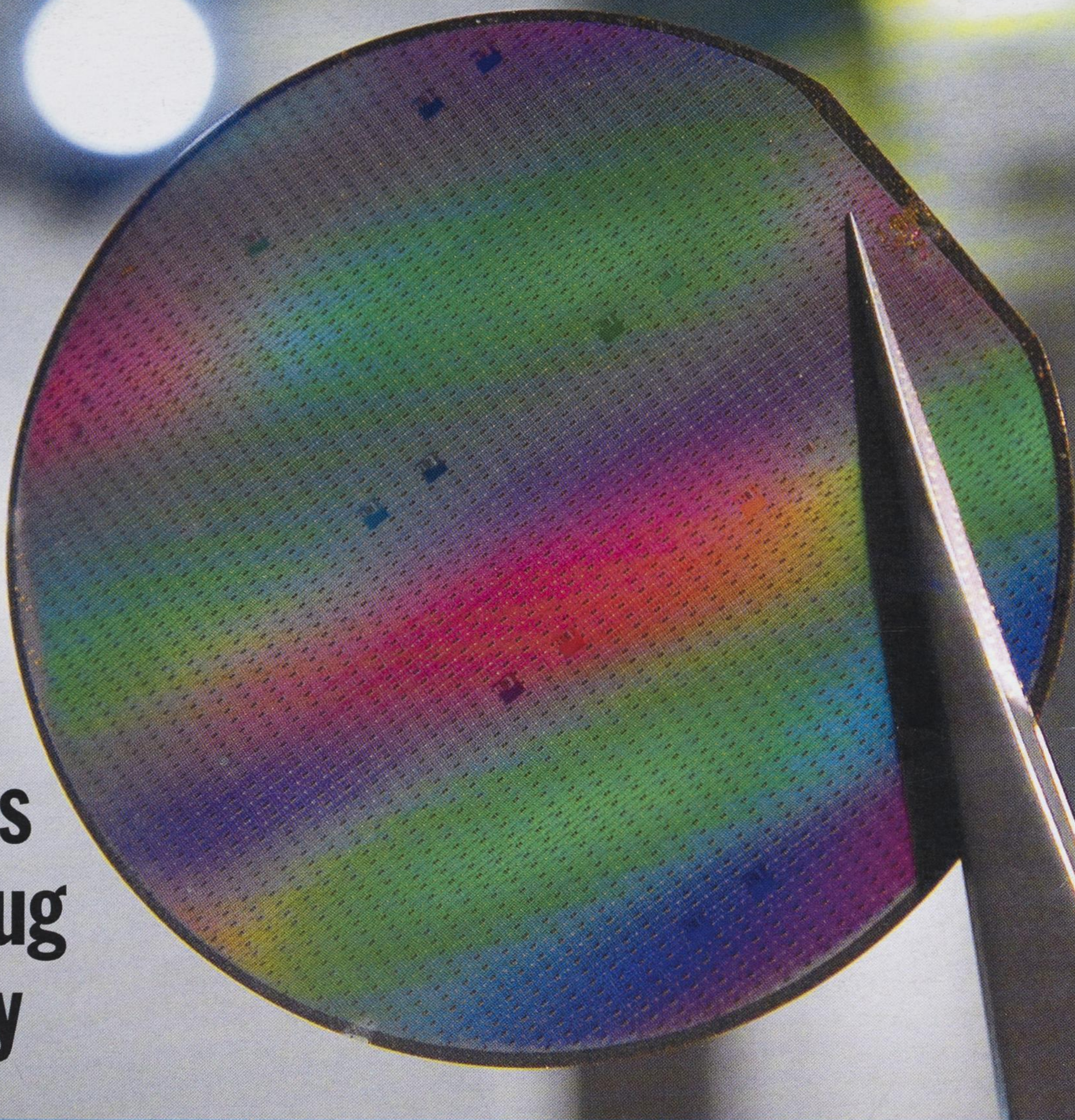


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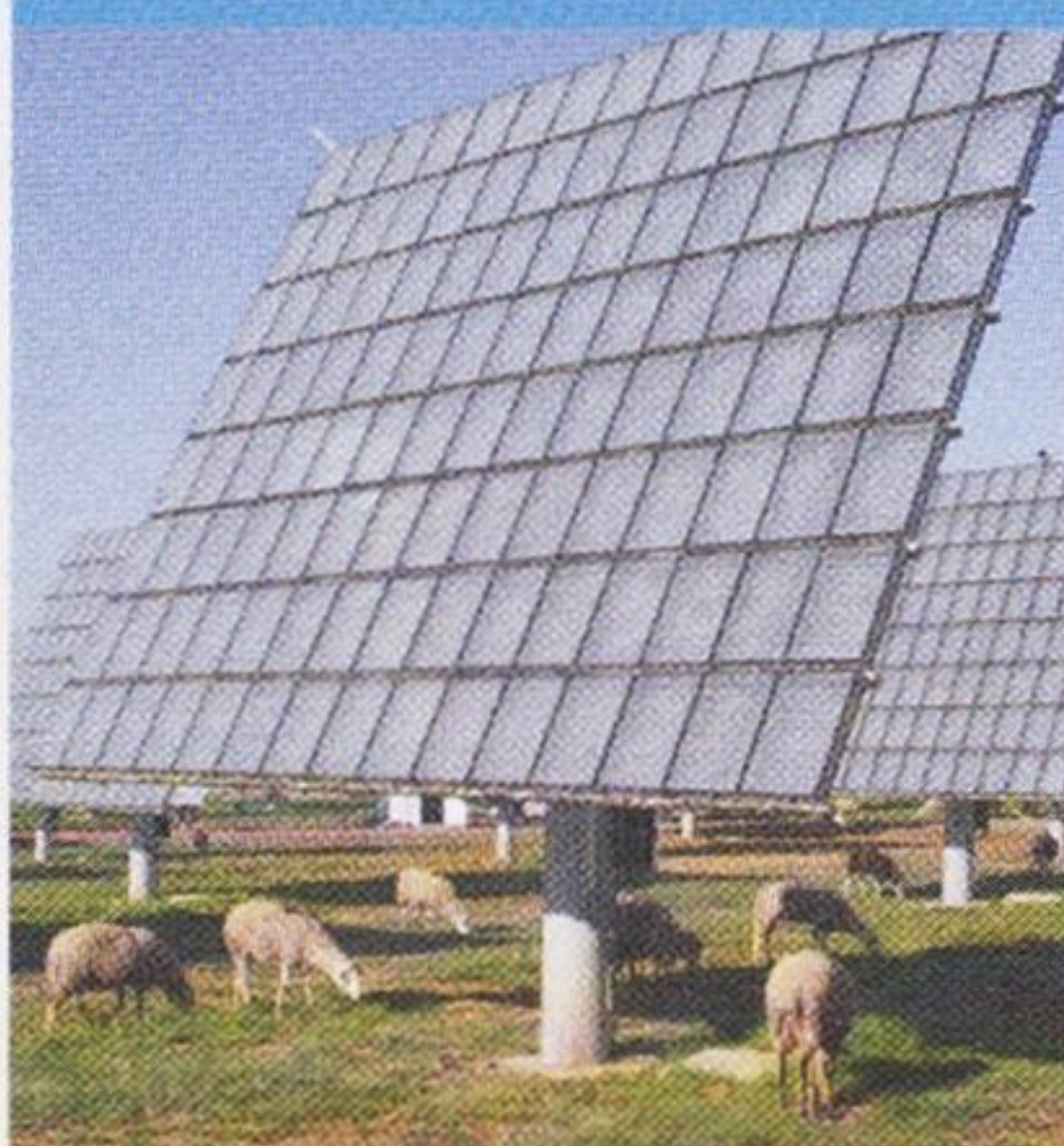


AC-DC
Epistar's
LEDs plug
and play

HEADLINE NEWS

RFMD diversifies
into GaN foundries
and solar p5

BEHIND THE HEADLINES



Solar futures

Can the concentrated photovoltaics industry address the issue of reliability and go on to be a success? **p17**

HIGH-POWER LASERS



Great shape

Alfalight's curved gratings give laser chips a brighter, cleaner emission profile. **p21**



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INDUSTRY

- 5** **Headline News:** LEDs lead the way in Taiwan's \$1 bn plan...RFMD prepares GaN foundry and solar...TriQuint signs \$50 m ZTE basestation deal.
- 6** **Industry Update:** Settlements clear the way for consolidation...\$21 m loss brings cost cuts at Veeco...III-V fabrication heads to the Middle East...CEO charm offensive gives Anadigics hope...Steady Skyworks minimizes its losses...II-VI wins \$5.2 m funding for SiC...Cree pushes LED performance limits...SEMI: time for LED makers to collaborate...SemiLEDs reveals 6 inch progress...Inlustra starts non-polar production...EPIR weds CdTe and multijunction solar...TranSiC welcomes electric car plan.



