, TriQuint Semiconductor is the prime contractor in a second project valued at \$15.8 million initially, which could rise to double that figure. Working with BAE Systems, Emcore, II-VI, Nitronex and Lockheed-Martin, TriQuint plans to develop high-power, wideband amplifiers and package technology in the first phase of the effort. The third DARPA-funded GaN project is believed to involve Raytheon and Cree.

Dwight Streit is vice-president of foundation technologies at Northrop Grumman Space Technology (NGST). Streit told *Compound Semiconductor*: "These awards offer an opportunity for GaN to come of age."

Streit says that the DARPA program for

GaN development is analogous to the agency's support of GaAs in the early 1990s, and he hopes that just as that initiative spawned a new industry and contributed directly to the phenomenal success of the cellular business, so the GaN project will lead to a similar achievement.

"There have been great demonstrations of GaN performance, but we don't yet have the production capability," said Streit, stressing that much of the NGST program will focus on moving GaN into full-scale production.

While NGST will work with Northrop Grumman Electronic Systems in Baltimore (formerly Westinghouse when it participated in the GaAs program of the early 1990s) to produce millimeter-wave devices and MMICs, the TriQuint collaboration will be concentrating on the 2–20 GHz frequency range.

The initial phase of the TriQuint program will cover the development of GaN material and devices, as well as improvements in performance and reliability. TriQuint says that its program goals for the second, optional, phase of the initiative call for the production of a module with 100 W power and 30% power-added efficiency.

"At the end of the program, TriQuint will have a reliable, reproducible, stable GaN process suitable for [defense] and commer-

cial applications," commented the Oregon-based chip manufacturer.

"GaN offers a five-fold improvement in power density compared with GaAs devices, which makes it ideal for high-power radar and communications," added TriQuint's R&D program manager Tony Balistreri.

Also involved in the TriQuint team are Michael Shur from Rensselaer Polytechnic Institute and Jesus del Alamo at Massachusetts Institute of Technology.

The implementation of GaN devices in military aircraft, which is likely to be some six or more years away, will give pilots and their crews more flexibility with the power available to a war plane. "On an aircraft, power is the number-one concern. The efficiency of the power amplifiers is [critical]," said Streit. "The more linear and efficient your power amplifier is, the more things you can do with the power available. The same is true in space. It enables the system to accomplish more."

Streit cites replacement of traveling-wave amplifier tubes for space applications as one use for GaN technology. The key advantage of the material is its higher power with better efficiency. At the end of the newly funded programs, DARPA will evaluate the progress that has been made with each team and decide which to continue to support financially.

Skyworks challenges RFMD for GaAs leadership

By chipping away at the cell-phone power-amplifier sector and taking market share from smaller players in other GaAs device applications, Skyworks Solutions has drawn level with RF Micro Devices (RFMD) as the industry's top supplier of GaAs devices.

Skyworks Solutions has stolen a march on both its main rival and other companies in the GaAs-manufacturing business over the past year. And, according to a report from analyst firm Strategy Analytics, Skyworks and RFMD are now neck and neck, each holding a 20% market share.

Asif Anwar, director of GaAs research at Strategy Analytics, told *Compound Semiconductor* that the total GaAs device market, including MMICs, discretes and digital ICs, grew 9% in 2004 to reach \$2.9 billion.

This growth was largely fueled by the bumper year for cell-phone handsets, with

GaAs-device revenue from this sector rising 20%. Skyworks was able to out-pace the overall market demand, and the Woburn, MA, company saw its own GaAs-device revenue grow 31% year on year.

Although Anwar still believes RFMD to be the biggest supplier of GaAs PAs, he expects Skyworks to continue chipping away at this lead. Skyworks is said to hold the advantage because of its expertise in modules, as well as the digital, RF and mixed-signal silicon technology that it inherited from Conexant.

RFMD, on the other hand, has had to rely more on external foundry relationships for key process technologies such as PHEMT for switches.

TriQuint remains the third-biggest supplier of GaAs devices, thanks largely to its broader product portfolio and its foundry operation. Anwar also believes that Japanese GaAs-

device suppliers have lost out to their top-tier US rivals in emerging Asian markets such as China and Taiwan.

All GaAs suppliers will have to deal with slower growth this year, however. Along with other market analysts, Anwar is expecting only 8% growth in cellular handsets in 2005. "The challenge now is for both companies to ride out slower growth...and to develop new products for new markets if there is to be a clear winner in the market-place."

Those new markets include dual-band wireless LAN and potentially WiMAX – provided that the latter uses a GaAs-friendly operating wavelength. Some momentum is also returning to the fiber-optic market for GaAs ICs, says Anwar.

● The report *All Change at the Top as Skyworks Topples RF Micro Devices* is available from Strategy Analytics.

Kopin achieves wafer milestone

Kopin Corporation has reached a milestone with the shipment of half a million of its GaAs HBT wafers.

"Because our vertical-transistor technology was so new in 1996, no-one could have imagined that we would ship 500,000 HBT wafers, generate several hundred million dollars of revenue for Kopin and help create billions of dollars of revenue for our power-amplifier customers," said Kopin CEO John Fan.

The Taunton, MA, firm ships thousands of 4 and 6 inch wafers each week, and is developing the technology for emerging application markets such as 3G phones and wireless connectivity protocols such as WiMAX.

When it released its fiscal year 2004 results recently, Kopin said that revenue from its HBT wafers soared 33% year on year. Sales were \$36 million for the year ended December 25, 2004. Fan says that the strong showing was due to the success of a long-term contract with its largest HBT customer. "The agreement has allowed both parties to work together to reduce costs and improve efficiencies," he said.



Half a million and counting: Kopin estimates that it has an 80% share of the merchant market for GaAs HBT wafers.

Having disposed of its LED-manufacturing wing through establishing an Asian joint-venture company, Kopin will be able to devote more time and resources to its HBT-wafer product line. The company is busy developing the next generation of wafers, which are based on the quaternary GaAsInN material.

Mimix acquires final assets of Celeritek

Houston-based GaAs MMIC supplier Mimix Broadband is to acquire the remaining assets of Celeritek for \$2.8 million in cash.

Celeritek's GaAs-component operation in Santa Clara, CA, includes a portfolio of products such as low-noise amplifiers, gain blocks and power-amplifier (PA) modules for both commercial and defense applications.

Under the agreement, Mimix will also take on liabilities of \$6 million. The deal does not include Celeritek's remaining cash, cash equivalents or certain other non-operating assets.

Celeritek exited the cell-phone handset PA business and decided to concentrate on defense markets in September 2003. That decision came after Motorola stopped second-sourcing its handset PAs from the company.

Shortly afterwards, Anadigics acquired the Tavanza handset PA design business from Celeritek, while the sale of its defense electronics business to Teledyne Technologies netted shareholders \$31.4 million, or \$3 per share.

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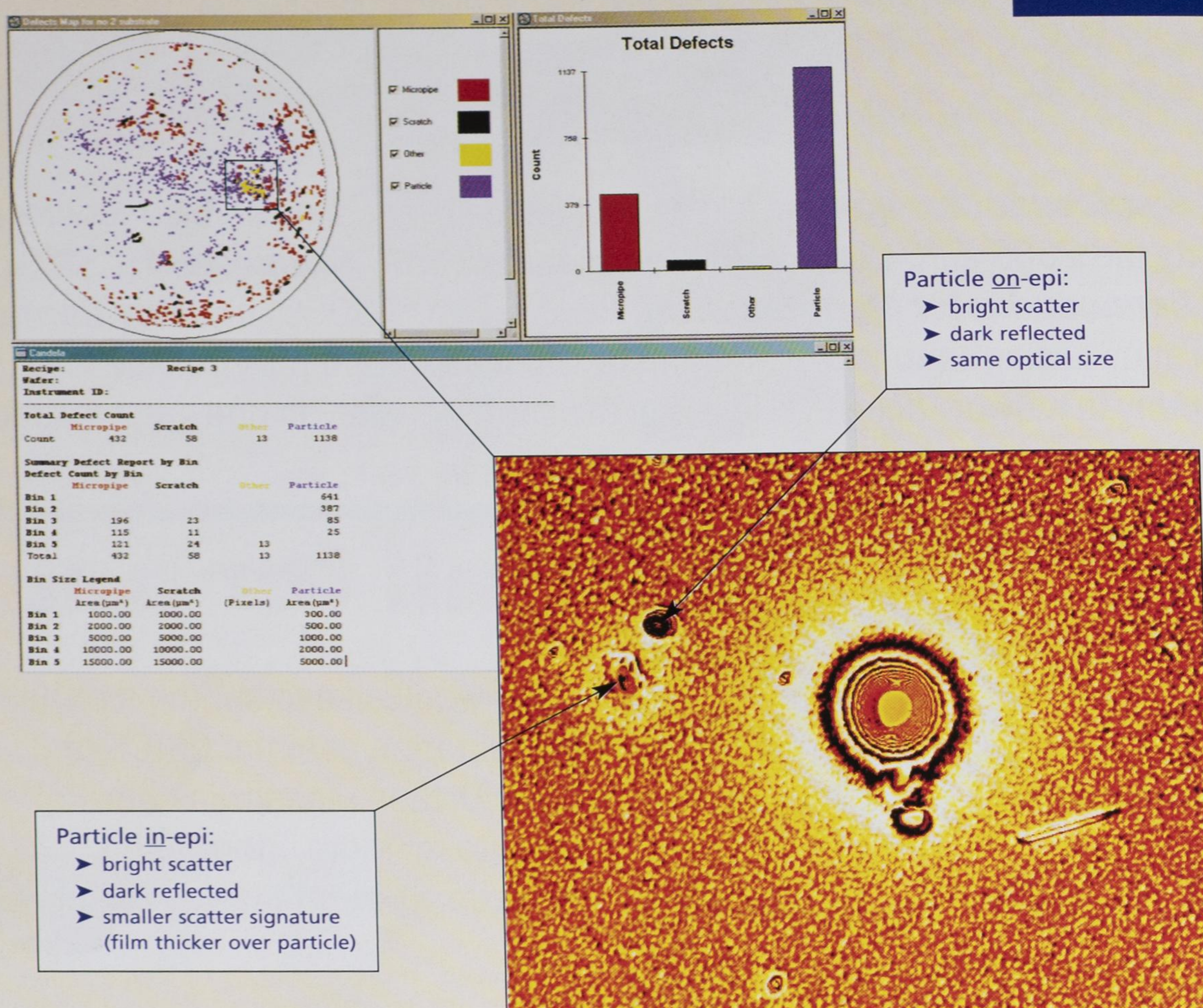
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3G-terminal supply triples in 8 months

The Global Mobile Suppliers Association (GSA) has confirmed that the availability of 3G wireless technology has boomed in the past few months.

According to the group, which is a forum representing leading firms in the wireless industry, 139 different 3G mobile terminals are now available following the 3GSM World Congress jamboree held in Cannes, France.

Last June, that figure stood at just 45 models, demonstrating the huge efforts being

made by manufacturers trying to entice consumers into using the new technology. Some 25 different suppliers have now launched wideband code-division multiple-access (W-CDMA) terminals, says the GSA.

And GaAs IC manufacturers have developed a raft of new power-amplifier products aimed at the 3G market.

W-CDMA is the most widely accepted 3G mobile technology globally, and there are now 64 such networks offering commercial ser-

vices in 31 different countries. Despite only 13.6 million new W-CDMA subscribers signing up for the technology in 2004, this still represents a five-fold increase on the 2003 figure, says the GSA.

The broadband mobile revolution is also set to continue with the emergence of a high-speed downlink packet-access protocol, the GSA predicts. This largely software-enabled evolution of W-CDMA technology is expected to reach the market at the end of this year.

ABI predicts rise in power-amplifier prices

The advent of new wireless-communication standards, such as EDGE and W-CDMA, could halt rapid drops in the average selling prices of power amplifiers (PAs), says market-analyst firm ABI Research.

ABI believes that the latest standards, which have more stringent linearity requirements, will drive up the price of handset PAs. Alan Varghese, ABI's principal analyst of semiconductor research, explains that vendors are using innovative methods, including adaptive pre-distortion and switching amplifier techniques, to increase efficiency without sacrificing linearity.

Increasing PA prices would buck the trend that has seen a combination of cellular-operator negotiating clout and intense vendor price

competition drive down PA prices year on year.

That would be good news for GaAs IC manufacturers, which have struggled to make profits despite booming handset sales.

Varghese also notes that for infrastructure applications, silicon-based LDMOS components are facing increased competition from GaN, a technology that's "finally getting on the runway".

ABI adds that even if news surrounding cellular markets is disconcerting, there will still be growth opportunities in areas such as broadband wireless, WiMAX, WLANs and Ultrawideband.

More information is provided in ABI's latest report: *RF Power Semiconductors: Transistors, FETs, ICs and Power Modules*.

'Superior' GaAs to become the technology of choice for cable-television operators

The transition from analog to digital television will drive the GaAs-based semiconductor content in cable television (CATV) from \$20 million in 2004 to \$47 million in 2009. That's according to Asif Anwar, director of Strategy Analytics' GaAs and compound semiconductor technologies service.

The chips are used in system amplifiers and line extenders to boost signals in cable networks. For this application, GaAs has advantages over silicon in terms of linearity and performance at high frequencies.

The superiority of GaAs will enable cable operators to deliver a greater choice of channels as well as improved formats, such as high-definition (HD) TV, says Anwar.

Signal amplification is achieved either with GaAs-based MMICs or hybrid devices with both silicon and GaAs content.

The North America and Asia Pacific regions will drive CATV infrastructure roll-out and account for 89% of new, digital CATV subscribers in 2009.

"North America will lead the world in the move to HDTV. Delivering this content via cable will require an upgraded network," added Anwar. "Asia-Pacific will be driven specifically by China, which has ambitious targets for digital-TV rollout."

According to Anwar, the take-up of GaAs technology could hurt component suppliers still biased toward silicon bipolar technology. These suppliers could risk losing market share unless they expand their GaAs portfolio.

Anwar predicts that the market for silicon semiconductors in CATV will grow at a compound annual growth rate of only 3% through 2009.



Young K Sohn, president of Agilent Technologies' semiconductor product group, is to leave the company. Dick Chang (pictured above) – currently the division's senior vice-president of new business development and formerly the man in charge – takes over on an interim basis. Sohn, who joined Agilent in October 2003, was due to leave by April 1. Agilent did not detail any reason for Sohn's departure.

Skyworks claims PA dominance in Taiwan

Skyworks Solutions claims to have captured 56% of the power-amplifier (PA) market in Taiwan. According to independent market-research figures quoted by the Woburn, MA, firm, Taiwanese handset makers have been impressed with the ability of Skyworks to pair PA technology with single-chip transceivers.

Skyworks says that companies such as BenQ and Quanta are now migrating to higher-value front-end modules required for EDGE and W-CDMA applications. As recently as 2003, Skyworks is thought to have had just a 20% share of Taiwan's PA market.

Gartner predicts modest growth in handset-sales volume in 2005

Analysts at market-research company Gartner say that it remains to be seen whether the 2004 record-breaking level of replacement cell-phone sales will continue through 2005.

Replacement sales in North America and Western Europe were a key driver behind the huge increase in sales volume recorded in 2004, which culminated in almost 200 million cell phones being sold in the fourth quarter of last year.

Gartner estimates that the final sales figure for 2004 is 674 million units, up 30% on 2003 – another record year. “The market exceeded even the most optimistic forecasts in 2004,” said Ben Wood, Gartner’s principal analyst for mobile-terminals research.

While Gartner predicts 8% unit growth to 730 million units in 2005, this will depend on consumers in established and emerging markets continuing to buy new phones.

“In mature markets, it remains to be seen whether the record-breaking levels of replacement sales can be sustained,” said Gartner’s Hugues De La Vergne, who specializes in cell-phone sales in the Americas. He adds that in emerging markets the key battleground will be sub-\$50 phones.

Nokia consolidated its position as the mar-

2004 rankings for sales of phones to end-users

Company	2004 share (%)	2003 share (%)
Nokia	30.7	34.8
Motorola	15.4	14.5
Samsung	12.6	10.5
Siemens	7.2	8.4
LG	6.3	5.0
Sony Ericsson	6.2	5.1
Other	21.6	21.7

Source: Gartner

ket leader in the most recent quarter with a 33% share of all handset sales. That gave the Finnish company a total share of 30.7% in a year that had started badly. Nokia’s share had fallen below 29% in the first half of 2004.

Meanwhile, Motorola has leapfrogged Samsung to reclaim second spot in the handset-sales rankings, thanks largely to the success of its ultraslim RAZR V3 phone.

Samsung had claimed second spot from Motorola earlier in 2004, but Gartner analysts now believe that the Korean company will need to change strategy and expand its line of high-volume, low-margin products to regain its momentum.

RFMD to halt WLAN-chipset R&D

RF Micro Devices (RFMD) is to stop its internal development of wireless LAN (WLAN) chipsets. However, the firm will continue to work on transceivers, power amplifiers and front-end modules for WLAN applications.

The move affects employees at RFMD’s San Jose location, while the company will also be closing its Moscow, Russia, and Leuven, Belgium, offices. While some employees will now switch to more profitable parts of the business, there will be some staff cuts.

Although the decision is expected to cost RFMD \$37 million–41 million up front, including \$3 million–4 million in cash due to employee severance payments and building-lease termination, it should have a positive effect on future company operations.

No product revenue was associated with the discontinued activity, and the move will significantly reduce RFMD’s research and development expenses. Overall, operating expenses are expected to drop by \$18 million–22 million per year. RFMD’s operating

profit in the first nine months of the current fiscal year was \$1.7 million.

CEO Bob Bruggeworth says that RFMD has struggled to get WLAN chipsets to market, something that the company believes is generally one of its core strengths.

“It’s never easy to let good people go, and this decision was not taken lightly,” remarked Bruggeworth. “[But the decision] was made with the overall growth and profitability of the company in mind.”

RFMD entered the WLAN-chipset business when it acquired Resonext in a \$133 million stock deal two years ago, at which point it had planned to become the leading supplier of WLAN chipsets.

While chipset activity has failed to live up to expectations, RFMD remains confident about its WLAN products in general, despite fierce competition and price erosion of 15–20% per year. It struck a deal to supply GaAs HBT WLAN transceivers to Japanese gaming giant Nintendo last year.

In brief

● **Anadigics** is shipping production volumes of its InGaP HBT power amplifiers to LG Electronics for the Korean firm’s VX8000 CDMA phone.

President of LG Telecommunications and Handset Company Mun Hwa Park said: “The convergence of multimedia and communication devices is exemplified by the outstanding level of video content that can be conveniently accessed by the VX8000 over broadband speeds supported by modern EV-DO networks.”

● **US start-up Xindium Technologies**, based in Crystal Lake, IL, has introduced a new power-amplifier (PA) module, the XIN9166. The device is said to provide GSM and GPRS handset makers with a new source of market-leading PA performance in the standard module size.

The XIN9166 is a quad-band, 6 × 6 mm GSM/GPRS InGaP HBT device with integrated power control. It migrates Xindium’s current offering to the 6 × 6 mm footprint without compromising the efficiency and ruggedness GSM/GPRS handset makers have come to expect in their latest products, says the firm. Xindium is also working on InP-based PAs for next-generation handsets.

● **RF Micro Devices** has released two GaAs HBT pre-driver power amplifiers targeted at cellular base-station applications. The Greensboro, NC, firm’s RF3807 amplifier gives 28.5 dBm output power and 40% power-added efficiency (PAE) in the UMTS band, while the RF3809 provides 33.5 dBm at 43% PAE.

● **TriQuint Semiconductor** has launched a power-amplifier module for GSM-EDGE for its handset product line. According to the firm, the device leads the market in efficiency and RF performance over extreme operating environments for linear EDGE applications.

● **Wireless component maker Skyworks Solutions** claims to have introduced the world’s most highly integrated RF transmit front-end modules for CDMA. Supporting cellular and PCS frequencies, the SKY77408 and SKY77409 combine the firm’s power amplifier, filter, input/output matching, power detector and duplexer technology into a 5 × 8 mm laminate package, saving handset developers significant design time and board space.

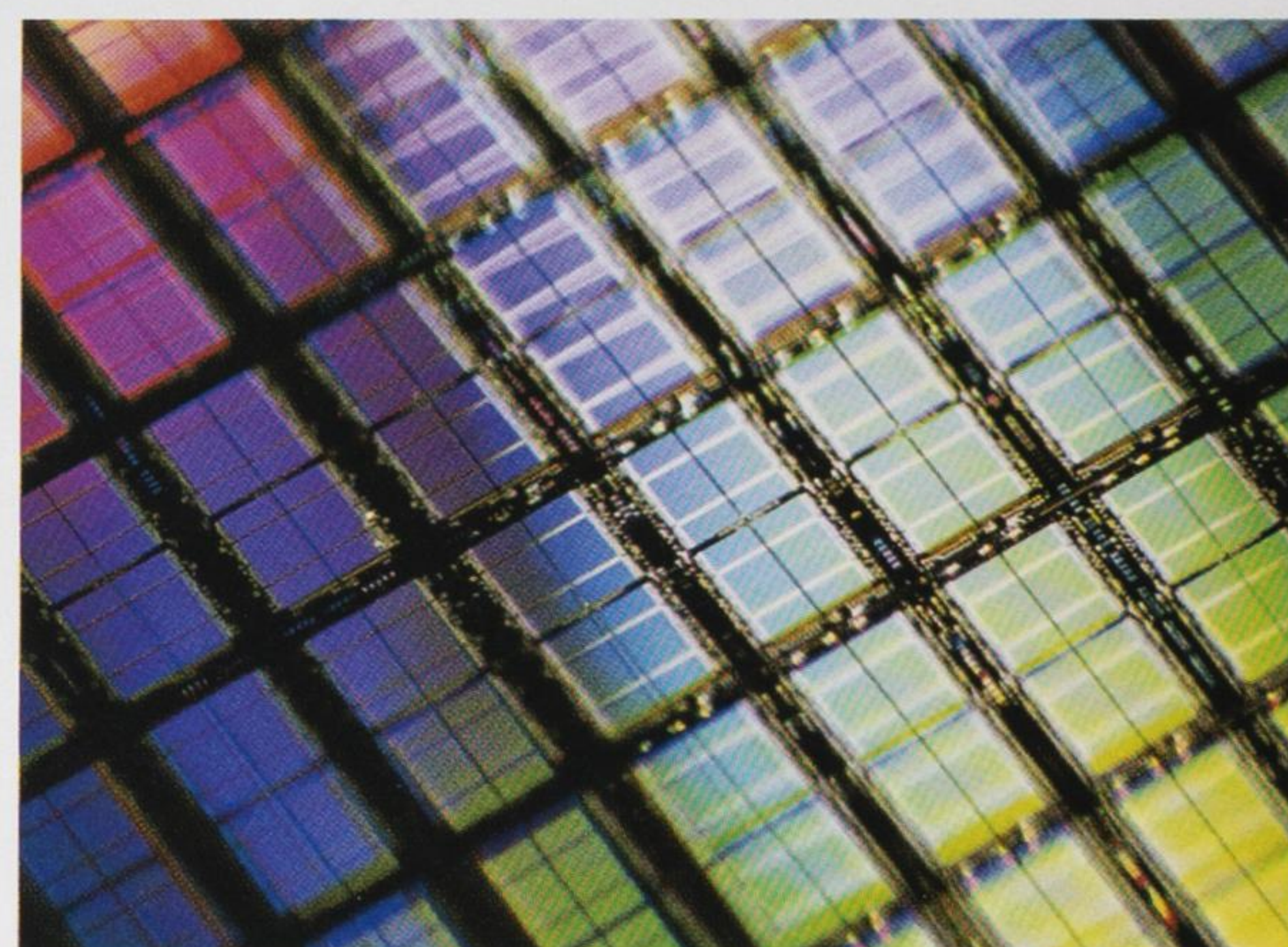


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SURFACE TECHNOLOGY SYSTEMS

'Big five' gather to discuss power-LED roadmaps at Strategies in Light 2005

By Tim Whitaker

The "big five" LED manufacturers, otherwise known as Cree, Lumileds, Nichia, Osram Opto Semiconductors and Toyoda Gosei, assembled for a panel session at the recent Strategies in Light conference to discuss advancements in, and new applications for, high-power LEDs.

Osram's CEO, Rüdiger Müller, highlighted four key areas of growth: miniature projection systems, flat-panel-display backlights, automotive headlights and general lighting. As well as reduced cost, key targets for these applications are improved color uniformity and increased surface brightness.

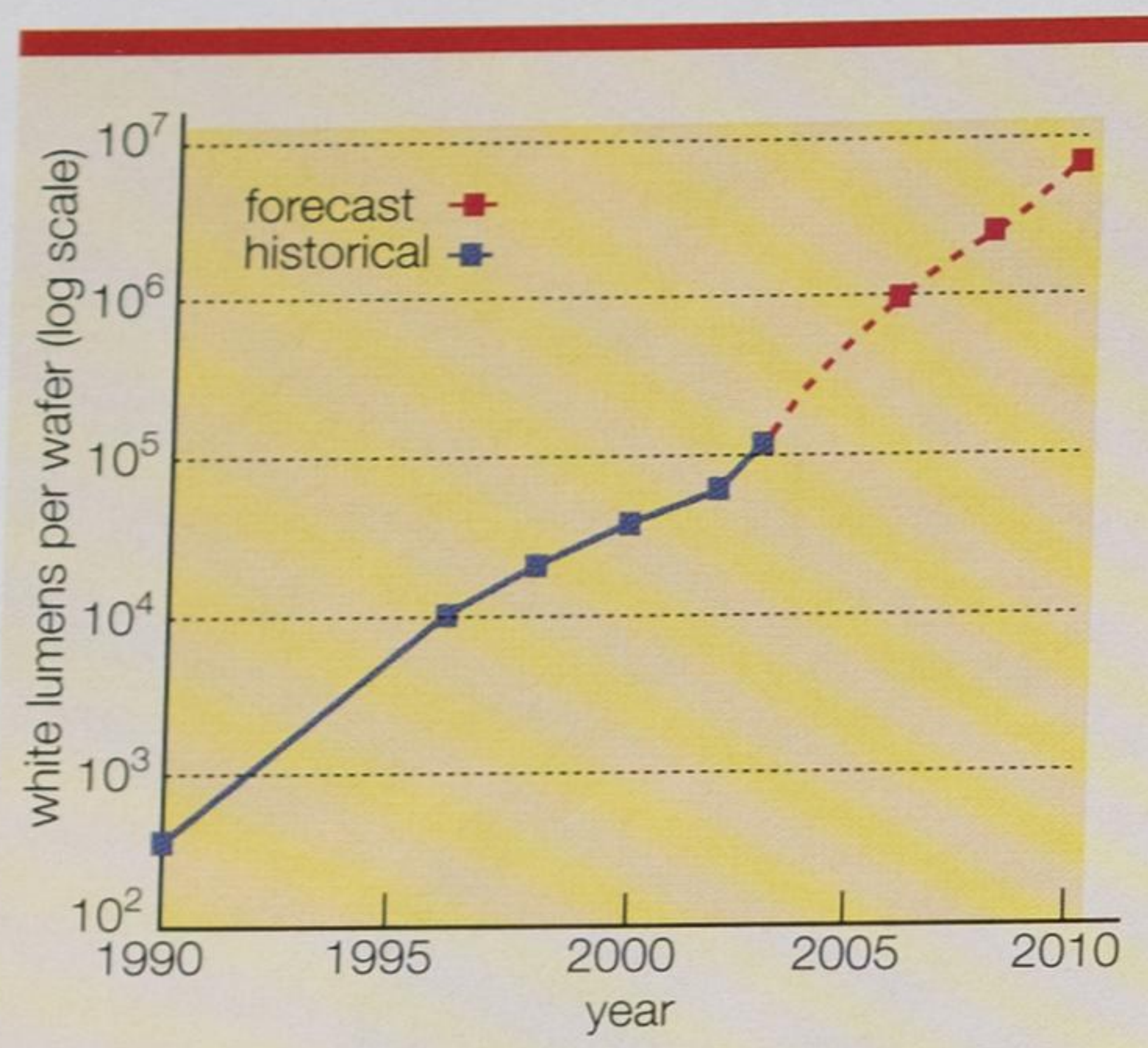
"LED technology will win where there is proven value over conventional technology; the battle is being fought application by application," said Jason Posselt, product marketing manager for Lumileds. "A focus on light sources, rather than discrete LEDs, will speed the adoption of solid-state-lighting technology."

To address a number of applications, Lumileds has announced a redesign of its Luxeon high-power LED product, which, when introduced this summer, will provide 65 lm at 350 mA and be more compatible with lighting assemblies than the current generation of devices. The LEDs will also boast a maximum junction temperature of 185 °C, improved moisture resistance and they will maintain their brightness for longer.

Breaking the barrier

For the longer term, Posselt highlighted cost targets of less than 1 cent/lm, coupled with hundreds or thousands of lumens per package. When pressed to say when he thought the 1 cent/lm barrier might be reached, he said, "Not this year. Probably not next year, but definitely within five years." Müller agreed with the three- to five-year estimate, saying it was "inevitable" that production costs would fall.

While Cree acknowledges that its lab demonstration of a 100 lm/W source (*Compound Semiconductor* March p5) will need a huge amount of work before it can be transferred into production, the result demonstrates that roadmaps showing progress toward and beyond the 100 lm/W barrier are not just wishful thinking. Cree's production white LEDs are likely to move to 50 lm/W this year.



Cree's ongoing conversion to 3 inch wafer fabrication is one of the factors pushing up its lumens-per-wafer metric.

Also on the panel, Cree's marketing manager Chris James showed a timeline detailing the company's progress in the lumens-per-wafer metric for white LEDs. This metric incorporates a number of factors, including efficiency, current density, chip size, yield and wafer diameter. James estimated that Cree's 100 lm/W figure and its ongoing conversion to 3 inch wafer production will bring it close to the 1 million lumens per wafer mark.

Shuji Muguruma of Nichia outlined the company's application focus, which covers four main areas: lighting, displays, automotive and mobile, with a different product set for each. On its product roadmap for lighting, Nichia has a 5 W package producing 200 lm. Muguruma also said that Nichia is expanding its Rigel series of 0.5 W devices with products incorporating secondary optics, and others targeting LCD backlights, as well as high-power and RGB models.

For Toyoda Gosei, Bill Kennedy presented a range of products, including a new power surface-mount LED, which is about to enter production. The device has only three components: a 1 × 1 mm chip, a phosphor and a package measuring 3.4 × 2.8 × 1.2 mm. The package provides "superior" heat dissipation through an inorganic submount, and Toyoda Gosei claims it is the world's smallest package capable of handling high current.

James said that over the next five years LED manufacturers will need to supply products that are easy to use by new designer com-

munities, and that can be applied over wide temperature and power-dissipation ranges.

When questioned about the attraction of moving some of their operations to China, panelists agreed that while some processes benefit from low labor costs, areas such as R&D and process development are best performed in a "special" environment – in part, this was a thinly veiled reference to the need to protect intellectual property.

Müller was more forthright: "In terms of intellectual property, if you move to some Asian countries you might as well post your recipe on the Internet." He later qualified the remark with reference to the stability of R&D workforces in Europe contrasting with the ease with which many engineers switch jobs in China, according to an Asian study.

Protecting property

Elsewhere at the conference, representatives from organizations in Taiwan and Korea were keen to stress their commitment to intellectual-property protection. "Intellectual property should be respected," said Pei-Jeh Wang, president of Arima Optoelectronics, one of Taiwan's largest HB-LED producers. "Also, MOCVD growth [of device layers] is an art. If you take some intellectual property and try to reproduce the device-layer growth, you won't be able to make a product."

Jed Dorsheimer, a semiconductor analyst with Adams Harkness, said that Taiwan and Korea should not be considered as "intellectual property-unfriendly" countries. "Companies, as well as organizations such as Taiwan's Industrial Technology Research Institute, have their own intellectual property," he said. "There's a lot of innovation, not just 'me too' products." This includes high-power LEDs from Asian companies outside Japan, notably Cotco and Seoul Semiconductor.

Nevertheless, intellectual property remains a contentious issue throughout the LED industry, and on the day of the panel session Lumileds issued a warning to manufacturers of mirror-substrate LEDs to check their position on intellectual property or face the consequences.

Tim Whitaker is editor of LEDs Magazine (ledsmagazine.com).

Lumileds, Agilent aim mid-power LED range at exterior car lighting

Agilent Technologies and Lumileds Lighting have launched a new range of low-cost, mid-power LEDs designed primarily for automobile exterior lighting.

The red, red-orange, and amber surface-mount LEDs, dubbed the Envisium range, combine high-performance transparent-substrate AlInGaP chips from Lumileds with standard plastic-lead chip-carrier (PLCC) packages from Agilent.

Agilent's existing PLCC LEDs typically emit a power of up to 200 mW, while Lumileds' devices operate at 1 W and above.

In the Envisium range the LED die is attached within the reflector cavity, and this cavity is encapsulated by a proprietary epoxy blend developed by Agilent.

Red LEDs in the new range emitting at 630 nm produce a luminous intensity of

630–1000 mcd and a total flux of 2.6 lm. The 617 nm red-orange devices emit between 1000 and 1580 mcd and have a total flux of 4.3 lm, while the 592 nm amber LEDs are rated at 630–1000 mcd and 3.0 lm.

As well as being useful for exterior lighting applications in cars, such as center high-mounted stoplights, front turn signals and rear combination lamps, the LEDs could also be used in interior automotive lights and general lighting and signage applications.

Agilent and Lumileds originally announced that they had begun working together on mid-power LED technology in July last year, and had initially expected to release the first products from the collaboration in the final quarter of 2004.

● See "Automotive LED take-up hinges on cost reduction" p35.



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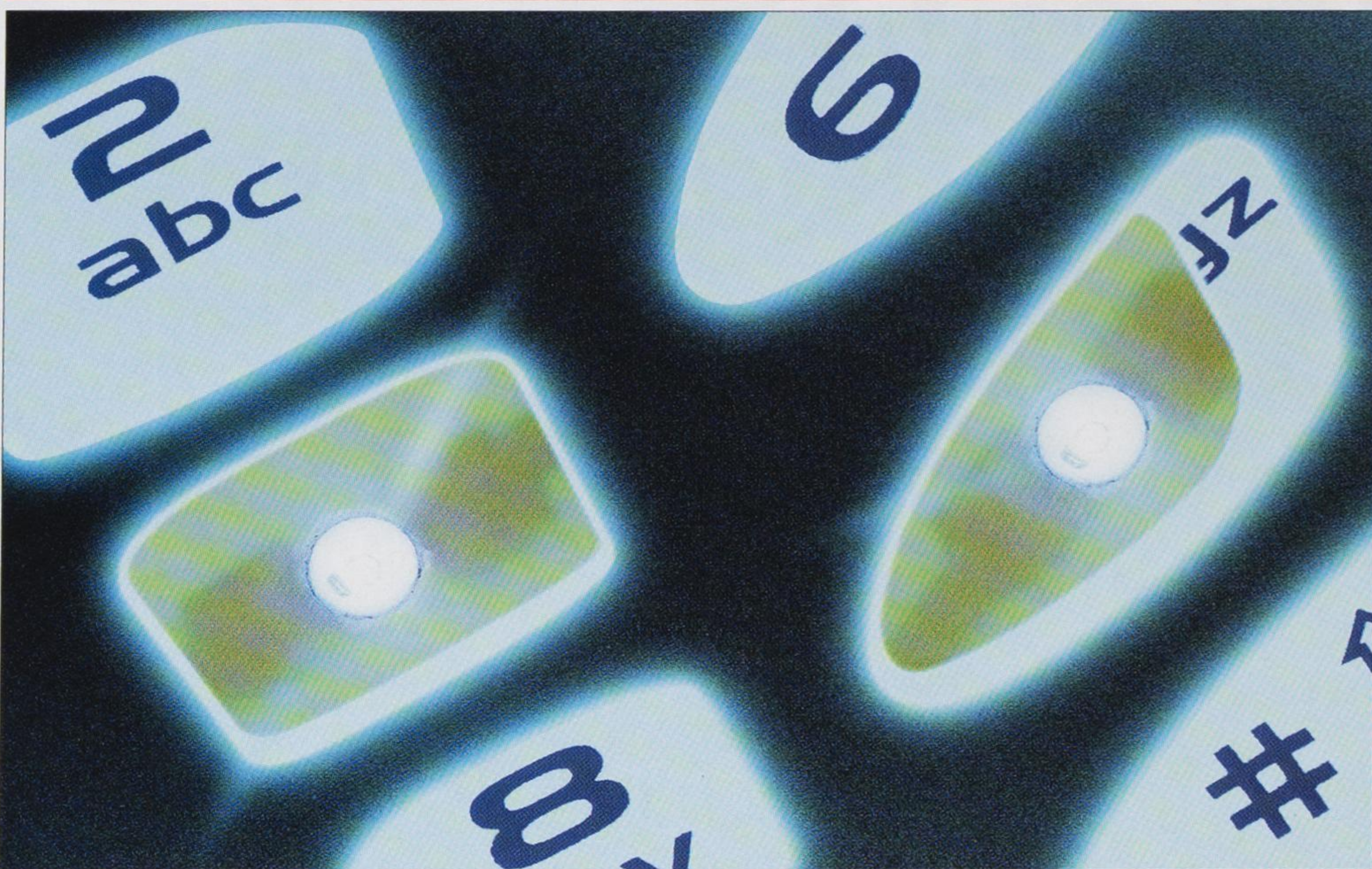
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Keypad backlighting is just one application area for Osram Opto Semiconductors' PointLED.

Osram develops tiny Thin-GaN white LED

Osram Opto Semiconductors has developed a high-efficiency white LED that measures just 2 mm in diameter and 0.775 mm in height.

The so-called PointLED is said to be the smallest LED with an integrated reflector, and is compatible with both surface-mount technology and zero-height mounting. The circu-

lar, flat package can be completely sunk into a printed circuit board and has a typical brightness of 800 mcd at a beam angle of 120°.

Osram says that the tiny new source can be used in a variety of applications areas, from the automotive industry to cell-phone keypad backlights. The Regensburg, Germany, company adds that the device could be used in cell-phone camera-flash systems, which is regarded as one of the key growth areas for LEDs in the short term.

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Price erosion puts brakes on laser-market growth

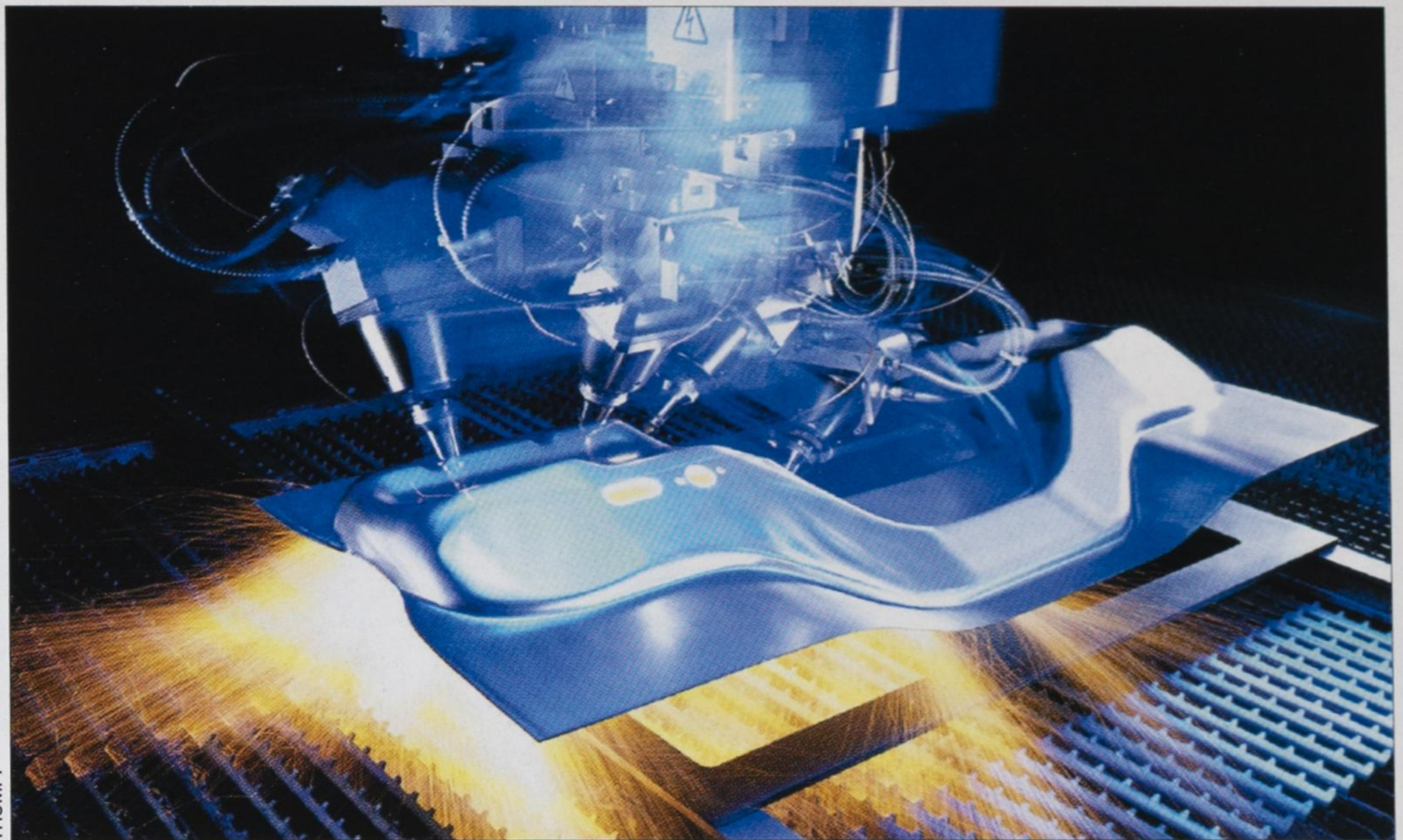
The laser-diode market continued to grow in 2004, but at a much slower rate than had been seen in the previous year. That is the conclusion of an annual review and forecast by market-research firm Strategies Unlimited.

According to industry analyst Bob Steele, who wrote the report, the overall market for diode lasers used in applications ranging from telecommunications to dentistry grew 4% last year to reach \$3.2 billion. That compares with 18% growth in 2003.

The major reason for the sluggish growth appears to be a decline in price across almost every diode-laser category. For example, despite a large increase in unit shipments of lasers used in optical data storage, the dollar value of that segment remained flat.

"It is not often that decreases are so widespread and of such magnitude in any given year," said Steele. Optical data-storage applications represented a \$1.84 billion market in 2004, with 644 million units shipped. Much of the production of devices used in applications such as DVD players and recorders has now shifted to Taiwan and, to a lesser extent, mainland China, resulting in an annual price erosion of as much as 35% in some cases.

However, the telecommunications market for diode lasers did recover significantly in 2004, growing 21% to reach \$943 million. Transmitter-laser unit shipments were up 31%,



The market for high-power diode lasers used in materials-processing applications such as automobile manufacture slumped 13% in 2004, largely due to a steep fall in selling prices.

while there was high growth in the 10 Gigabit Ethernet sector. Steele says that prices may stabilize in 2005, and is expecting 20% growth in revenue for transmitter lasers this year.

The third-largest market segment for diode lasers – high-power laser systems for materials processing – saw revenue decline 13% to \$110 million in 2004 – again, despite growth

in unit shipments. And after rapid growth in 2003, the medical market for diode lasers slowed considerably, increasing just 7% to \$62 million.

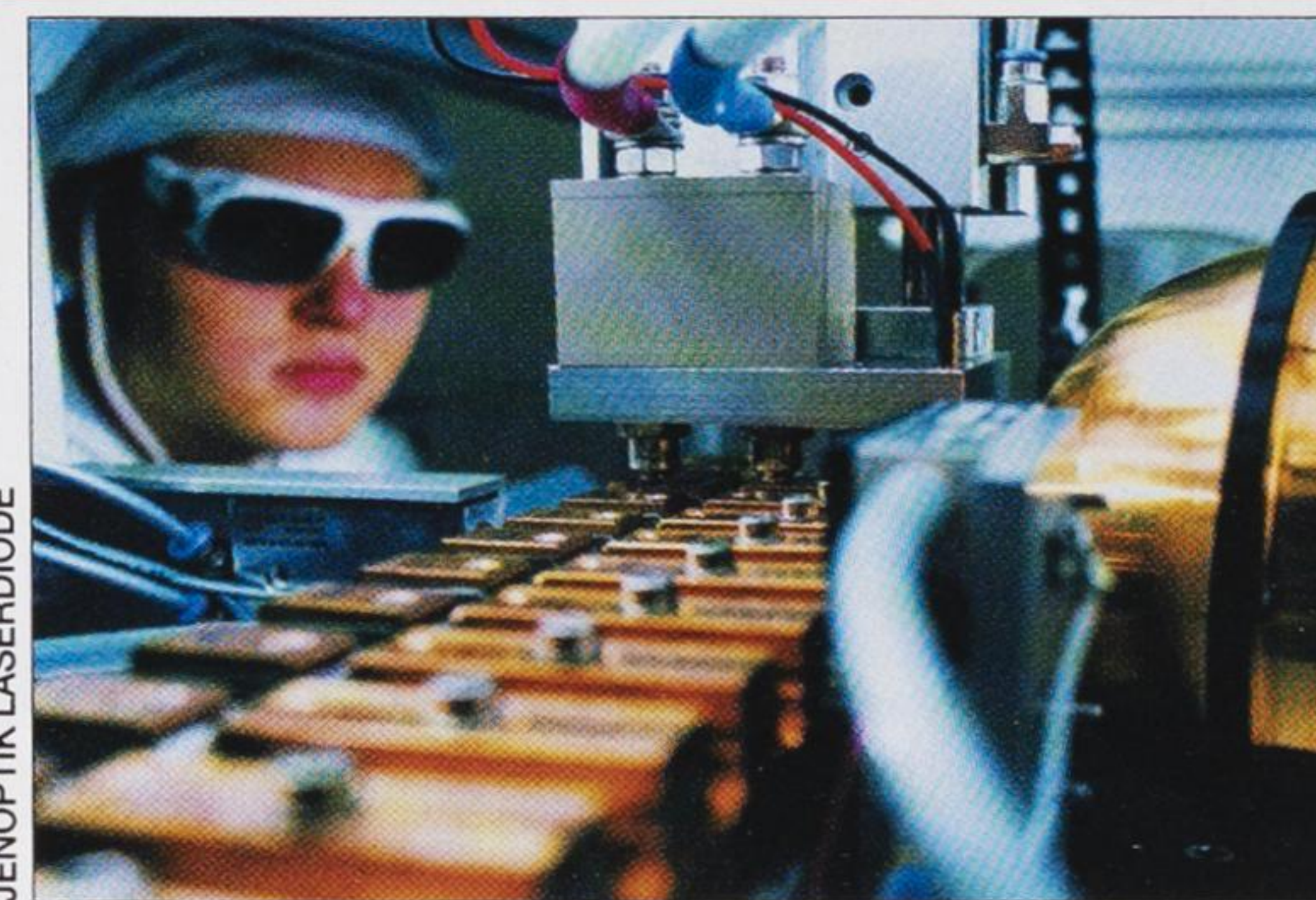
Steele is optimistic about prospects for 2005, predicting overall growth of 12% to about \$3.6 billion. The largest sector – optical storage – is expected to grow 9%.

High-power GaAs laser outfit plans to ramp up production

Germany-based GaAs laser developer Jenoptik Diode Lab is to increase production of its high-power chips in early 2006. The small firm, which was set up three years ago as a spin-out of the Ferdinand Braun Institute for High-Frequency Technology, will build a facility in Berlin-Adlershof to make the chips.

The complex will include 500 m² of clean-rooms for 3 inch GaAs production, as well as in-house research and development laboratories and offices. With the addition of 40 jobs, the company's workforce will swell considerably from its current 8 employees. Work on the site is due to begin this spring.

Diode Lab will principally be making lasers for its parent company Jenoptik Laserdiode, with the lasers destined for applications in materials processing, medicine and displays technology.



Parent company Jenoptik Laserdiode will be the principal customer for Diode Lab when production of high-power GaAs lasers begins early next year.

"The new [manufacturing] site in Berlin will allow Jenoptik's photonics group to react more flexibly to market demand," said the company in a statement. However, Jenoptik Diode Lab will also be free to deliver components to external companies.

Diode Lab sells 808, 915 and 940 nm laser bars with output powers of 40 W and more.

Apple bolsters Blu-ray board

The Blu-ray Disc Association (BDA) spearheaded by Sony has received a major boost with a decision by Apple to join the industry group as a board member.

The move should lead to consumers being able to create high-definition video and burn the content onto next-generation DVDs.

"Apple is pleased to join the BDA board as part of our efforts to drive consumer adoption of high-definition [technology]," said Apple chief Steve Jobs. "Consumers are already creating stunning high-definition content and are anxiously awaiting a way to burn their own high-definition DVDs."

Blu-ray technology, which is set for a major launch effort later this year, is rivaling the alternative high-definition DVD standard that has been developed by Toshiba, NEC and others to gain market acceptance. Both formats rely on GaN-based blue lasers.

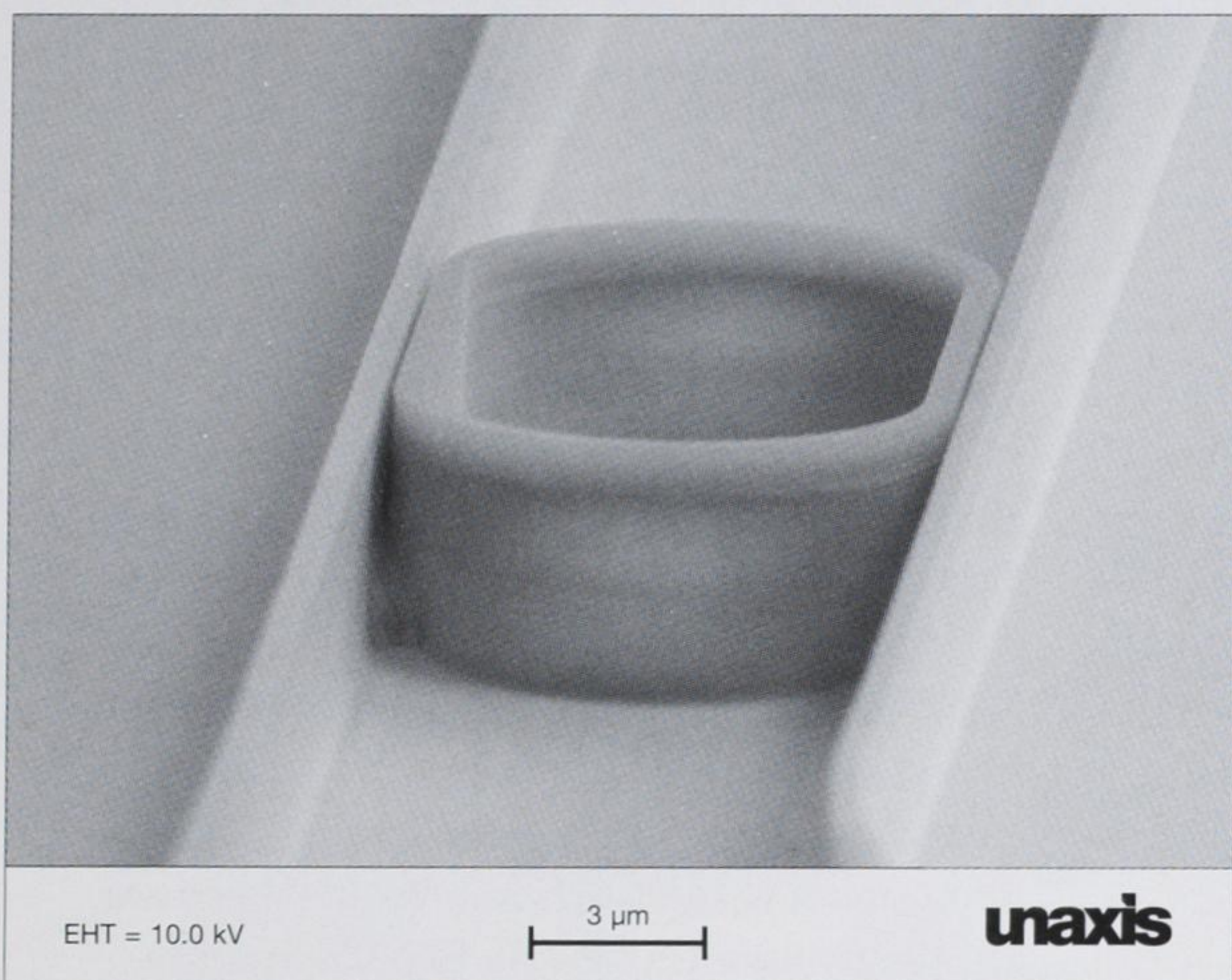
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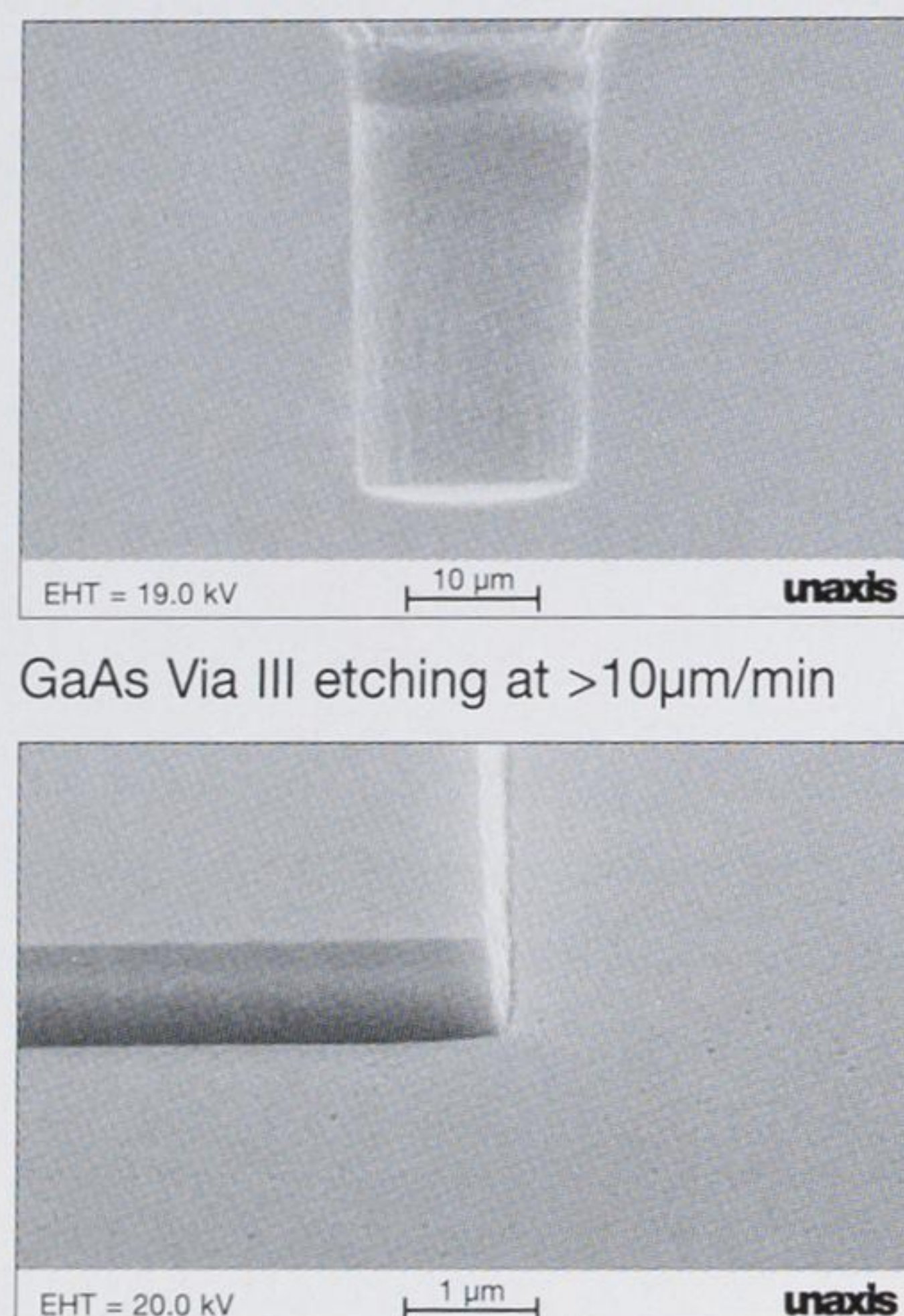
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GaN-on-insulator wafers could be custom-made

Picogiga International, a French substrate supplier, has made what is believed to be the world's first single-crystal GaN-on-insulator substrate. According to the Soitec subsidiary, the technology could lead to improvements in the performance of GaN-based devices such as blue and white LEDs and high-power microwave components.

Silicon-on-insulator technology has already penetrated the mainstream electronics market, resulting in improved device performance.

Picogiga says that the substrates, which are made using the commercial "Smart Cut" process that Soitec employs to manufacture

silicon-on-insulator wafers, will allow homo-epitaxial growth of active GaN structures. This will mean that devices based on the wide-bandgap material will be of better quality, in terms of dislocation density and stress, than those grown using current hetero-epitaxy.

"The carrier material (backside wafer) will be selected independently from the topside layer," said Picogiga. "That will allow the substrate to be tailored and optimized for thermal management, packaging and assembly, or mechanical-stress management."

The procedure should help to reduce the thermal limitations of bulk GaN material in

RF transistors, while also helping to improve LED efficiency.

Picogiga has so far produced only 2 inch diameter GaN-on-insulator wafers, but says that the technique will be suitable for larger substrates as soon as these become available. However, production quantities of GaN-on-insulator wafers will not be possible until bulk GaN substrates become more affordable and widely used, with Picogiga not expecting commercialization until 2006 or 2007.

On a positive note, the company did say that it had several customers who were "eager to try" the engineered substrates.

II-VI plans 100 mm SiC scale-up with \$7.5 million funding

The wide-bandgap materials division (WBG) of US substrate supplier II-VI plans to produce 100 mm diameter semi-insulating SiC substrates for military and commercial uses.

With \$7.5 million to spend on a three-year project – largely funded by the US military – II-VI plans to address technical and manufacturing issues to do with the development of substrates that will be used to make wide-bandgap chips for high-power radar applications.

II-VI already sells SiC substrates commercially, and will use the funds to scale up its advanced physical vapor transport technology to produce the larger products. Systems based on SiC should operate at higher power efficiencies, with greater power-bandwidth RF performance than current technologies, and should require less supporting infrastructure.

"Next-generation [SiC] device development will rely on 100 mm substrates," said Andy Souzis, technology and program manager for II-VI's WBG group. "Currently, such substrates are not commercially available and suffer from inadequate quality."

Nordic spin-out wins \$26 million investment in SiC development

Norstel AB, a spin-out from Finland-based silicon-wafer supplier Okmetic Oyj, has won more than €20 million (\$26.5 million) in venture and government funding to develop and manufacture SiC wafers. Based in Linköping, Sweden, Norstel's business is based on its proprietary high-temperature CVD technology, which was developed over 10 years through Linköping University, Okmetic and the Swedish industrial giant ABB.

Nordic technology investor companies – Creandum, Eqvitec Partners and Northzone Ventures – have added their financial muscle to Norstel, which will receive €6 million funding from the Swedish government over the next three years.

Norstel will target its wafers at high-voltage and high-frequency applications of SiC devices. Product development and manufacturing will be located in Norrköping, Sweden, with manufacturing expected to begin during 2006. Initially Norstel will employ about 50 people in manufacturing and advanced product development.

Applications involving conversion, trans-

mission and management of electric power are prime candidates for SiC chips, which are expected to reduce transmission loss and power consumption in domestic appliances and industrial systems.

Similar applications to improve the power performance of solar-power modules and hybrid cars are also expected in the future.

And Norstel has already lined up what it describes as a major contract to deliver SiC wafers for high-frequency transistors to be used in a new, military radar system. The contract is with the Swedish Defense Materiel Administration.

According to Norstel CEO Asko Vehanen, the spin-out company was the only European source of SiC high-frequency wafers able to meet stringent quality demands. Additional business for Norstel will come from the jewelry sector, with US company Charles and Colvard – a near neighbor and customer of SiC specialist Cree in the Research Triangle Park in North Carolina – placing a \$4 million, three-year order with Norstel for material to be used in its Moissanite jewels.

In brief

- **Eudyna Devices**, the Japanese company formed a year ago by the merger of the Electronic Devices Group of Sumitomo Electric Industries and Fujitsu Quantum Devices, says it will launch GaN-based microwave devices this year. Fujitsu Labs, the research wing of Eudyna's parent firm, has further developed GaN-based HEMTs

by using an AlN film on a SiC substrate.

- Japanese electronics giant **Furukawa** is to begin making 2 inch GaN substrates at the end of this year, claims online business newspaper *Nikkei.net*. The report says that Furukawa will target next-generation DVD applications when it begins production, adding that it plans to manufacture

5000–6000 units per month by 2008, which is expected to result in sales of ¥8 billion (\$77 million) per year. In Furukawa's process, gaseous GaCl reacts with ammonia to form GaN films. Test production has reportedly begun, with the firm expected to invest a further ¥900 million to expand its production facilities.

Avanex debuts opto chip-manufacturing services

Avanex is to offer foundry services for custom GaAs and InP optoelectronic chip making.