VOLVO

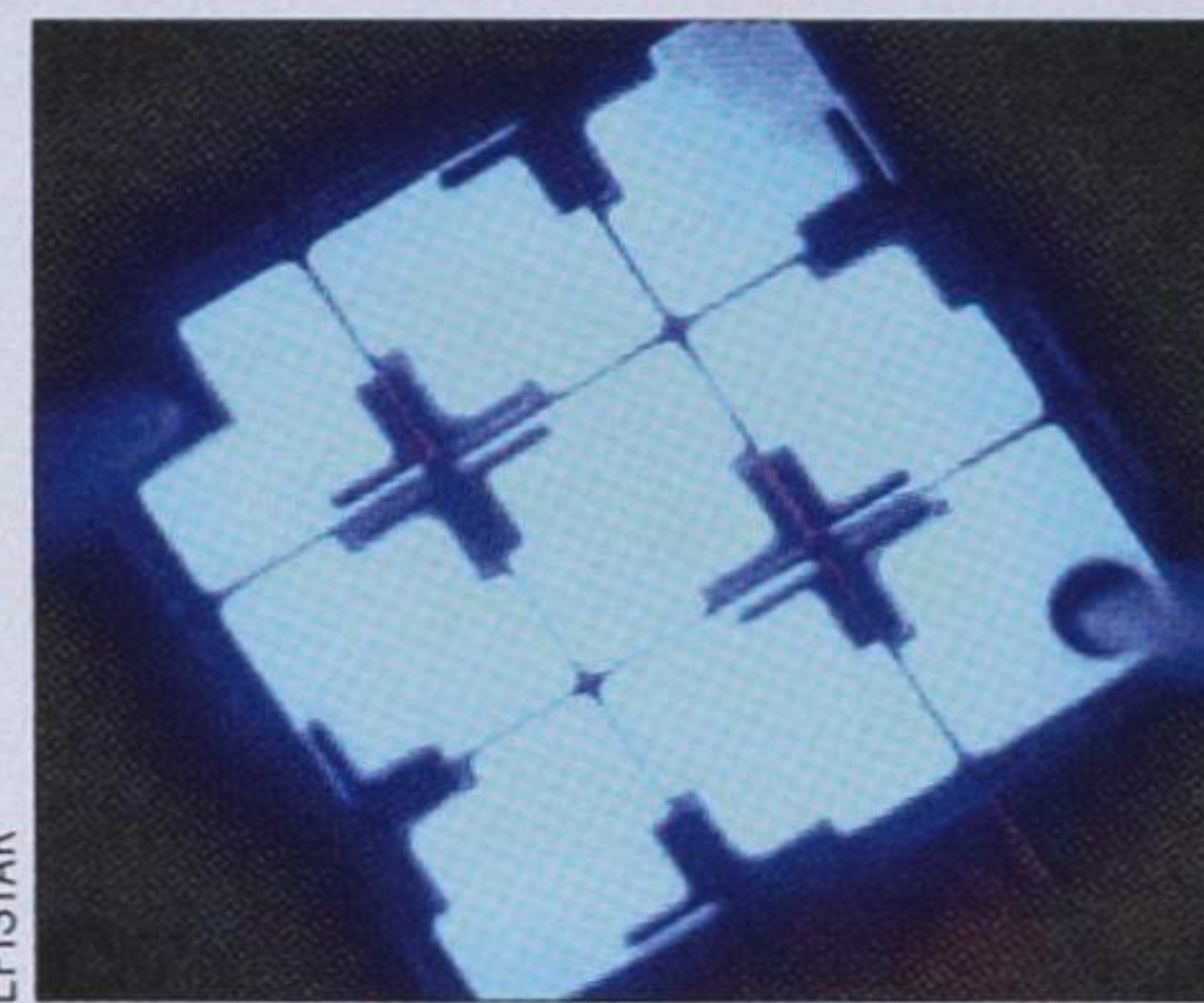
Electric drive

The Swedish government is hoping to accelerate sales of electric and hybrid electric vehicles, like this Volvo ReCharge concept car. **p11**

- 12** **Portfolio: III-V industry stocks reach bottom?** The NASDAQ stock exchange has lost 40% of its value in the last 12 months, and the shares of most III-V players have fared worse. Well chosen acquisitions and manufacturing efficiency separate the winners and losers, finds Andy Extance.
- 14** **Behind the Headlines: China's LED production begins to fulfill domestic demands** As recent as 2002, China imported all of its LED chips. It is now meeting half of this demand with domestic production and making the transition from incandescents to solid-state lighting. Richard Stevenson catches up with progress.
- 17** **Opinion: Unsettled outlook hangs over CPV** Typically based on III-V solar cells, concentrated photovoltaics has the potential to be a fantastic source of renewable energy. But in a world where private finance has all but disappeared, Michael Hatcher wonders whether this fledgling industry has a future.

TECHNOLOGY

- 18** **Epistar's chips plug and play:** Conventional LEDs that are used for solid-state lighting have to be connected to an AC-to-DC converter. But this bulky power supply impacts efficiency and reliability, and can be discarded by turning to Epistar's AC-LEDs that feature on-chip rectification circuits, says Carson Hsieh.



EPISTAR

Powering LEDs

Epistar has developed LEDs that can be powered by an AC source. **p18**

- 21** **Novel grating boosts brightness:** Alfalight's top-emitting laser produces far higher output powers than edge-emitters thanks to a curved grating that runs along the underside of the chip. This radical design allows beam-focusing with simple optics and is ideal for pumping fiber lasers, say Manoj Kanskar and Francois Brunet.
- 24** **Materials Update: SiC foundations assist AlN growth** Although AlN substrates have some great characteristics for UV-LED fabrication, it is very difficult to make this material. However, a fast sublimation growth process that deposits AlN onto SiC is producing very encouraging results, including incredibly low defect densities, say Mikael Syväjärvi, Reza Yazdi and Rositza Yakimova from Linköping University.
- 25** **Dots speed datacom VCSELs:** Transmitters operating well beyond 10 Gbit/s are needed for emerging communication standards. Quantum-dot VCSELs can operate at four times this, and even higher rates are promised with a design incorporating a modulator in the top mirror, says VI Systems' Nikolai Ledentsov.
- 28** **Research Review:** Nitrogen radicals repair InN epilayers...HfO₂ dielectric layer increases output power...Native platform extends emitter life.

Main cover image: Epistar has developed a process for producing LEDs that can be plugged directly into the mains. These chips feature diode-based rectification circuits. See p19. Credit: ITRI.

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Party like it's 1973



It's 1973 and the oil crisis has triggered a global slump. The world has entered a recession. Does this sound familiar yet?

Meanwhile, the silicon semiconductor industry is embarking on a transition that will ultimately usher in an explosion in demand for consumer electronics many years later.

That transition didn't take long. In attempting to make more efficient use of the supply of silicon, wafer suppliers convened a standards meeting. Under the supervision of a SEMI industry group, those suppliers agreed a simple draft for 2 and 3 inch wafers. Just a year after the first standards were drafted, between 80 and 85% of wafers conformed.

That was the starting gun for the silicon revolution. At 1976 transistor dimensions and prices, an Apple iPod would be big enough to live in and would cost a cool \$1 billion. The application of standards went a long way to creating the \$200, handheld iPod.

The LED industry now stands where the silicon industry did in the mid-1970s. That's what SEMI president Stan Myers told LED industry representatives at an event organized by the US Department of Energy (DOE). He said that although innovation will go some way to meeting the DOE's white LED goals of 200 lm/W and \$2 per kilolumen by 2015, the

industry must now collaborate on cost reduction.

He's right. Today's kilolumen-scale LEDs cost about \$25. So even if device efficacy is doubled, far more is needed to achieve the cost goal. Standards – and, more fundamentally, industry collaboration – are required to create the additional yield improvements, productivity gains and manufacturing cost reductions that are needed.

Right now, the leading LED manufacturers might not be too keen on that collaboration, preferring instead to protect their profit margins by maintaining proprietary designs and processes. However, much of the silicon industry felt the same way back in 1973.

There is an important difference. Governments around the world, from Korea and China to the US, are using taxpayers' money in the form of stimulus packages to create the very demand for high-brightness LEDs that those leading manufacturers stand to benefit from.

In the interest of making a serious impact on electricity consumption, and giving the world's taxpayers better value for money, LED makers should take Myers' idea forwards. In the end, like the silicon manufacturers before them, they will benefit from a massive market expansion.