The Fremont, CA, firm, which acquired its epitaxy and wafer-processing capability from Alcatel Optronics and Corning back in 2003, is also launching a set of standard optoelectronic InP and GaAs chips.

Backed by extensive Class 100 and Class 1000 cleanrooms, the foundry services on offer include custom chip design, epitaxy, wafer processing at a variety of wafer sizes, optical- and structural-analysis techniques and materials characterization. Other pro-

cesses available include electron-beam evaporation, sputtering, wet and dry etching and photolithography.

"We have more than 15 years' experience with InP and lithium niobate processes, and four years' experience in field-proven GaAs technology," said Avanex CEO Jo Major.

The transition should help the optoelectronics industry move closer to the standard electronic manufacturing model, something that will be necessary if the cost of InP technology is to drop to meet the demands of the emerging fiber-to-the-home market.

Quantum-dot amplifier restores 40 Gbit/s signals

Japanese researchers claim to have developed the first quantum-dot device capable of restoring optical signals to their original quality without electronic conversion. As well as re-amplifying a degraded 1550 nm optical signal, the semiconductor optical amplifier (SOA) also suppresses noise (re-shaping) and reduces timing jitter (re-timing).

Optical signals in current networks are usually restored only after being converted into electronic signals. Fujitsu's SOA, which was developed under a Japanese government-funded project, promises to shrink optical regenerators in future networks.

According to the company, using an improved InAs quantum-dot structure based on an InP substrate accelerated the gain-saturation response time of the SOA by a factor of 1000. This improvement in response time means that the waveform is not degraded to as large an extent as normal during optical regeneration. According to Fujitsu, conventional SOAs typically have a response time of several nanoseconds, which makes them useless for all-optical regeneration.

Fujitsu admits that further development of the device is needed, however. For example, fluctuations seen during the off-cycle of the signal still need to be reduced.

As a result, commercial deployment of the technology is still a long way off, with Fujitsu believing that the SOA will only become a practical technology for wavelength-division multiplexing applications around 2010.

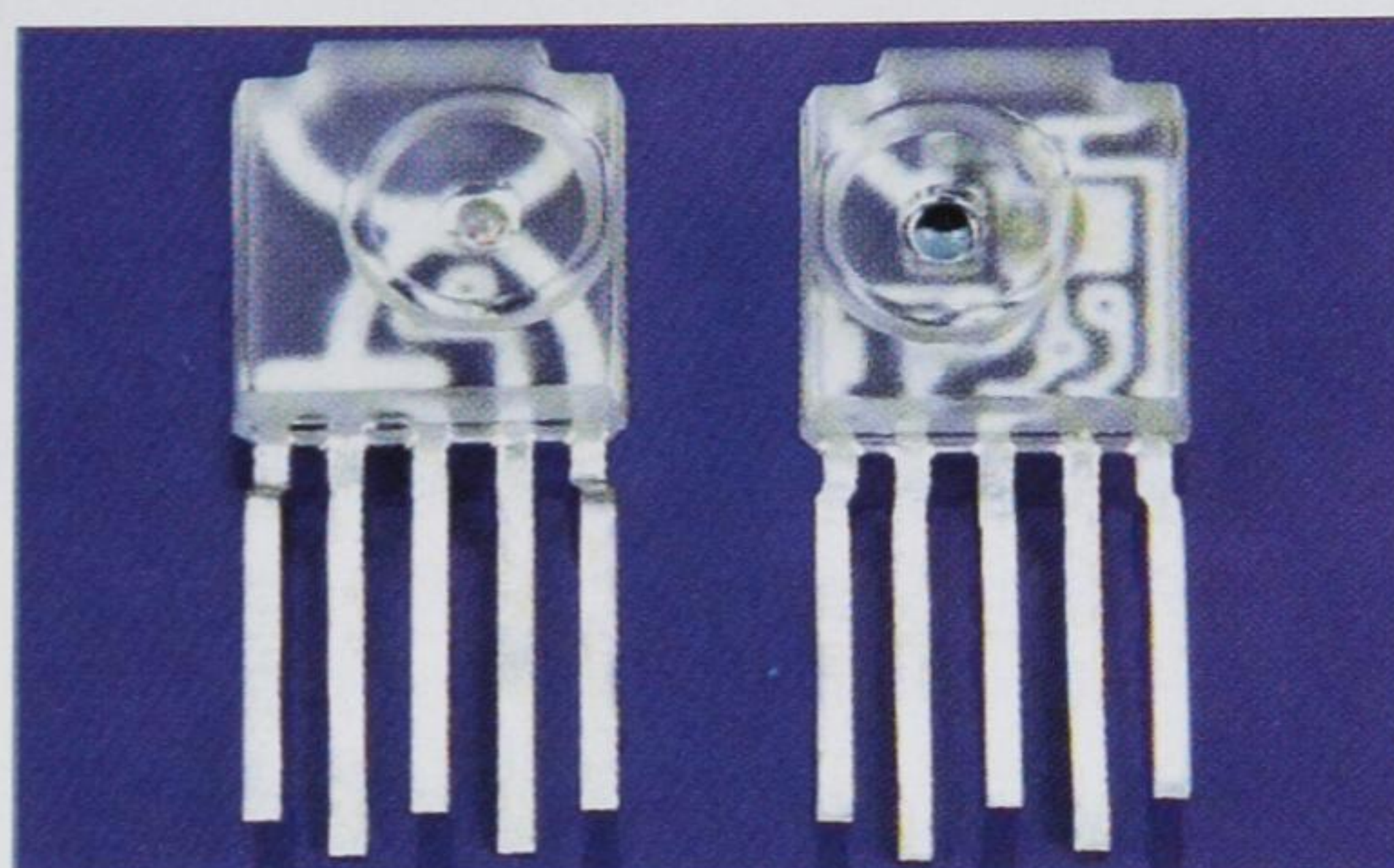
Renault car gets a multimedia POF network

French car manufacturer Renault has wired up one of its Espace models with a high-speed plastic optical-fiber (POF) network that contains resonant-cavity LED transceivers produced by Irish start-up Firecomms.

The proof-of-concept network pipes DVD movies, digital TV, video games and GPS maps to LCD screens mounted in the car's dashboard and rear seats. The driver and passengers can make individual choices of what they want to view via a menu on the touch-sensitive screens.

The Espace also features Consumer Convenience Ports, which allow the driver and passengers to plug their own electronic devices such as MP3/CD players, video-game players and laptops into the car's network.

The network supports the IEEE 1394



Firecomms resonant cavity LED transceivers, which form part of the plastic optical-fiber network, can transmit data at speeds of up to 250 Mbit/s.

(Firewire) standard, which is used for transferring data between PCs and equipment such as Apple iPods and digital camcorders.

In brief

- Sunnyvale-based fiber-optic subsystem vendor **Finisar** made sales of \$73.1 million in the quarter ended January 31—a record high for the company. Revenue should continue an upward trend in the next quarter following Finisar's recent acquisition of part of Infineon's fiber-optic business unit.

- The brand, intellectual property, stock and several pieces of equipment belonging to UK business **Kamelian**, which entered into receivership in July 2004, have been bought by Scottish firm **Amphotonix**. Operating as a fabless company with initial funding of \$1.5 million, Amphotonix will

have its chip manufacturing carried out by Compound Semiconductor Technologies Global of Glasgow, UK, and module assembly by Scottish firm Optocap. "We have already re-established the product line and are currently taking orders," said Amphotonix COO Craig Tombling.

- **Optillion**, the fiber-optic transceiver maker based in Stockholm, Sweden, has filed for bankruptcy. The organization, which had a workforce of around 70, specialized in transceiver production for 10 Gbit/s Ethernet applications.

- **Bookham** has licensed a portfolio of silicon photonics patents to US company

Kotura on a non-exclusive basis. Kotura, which was founded in 2003 through the merger of Arroyo Optics and LightCross, already owns a number of similar patents.

- US-based fiber-optics company **K2 Optronics**, which specializes in external-cavity lasers, has been backed by chip-maker **Emcore** in its latest funding round. As well as joining the Series C round, Emcore will partner K2 on developing advanced technologies for next-generation laser products to be used in broadband applications, say the firms. Target markets for these products will include fiber-to-the-premises and cable-television applications.

EPIWAFER CHARACTERIZATION

Precision profiler sets bar for epiwafer doping gauge

Electrochemical capacitance–voltage (ECV) profiling is a widespread metrology technique that offers a versatile and powerful approach to determining doping levels at various depths within a semiconductor structure.

Most of the tools in use today hardly differ from the original ECV products that were launched onto the R&D market in the 1980s. This lack of evolution means that, compared with other ubiquitous compound semiconductor metrology techniques such as photoluminescence and X-ray diffraction, ECV has failed to mature in terms of accuracy, reproducibility and automation. However, we believe that a new tool represents a step forward in terms of ECV measurement performance, with significant improvements in repeatability and reproducibility.

ECV profiling was invented in the early 1970s (Ambridge and Faktor 1974) at the British Post Office Research Centre. The researchers required a convenient, high-depth-resolution method to reveal carrier-concentration variations through complex epitaxial layer structures. Their solution was an extension of the well-established CV technique that calculates the average carrier concentration from capacitance measurements across a Schottky-barrier depletion region.

Automated profiling

The modified approach substitutes an electrolyte for the conventional metal contact. By formulating the electrolyte so that it produces a well-defined electrochemical dissolution reaction with the semiconductor material, the researchers developed an automated ECV profiling system with nanometer-etch-depth resolution across a dynamic doping concentration range of 1×10^{13} to $1 \times 10^{20} \text{ cm}^{-3}$. Today, a number of electrolytes enables profiling through most III-V, II-VI and group IV materials.

The ECV profile measures the “net electrical effect” of the dopant atoms introduced into the epitaxial layer during growth, hence the effective depth resolution is limited to around a Debye length, and is, therefore, inversely proportional to the square root of the doping

Challenging the view that electrochemical measurements are awkward to perform and are imprecise is a new profiler that delivers a five-fold improvement in precision. **Gyles Webster** details progress in electrochemical capacitance–voltage profiling.

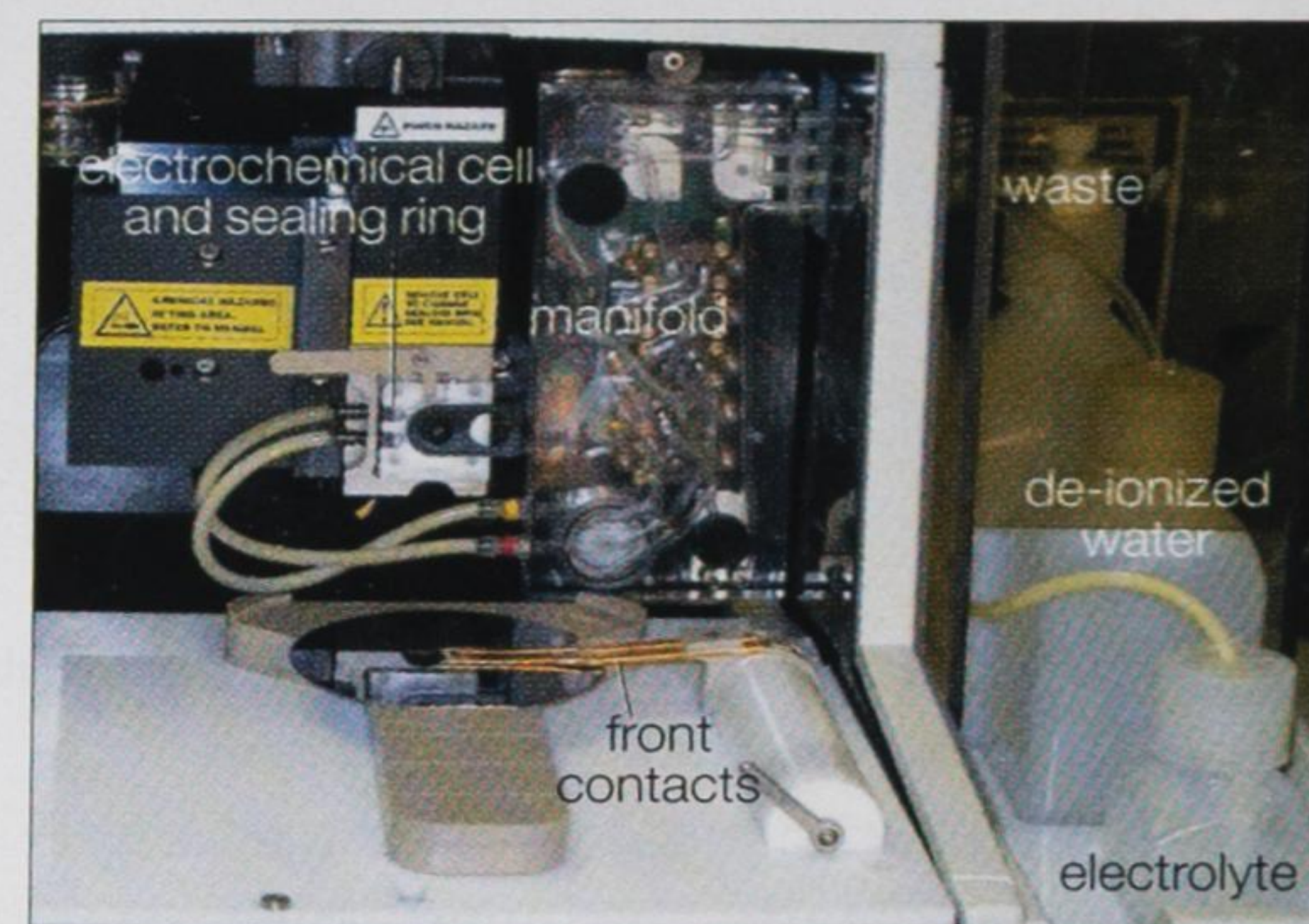
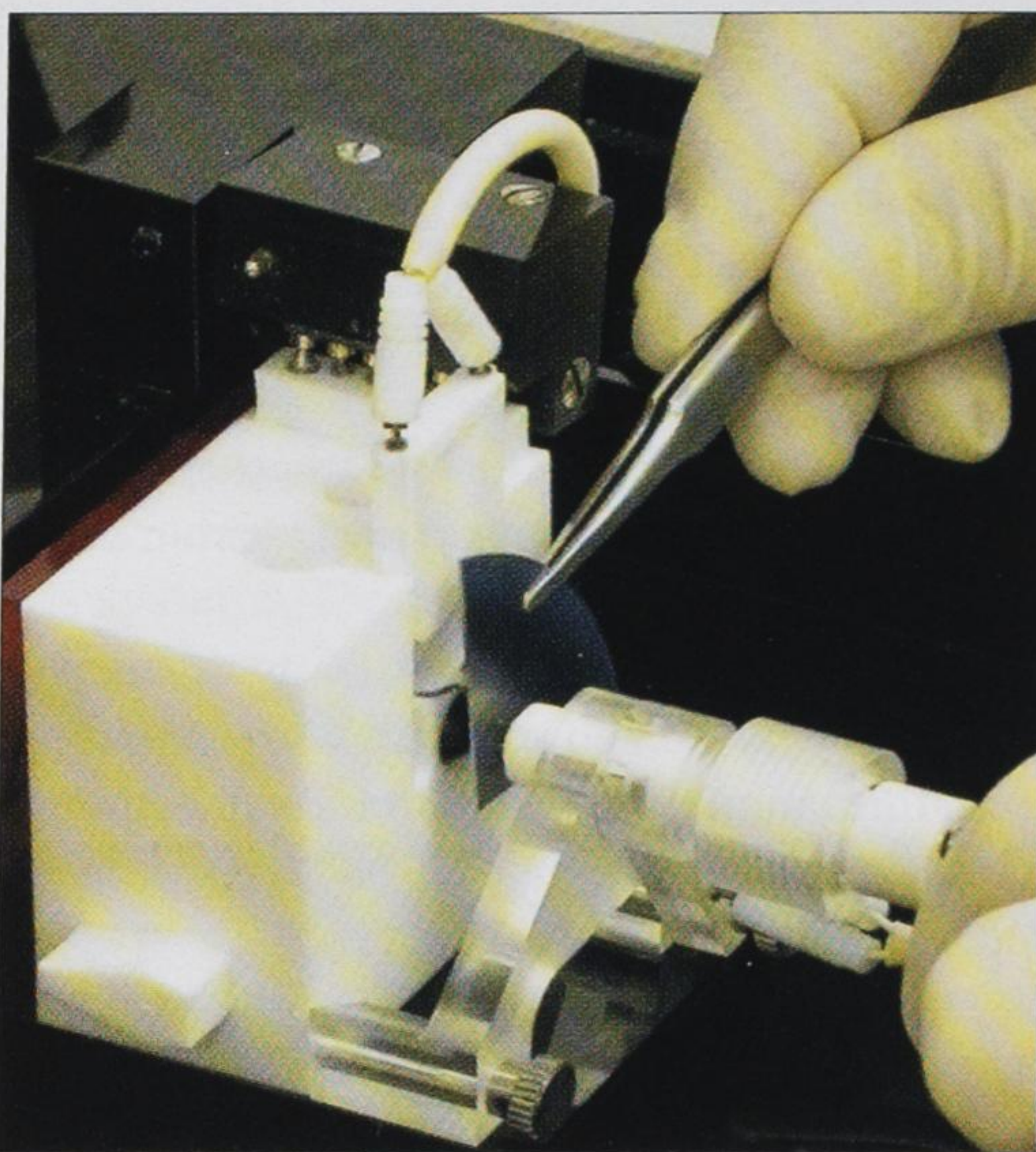


Fig. 1. (Left.) Manual loading, which has formed part of the ECV measurement process for the last 30 years, introduces variability between measurements. Fig. 2. (Above.) The ECVPro tool features built-in automated electrolyte handling.

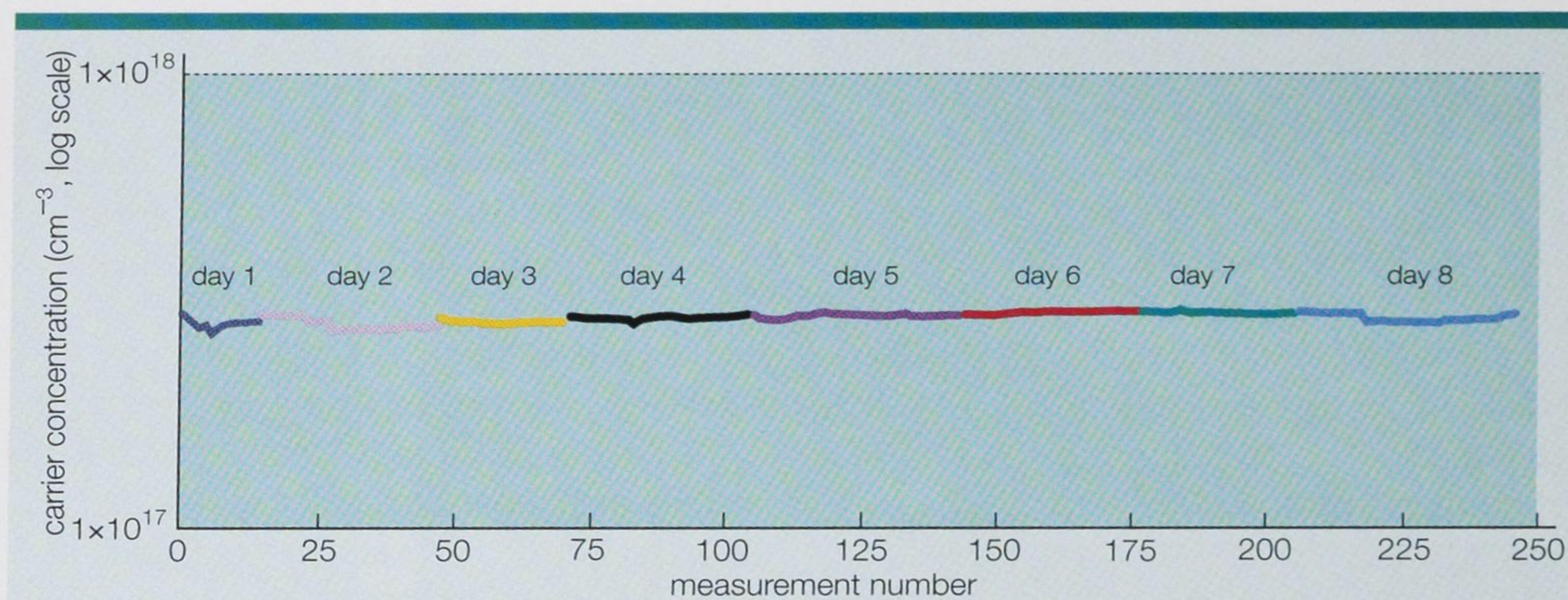


Fig. 3. The ECVPro slashes the standard deviation for doping measurements in AlInGaP from around 20% to only 4%, which ought to be of great benefit to LED manufacturers. A total of 245 measurements were carried out by three operators over eight days.

concentration. The electrically active nature of an ECV profile complements secondary-ion mass spectrometry (SIMS), an accepted but more expensive way to depth profile the atomic distribution of dopant atoms.

Because they were originally designed for an R&D environment, where flexibility is paramount, and manual handling of electrolytes and wafers are secondary issues,

today’s instruments are not suited to a volume-manufacturing environment. Now the ever-maturing compound semiconductor industry demands greater accuracy, reproducibility and ease of use, and this has mandated a fresh look at the technique.

Many of the limitations associated with ECV profiling can be traced to the electrochemical cell design. ECV measurements

EPIWAFFER CHARACTERIZATION



Fig. 4. The ECV profiler can be used to analyze distributed-Bragg-reflector structures with an etch flatness of about 5 nm. Sequential images recorded by the *in situ* camera monitor the effective oxide film removal while etching through an AlGaAs/GaAs interface.

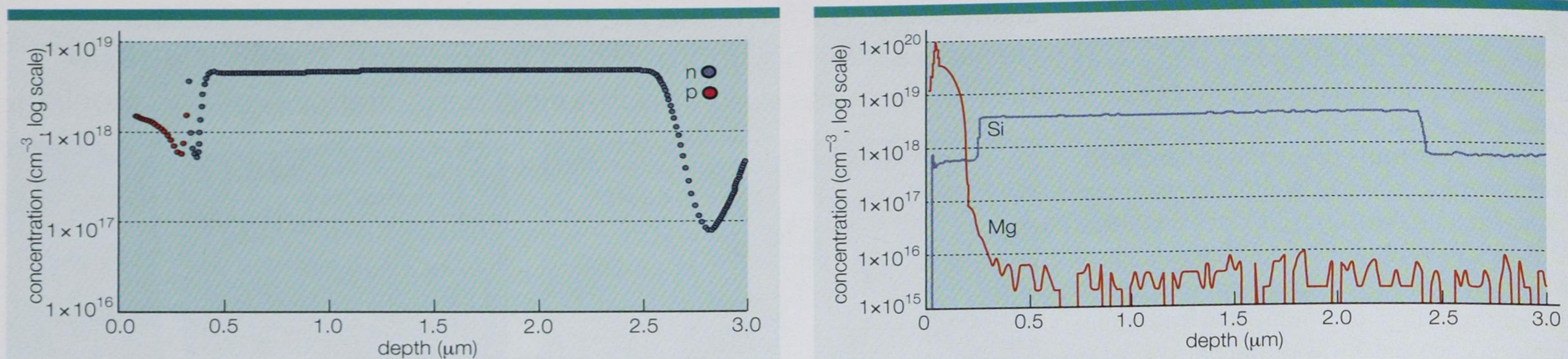


Fig. 5. ECV (left) and SIMS (right) can determine the doping concentration and atomic concentration, respectively, in a GaN LED structure.

usually involve manually loading a sample against a specially designed O-ring that defines the electrolyte's contact area on the sample. The O-ring must be soft enough to form a seal with variable semiconductor surfaces, but sufficiently rigid to precisely define the Schottky contact area. Since sample loading is operator dependent, this process inevitably is subject to run-to-run variability.

Absolute accuracy of the carrier concentration and etch depth depends on a precise measurement of the contact area. This critically important calibration is often ignored, and even if it is performed, it is not updated frequently enough to track gradual changes in area over time. Additional inaccuracies can arise from bubbles in the O-ring or O-ring distortion and wear resulting from unintentional variations in the pressure holding the sample against it.

Electrical-contact problems can also introduce measurement variations. To determine capacitance, an ohmic contact is formed either via a back contact to a conducting substrate or directly through a front contact to the epitaxial layers. Contact quality on older systems can vary and lead to unreliable results. Other issues can arise from samples with too high a series resistance for the over-simplified electronics and modeling of the semiconductor-electrolyte interface.

Sometimes the materials themselves require etch-method improvements. GaN and its ternary compounds, for example, present dif-

ficult chemistry for ECV profiling that can be overcome by pulsed etching, with sequential film formation followed by removal. Although older ECV tools include software features for pulsed etching, they lack sufficient electrolyte-circulation control and refreshment to carry out this process effectively.

Eliminating the wet bench

Addressing these limitations, Accent has launched a completely redesigned profiler, the ECVPro, which greatly simplifies sample handling by allowing whole wafers to be placed onto a horizontal stage (see figure 2). The automated electrolyte handling reduces operator contact with the chemicals and eliminates the need for an adjacent wet bench.

To determine the doping concentration, the wafer is positioned on the horizontal stage and front-surface contacts are lowered to make an ohmic contact. The stage is then raised to the vertical position and the electrochemical cell moves forward, applying a consistent pressure between the wafer and the O-ring. Electrolyte then circulates through the O-ring, removing any trapped bubbles and preparing the sample surface for profiling.

The electronics and modeling software have also been dramatically improved, partly through introduction of multifrequency capabilities. To ensure traceability of results in a manufacturing environment, the system now automatically compares capacitance measurements to a built-in traceable standard.

These refinements deliver a major improvement in reproducibility, which has been verified externally. Data provided by a major LED manufacturer show a standard deviation of 4% in measured carrier concentrations. Variance was calculated for 245 measurements taken with full load/unload cycles and different operators (figure 3). To put this figure in perspective, identical tests using the previous generation of tools produced a standard deviation of 20%.

To reduce errors resulting from an imprecise measurement of the contact area, a built-in camera is incorporated into the ECVPro's etch cell. This camera gives a calibrated, high-resolution image of the etch area after the profile is completed. Software then calculates and logs the contact area determined from the camera image, maintaining a calibration history of the O-ring. Tool calibration then ceases to depend on the operator, ensuring a high level of accuracy and repeatability.

To test these capabilities, an epiwafer manufacturer provided a highly uniform GaAs epilayer on a semi-insulating substrate. Non-contact resistivity mapping confirmed the wafer's excellent uniformity. The resistivity contour map revealed a circular pattern with a slightly lower resistivity in the wafer center.

To evaluate the ECVPro's repeatability, 50 ECV measurements were taken on the wafer, roughly following the circular contours of the resistivity map. The standard deviation calculated from all 50 measurements was 1.5%.

However, variations in resistivity across the wafer are probably due to changes in carrier concentration rather than thickness fluctuations, so the standard deviation describing repeatability is actually less than 1%.

The built-in camera provides additional benefits, such as dynamic observation of bubble formation and removal, and the option to view and record images of the electrolyte-semiconductor interface throughout the profile-etching process. When profiling complex heterostructures, these images show the physical interfaces between heterostructure layers that are reached during the etching process (see figure 4).

The images can also show material defects revealed through localized changes in etching current densities, a particularly useful feature when profiling less mature material systems, such as nitrides.

The III-nitride material system presents a tougher challenge for ECV profiling. Although *n*-type GaN, InGaN and AlGaN layers are reasonably easy to profile if the correct electrolyte concentration and etching procedure is used, *p*-type GaN is much more awk-

ward. Problems result from a combination of poor conductivity, rough surfaces and high defect densities. However, GaN-based LED profiles are possible with a custom process that uses lower measurement frequencies and accurate electrical models.

An ECV profile of a standard GaN-based LED structure supplied by a European MOCVD equipment supplier is shown in figure 5, alongside SIMS measurements on the same sample. *N*-type layer measurements by ECV and SIMS provide similar values for the carrier concentration. However, the *p*-type ECV carrier concentration level is one-tenth of the atomic magnesium concentration obtained by SIMS. This difference reveals the complementary nature of the techniques; only a fraction of the magnesium acceptors contribute to the hole conductivity, and that proportion can be determined by examining the ratio of the two measurements.

ECV profiling is a flexible technique that can be adapted to continually evolving materials systems. Despite its presence as a mainstay characterization approach, ECV profiling has always had a reputation as a troublesome

and highly operator-dependent technique. In the GaN world it is widely believed that accurate ECV profiling is just plain impossible. However, we believe that the improvements incorporated in the new generation of ECV profilers enables ECV profiling as a viable, accurate and highly reproducible technique, equally at home in development and high-volume manufacturing environments.

ECV profiling provides powerful insights into doping profiles and variations in simple and complicated heterostructures across a range of material systems. It represents a low-cost and in-house alternative to SIMS that is reliable and free of operator error. ●

Further reading

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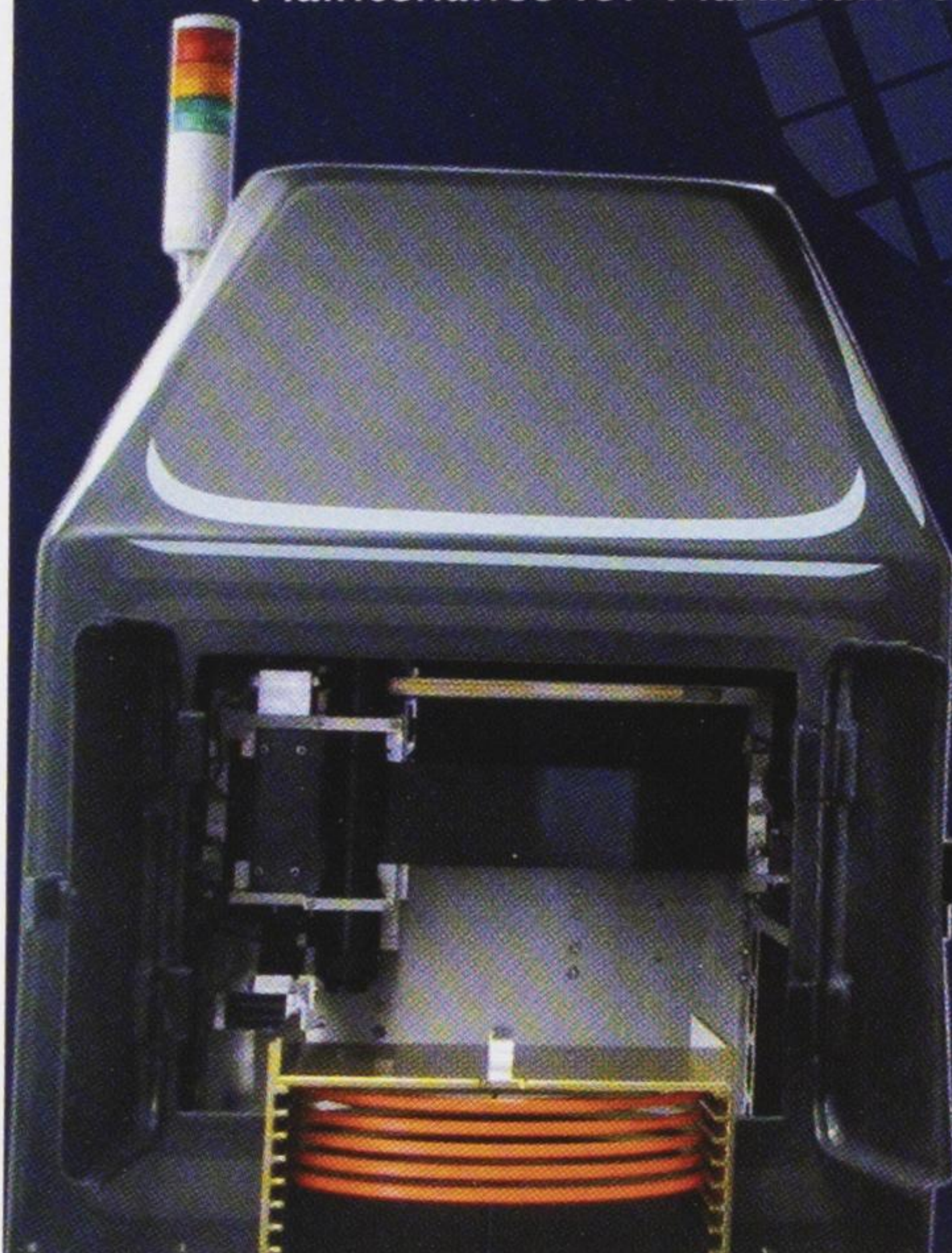
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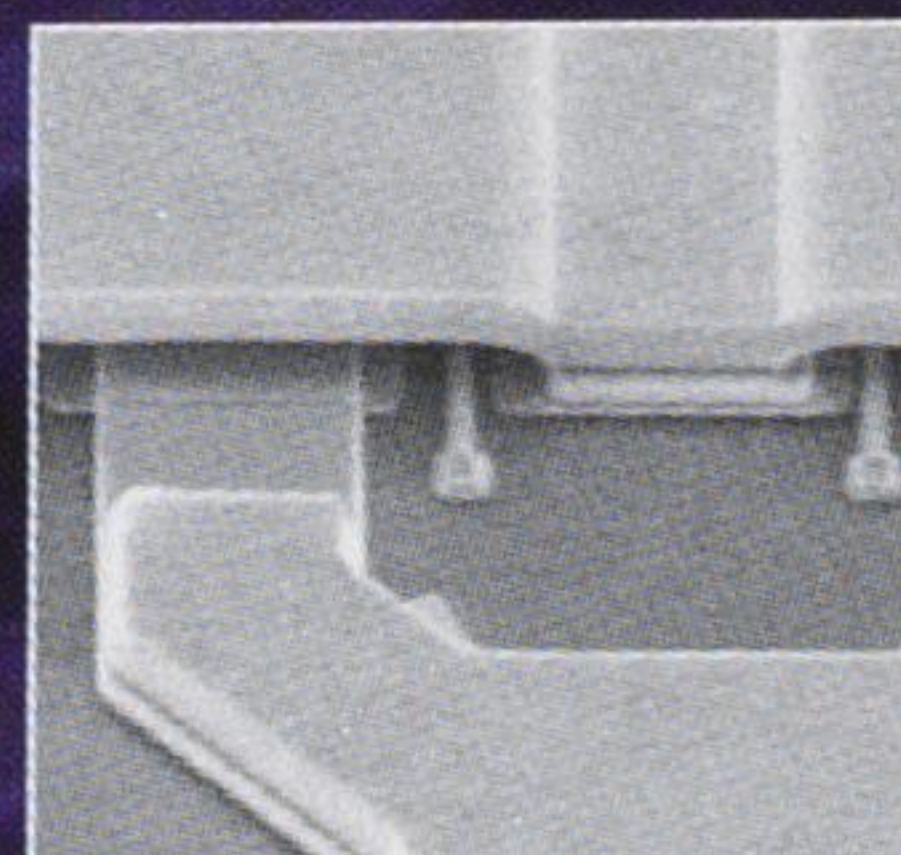
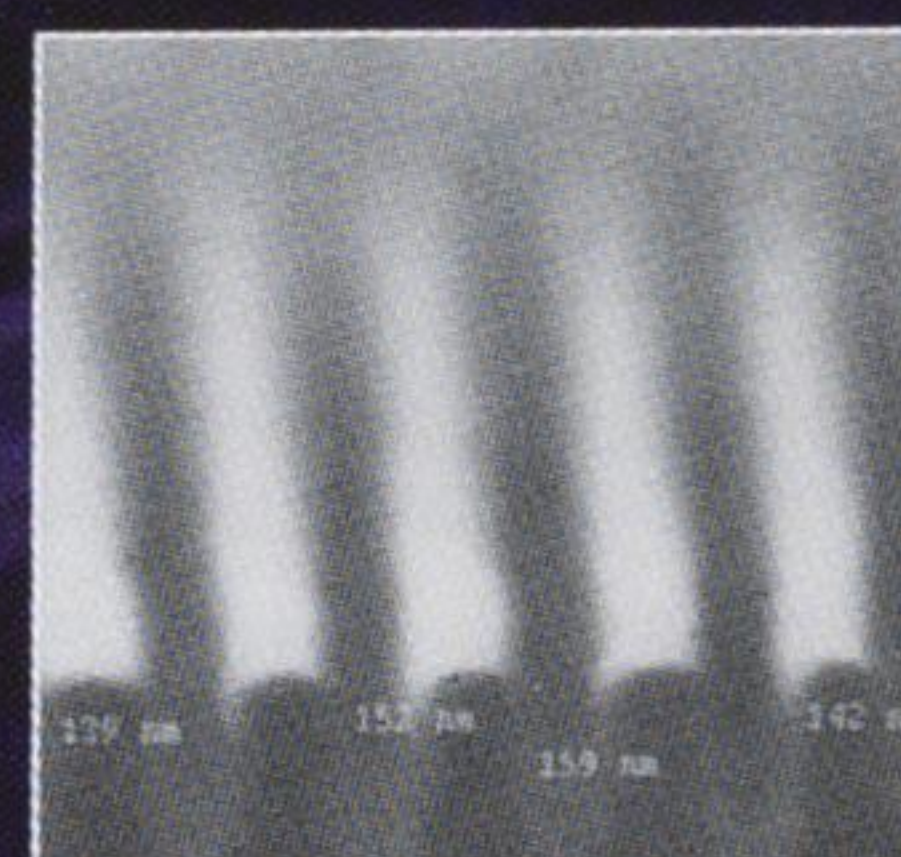
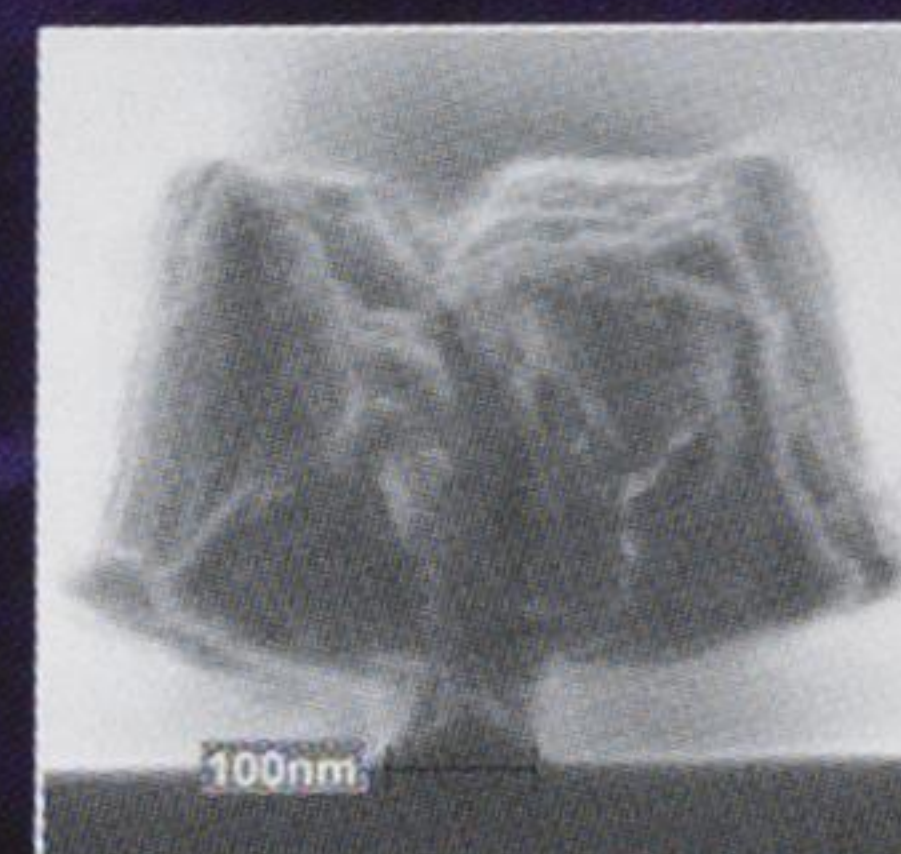
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SUBSTRATE CHARACTERIZATION

Automated wafer inspection

Optical surface analyzers offer a fast method of examining transparent substrate surfaces and classifying defect types.

Laurie Bechtler describes the technique and the insights it has provided to researchers making GaN HEMTs at Hitachi Cable.

GaN-based devices are currently penetrating various markets, including high-power electronics for military and commercial communications, high-temperature electronics for hostile environments such as automotive applications, and LED-based solid-state lighting. Performance, however, is not the sole driver for the wide-scale adoption of GaN-based technology. Cost often determines a product's commercial success, so, increasing production volume and reducing yield loss are critical to the GaN-wafer manufacturing process.

To make the transition to volume manufacturing, standard metrics are required to monitor and improve wafer quality. GaN epitaxial layers have various defects caused by substrate and epilayer growth. Although these defects can be catalogued by human operators using a microscope inspection technique, this method is time-intensive, and, in practice, can only be used to check part of the surface of a handful of wafers. In fact, such sampling can lead to erroneous conclusions about the occurrence of process defects.

An automated, high-throughput technique exists that reveals the size and type of defects across a wafer's surface by analyzing laser light that is scattered or reflected from it. Identifying defect type is important; surface particles can be cleaned off, but pits can drastically cut the device yield. This inspection process allows measurement of many more wafers, early detection of some process problems, and an opportunity to investigate the yield impact of different types of defects. The technique was restricted to opaque wafers, but now it has been extended to transparent material systems, including those based on GaN.

Hitachi Cable in Japan, which manufactures GaN HEMTs on both sapphire and silicon carbide substrates, has used an optical surface analyzer (OSA) designed by KLA-Tencor, of San Jose, CA, to detect and classify defects in various GaN epilayers. An OSA verifies substrate quality prior to growth and assesses the

post-growth surface. This information has shown that substrate scratches tend to be smoothed out by the initial buffer epilayer, and are consequently less problematic than other types of defects, such as micropipes in SiC.

Disk-drive origins

The CS1 inspection tool used by Hitachi Cable is one of a family of OSA instruments produced by KLA-Tencor. The core technology was first developed for the magnetic hard-disk-drive industry and dates back to 1989 (Meeks 2000). The rapidly decreasing size of storage bits on disk substrates drove the need to reduce the occurrence of smaller and smaller substrate defects, in a manner analogous to the silicon IC industry. Candela Instruments, which was acquired by KLA-Tencor in late 2004, was founded to develop the CS1 automated tool.

The instrument had to be capable of inspecting transparent materials, because the disk industry had moved from using metal to glass substrates, which have higher bit densities and greater reliability owing to their stiffer, smoother nature. The tool's capabilities can also be applied to other transparent materials commonly used in the III-V industry, such as sapphire, silicon carbide, lithium niobate and lithium tantalate.

The OSA illuminates a $4 \times 8 \mu\text{m}$ area of a sample surface with linearly polarized light from a 632 nm laser. It monitors reflections with a combination of detectors to measure specularly reflected intensity, phase shift, scattered light and surface topography (figure 4). The scattered-light detector is positioned directly above the measurement spot, and a separate assembly, containing the three other detectors, sits in the path of the reflected light.

Measuring signals from several different types of detector is important for defect classification, providing much more information than a conventional scatterometer. Different types of defect exhibit varying signal levels in the different channels, resulting in signatures that can be used to classify defects.

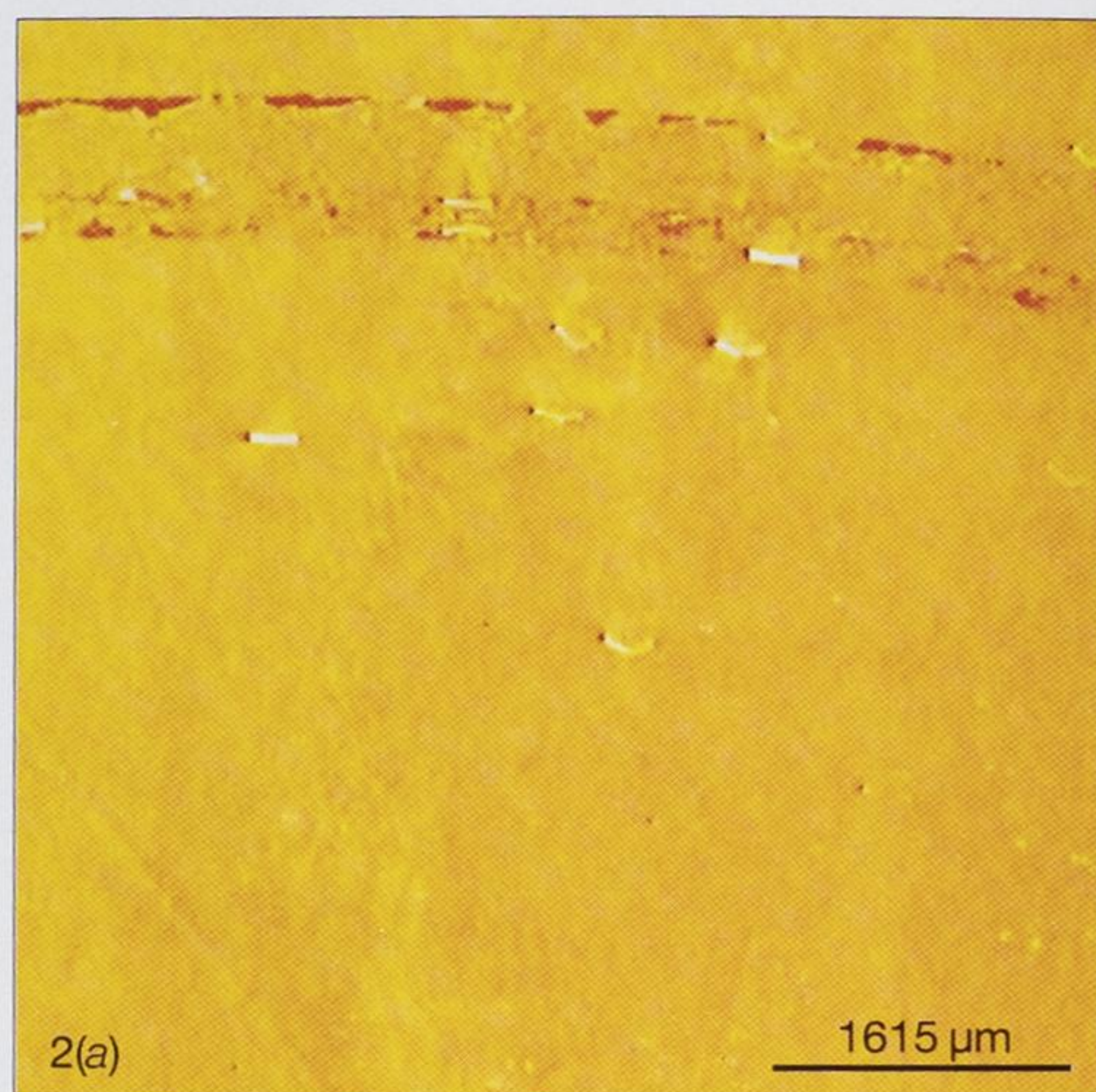
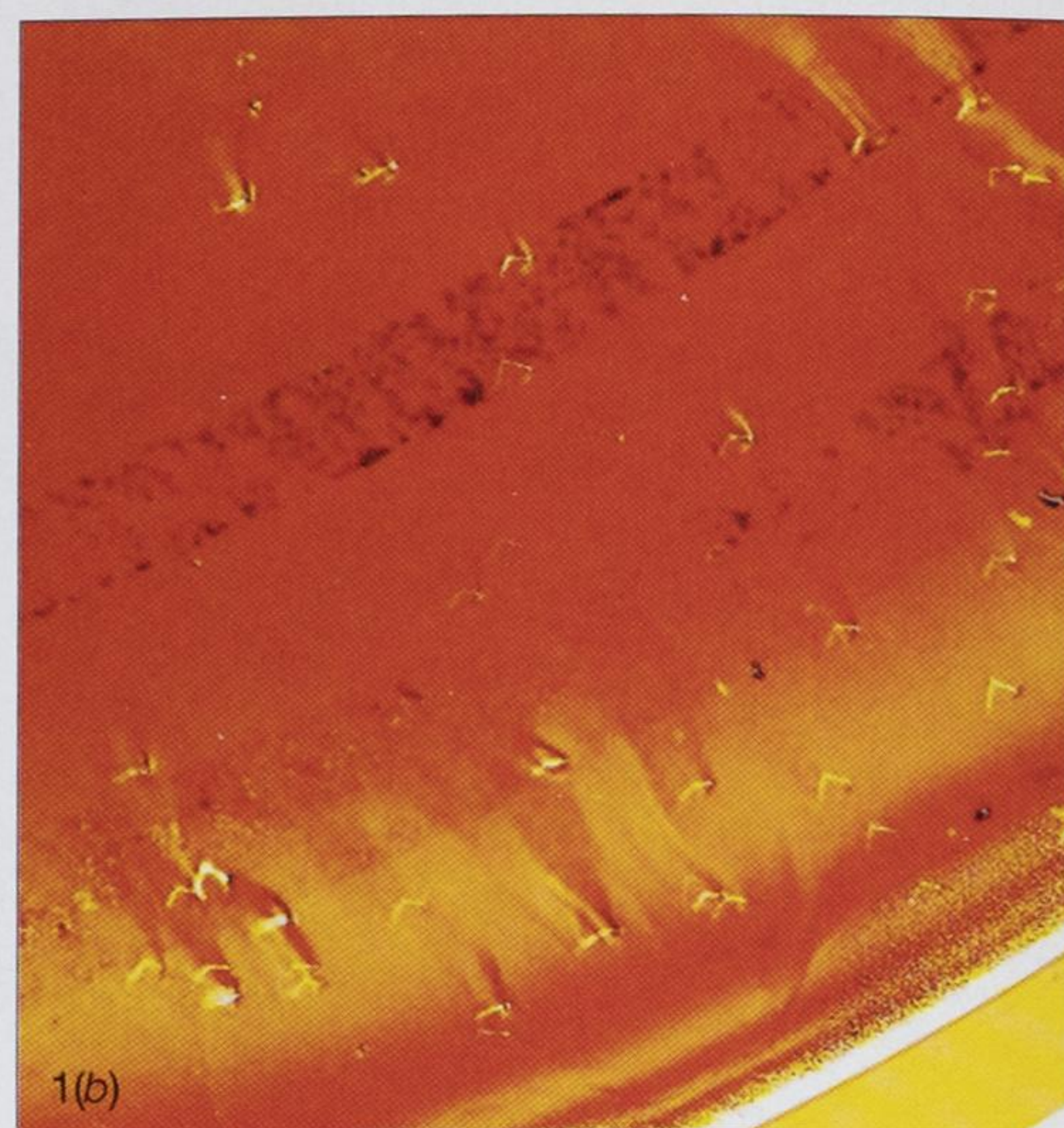
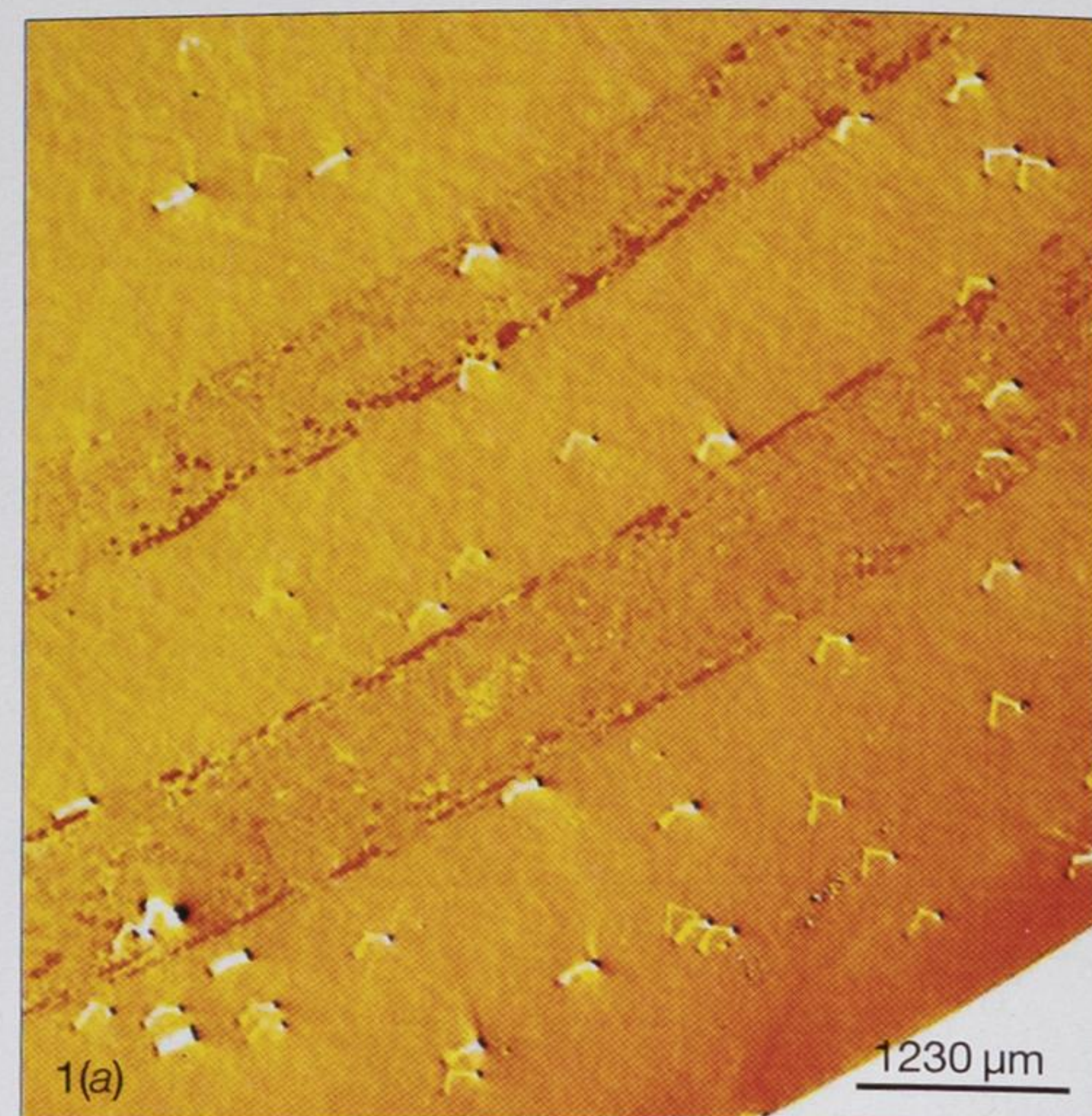


Fig. 1. The pre-growth images of the SiC wafer surface. The structure of the AIN buffer layer is visible. The surface rings are visible. Micropipes extend to the edge of the wafer. Also, linear defects are visible, which are located within the buffer layer. The defects are seen through the structure of the AIN buffer layer. The region shows possibly substrate interference caused by the growth of the epilayer.

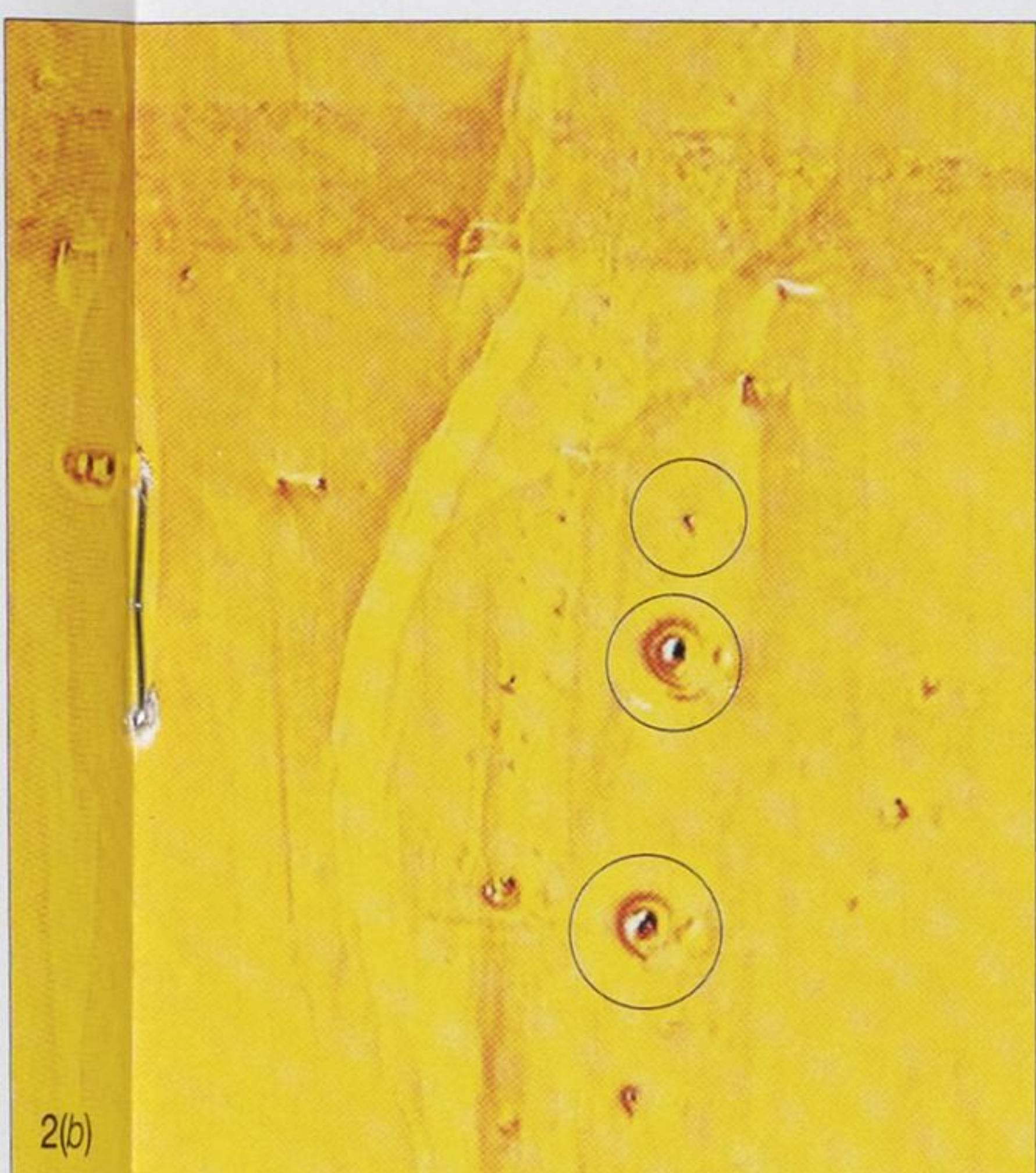


Fig. 2. Comparing the two SZc signal images of a SiC wafer surface, reveals that the defects circled in (b) were not present in the pre-growth image, and were, therefore, generated during growth.

on aids GaN HEMT morphology

Fig. 1. The two images on the left are (a) pre-growth and (b) post-growth SZc signal images of an Hitachi Cable GaN HEMT structure deposited on a SiC substrate. The structure, grown by MOCVD, consists of an AlN buffer layer, a GaN layer and an AlGaIn surface layer. Visible in both images are two rings resulting from a vacuum chuck.

Micropipes – open-core dislocations that extend through the depth of a wafer – can also be seen. In (a), micropipes appear as linear or V-shaped defects. On closer inspection, a dark spot (low signal level) – which is a surface pit – is visible at one end, located next to a bright line caused by reflection from the full length of the defect within the wafer. All of the micropipes seen in the bare substrate scan are still visible through the epitaxial layer (b), and many of the streaks in the post-growth layer scan are seen originating from these micropipe locations. These streaks are caused by changes in the physical properties of each of the epitaxial layers (either thickness or refractive index), and reveal disturbances in the growth process caused by micropipes. The region at the edge of the wafer also shows patches of high surface roughness, possibly indicating polytype defects in the substrate. Toward the bottom of (b), interference fringes can be seen that are caused by sudden changes in the thickness of the epitaxial layers near the wafer's edge.



of a SiC wafer (a) with and (b) without epitaxial are not present on the substrate prior to during growth of the epitaxial layer.