Michael Hatcher *Editor*

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Riber	11	Spire Semiconductor LLC	7

SiC Material Defects Impact Device Performance



By Tom Pierson

Product Marketing Manager,
Growth and Emerging
Markets Group
thomas.pierson@kla-tencor.com

Reducing silicon carbide (SiC) material defects and increasing reliability of SiC devices will accelerate the commercial potential of this technology. One of the most opportune and exciting commercial opportunities ahead for SiC is the hybrid electric vehicle (HEV). HEV components are moving from silicon-based devices to SiC-based devices to power the electric motor. The reason is simple - the silicon chip has to be cooled to maintain device junction temperature around 85°C. To accomplish this, a dedicated water-cooling system different from the one responsible for the engine is required. HEV manufacturers are aiming to reduce cost by implementing SiC-based electronics that can readily withstand temperatures exceeding 150°C, thereby eliminating the need for a second water-cooling system. This transition will enable power module savings of approximately 15%.¹

The strict reliability requirements of the automobile industry demand that SiC device quality control begin at the substrate level. A recent article published by National Institute of Advanced Industrial Science and Technology (AIST) reports on the use of optical surface analyzer (OSA) technology for improved quality control of SiC materials.² OSA inspection combines the elemental principles of scatterometry, ellipsometry, reflectometry, and topographical analysis to detect and classify defects in substrates and epitaxial layers. Figure 1 shows data images collected from OSA scans. Defects shown include: SiC triangle defect (upper left), sapphire substrate scratch (lower left), SiC polytype defect (center), SiC wafer edge scratches (upper right), and GaN epi pit (lower right).

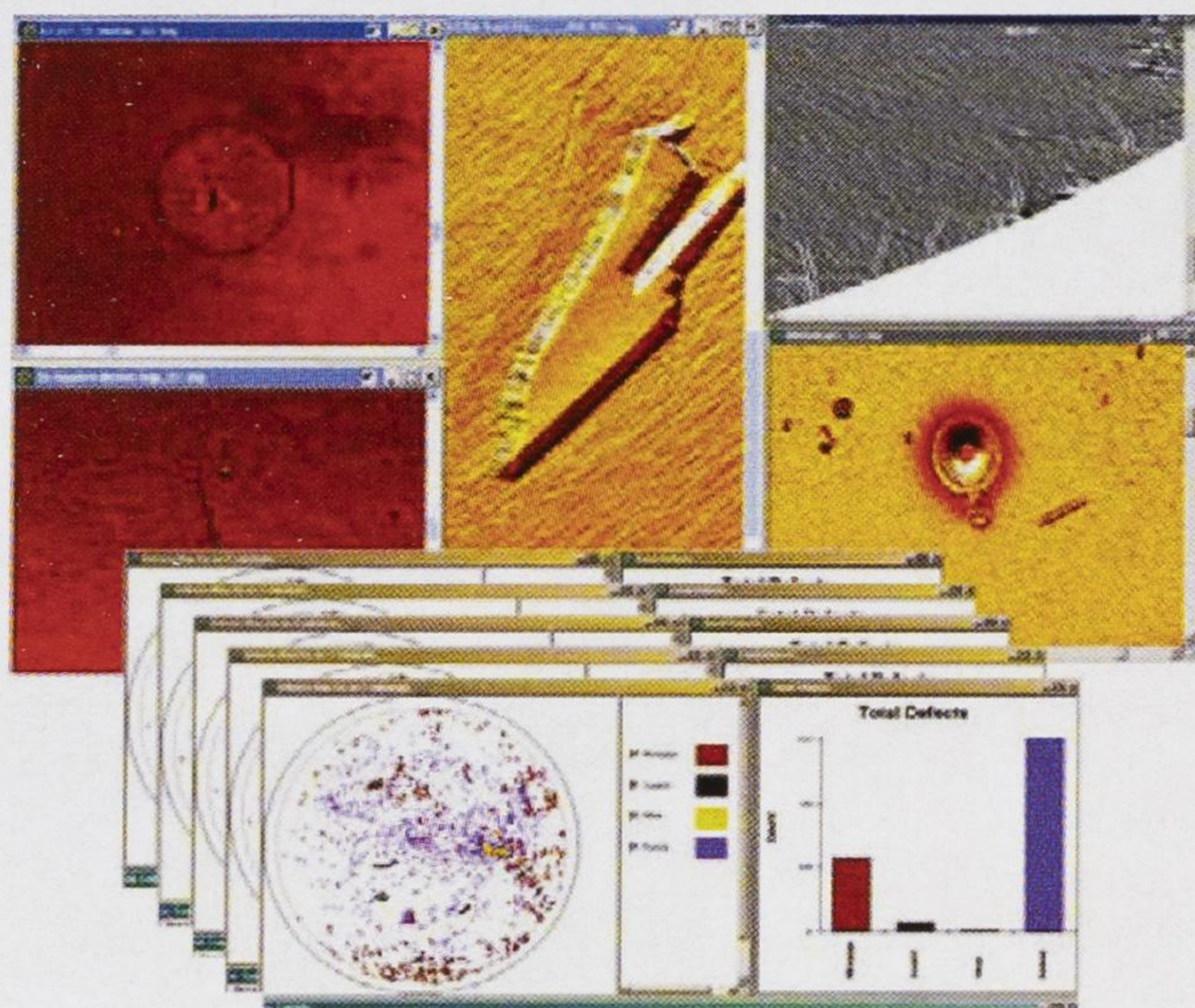


Figure 1. Advanced 4-channel imaging of OSA technology for defect analysis and identification of mission-critical defects of interest (DOI). Automatic defect classification software provides the most advanced recipe creation for DOI classification. High-throughput scanning analysis delivers summary reports including defect maps, log files, and automated pass/fail assignments.