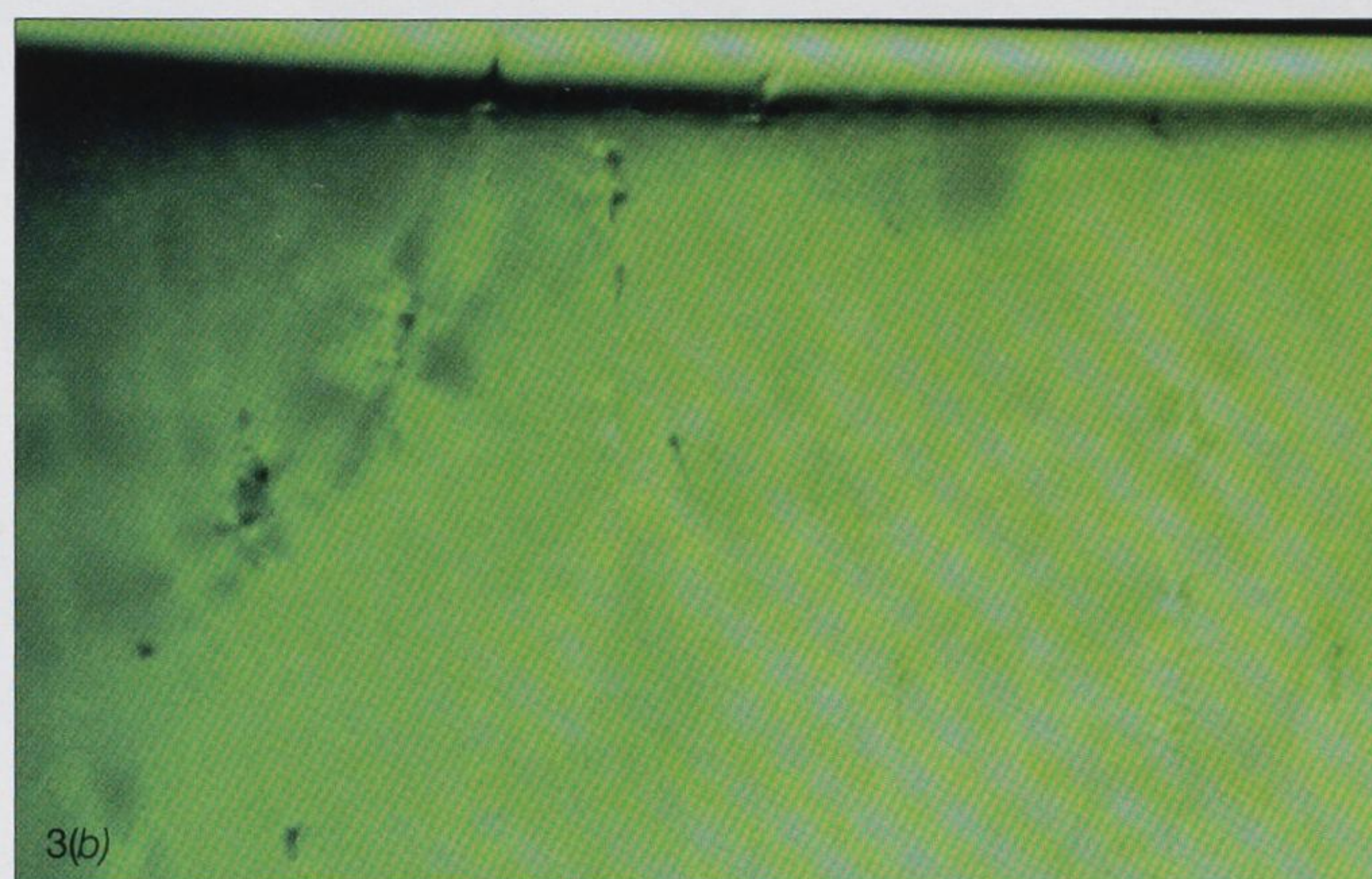


Fig. 3. The SZc image of the GaN HEMT structure (a) is clearer and more detailed than the corresponding microscope image (b).

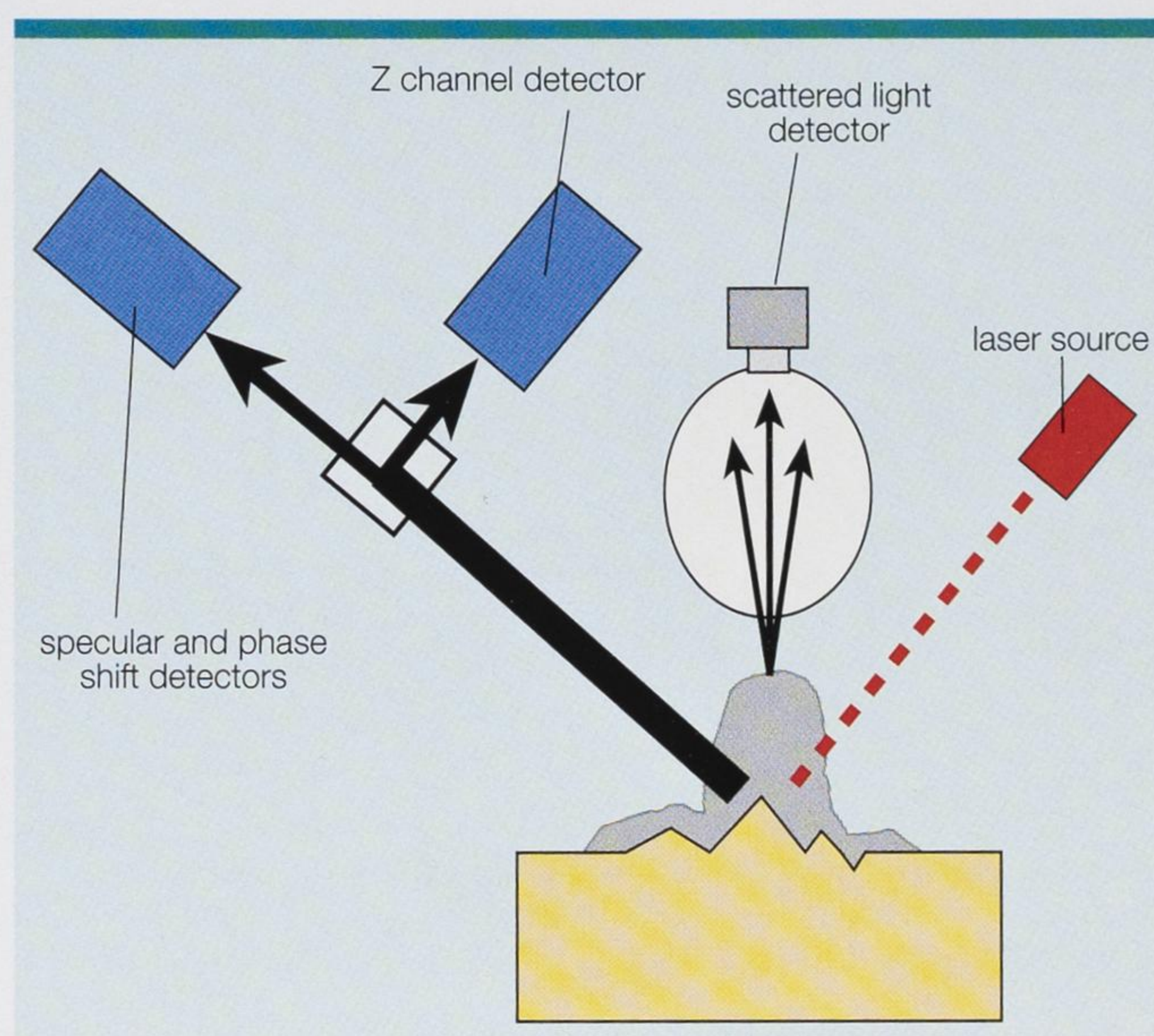


Fig. 4. The optical surface analyzer's four detectors record the specularly reflected intensity, phase shift, scattered light, and a signal that provides a measure of the surface topography.

A spatial filter, or aperture, is used to prevent the detection of laser light that is refracted through the wafer surface and then reflected off of the backside of the substrate before traveling toward the detector. These backside signals often prevent conventional scatterometers from measuring transparent wafers, but the Candela tools are suitable for transparent wafers as thin as 250 μm .

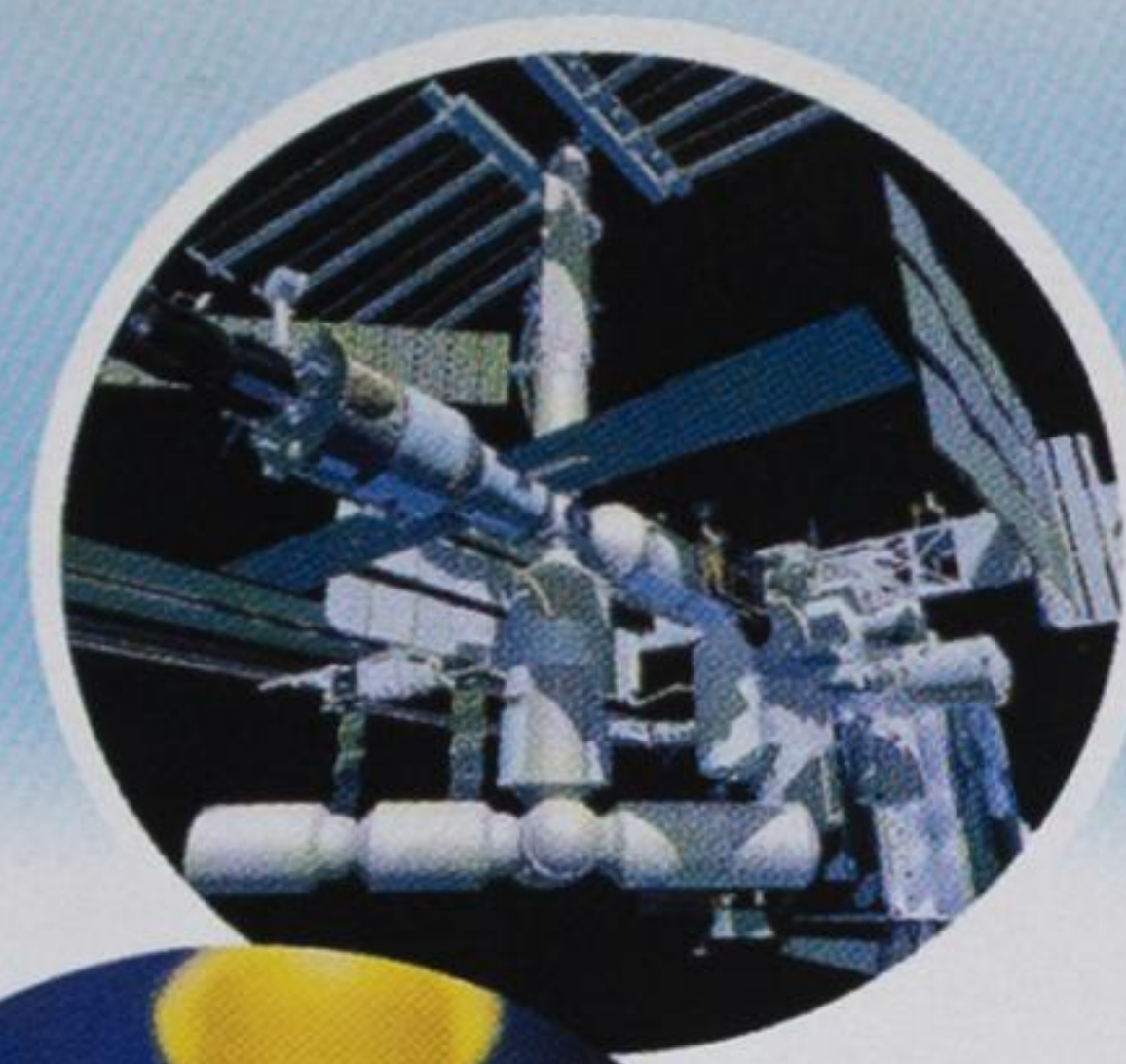
The entire wafer surface can be analyzed by rotating it while a measurement head moves from the wafer's outer edge to its center. Thousands of data points are measured in a typical scan, providing information about defect types, sizes and densities. By assigning brightness levels proportional to the amplitude of the detected signal, output from the various detectors can also be converted into images similar to those produced by a microscope.

Defect classification

Hitachi Cable has used an OSA to investigate the surface of a typical GaN HEMT containing an AlN buffer layer, a GaN layer and an $\text{Al}_{0.28}\text{Ga}_{0.72}\text{N}$ surface layer grown on a SiC substrate. Figure 1 shows two images of an area of a wafer, before and after epitaxial growth. The images were generated by detecting SZc, the magnitude of the deflection of the reflected light. The SZc response is well-suited to defect detection because of its sensitivity to variations in surface height and reflectivity.

An OSA can also determine the origin of defects generated during the epitaxial process, as demonstrated in figure 2. For example, films, residues and particles on the substrate can cause pitting at the original defect site (a particle defect may not even be present at the end of the process). Wafer yield is reduced if particles fall on the substrate during the growth process, resulting in pitting, and scratches on a substrate can lead to deformed epitaxial layers that follow the outline of the scratch.

Other types of defect, such as stains and surface particles, that do not disturb the epitaxial layers, can also be identified with an OSA. Stain defects are revealed by the reflected light signal, while surface particles can also be seen in the scattered-light channel. Figure 3 shows images of the GaN HEMT surface obtained from a microscope and the SZc signal from an OSA. Figure 5 reveals the alternative per-



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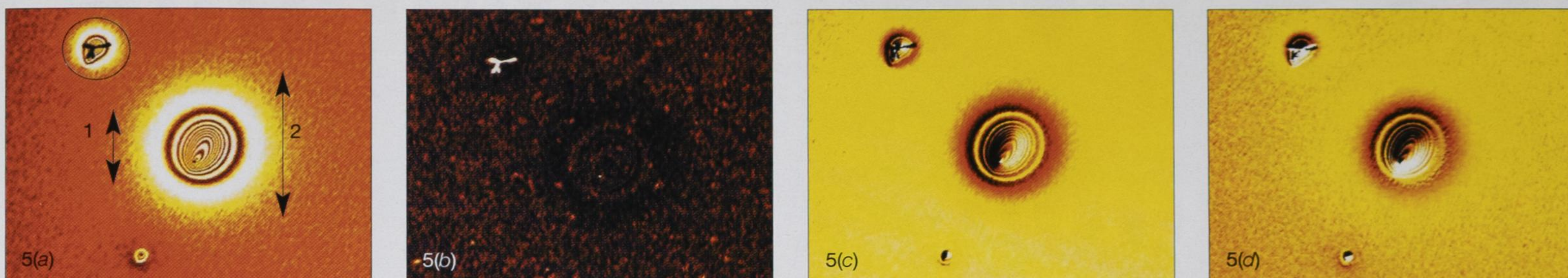


Fig. 5. The OSA enables defect identification by providing four complementary images: (a) specular reflectivity, (b) scattered light, (c) circumferential topography and (d) radial topography. The pit highlighted in (a) has a particle embedded within it, as revealed by the high (bright) scattering signal in (b). The large, central defect is roughly 650 μm in diameter (1); its specular intensity signal (a) is affected across a region approximately twice as wide (2), indicating variations in the epitaxial layer's thickness and optical properties.

spectives provided by each image-acquisition mode. Combining the information from the various images can distinguish between defects generated by particles and those formed by irregularities in the substrate.

Using an OSA to investigate the epiwafer quality of GaN HEMTs has enabled defects in the substrate, such as micropipes that cause many surface defects, to be distinguished from their epi-originating counterparts. This information, which is useful in driving improvements in the overall defect density, has led

to Hitachi Cable scanning all of its SiC substrates before growth to screen out low-quality wafers that are not suitable for production.

Although the work at Hitachi Cable has shown that OSA images are suitable for troubleshooting engineering processes, automated defect detection and classification is more valuable to a production environment. This latter function is also possible using an OSA, which can count and report defects in a standardized way, enabling comparison between wafers, runs and process tools.

Acknowledgments

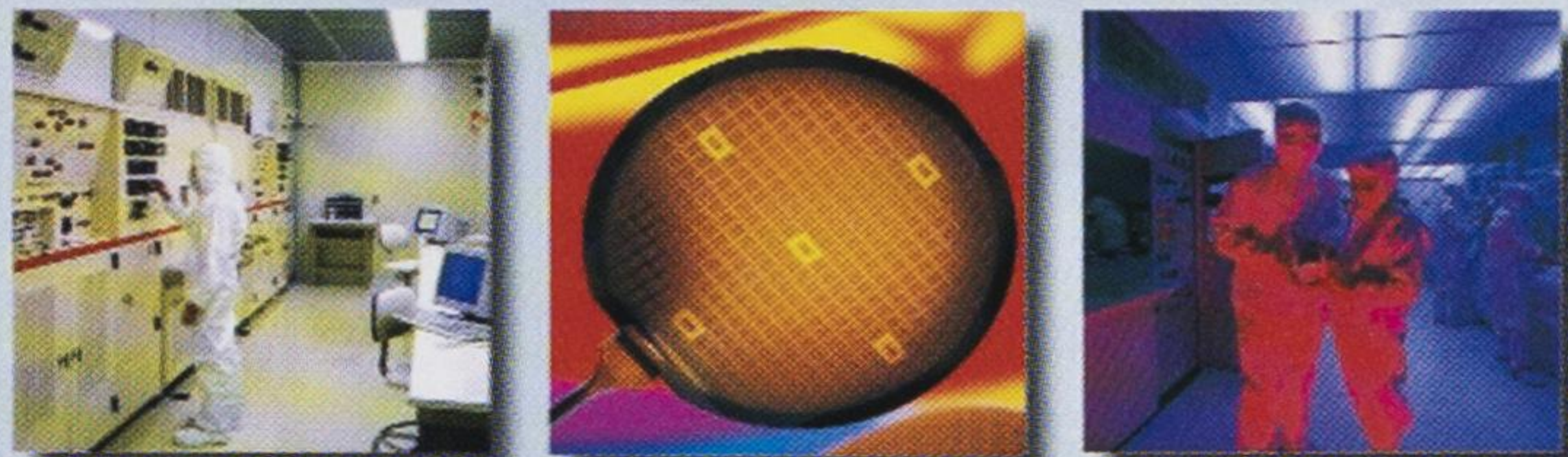
Laurie Bechtler would like to thank Steven Meeks, Vamsi Velidandla, Yohei Otoki, Takeshi Tanaka and Yoshiharu Koji.

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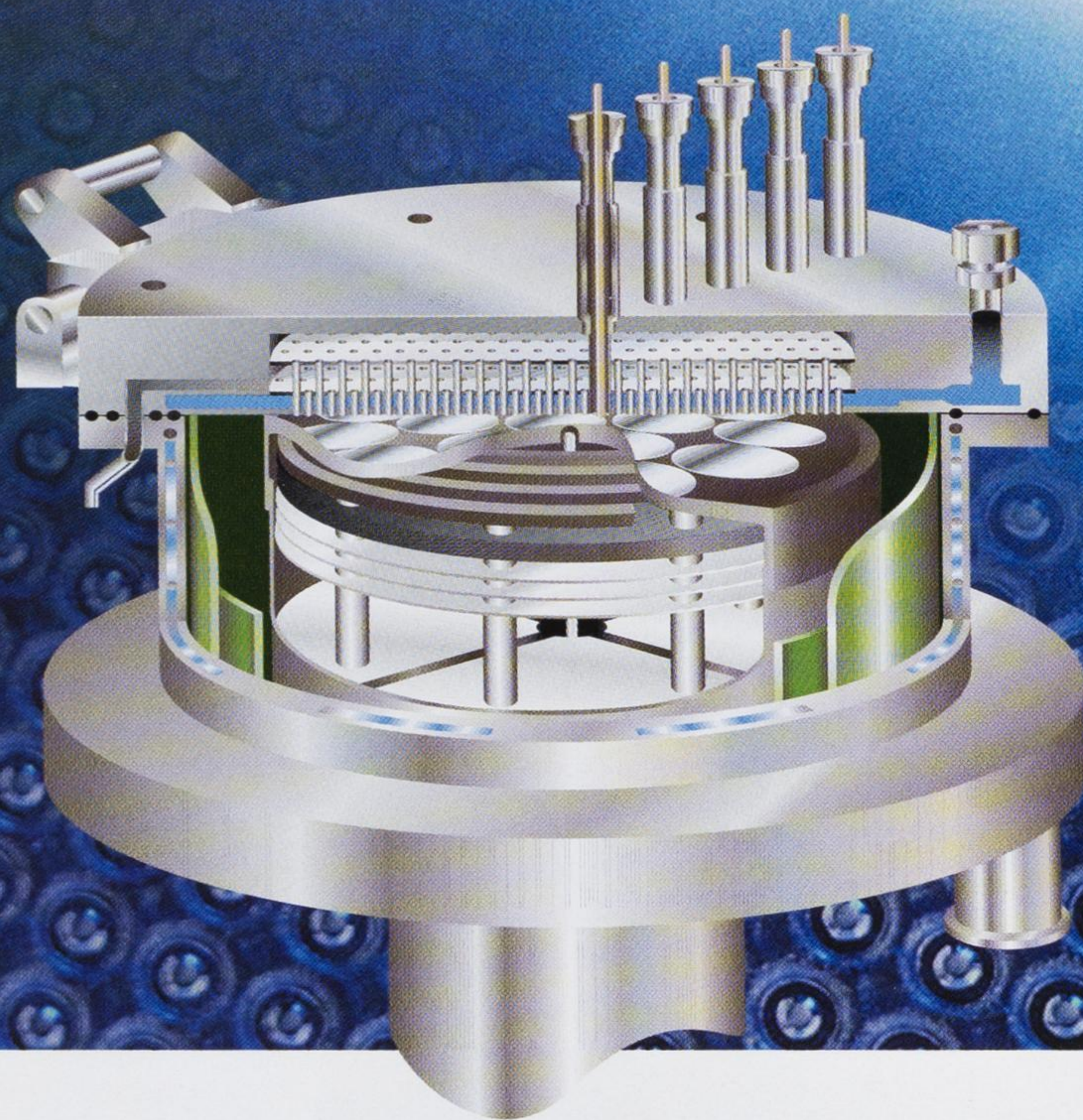
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Migration-enhanced MOCVD advances AlGaN performance

Reduced screw dislocation density and faster deposition than conventional MOCVD are just two of the benefits of so-called migration-enhanced MOCVD. The technique shows impressive results when it comes to AlGaN device fabrication, producing relatively efficient deep-ultraviolet LEDs and improved transistor performance, reports Sensor Electronic Technology's **Remis Gaska**.

While both MBE and MOCVD have proved successful film-growth mechanisms for a variety of compound semiconductor technologies, the two techniques do have a number of drawbacks.

In particular, these mainstay film-growth methods of the industry are not exactly ideal for nitride deposition, an application area that will inevitably become an increasingly important part of the III-V business.

Now, a related technique known as migration-enhanced (ME) MOCVD promises to solve some of the problems encountered with MBE and MOCVD, especially for making devices that have a high aluminum content, including AlGaN HEMTs and UV-LEDs.

The key difference between ME-MOCVD and conventional film growth is the way in which gases are introduced into the reaction chamber, which results in fewer collisions between metalorganic and ammonia gas molecules. The upshot is faster growth speeds and a lower density of screw dislocations, which are detrimental to device performance.

Transport mechanisms

When used for III-nitride manufacture, MBE and MOCVD differ substantially in regard to the source materials used, and fundamentally in terms of their source-material transport mechanisms. These different mechanisms can be described by the so-called Knudsen parameter (K_n), which is the mean free path of the gas to reactor dimensions ratio.

The mean free path of a gas is the average distance traveled by a molecule or atom before it collides with another. For MBE, K_n is usually close to, and sometimes greater than, unity, meaning that source molecules can reach the reaction surface without experiencing any collisions. This is possible because a low reactor pressure is maintained during MBE.

On the other hand, K_n for CVD is typically in the 10^{-2} to 10^{-3} range (for low-pressure CVD) or 10^{-5} to 10^{-6} (for atmospheric-pres-

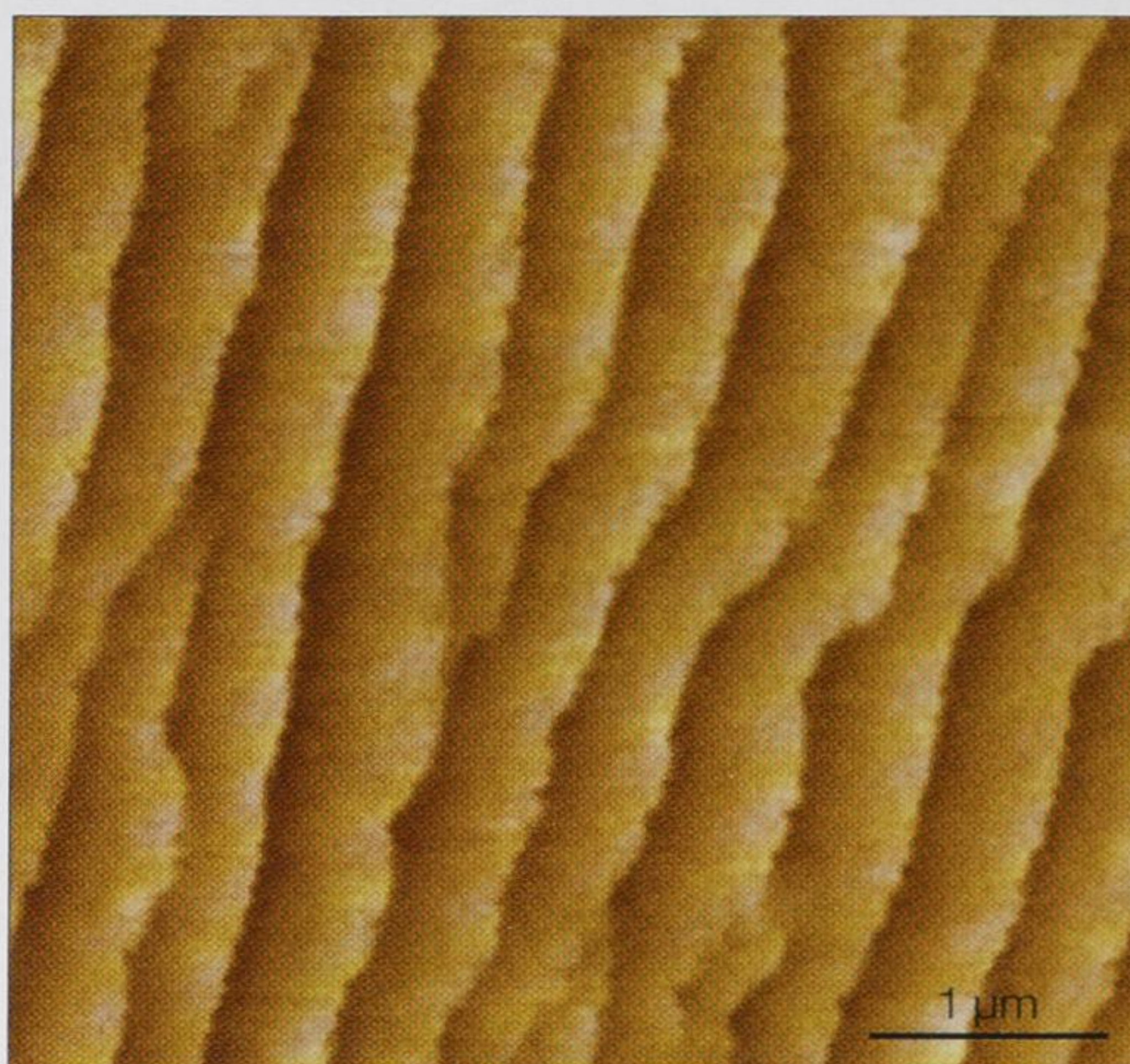


Fig. 1. The high-quality ME-MOCVD-grown AlN layer (0001) on a sapphire substrate has a surface roughness of only 0.6 nm (RMS).

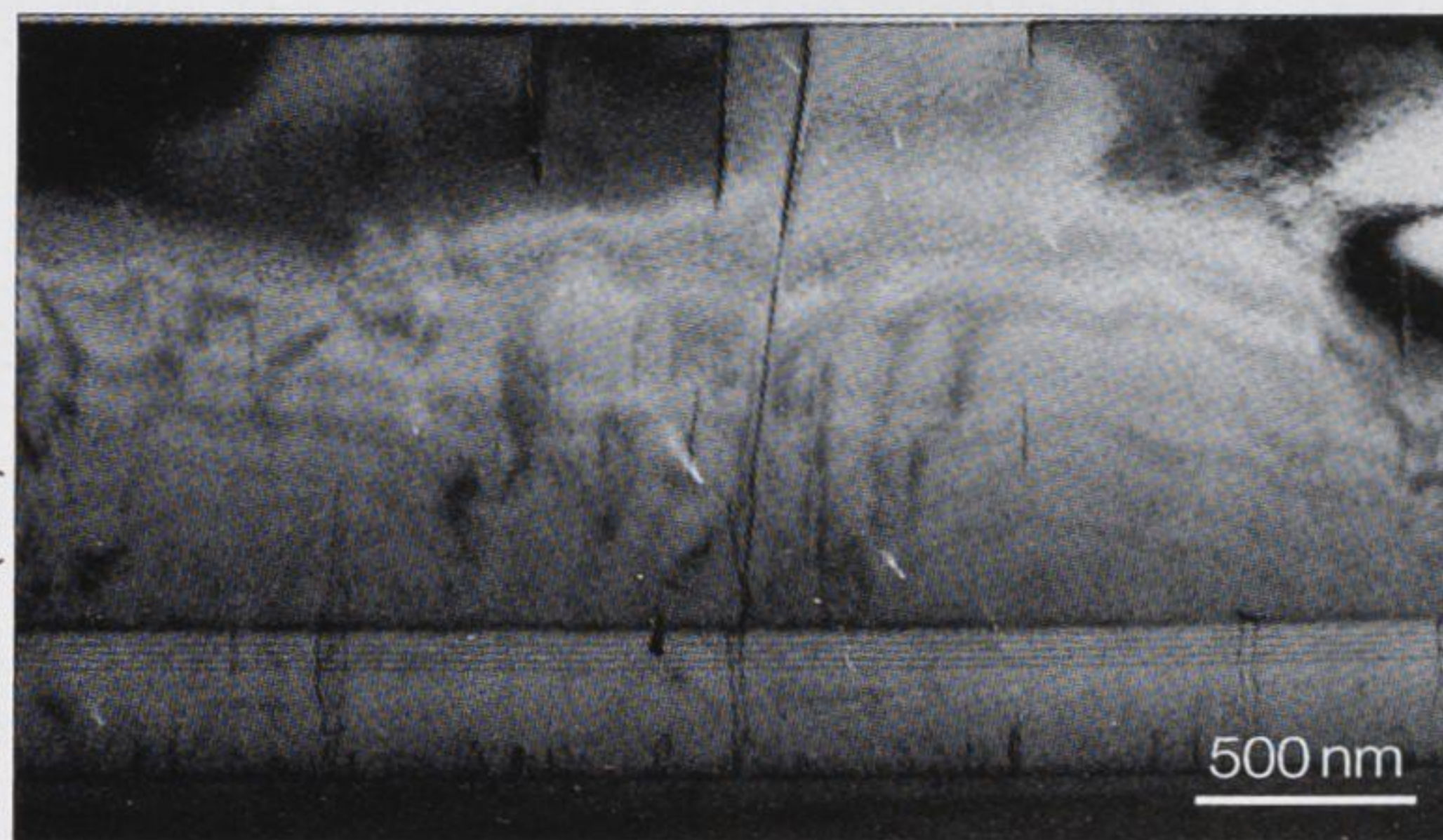


Fig. 2. A TEM section of ME-MOCVD-grown *n*-AlGaIn, AlN/AlGaIn superlattice and AlN.

sure CVD). This means that a large number of collisions will take place before a molecule reaches the reaction surface. As a result, CVD material transport is actually governed by fluid mechanics. Important effects include: bulk transport toward the reaction surface by diffusion; diffusion through a stagnant boundary layer that is formed above the reaction surface; and surface diffusion and incorporation/decomposition.