The article from AIST states, *"There is a great need for an in-line, high-speed and non-destructive inspection system capable of evaluating and analyzing the quality SiC wafers for SiC power devices. We have examined whether the laser-based optical non-destructive inspection system by KLA-Tencor meets these requirements."*

As SiC high-power devices move to larger-area dies, substrate and epi defectivity becomes more critical than ever. The Hatakeyama, et. al. report continues, *"At present, the defect density of a commercial device-grade SiC wafer may be between 5 and 10 cm⁻², the target defect density is less than 0.5 cm⁻²."* It is reported that high defect densities on epitaxial wafers will pose a major yield problem during mass production of SiC devices. To investigate the impact of epi defects on device characteristics, the AIST research team fabricated MOS capacitors. Time zero dielectric breakdown (TZBD) and lifetime tests were performed and it was reported that the poor quality of epi degraded both the breakdown voltage and reliability of the MOS capacitors.

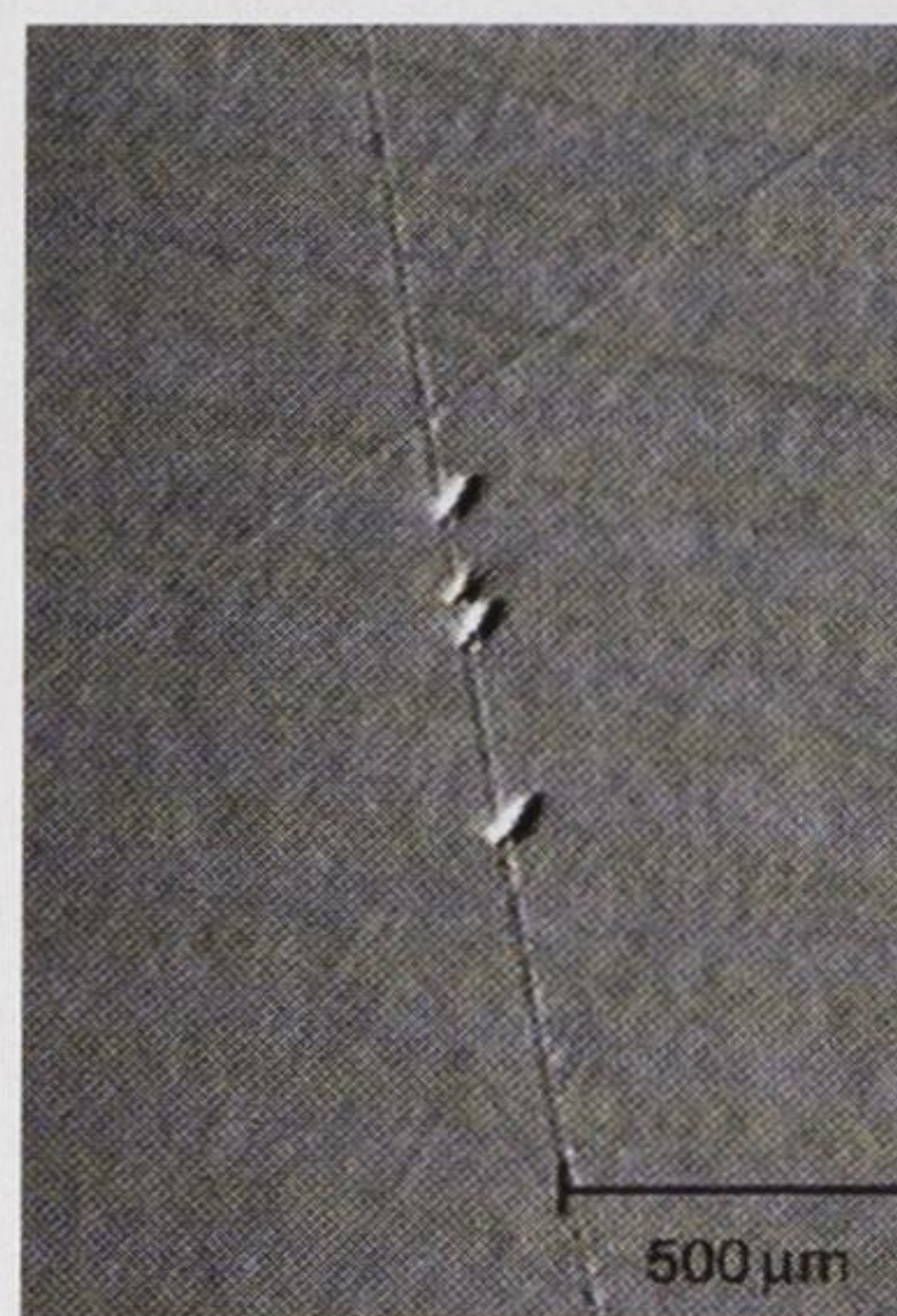


Figure 2. Topographic OSA image of SiC carrot epitaxial defect caused by substrate scratch.

The AIST research team also investigated micropipes which are known killer defects on SiC wafers that have long impacted device yield. The researchers used OSA inspection to automate the detection and classification of micropipes to map the density and location. Micropipes were later verified by stereomicroscope. The team also linked SiC substrate scratches to subsequently grown "carrot" epitaxial defects formed along the substrate scratches as shown in Figure 2.

OSA technology is being used by industry leaders to monitor production lines, identify mission critical defects of interest, and create process-specific recipes to detect and classify killer defects. Today more than half of all SiC wafers produced worldwide are inspected with OSA technology.