So, depending on the conditions used, film growth is limited either by gas-phase transport or surface-reaction kinetics. Optimized nitride growth with MOCVD is limited by

gas-phase transport, except for the low-temperature deposition of the nucleation layer. In this region the growth rate and layer composition can be controlled by adjusting the flow of source material at the inlet.

The stagnant boundary layer plays an important role in the transport process. Its thickness directly affects the source materials' composition gradient in the stagnant layer, which in turn determines the diffusion fluxes of incorporation and decomposition. In short, the stagnant boundary layer can effectively alter film growth and decomposition rates. Being able to play with the dimensions of the stagnant boundary layer allows more growth control in MOCVD than in MBE.

Problems with MOCVD

The small K_n associated with nitride growth by MOCVD can interrupt the epitaxial process because of the increased propensity for gas-phase reactions. The metalorganic source materials, especially the widely used trimethylaluminum (TMA), readily react with ammonia molecules when collisions between the two take place.

These reactions produce small particles that may fall onto the reaction surface and then act as new, unwanted nucleation centers that terminate epitaxial growth. The result is surface roughening and extended defect generation. During AlGaIn growth by MOCVD, the gas-phase reactions clearly manifest themselves, causing "V" defects on the surface.

These reactions also limit the nitride growth rate possible with MOCVD because increasing the influx of source materials will result in more surface defects. Another problem is that the strong aluminum-nitrogen bond allows only a very short surface-diffusion length. This greatly reduces the ability of aluminum and gallium adatoms to incorporate into energy-favorable sites, which leads to random growth of 3D islands and deterioration of epilayer quality. →

The thinking behind ME-MOCVD is to separate ammonia and metalorganic molecules, which ought to reduce the likelihood of gas-phase reactions and enhance adatom surface migration. At Sensor Electronic Technology (SET), we can optimize source waveforms and overlaps to refine material quality. And unlike other flow-modulation growth techniques, ME-MOCVD allows the freedom to work with the stagnant boundary layer.

As mentioned earlier, the stagnant boundary layer has a significant effect on material incorporation and decomposition. The layer thickness depends on the flow of gas into the reaction chamber and is proportional to the square root of the kinetic viscosity of the gas divided by its velocity. During ME-MOCVD AlGaIn growth, ammonia has the greatest modulated flow. So, AlGaIn growth with ME-MOCVD presents two options.

The first is to switch off the flow of ammonia and simultaneously switch on a compensation gas, for example nitrogen or argon. The kinetic viscosity and velocity of the gas can be changed to produce a consistent boundary-layer thickness, or to make the layer thinner. If the layer is made thinner, metalorganics can diffuse through the boundary layer to reach the growth surface more quickly, maintaining a fast growth rate and greatly enhancing surface migration. However, because the V/III ratio is vanishing and the stagnant boundary layer is therefore becoming thinner, decomposition is also enhanced. As a result, point defects – mainly nitrogen vacancies – become more likely.

The second option is to switch off the ammonia flow without introducing any compensation gas. This means that the main chamber flow quickly becomes dominated by hydrogen, which has a much larger kinetic viscosity than the hydrogen/ammonia mixture used in MOCVD and thus reduces the gas velocity. This approach creates a thicker stagnant boundary layer, which can still enhance surface migration (because of the vanishing V/III ratio), but at a lower decomposition rate.

Benefits for AlN and AlGaIn

We have found ME-MOCVD to be efficient in improving AlN and AlGaIn material quality. Under optimum growth conditions a step-flow mode was used to grow AlN on vicinal (0001) sapphire substrates (figure 1), which enhanced aluminum–adatom surface migration.

The growth rate for AlN with ME-MOCVD was three times as fast as that seen with conventional MOCVD under the same flow of

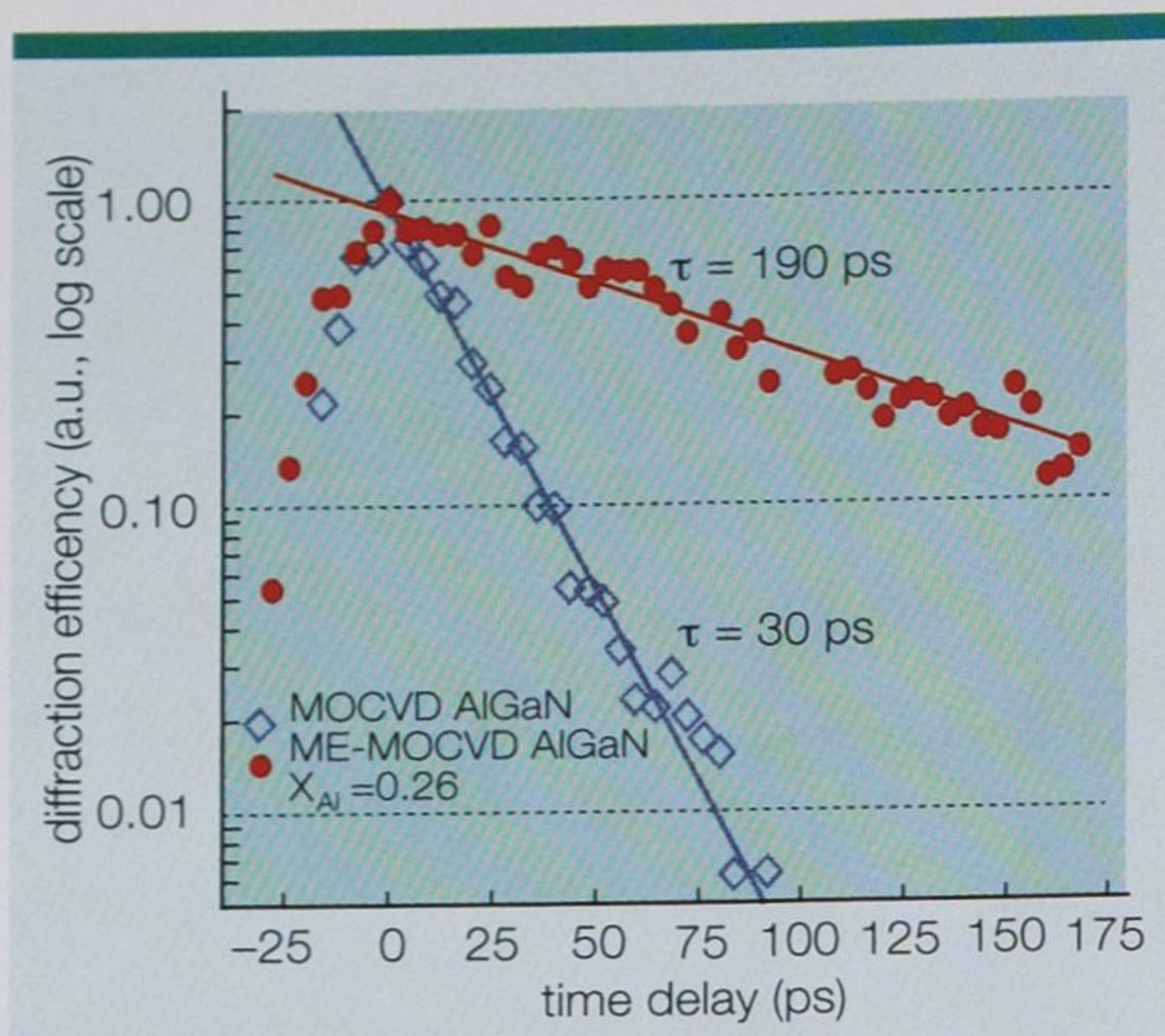


Fig. 3. The 190 ps minority carrier lifetime of ME-MOCVD-grown n-AlGaIn indicates better electro-optical conversion efficiency.

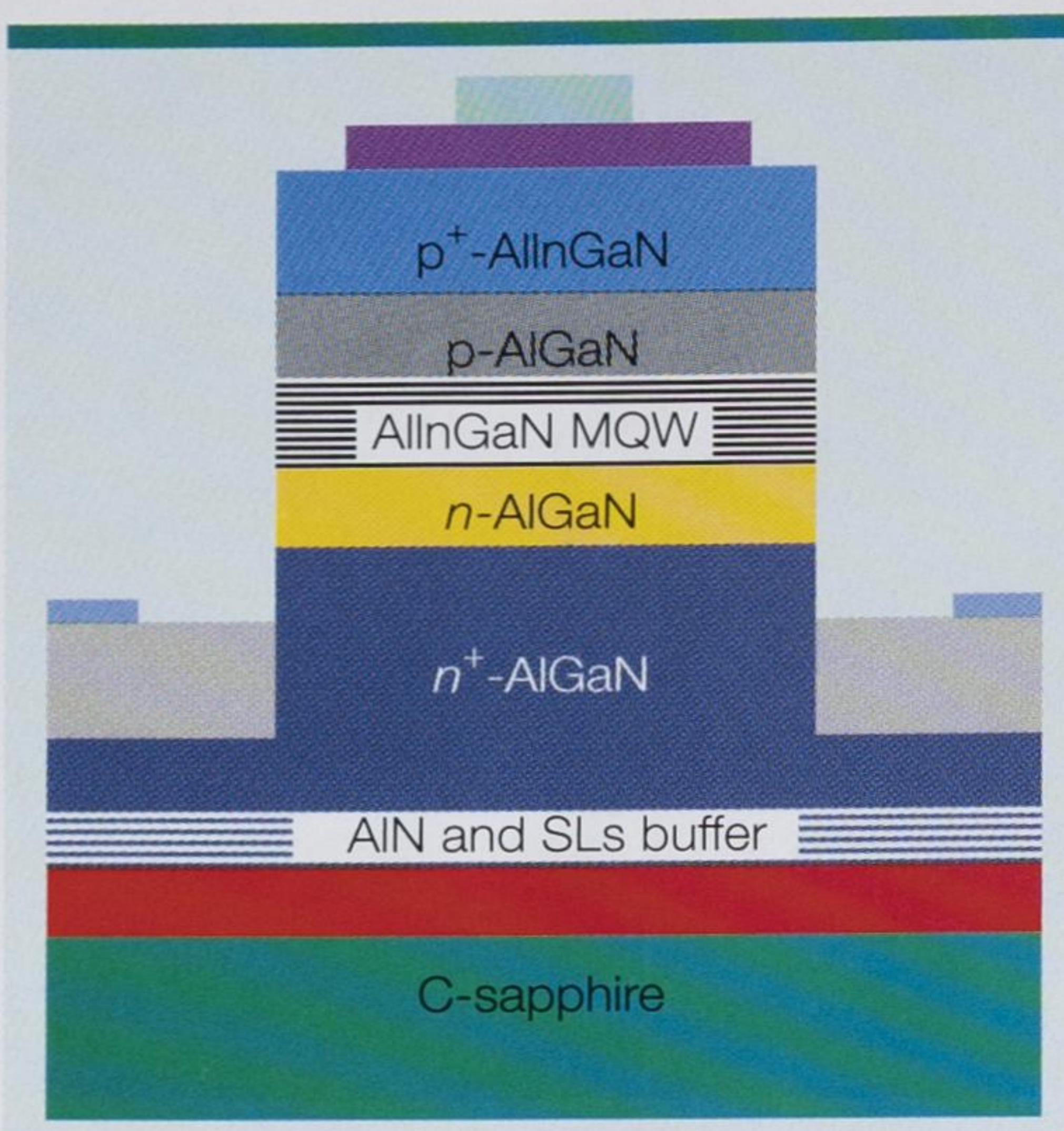


Fig. 4. Sensor Electronic Technology developed this structure for deep-UV-LEDs in close collaboration with Asif Khan at the University of South Carolina.

TMA. Comprehensive characterizations also revealed a superior material quality and, in particular, demonstrated a reduction in the density of screw dislocations.

Figure 2 shows a TEM micrograph of SET's patent-pending UV-LED buffer structure, which consists of an ME-MOCVD-grown AlN and AlN/AlGaIn superlattice, and a thick layer of silicon-doped AlGaIn. The screw dislocation density in the structure, starting from the thin AlN layer, is only $3 \times 10^8 \text{ cm}^{-2}$. This is about one-hundredth the screw dislocation density of conventional MOCVD-grown, thin AlN.

So, as well as faster deposition, AlGaIn layers grown by ME-MOCVD clearly have better structural quality. Among other evidence that we have obtained through different characterization techniques, the minority carrier

lifetime data is of great importance, since this is directly related to the light-emission efficiency of the device. Figure 3 shows a comparison between the lifetime measurement data obtained through ME-MOCVD- and MOCVD-grown AlGaIn layers with an identical aluminum fraction and thickness.

The lifetime of AlGaIn grown by ME-MOCVD is about six times as long as that produced by MOCVD (190 ps versus 30 ps), indicating a far lower incidence of non-radiative-decay processes and consequently higher light-output efficiency. At SET, we first developed ME-MOCVD for a single 2 inch wafer chamber. More recently, we have successfully scaled this technology to a multiple-wafer reactor (3×2 inch) set-up.

AlGaIn device development

SET is actively working on III-nitride technology for two types of device, namely deep-UV-LEDs (figure 4) and HEMTs. Although these devices require different substrates, ME-MOCVD benefits both in the sense that it builds a much higher quality buffer on which the device structures reside.

The high-quality AlN and AlN/AlGaIn superlattices enhance the n-AlGaIn mosaic block dimensions (a larger mosaic size equates to a better epilayer quality), which directly reduces tensile strain between AlGaIn blocks and alleviates cracking in thick, conducting AlGaIn layers. This development has resulted in increased power output from deep-UV-LEDs, which have an emission peak at around 280 nm at a drive current of 20 mA. SET began shipping these LEDs in August 2004. The current devices have a continuous-wave power exceeding 1 mW at 20 mA. Our plan is to produce deep-UV-LEDs with a wall-plug-efficiency of more than 2% in the next two years.

On the microelectronics side, we used ME-MOCVD instead of MOCVD to fabricate the AlN transition layer between a semi-insulating 4H-SiC substrate and GaN. The AlGaIn cap layer has also been grown by ME-MOCVD. Using the new technique greatly improved HEMT wafer quality and device performance. For example, the transistors showed reduced drain-current collapse and increased gate-drain breakdown voltage. SET is now capable of supplying 2, 3 and 4 inch GaN HEMT wafers, and the multiple-wafer ME-MOCVD chamber has greatly enhanced our wafer-production capacity.

Remis Gaska is CEO of Sensor Electronic Technology. E-mail gaska@s-et.com.

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Oil-free Korea prioritizes solid-state lighting project

With no domestic oil supply, the Korean government is very keen on LED technology and is pouring hundreds of millions of dollars into "LED Valley". **Richard Stevenson** reports.



The Korean and Chinese governments see LED-based lighting as a key part of their strategies to tackle rapidly rising energy consumption and the reliance on oil. Much of Korea's photonics innovation takes place at the KOPTI site (left) in Gwangju. An LED lighting system from TIR Systems (right) lights up the 52 m (170 ft) high Full Moon Tower at Galaxy Park – a leisure complex in Tianjin, China.

Energy savings and the environment are the key driving forces behind Korea's semiconductor-lighting national program, explained Young Moon Yu, as he addressed delegates at the recent Strategies in Light conference. Yu, who is the director of the LED research and business development division at the Korea Photonics Technology Institute (KOPTI), and the organizer of the national LED and semiconductor lighting program, explained: "The Korean government has a strong interest in energy savings, because we don't have any crude oil."

In 2002 Korea consumed 278 TWh of electricity at a cost of \$20 billion. More than 20% of this energy was used for lighting. According to Yu, if LEDs achieved complete penetration of the lighting market they would reduce the national power demand by the output equivalent of three nuclear power stations.

"The Korean government wants to [adhere to] environmental pollution agreements," added Yu, who points out that reducing Korea's energy requirements would help to

decrease carbon dioxide emissions and allow the country to meet targets set by the Kyoto Protocol. Yu also notes that an increased dependence on LED-based lighting would reduce the use of glass, phosphors and heavy metals, and would help adherence to new environmental regulations coming into force on July 1, 2006.

Three-stage development

Korea's LED industry has evolved in three stages. Early research and development was undertaken by LG and Samsung, the two domestic companies that continue to dominate Korea's consumer electronics industry and LED efforts, along with several universities and a program organized by the Korea Research Institute for Standards and Science that ran from 1993 to 1996. A business phase followed between 1999 and 2000, with several firms funded through venture capital and initial production runs at LG and Samsung.

The current activation phase, which began in 2001, has seen the number of companies

involved in the LED industry rise to more than 340. This has provided Korea with a research and development manpower of about 1000 for the III-nitride industry alone. Key research topics now include high-efficiency and high-reliability devices, UV-LEDs, GaN on silicon and other non-sapphire substrates, ZnO LEDs, high-power packaging and modules, and phosphors for blue LEDs.

KOPTI is central to much of the current development. The government-backed organization is located in Gwangju, in south-west Korea, and is devoted to the development of the photonics industry. Its roles are to help commercialize basic and applied photonics technologies, to build an advanced technology infrastructure and to implement a comprehensive industrial support system.

Housed in a 35,640 m² building that includes a 1789 m² cleanroom, KOPTI owns 384 pieces of equipment that have a combined value of \$65 million, and has access to funding of \$20 million each year. It employs 70 PhD-educated staff, a number that will rise to

Update on China's five-year plan and LEDs

By Tim Whitaker

Ling Wu, director of the China Solid-State Lighting Program office, told delegates at Strategies in Light that China could save 100 billion kWh annually by 2015, provided that LED efficacy reaches 150 lm/W and the technology penetrates 40% of China's incandescent lighting market. Such savings would be more than the output of the massive Three Gorges hydroelectric project, she says (see *Compound Semiconductor* December 2004 p25).

The China National Solid-State Lighting Program kicked off in June 2004 when the Ministry of Science and Technology pulled together the activities of a number of different regional development groups. The program has already received RMB 140 million (\$17 million) from central government, with 15 research institutions and more than 50 enterprises now involved.

Comprehensive strategy research, industry-standard preparation and intellectual-property (IP) research programs have already been initiated through the effort, and a major investment in solid-state lighting is expected when China's 11th five-year plan is unveiled in July.

In October 2004, a group called the China R&D and Industry Alliance for Solid-State Lighting was formed with the aim of making China's LED industry more competitive. The

alliance will develop mechanisms to share resources such as technology and IP, while encouraging regional collaboration and international co-operation.

According to Wu, China is making progress with its LED chips, with domestic companies supplying 12 mm blue chips at 6–8 mW (20 mA) and power chips at 120 mW (350 mA). Packaging companies are able to supply white LEDs rated at 20–25 lm/W when using domestic blue chips, and 30–35 lm/W using higher brightness imported chips – which gives a good indication of the status of China's LED industry relative to the rest of the world.

Of course, China is a newcomer: as recently as 2002, the country's LED packaging industry imported all of its blue chips. Since then, the domestic chip industry has ramped to supply 5% of the demand in 2003. That figure grew to 20% in 2004, with Chinese companies also supplying GaN-based epiwafers. The target for 2005 has been set at 40%.

China's LED industry had sales of RMB 12 billion in 2004, up from RMB 10 billion in 2003. Wu estimates that more than 600 Chinese enterprises, with more than 40,000 employees in total, are now directly related to the LED industry.

Tim Whitaker is editor of LEDs Magazine.

150 in 2008. Its facilities cover all aspects of LED production, from InP, GaAs and GaN epitaxial growth on 2 to 4 inch substrates, through materials characterization and various processing stages, to packaging and performance and reliability testing. The national government meets 73.1% of KOPTI's costs, with Gwangju city (16.5%) and industry (10.4%) making up the remainder.

Korea's LED infrastructure is now benefiting from the launch of a national program for the display industry, in which Samsung and LG are big players internationally. This program covers development of LCDs, electronic paper and organic electroluminescence, and runs from 2004 to 2008. In Gwangju, which is also known as the "city of light", a mixture of national and local government and private-sector investment has been funding LED development since 2000.

Through the so-called LED Valley project, the region will also receive \$100 million

between 2005 and 2008 toward high-brightness (HB) LED development. This initiative will involve the construction of 310,000 m² of building space, while a solid-state lighting and display center with research and development support will also be established.

Gwangju is also set to receive a further \$430 million over the next four years, which will be split between the second phase of a photonics industry project investigating HB-LEDs and a venture to deploy fiber-to-the-home networks to 20,000 households.

With all this funding in place, Yu predicts that the larger companies will first look to penetrate television-backlighting application markets in 2006, before re-focusing efforts on external car lighting in 2008. Domestic lighting applications are expected to follow at the end of the decade. The smaller companies will concentrate on municipal lighting applications, such as the illumination of bridges, roadsides and other public spaces.

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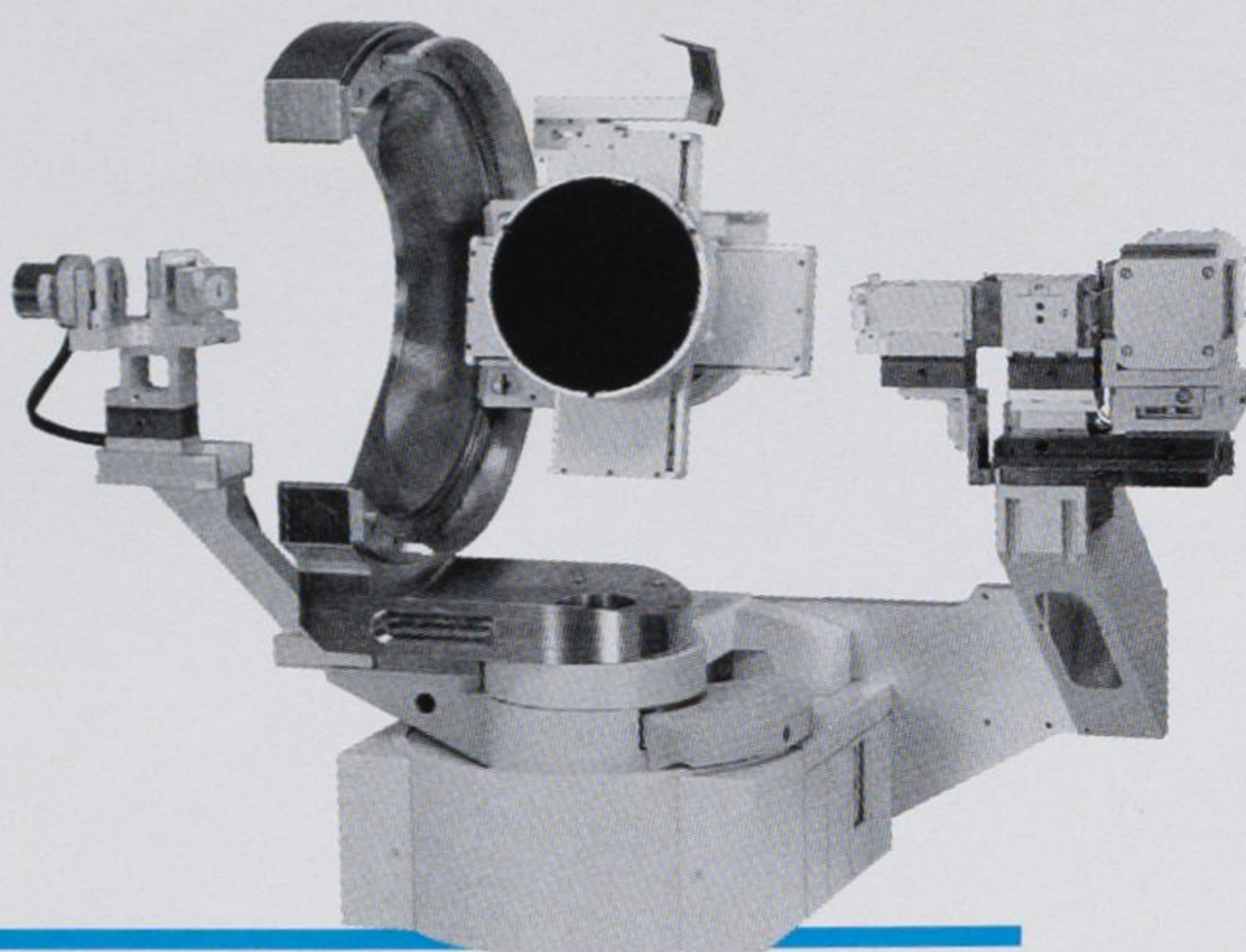
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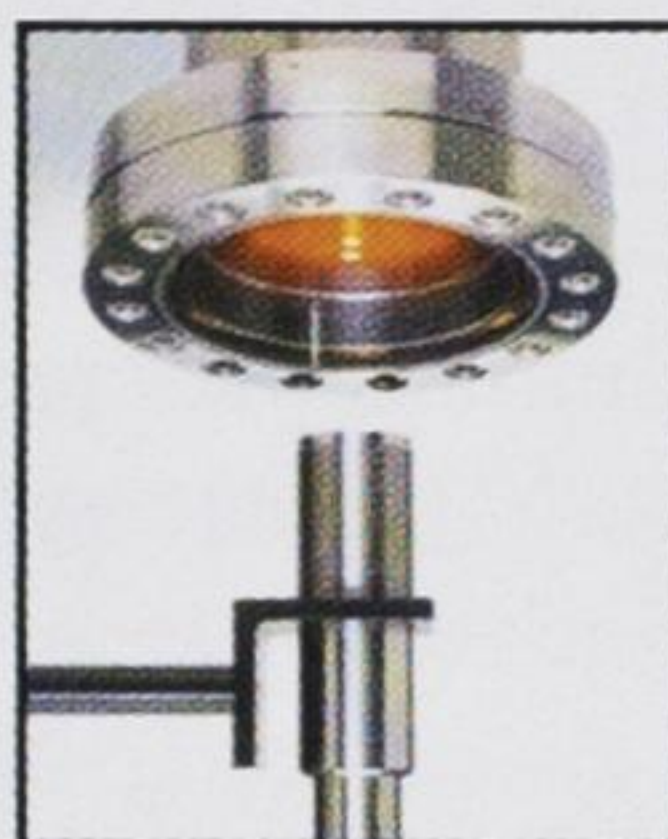
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Automotive LED take-up hinges on cost reduction

Today, automobile manufacturers are wooing customers with cars that are safer, more environmentally friendly, better designed and more fuel efficient than ever. These new models must also conform to the latest legislation, resulting in the implementation of new technology. In the US, for example, by 2007 all new registered cars will be fitted with a tire-pressure monitoring system. Fulfilling the separate demands from consumers and governments will require greater optical content within the automobile.

The LED is one of the optical components that will be increasingly used in cars, providing improvements to safety and design. While significant market penetration has already been seen through automobile internal lighting with standard LEDs (table 1), their high-brightness counterparts will benefit from the next big market opportunity: external rear- and front-lighting systems, such as headlights, low beams, turning lights, sidelights and daytime lamps. This area is a fashionable research topic, with emphasis directed toward decreasing price and increasing performance.

Pluses and minuses

The low power consumption and long lifetime of LEDs are attractive features for automobile designers. For example, the typical LED lifetime of 10,000 hours greatly exceeds the 3000 hours stipulated for low-beam lighting. The spectral quality of white LEDs, with an associated color-rendering index of 85, combined with their small size – which creates more flexibility for designers – offers further advantages. And LEDs, which have a 250 ms faster lighting-up time than conventional bulbs, can also prevent some car accidents: the stopping distance of a vehicle traveling at 100 km/h following a car fitted with LED-based brake lights is reduced by 7 m.

However, today's LEDs still have a number of drawbacks. Most crucially, they don't deliver enough lumens per watt for external lighting, while the high cost of white and blue high-brightness (HB) LEDs prohibits significant market penetration. Also, the operating temperature of LEDs is restricted to below

100 °C, which is too low for automobiles and well below the 200 °C figure of conventional bulbs. The performances and prices of commercially available HB-LEDs and the cost requirements that must be met to enable greater diffusion into the automobile market are summarized in table 2.



Osram Opto Semiconductor's "ThinGaN" HB-LEDs, which boast an efficiency of 50 lm/W, were chosen by Ford to provide the lighting source for the headlamps of the Shelby GR-1 concept car. According to the automotive industry, we will see the transition of HB-LEDs from concept cars to production vehicles in 2007, although the Optoelectronics Industry Development Association believes that the change will not occur until 2010.

According to the Optoelectronics Industry Development Association, it will be 2010 before the cost-to-performance ratio falls to the 10 \$/klm (or 100 lm/\$) level that is required by car manufacturers. The car industry's take is more optimistic, with HB-LEDs expected to feature in high-end cars in 2007. The industry claims that headlamps will require between 15 and 50 LEDs to achieve the necessary functions. The lamps must comply with legislation dictating that low beams and high beams, which vary only in light-intensity distribution, must deliver between 350 and 1000 lm.

Industry regulations present another difficulty: currently only the US permits LED usage for front lighting. However, Japan and Europe should follow suit, with Europe

expected to allow LED-based low-beam lighting in 2007. Audi has pioneered the use of LED technology and last year it launched a new version of the Audi A8 that was fitted with front lights containing five Luxeon LEDs generating a total output of 350 lm – powerful enough for daytime running lights, but insufficient for low- and high-beam applications.

The HB-LED market for automotive external lighting is in its infancy, but we expect that it will expand at a compound annual growth rate (CAGR) of 72% over the next four years (figure 1). By 2009 the white HB-LED market will be worth \$90 million, with Lumileds, Osram, Nichia, Toyoda Gosei and Cree competing for market share. By comparison, the market for internal automobile LED lighting, valued at \$350 million in 2003, will increase with a CAGR of only 5% through 2009.

LEDs are also suitable for rear-lighting applications, such as center high-mounted stop lamps (CHMSLs) and LED-based rear combination lamps (LED-RCLs) incorporating tail, stop, indicator and reverse functions. →

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Table 1. LED categories

Conventional nitride LEDs	HB-LEDs	White UltraHB-LEDs
350 × 350 µm die	up to 2 × 2 mm die	up to 5 × 5 mm die
30 mA, 3.5 V supply	350 mA, 3.5 V supply	> 50 A/cm
< 200 mW power	up to 1 W power	up to 5 W power
external quantum efficiency about 20%	external quantum efficiency > 30%	external quantum efficiency > 30%
20 lm/W	> 30 lm/W	> 50 lm/W
1–3 lm generated	5–30 lm generated	> 1000 lm generated
typical epoxy housing	specific packaging	color-rendering index of 85 specific packaging

Although car manufacturers use conventional nitride LEDs for interior applications, brighter HB-LEDs are required for applications such as headlights, turning lights and sidelights.

Table 2. LED cost per lumen

Color	2004 luminous efficacy (lm/W)	2004 cost (lm/\$)	Cost objective (lm/\$)
Red (633 nm)	108	20	50
Amber (617 nm)	100	30	60
White	38	about 17 (0.06 \$/lm)	100 to 150

Today's lumen-per-dollar figure falls short of automotive-industry requirements, in particular for white LEDs, which will require nearly a 10-fold improvement.