ACKNOWLEDGMENTS

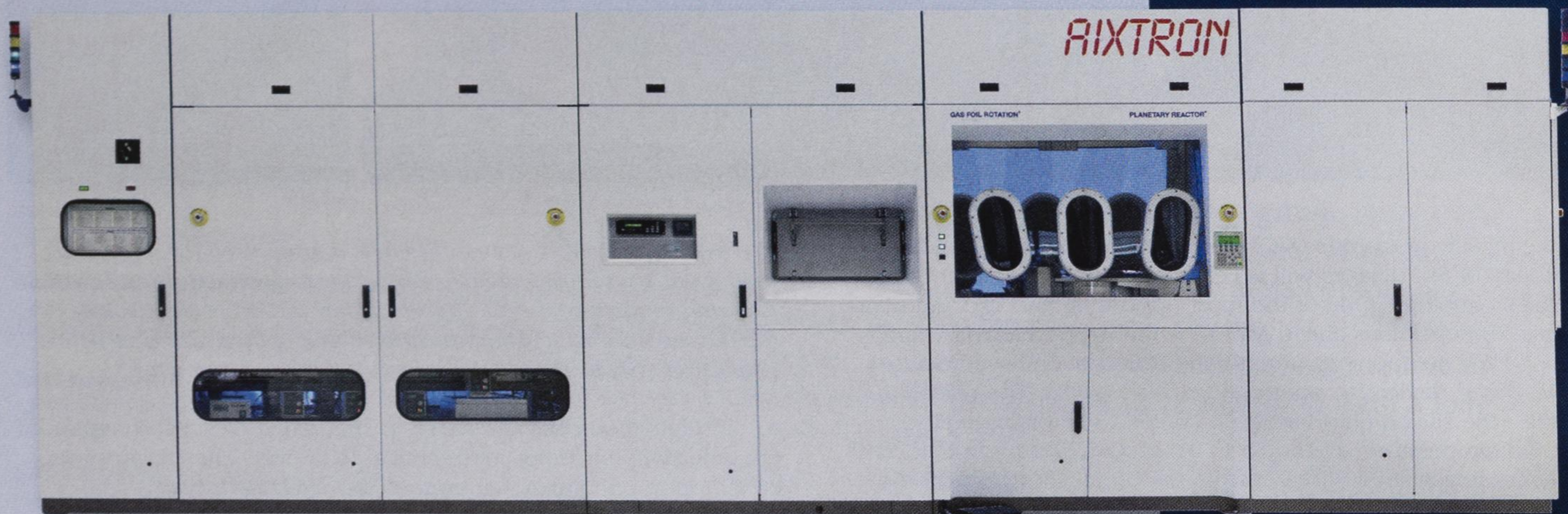
KLA-Tencor would like to thank the research team at AIST for their investigation and report.

1. *Status of the SiC power devices market: If only we had a switch...*
Yole Development, July 19, 2007.

2. T.Hatakeyama, et. al. *Evaluation of the quality of commercial silicon carbide wafers by an optical non-destructive inspection technique.*
National Institute of Advanced Industrial Science and Technology (AIST),
Journal of Crystal Growth 310 (2008) 988-992

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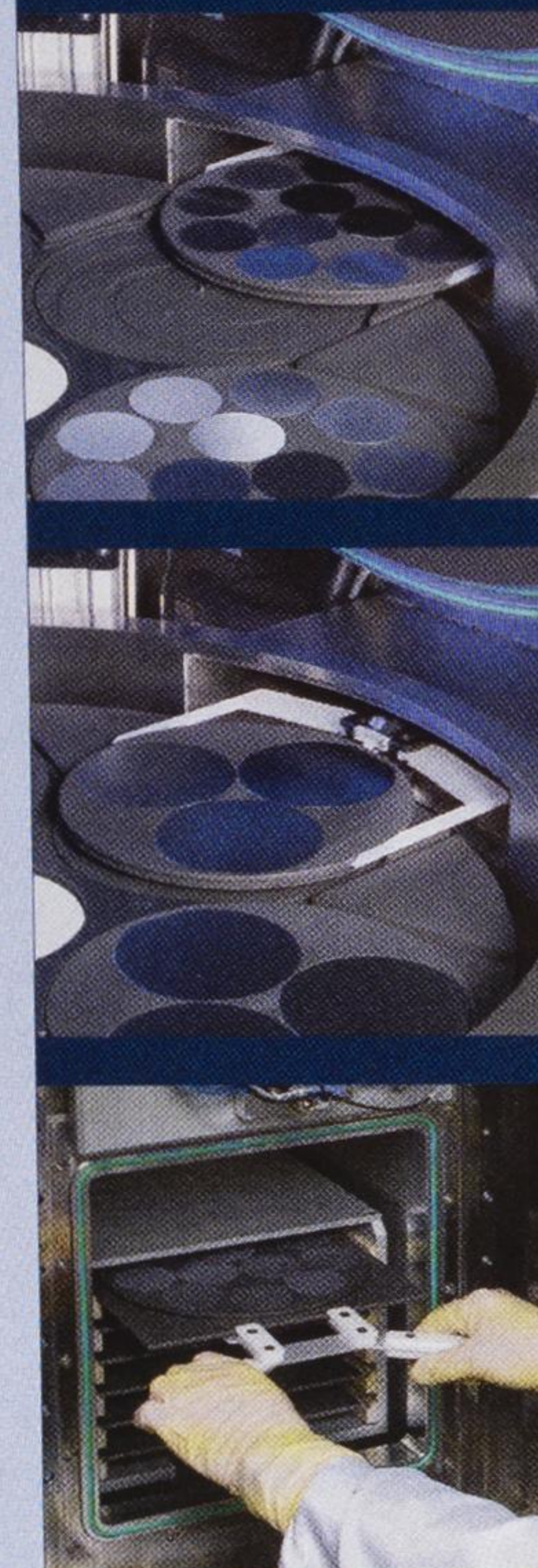
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ECONOMIC STIMULUS

LEDs lead the way in Taiwan's \$1 bn plan

Taiwan's cabinet has passed a motion calling for a NT\$45 billion (\$1 billion) investment in "green energy" technology, which will benefit the country's LED industry.