Today, red HB-LEDs are increasingly used for rear lighting, and have already been fitted on 18% of new European cars. These LEDs were first fitted into CHMSLs in the 1990s, and we expect that by 2010 they will feature in brake lights installed in more than half of all cars.

This year, Hella – a Germany-based manufacturer of electronics and lighting products for the automotive industry – will launch the first RCLs solely containing LEDs. We expect that within five years, 10% of cars will be fitted with LED-RCLs. The future will also see the development of smart rear lighting. By 2010 we expect to see cars fitted with LED-RCLs featuring brake-force display, a system that will react to road and driving conditions with actions such as the automatic activation of hazard lights, increasing the lit brake-lamp area, or flashing of the CHMSL.

Photonics is part of the solution for increased safety, greater comfort for drivers and passengers and improved aesthetics in cars. However, because any changes are restricted by strong regulations within the car industry, the typical time taken to implement a new standard is at least five years. This sluggishness means that car, system and chip makers must work together to further HB-LED deployment in cars. Actions such as Audi's launch of the first car with LED-based daytime running lamps will, we hope, inspire other manufacturers to investigate the potential of solid-state lighting. LED penetration

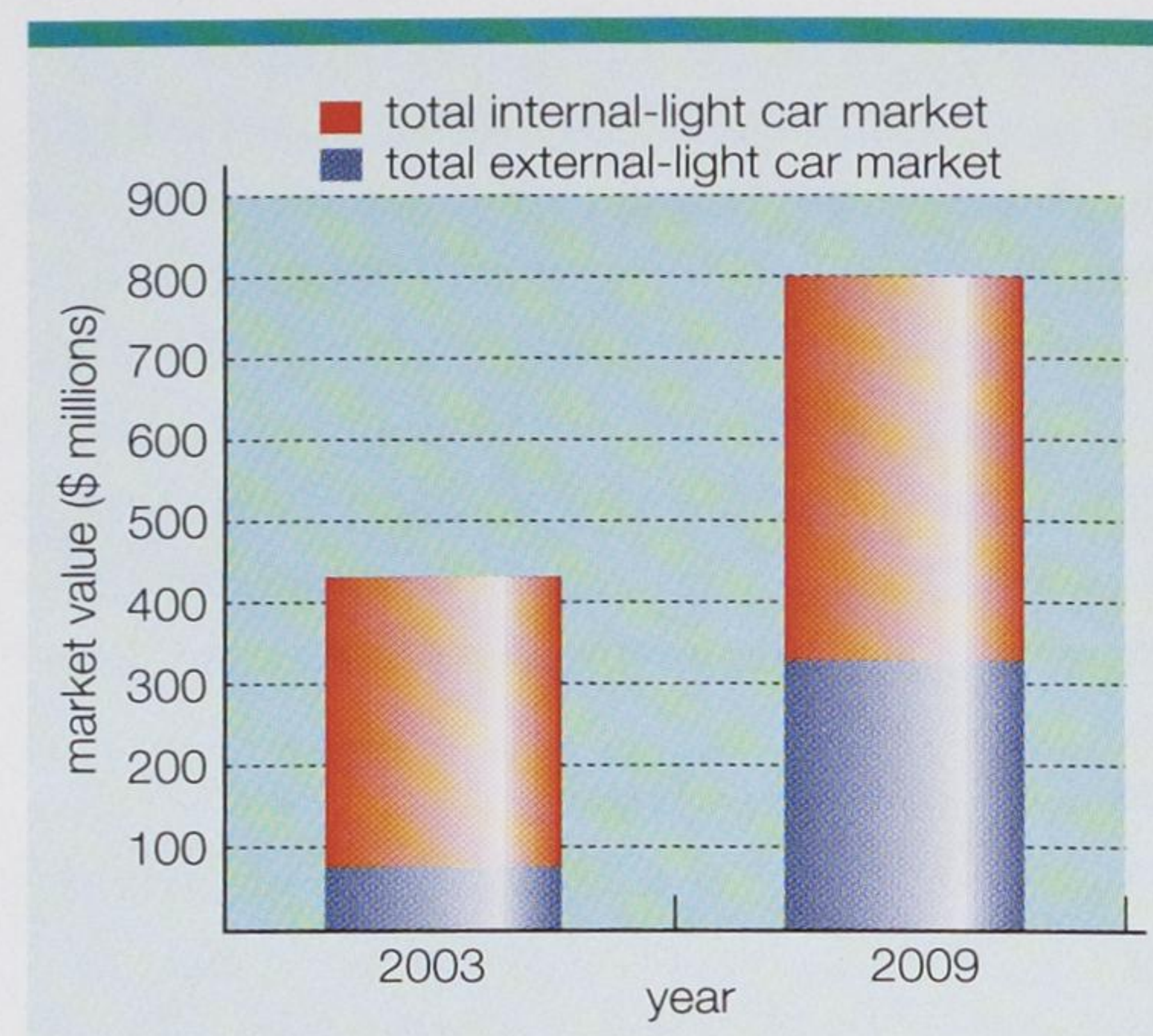


Fig. 1. External lighting applications will grow rapidly over the next five years, but interior-use LEDs will still represent the majority of the market for car-based LEDs in 2009.

has already been realized in rear lighting, with a growing number of luxury cars now fitted with integrated LED-based lamps. Cars with LED-based rear combination lamps are expected to impact the market shortly.

● The European Photonic Industry Consortium and Yole Développement report *Opportunities & Challenges for Photonics in the Automobile* is now available. E-mail David Jourdan at jourdan@yole.fr.

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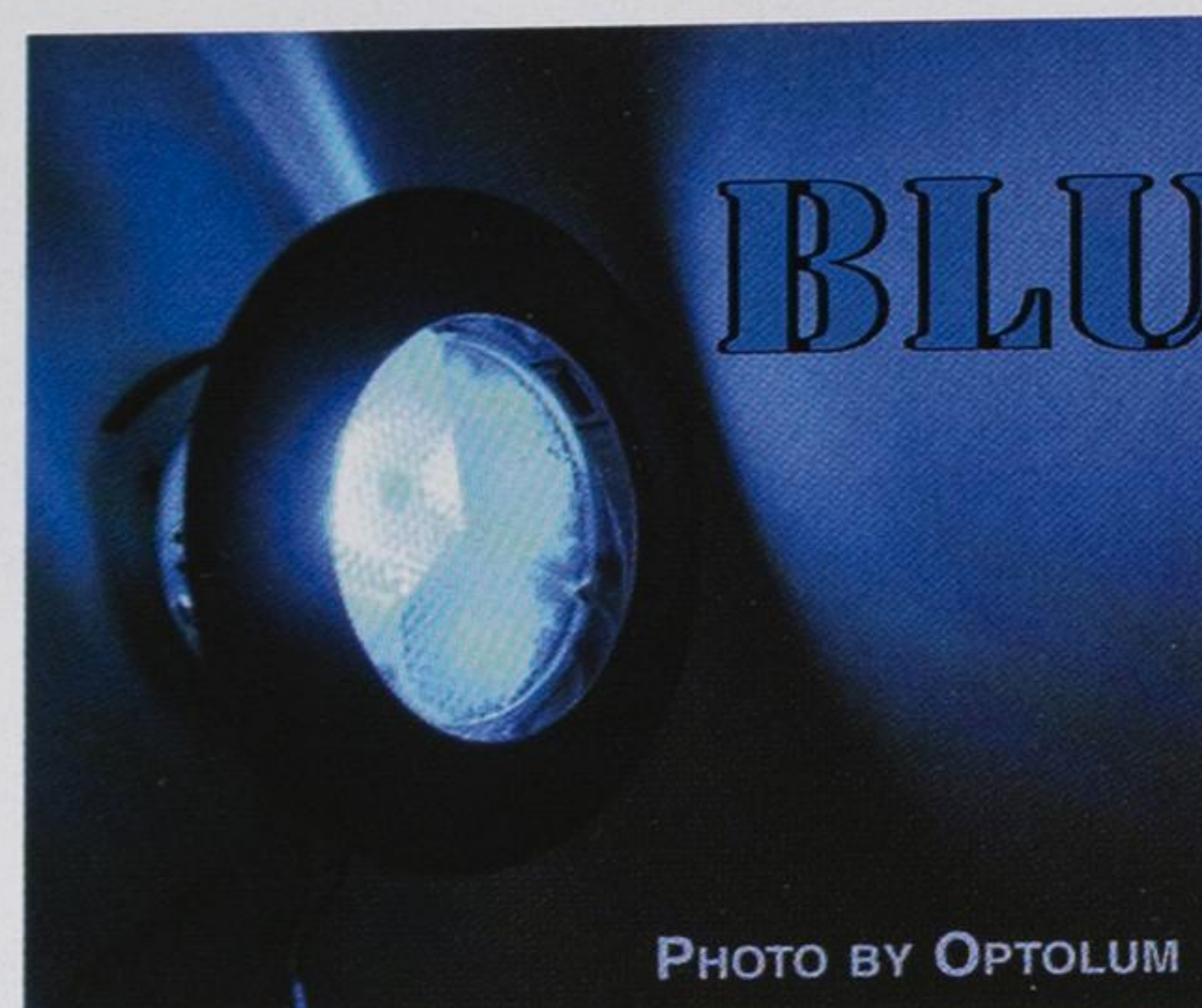
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Veeco plans 'aggressive' measures to boost TurboDisc division profitability

Veeco Instruments has completed its internal investigation of improper accounting transactions at its TurboDisc business unit. Recalculated revenue for the first three quarters of 2004 is \$2.2 million lower than previously reported, and the company's pre-tax loss increased by \$10.2 million.

Jefferson Wells, a forensic accounting firm brought in by the audit committee of Veeco's board of directors, concluded that improper entries were made by an individual at TurboDisc whose employment had been terminated before the investigation began. No motive was uncovered and no evidence found of either embezzlement or division of corporate assets.

The company restated its revenue for the first three quarters of 2004 as follows: quarter 1: \$90.9 million (down \$3.6 million); quarter 2: \$99.2 million (down \$3.6 million); and quarter 3: \$97.4 million (up \$5.0 million).

"While revenue adjustments impacted individual quarters, these adjustments in the aggregate do not reduce TurboDisc revenue recognized for the 2004 year," explained Veeco CEO Edward Braun. Despite the relatively small impact on the top line, Veeco's earnings for the equivalent period were badly hit, with adjusted pre-tax loss \$10.2 million worse than previously reported.

The turmoil at Veeco led to the dismissal of the controller of its TurboDisc division. The company has now appointed Richard Wissenbach as general manager of the compound semiconductor/epitaxial process equipment group that includes both the TurboDisc operation in Somerset, NJ, and the MBE unit at St Paul, MN.

Low profit margins

"What is particularly disturbing about these accounting errors, in addition to the control problem at TurboDisc, is that they prevented early awareness of the true profitability of the business," added Veeco CFO John Rein. The division had effectively been selling its MOCVD equipment at a price too low for the desired profit margin for most of 2004 (see *Compound Semiconductor* March p5). "The epitaxial group had a combined gross margin of 24% on revenue of \$93.6 million for 2004. These margin levels are completely unacceptable and we have an aggressive plan to attack the problem in the coming quarters."



Veeco's investigation into improper accounting at its TurboDisc MOCVD division revealed no evidence of embezzlement, but saw the division's controller dismissed.

Rein explains that improvements to the gross margin for the epitaxial division can be achieved through progress in design efficiency, better supply-chain management, standardization of product offerings, and reduced warranty costs. Currently the TurboDisc products have an associated warranty expense equating to 8% of revenue. According to Rein, this figure should be only 2–3%, a target that he believes can be attained through changes to just one or two components within the reactor. He believes the improvement program will increase the division's gross margins from 25 to 34% over the 2004–2005 timeframe.

Veeco also reported its fourth-quarter figures, which Braun labeled "a disappointment". Revenue for the fourth quarter ending December 31, 2004, was \$103 million, up \$5.6 million sequentially, and a 34% increase year on year. Operating loss was \$6.7 million, well up on the \$3.5 million recorded for the previous quarter.

However, Veeco's order backlog improved during the fourth quarter, rising 24% sequentially to \$99 million, driven primarily by increased customer spending from the data storage and silicon industries. Excess capacity of epitaxial equipment is still a problem for the company, particularly in the Asia-Pacific region, and Veeco expects revenue

from this product line to fall between 20 and 24% in 2005. However, the sector is expected to pick up again in 2006, as markets for high-brightness LEDs expand from cell-phone applications to incorporate backlighting television screens, automotive applications and general lighting.

Knock-on effects

Veeco's recent financial difficulties have also impacted Emcore, which sold the TurboDisc division to Veeco in November 2003. The original earn-out deal stated that Emcore would receive 50% of all TurboDisc revenue that exceeded \$40 million in the two years beginning January 1, 2004, with a maximum payout of \$20 million.

Since revealing the problems with the TurboDisc accounts, Veeco has written to Emcore with a preliminary earn-out statement. The statement says that TurboDisc net sales amounted to \$64.9 million in 2004, which would mean a payment of \$12.5 million to Emcore.

Veeco will be in contact with Emcore again, now that it has restated its financial results, but at this stage it is unclear how much money Emcore will receive. Based on Veeco's 2005 outlook, Emcore does expect to receive the earn-out balance in 2006.

Trikon plans Aviza merger

UK-based wafer-fabrication equipment producer Trikon is intending to merge with Aviza Technology, a supplier of thermal process and atomic-layer deposition (ALD) systems, headquartered in Scotts Valley, CA.

Aviza's stockholders have agreed to the consolidation, but the deal is still subject to the approval of Trikon's shareholders.

The new firm, also called Aviza Technology, will have 700 employees and should generate

annual revenue in the region of \$160 million. Aviza stockholders will own 60% of the new company, with Trikon stockholders accounting for the remaining 40%.

Aviza's current CEO, Jerry Cutini, and present CFO, Patrick O'Connor, will continue in these roles at the new company, while Trikon's CEO, John Macneil, will be appointed CTO.

"Trikon's product portfolio, consisting of plasma etch, physical vapor deposition and chemical vapor deposition systems, combined with Aviza's thermal processing and ALD tools, will allow us to expand and provide a broader solution set," said Macneil.

AXT cuts staff numbers and appoints CEO

Substrate manufacturer AXT is cutting 100 staff from its Beijing, China facility. The company cites ongoing efforts to reduce its cost structure, as well as bringing capacity in line with current demand, as the reasons for reducing the Chinese workforce by 15%.

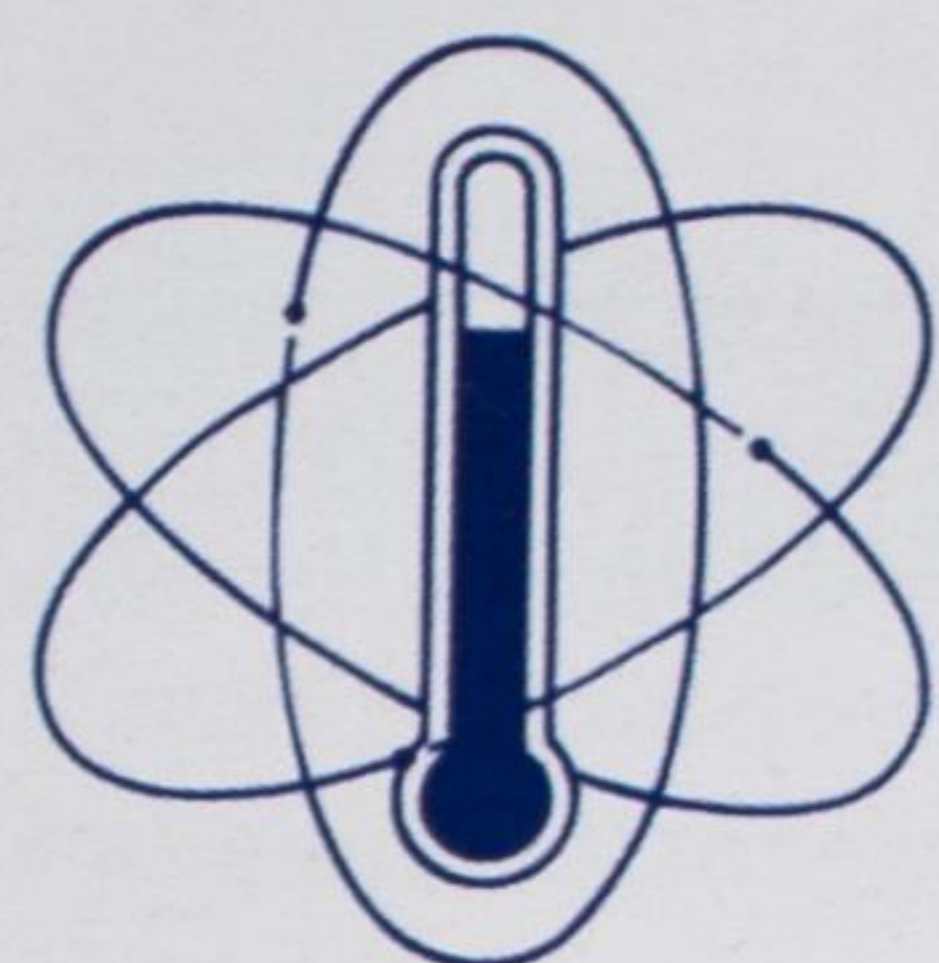
The company will record a restructuring charge of \$0.1 million in its first quarter related to the headcount reduction, which it

will complete in 2005. AXT expects that this move will produce annual payroll and related expense savings of \$0.3 million.

The firm has also appointed Philip Yin as CEO, effective from March 28, replacing Donald Tatzin. Yin was Aixtron's general manager for North America and has been president of ATMI Epitaxial Services, and has held senior roles at Crystec and Mitsubishi.

In brief

- Semiconductor manufacturing equipment supplier **Mykrolis** has acquired Extraction Systems for \$25 million in cash. Extraction Systems, which is based in Franklin, MA, sells products that are used to measure and remove airborne molecular contaminants in the semiconductor manufacturing process.
- UK-based pump supplier **BOC Edwards** has signed a deal with MOCVD equipment specialist Aixtron that will see the German firm incorporate BOC Edwards pump and abatement systems in deposition equipment used for GaAs and InP growth.
- French MBE equipment provider **Riber** has sold research machines to The Braun Center for Submicron Research, which is located at the Weizmann Institute of Science in Israel, and the University of Arkansas in Fayetteville.
- **PVA TePla** of Germany has reported annual revenue for 2004 of €44.2 million (\$59 million), up €5.3 million sequentially.



Accurate Gas Control Systems



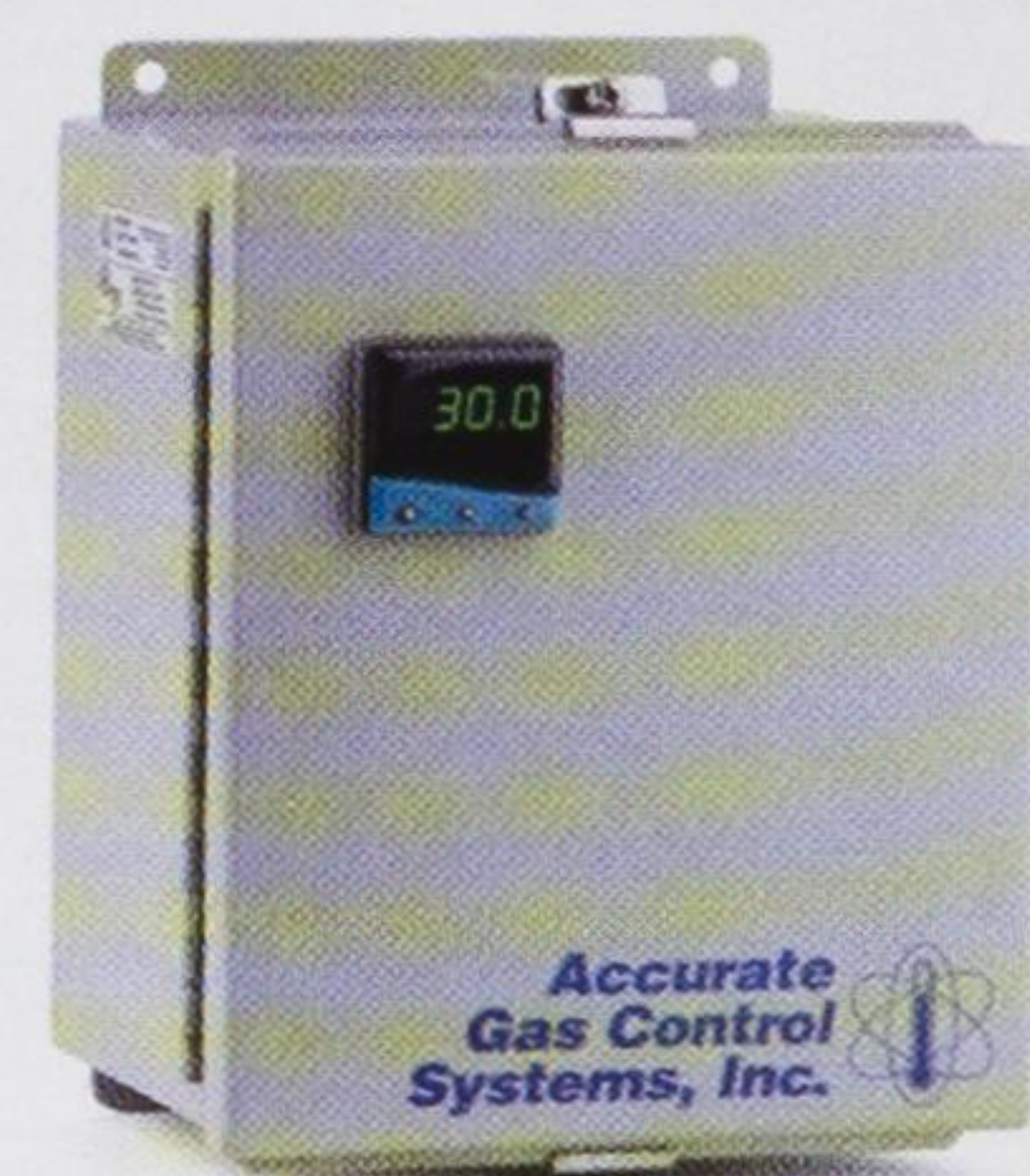
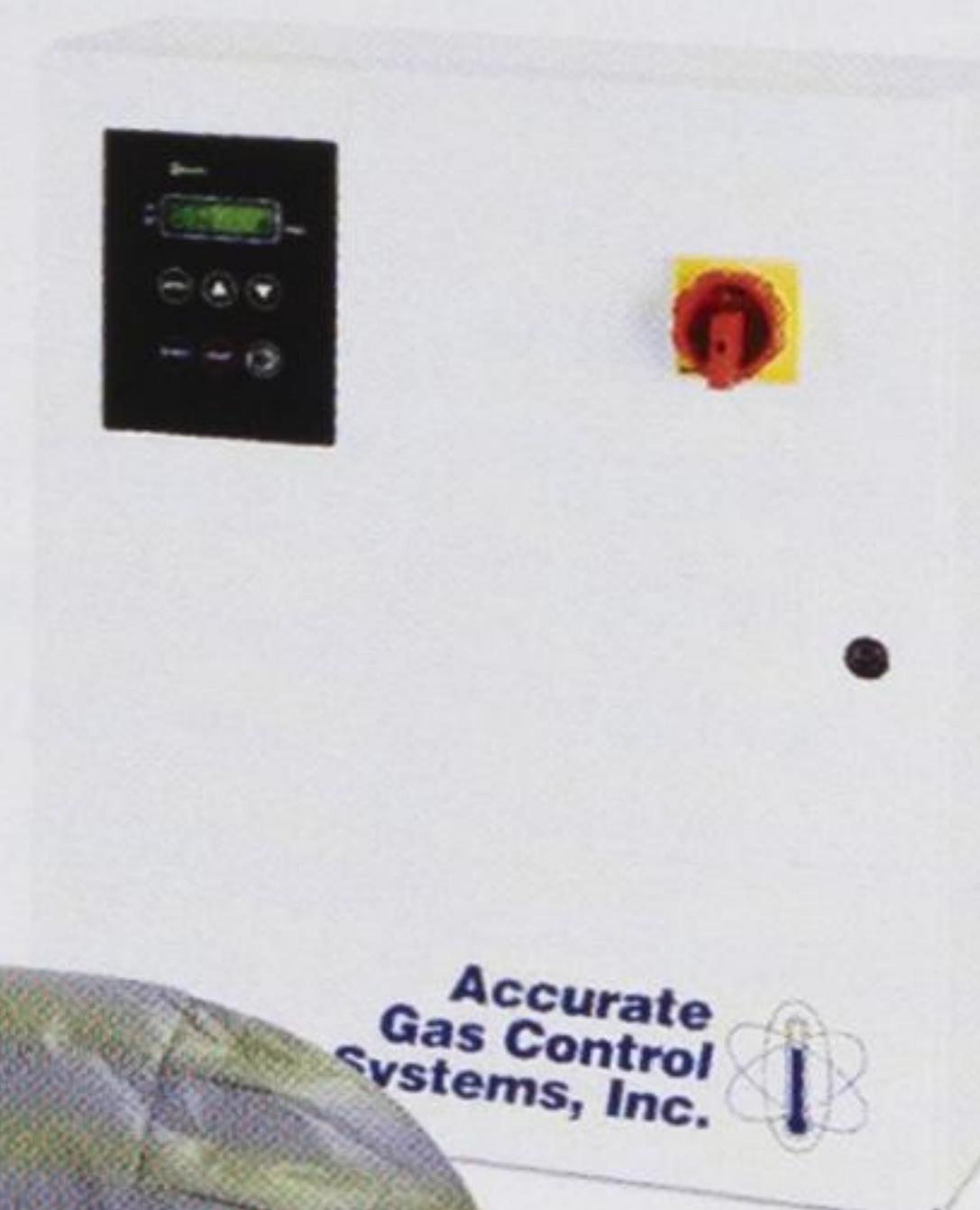
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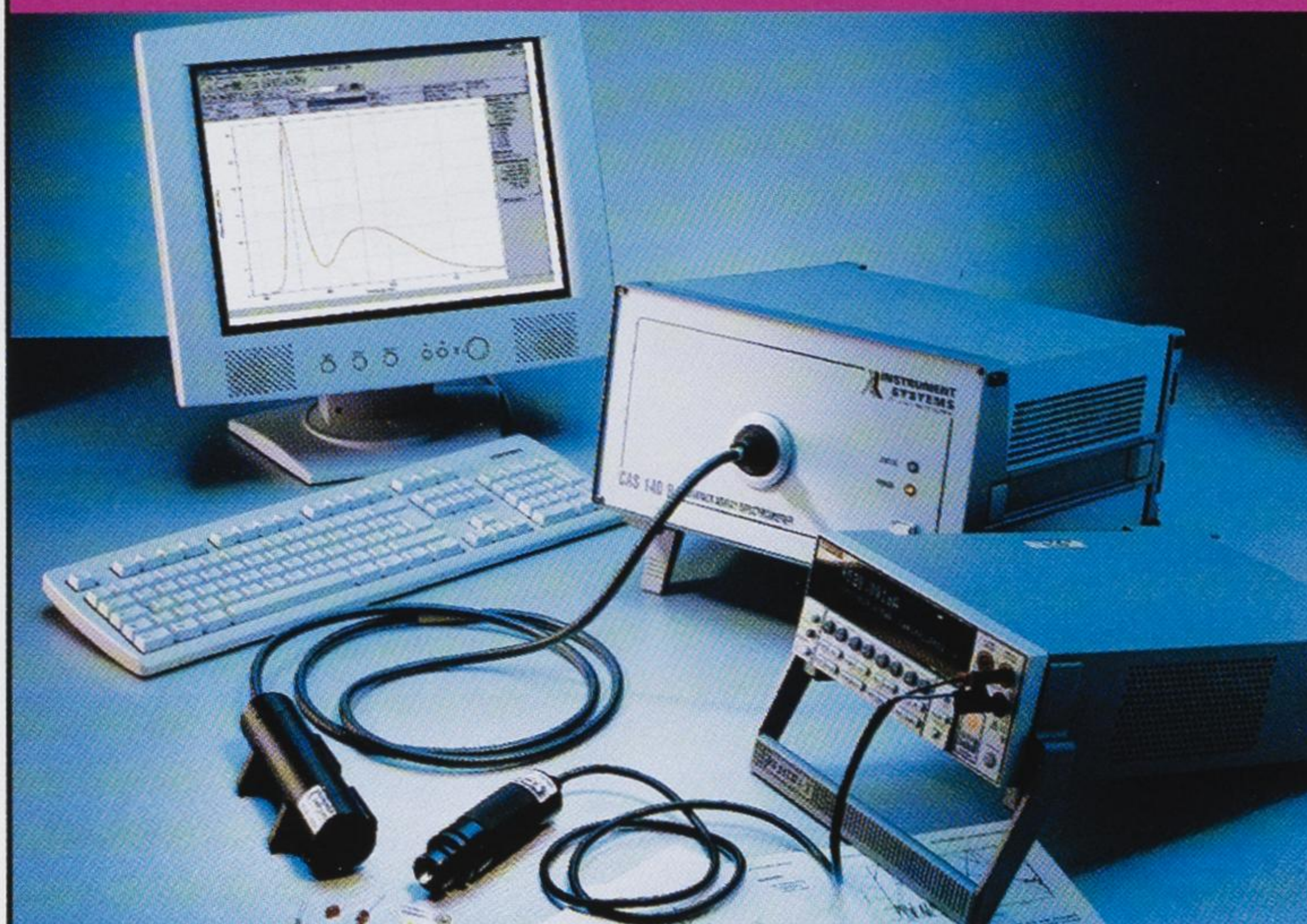
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Aixtron finalizes acquisition of Genus

Germany-headquartered MOCVD equipment manufacturer Aixtron has finally acquired US-based Genus, a supplier of atomic-layer-deposition (ALD) technology to the semiconductor and hard-disk-drive industries.

Aixtron first announced the planned merger with Genus back in July 2004, but the deal was only clinched on March 10 at a special meeting of Genus' shareholders, where 61% of the vote was in favor of the acquisition.

Genus's shareholders have now been

issued with Aixtron American Depository Shares (ADS), equivalent in value to Aixtron ordinary shares. The Aixtron ADS started trading on the NASDAQ stock exchange on March 11.

"We would like to thank all of our shareholders for their support on this very important strategic move," said Genus CEO Bill Elder. "In the combined companies' portfolio, Aixtron's leading MOCVD equipment for the production of LEDs, high-frequency chips

and lasers, and in particular their atomic vapor deposition technology, will nicely complement Genus's ALD technology, which is required in the production of advanced semiconductors and hard-disk drives."

Paul Hyland, Aixtron CEO, added: "This transaction enables us to leverage the two companies' complementary strengths and gain the critical mass required to successfully compete in both the compound semiconductor and the semiconductor-equipment industries."

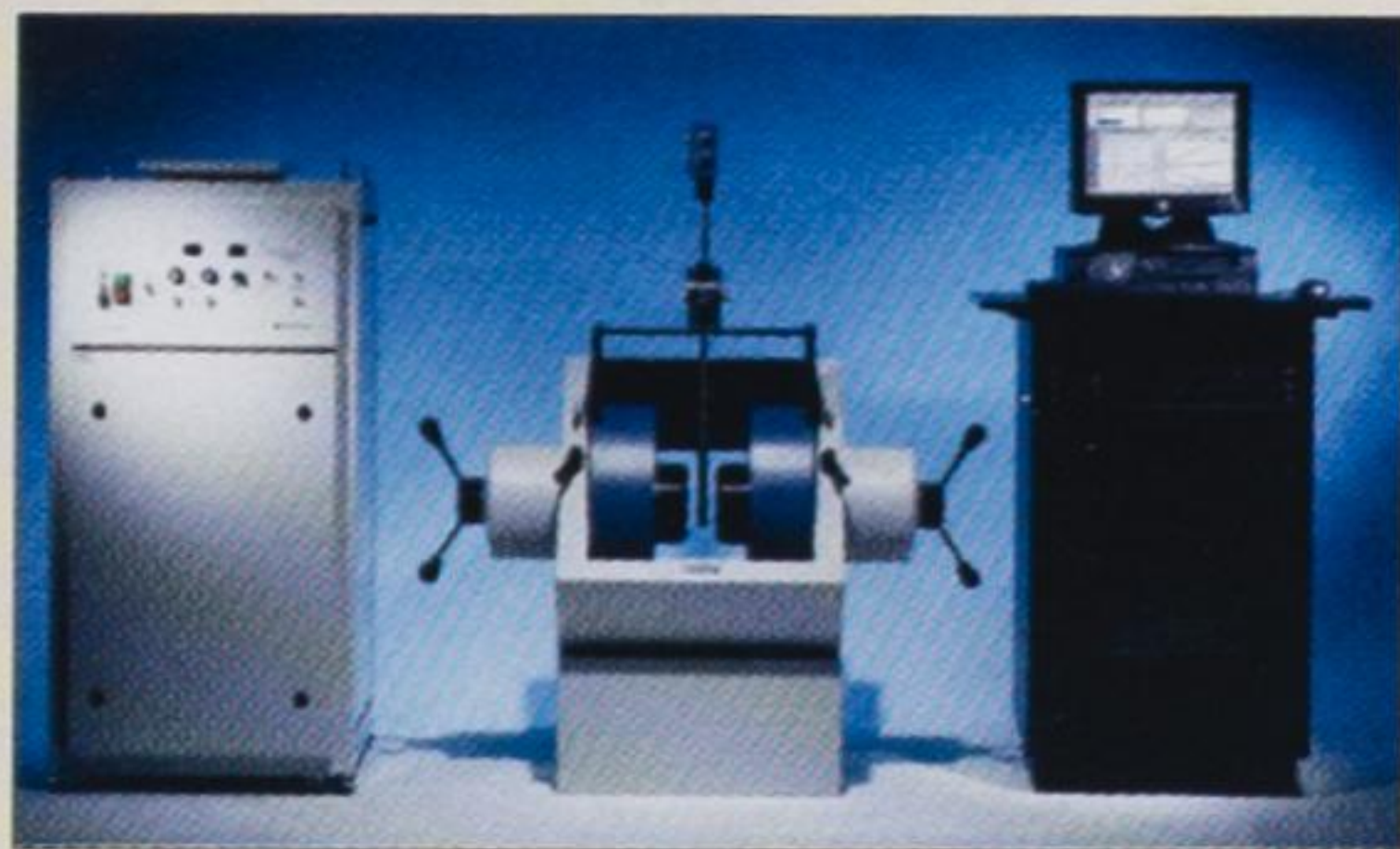
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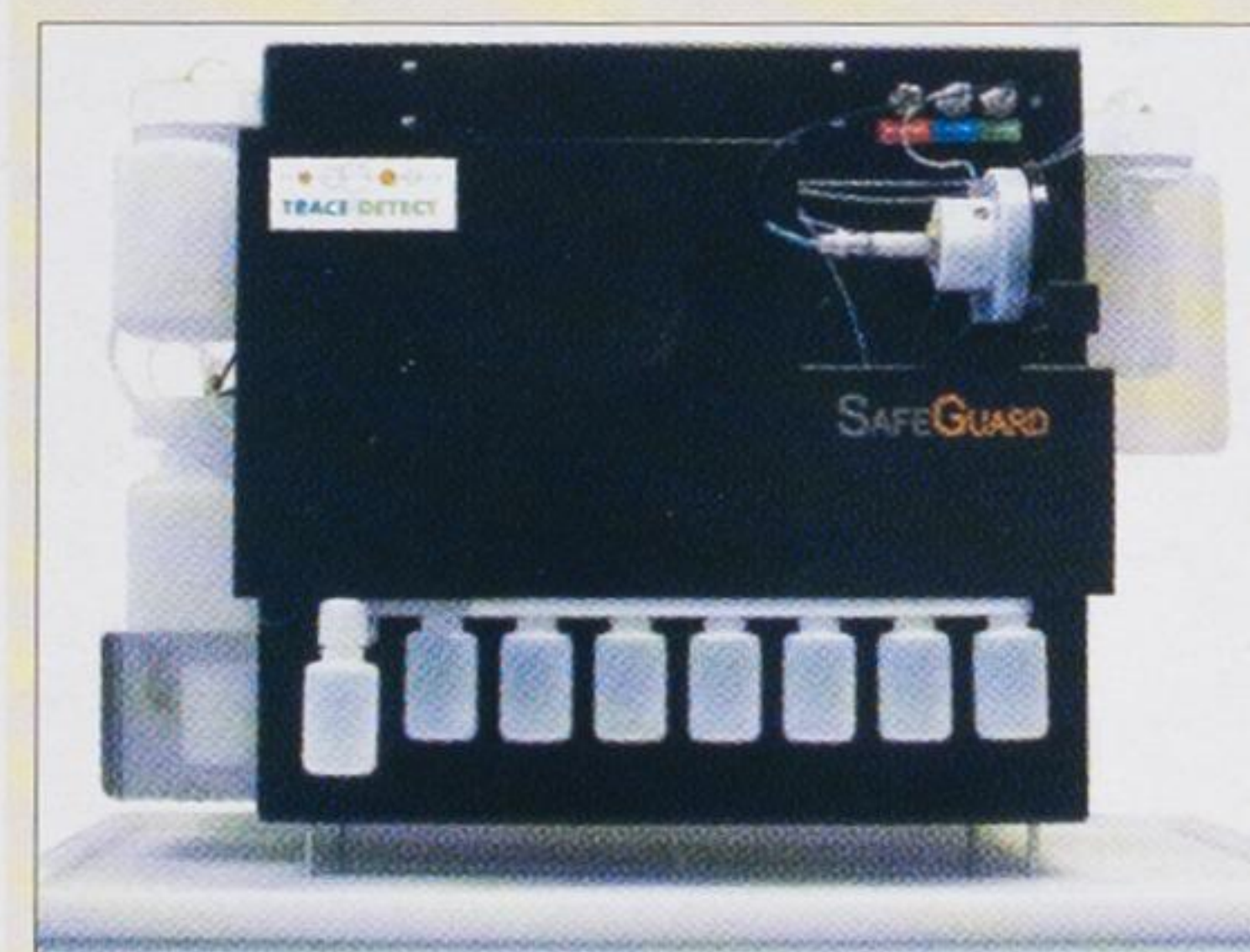


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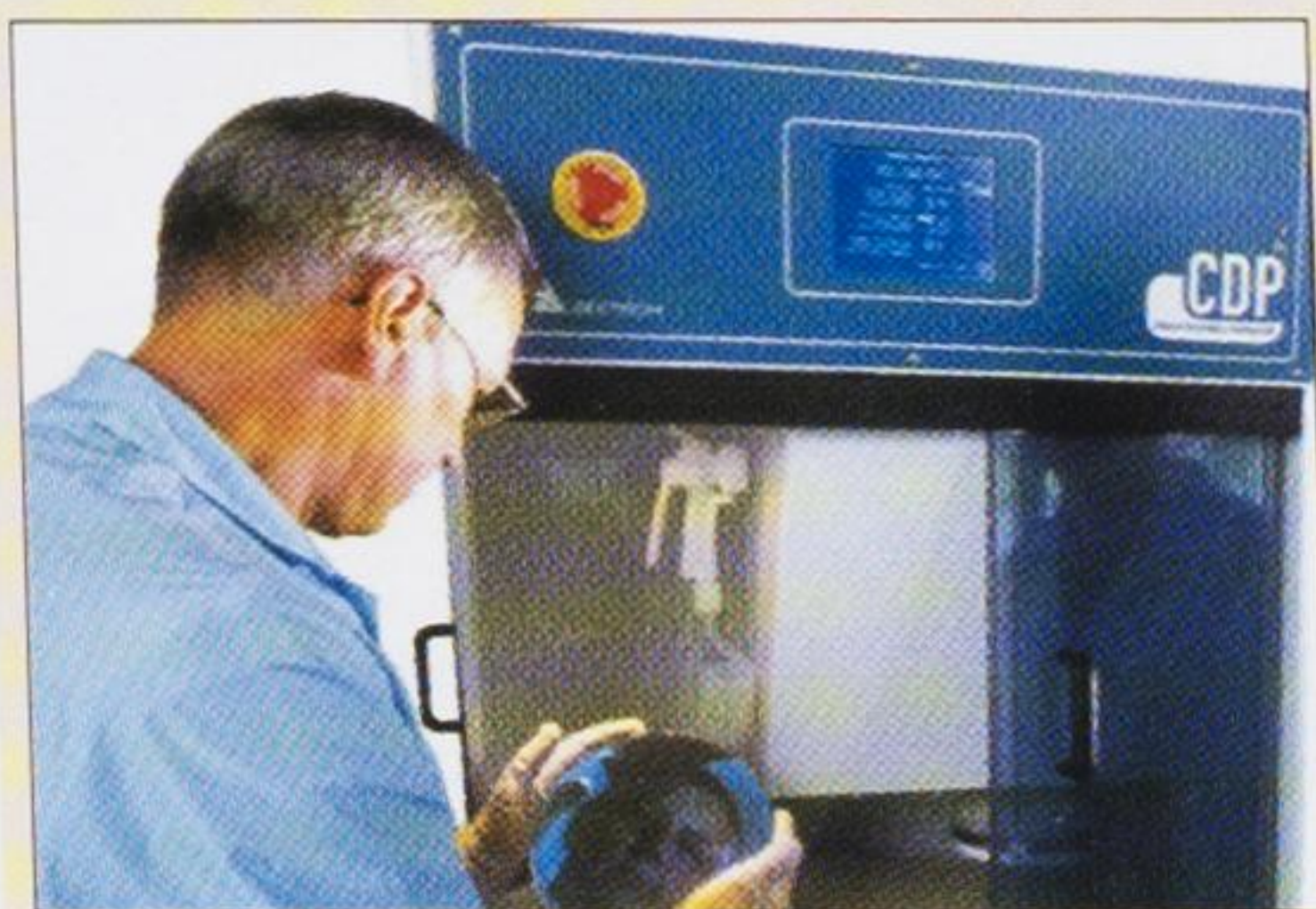
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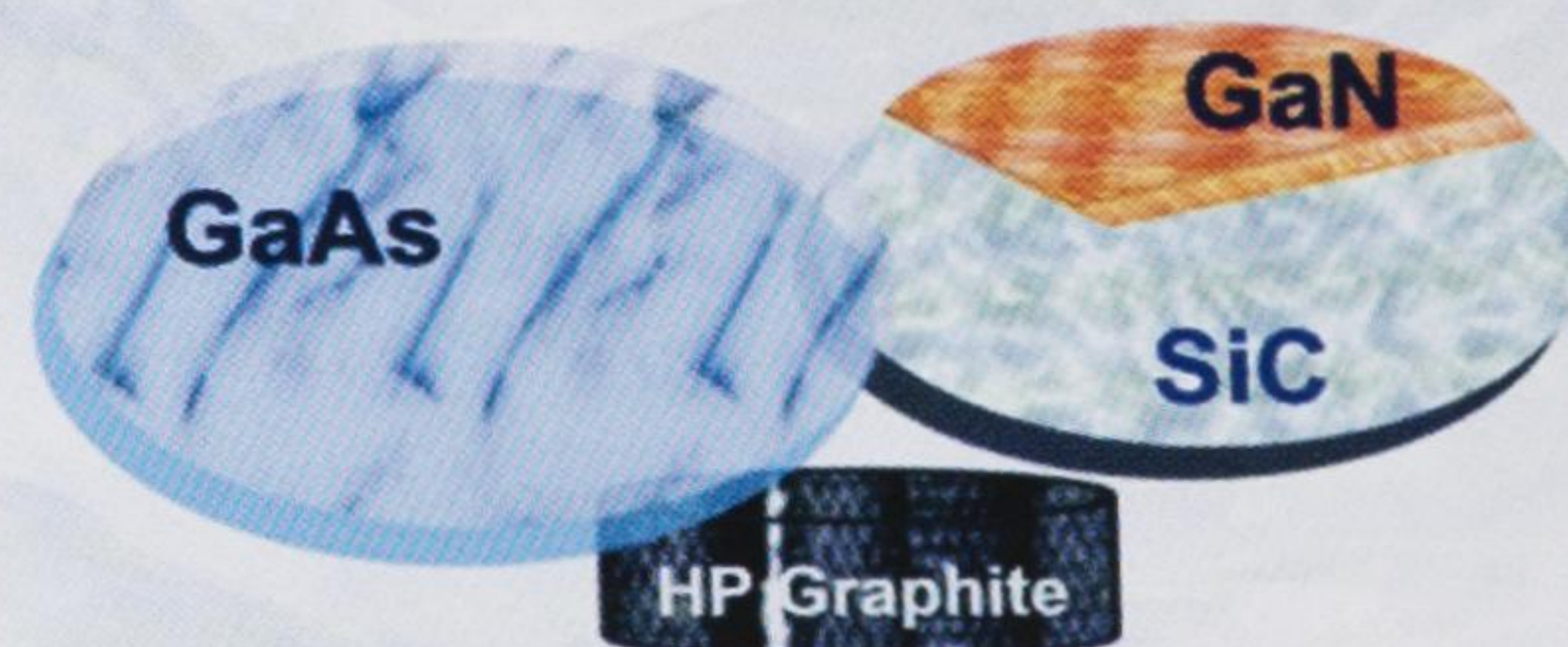
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Rugged, compact 4H-SiC avalanche photodiodes reach the quantum limit

A US research team has built the first silicon carbide (SiC) avalanche photodiode capable of single-photon counting (*Elec. Lett.* **41** 212). The UV detector, produced in a collaboration between Rutgers University, NASA, Raytheon and United Silicon Carbide, is smaller than today's commercial photomultiplier tubes (PMTs) and has a wider spectral range than solid-state single-photon counters.

PMTs are often used for single-photon counting due to their high gain and relatively low dark-count rate, but SiC has the edge in terms of ruggedness and compactness says team member Jian Zhao of Rutgers University. Zhao explains that SiC detectors are not only potentially more affordable than PMTs, but are

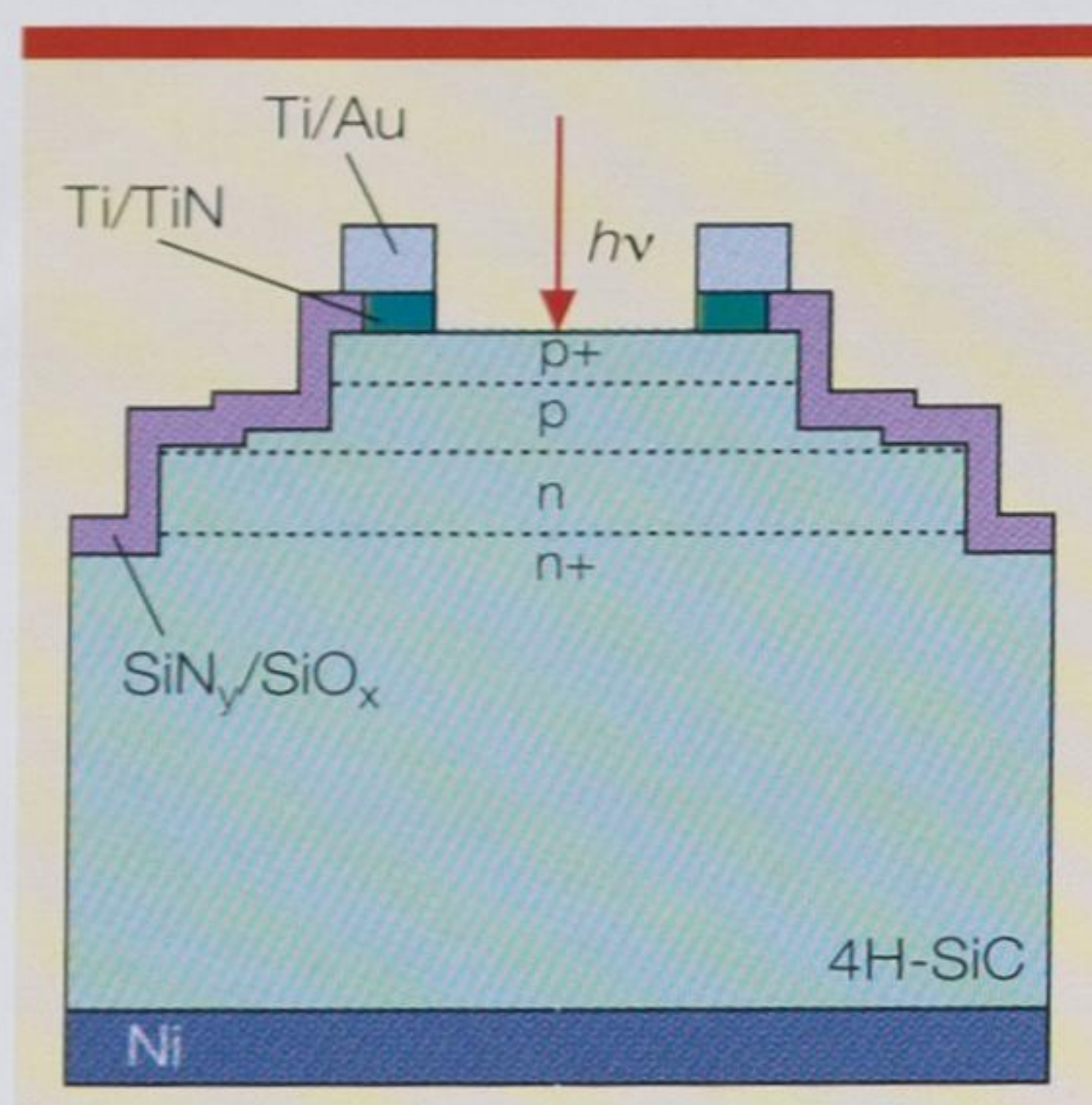


Fig. 1. At 270 nm, SiC single-photon avalanche photodiodes have a peak quantum efficiency of 20%.

also insensitive to magnetic fields, can operate across a wider temperature range, have higher radiation tolerances, require lower bias voltages and have a lower dark current.

SiC single-photon avalanche diodes (SPADs) also compare favorably with detectors constructed from silicon, InGaAs and InP, which have a poor spectral response in the UV region. Although GaN is suitable for UV detection, Zhao says that avalanche photodiodes produced from this material "typically die after a few measurements".

The team's $160 \times 160 \mu\text{m}$ SiC SPADs have a $74 \times 34 \mu\text{m}$ optical window and are produced by depositing $4 \mu\text{m}$ *n*-doped, $0.2 \mu\text{m}$ *p*-doped, and $0.15 \mu\text{m}$ heavily *p*-doped SiC epilayers on a 4H-SiC substrate. Nickel and titanium form *n*- and *p*-type ohmic contacts, respectively.

The device has a peak quantum efficiency of 20% at 270 nm. At longer wavelengths the indirect nature of the 4H-SiC bandgap leads to a decrease in the detector's response, and at shorter wavelengths the quantum efficiency declines through surface-recombination effects. According to the team, substantial improvements in efficiency – leading to photon-counting efficiencies in excess of 40% – could be achieved by using separate absorption and multiplication structures.

Swiss scientists boost quantity of aluminum in AlGaN crystals

Researchers from ETH Zurich, Switzerland, have produced AlGaN crystals that have an aluminum content of 27%, which is a 17% improvement on all previously reported results (*Appl. Phys. Lett.* **86** 081908). These crystals, unlike those made from GaN, could enable lattice-matched growth of aluminum- and indium-containing ternary and quaternary compounds.

The team grew the AlGaN crystals in a cubic anvil cell loaded with

liquid gallium, small pieces of aluminum and GaN powder to provide the nitrogen source. Crystal growth, at 1750°C and 30 kbar, took between 12 and 60 hours and produced colorless and slightly brown crystals in a variety of shapes ranging from needles to discs. The aluminum fraction of 0.27 ± 0.02 was estimated from a combination of mass spectrometry, single-crystal X-ray diffraction and photoluminescence measurements.

According to Peter Geiser, a member of the team, scaling this process from the $0.6 \times 0.4 \times 0.2 \text{ mm}$ crystals produced so far to sizes suitable for commercial wafer production will require similar efforts to those directed toward GaN growth over the last decade.

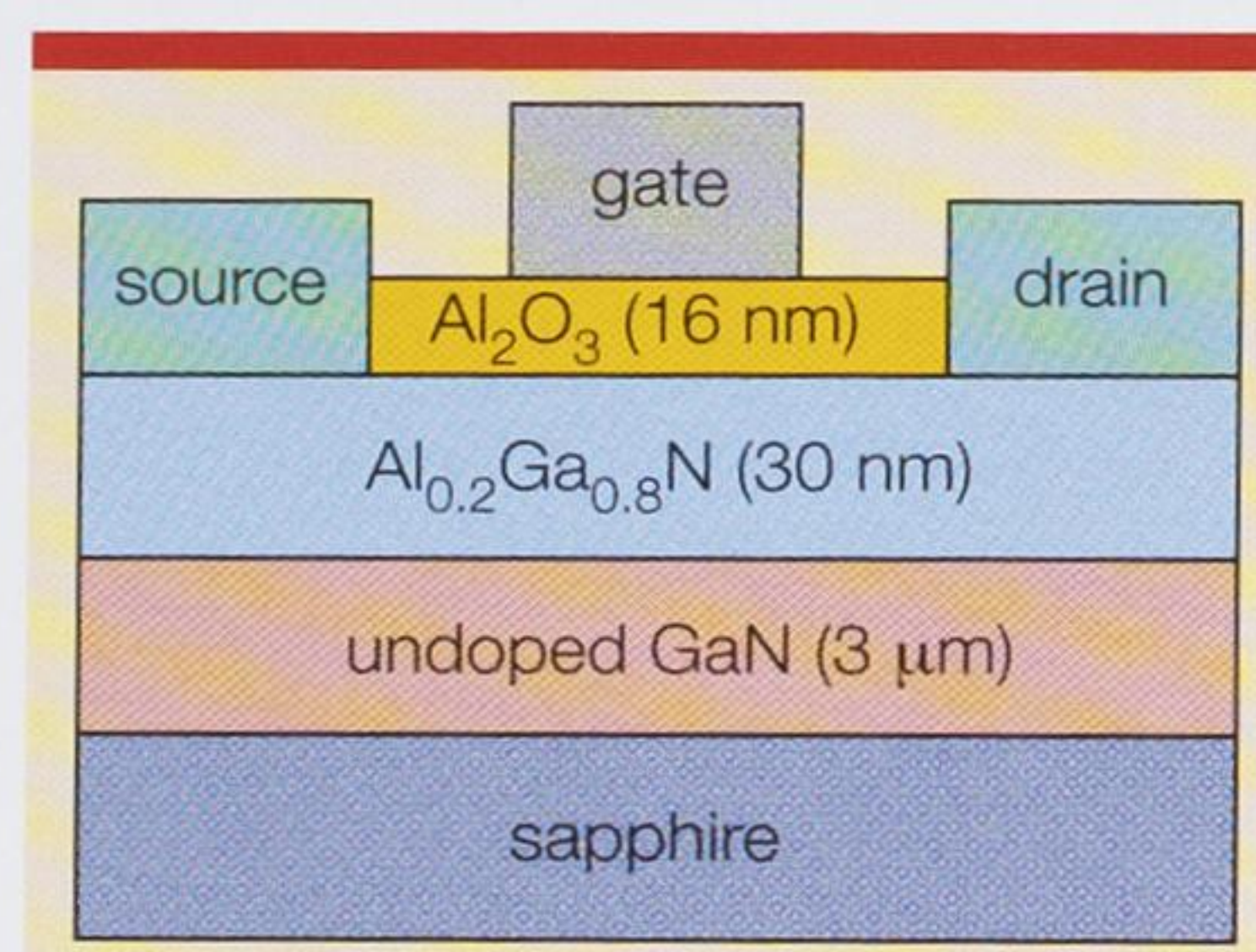
Al₂O₃ dielectric layer improves GaN HEMT reliability

A team from Agere Systems, ASM America and Lehigh University has improved the reliability of GaN-based HEMTs by using atomic-layer deposition (ALD) to insert a 16 nm-thick Al₂O₃ dielectric layer below the gate contact (*Appl. Phys. Lett.* **86** 063501).

The researchers compared the metal-oxide-semiconductor (MOS)-HEMT device characteristics (see figure) with a typical GaN HEMT. Under a 2 V positive gate bias the gate leakage current density of the MOS-HEMT was less than one-millionth that of a standard HEMT. The MOS-HEMT's breakdown voltage was also a vast improvement over that of a standard HEMT, failing at 12 V instead of only 2 V.

The US scientists were the first group to investigate the benefits of inserting an oxide layer by ALD: "I tried ALD grown HfO₂ and sputtering Al₂O₃, but neither one was as successful as ALD of Al₂O₃," said team member Peide Ye of Agere.

Compared with sputtering and electron-beam deposition, ALD offers better film quality. It is a surface-controlled layer-by-layer growth technique for thin-film deposition with atomic-level precision and is



In MOS-HEMTs, an amorphous Al₂O₃ layer cuts the gate leakage current density to one-millionth that of standard HEMT devices.

ALD at 300°C , before the structure is annealed for 60 s at 600°C . Source and drain regions are defined with diluted HF etching, before electron-beam deposition forms the metallic ohmic contacts.

widely used by silicon-chip makers. "The silicon industry's semiconductor roadmap supposes that ALD-grown high *k*-dielectrics will replace all SiO₂ manufacture in 2008," explained Ye.

The GaN MOS-HEMT structure, grown by MOCVD on a 2 inch sapphire substrate, consists of a 40 nm buffer layer, followed by a $3 \mu\text{m}$ -thick undoped GaN layer and a 30 nm undoped Al_{0.2}Ga_{0.8}N. The 16 nm-thick Al₂O₃ layer is then deposited by

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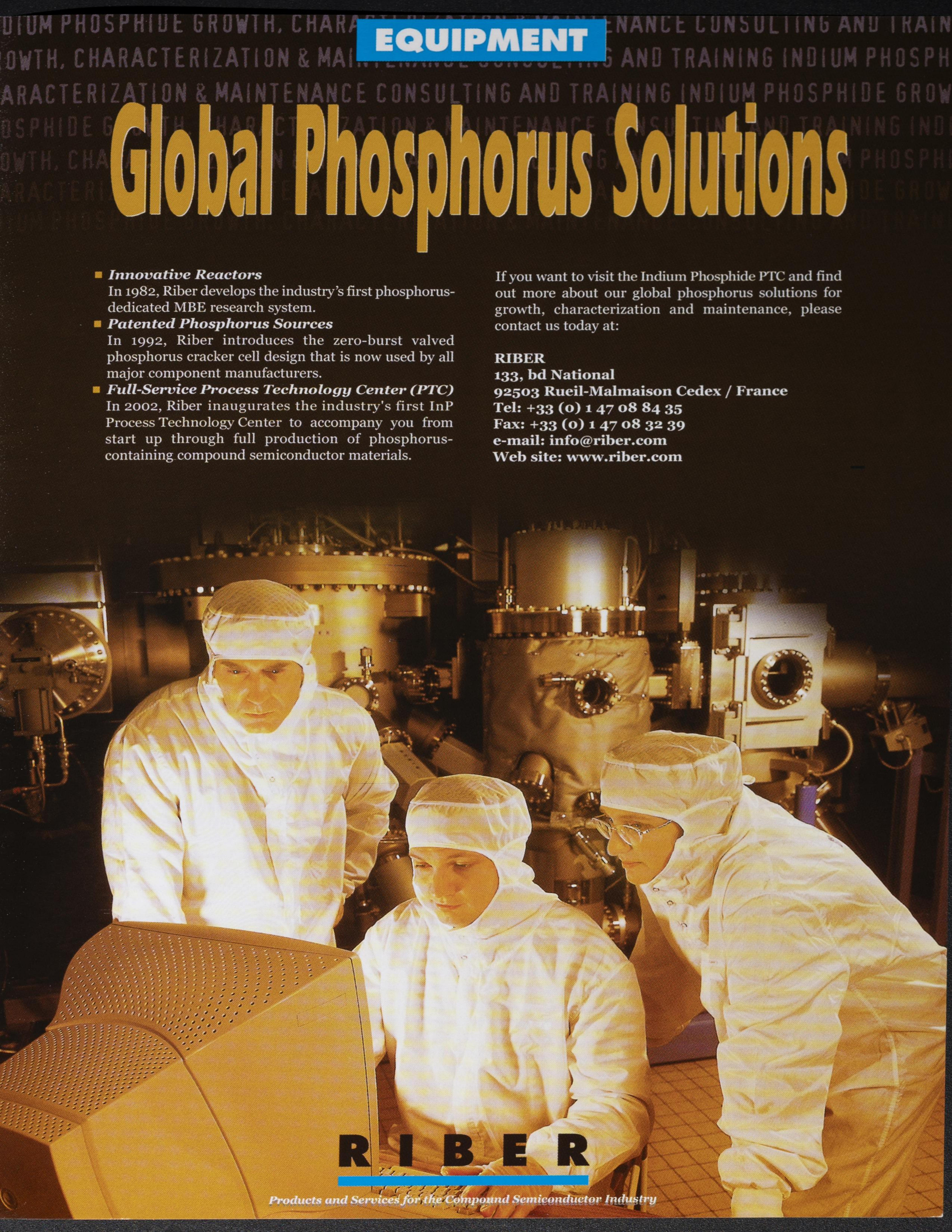
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