NT\$20 billion is earmarked for research and development, and NT\$25 billion for infrastructure deployment projects and subsidies over the next five years. Specific infrastructure elements include installing 700,000 LED traffic lights and building Asia's largest solar power plant.

Ian Chan of the Industrial and Technical Research Institute (ITRI) of Taiwan says that NT\$4 billion will be spent directly on LED technical research. Chan, who is vice-president and general director of ITRI's Electronics and Optoelectronics Research Laboratories, says that subsidies would also increase domestic LED demand by NT\$40 billion.

LED component and system makers are most likely to benefit from the plan, Chan says, including companies such as Everlight, Unity Opto Tech and BrightLED. However, funds will undoubtedly trickle down to die



Taiwan's premier Liu Chao-shiuan announces his country's renewable energy plan, which aims to make "green" technologies responsible for 6% of Taiwan's manufacturing revenue and create 110,000 jobs.

producers. "In the short-term, this plan will encourage investment and will help the Taiwan LED industry overcome the financial tsunami," Chan told *Compound Semiconductor*. "It can also speed up building a complete LED lighting industrial chain."

The purpose of the overall plan is to turn green energy into a NT\$1.15 trillion industry by 2015. Economy minister Yiin Chii-ming says that the research and development ele-

ment is designed to induce NT\$200 billion investment from the private sector.

The ITRI plays an important role in developing Taiwan's industrial technology, Chan points out, and the renewable energy sector is no different. "We are really optimistic about this NT\$1 trillion target," Chan said. "With support from government and impetus from the ITRI, the industry will definitely usher in a new era."

However, a substantial part of the plan hinges on the passage of a long-stalled bill through Taiwan's legislature prior to the end of the current session, which concludes in July. Taiwanese President Ma Ying-jeou has stressed the need to integrate the seven proposed versions of the bill, which should provide a legal basis for the procurement and production of renewable energy, into one.

The bill, which has lain idle in the legislature for six years, should establish a viable market and remove hurdles to alternative energy development. With photovoltaics, wind power and biofuels all covered by the plan, this could be a key stumbling block.

III-V MANUFACTURING

RFMD prepares GaN foundry and solar

GaAs chip pioneer RF Micro Devices (RFMD) is readying two departures from its traditional business model, as it enters the foundry services and solar-cell markets.

In the biggest leap from its staple handset chip market, RFMD has partnered with the US National Renewable Energy Laboratory (NREL) on photovoltaics.

"RFMD and NREL have agreed to collaborate on a commercially viable, high-volume process for manufacturing compound semiconductor photovoltaic cells based on NREL's record-holding tech-

nology," said Konrad Alvarino, general manager of RFMD's new technology commercialization center.

The Greensboro, NC, company will produce cells for use in concentrated photovoltaic systems in its existing wafer fabrication facilities. It will release specific details of the products that it plans to offer over the next 12–18 months.

Meanwhile, a high level of interest from customers wanting to implement their own chip designs has caused RFMD to prepare a GaN foundry service.

The official launch will be at June's MTT-S International Microwave Symposium in Boston, MA. The foundry will run 3 inch GaN-on-SiC wafers in RFMD's Greensboro fabs and is already performing

qualification work.

These moves come as RFMD seeks a return to profitability, after recording six consecutive quarterly net losses. In the three months ended March, RFMD's net loss nearly trebled to \$49.6 million from \$17.2 million for the same period in 2008.

Nevertheless, RFMD CEO Bob Bruggeworth remains optimistic. "We are confident in our ability to leverage our expertise, and our components and compound semiconductors in multiple markets," he assured investors when announcing the latest results.

"We expect that our strategic focus will serve us well whether the environment presents challenges as it has in the current downturn or presents new opportunities for growth and profitability as it does today."

WIRELESS INFRASTRUCTURE

TriQuint signs \$50 m ZTE basestation deal

TriQuint Semiconductor was the lone GaAs industry participant in a US–China forum that saw \$5.7 billion worth of contracts signed, agreeing a supply contract with telecom equipment maker ZTE.

ZTE will buy no less than \$50 million of TriQuint components for GSM, CDMA and WCDMA infrastructure before the end of 2009. The agreement was formalized at the wider US–China business signing ceremony in Chicago, IL, on April 28.

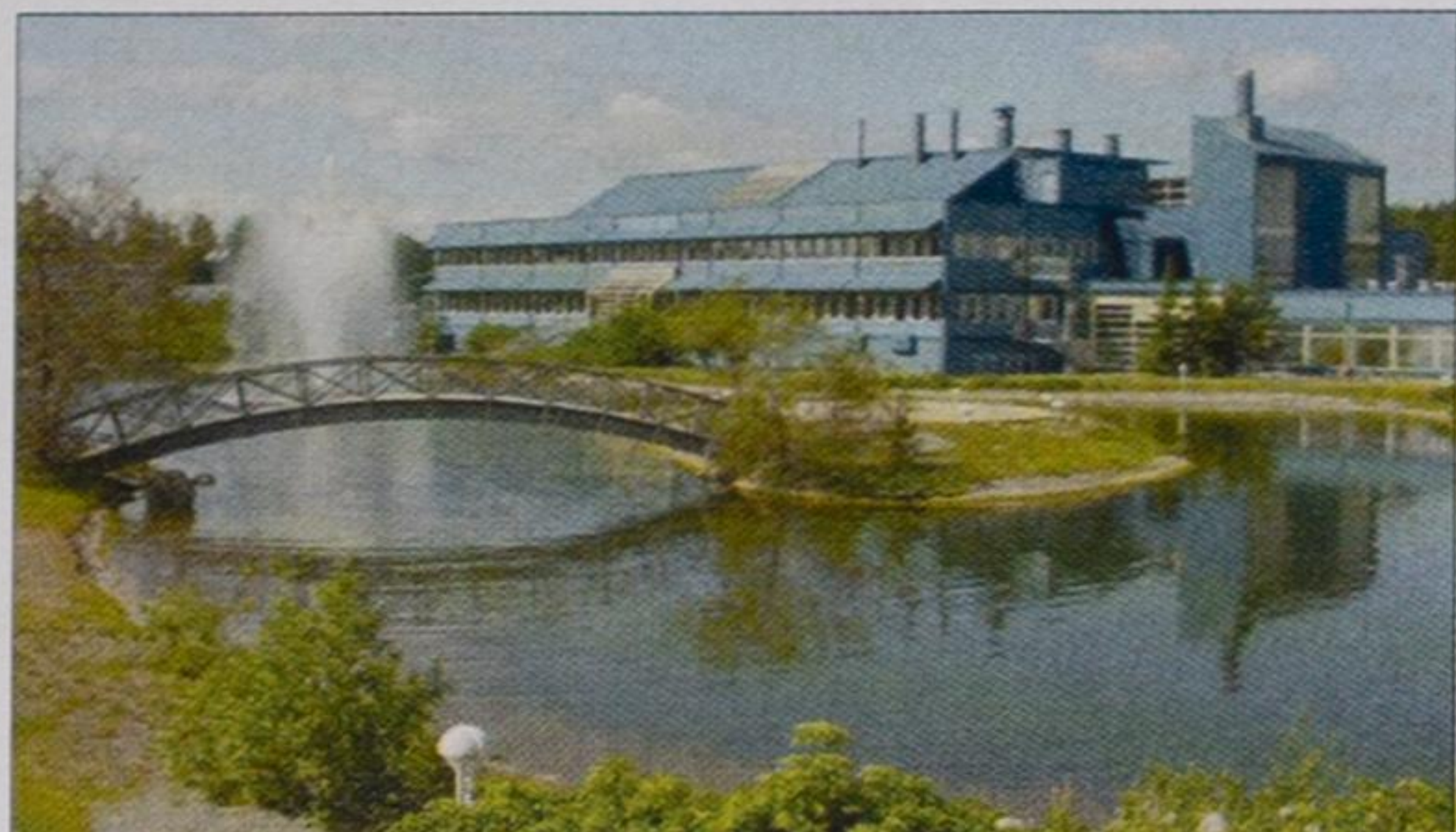
TriQuint has already said that it expects a sharp uptick in revenues in the coming months, as demand for its products bounces back from a recession-hit first quarter.

Reporting the Oregon company's financial results for the opening three months of 2009, senior executives revealed first-quarter revenues of just under \$119 million – down 20% on the closing quarter of 2008 – and a net loss of \$15.6 million.

The company predicts that the 20% fall will be reversed in the June quarter, bringing revenues back to between \$140 million and \$150 million.

OPTICAL COMMUNICATIONS

Settlements clear the way for consolidation



Syntune bought the controlling stake of Swedish InP fab Svedice (shown above) in April 2008.

Bookham and Syntune have ended their legal battles with JDSU over InP tunable lasers, ahead of key merger deals.

Norwegian fiber-optic technology firm Ignis ASA agreed to buy Syntune, after the Swedish InP tunable laser developer skirted its US competitor's legal might.

On March 20, JDSU filed a motion to terminate the US International Trade Commission case that it had brought against Syntune and its US collaborator Cyoptics. "JDSU, Syntune and Cyoptics have reached a settlement and compromise, such that issues of validity, enforceability and infringement are no longer in dispute," the motion said.

That settlement also covers the companies' dispute over the same tunable laser patents due to be heard in California but consequently dismissed on April 16. According to court documents, JDSU acknowledges that a redesign of Syntune's tunable laser set for future availability does not infringe its patents.

Most of the other details of the settlement remain confidential. However, any damages are likely to be lighter than those felt by Bookham, the other chip-making defendant in the ITC suit. With the San Jose-headquartered company unable to execute any similarly evasive maneuvers, it will pay up to \$8 million. This comprises an initial \$3 million and "up to" \$1 million per year for the next five years.

Having concluded the lawsuit, Bookham officially united with fellow optical component manufacturer Avanex under the name Oclaro on April 27. Alain Couder, who moves from being CEO of Bookham to taking over the same role at Oclaro, claims that his company's tunable lasers are taking an increasing share of the available market.

Passive optical component producer Ignis signed off its agreement to purchase Syntune on April 17. "Syntune has invested a significant amount of time and resources in

the development of very promising tunable laser products," said Thomas Ramm, CEO of Ignis ASA. "We believe that Syntune grants us access to technologies and expertise that will be crucial to compete in the integrated optics markets of the future."

Subject to agreement at an Ignis shareholder meeting on May 15, Syntune's current owners will receive 8.05 million Ignis shares in return for their equity. With Ignis' stock valued at 4.05 Norwegian Krone (\$0.61) per share when the deal was announced, that alone would make Syntune worth \$4.9 million.

Ignis will take on Syntune's existing debts of 41.8 million Swedish Krone (\$5 million). However, the deal is contingent on Syntune's current owners contributing 25 million Swedish Krone in return for additional Ignis shares to offset this debt.

JDSU is also rationalizing its own business, integrating its entire III-V chip manufacturing into one site. Production at the Louisville, CO, facility that JDSU gained when it bought Picolight in 2007 will move to its San Jose, CA, InP and GaAs fab.

GaAs VCSEL production at the Colorado fab will cease before the end of September, combining all of JDSU's chip manufacturing in a single location. When it was purchased, the facility housed 130 employees.

DEPOSITION EQUIPMENT

\$21 m loss brings cost cuts at Veeco

Deposition system maker Veeco will shut down production and reduce its employees' salaries in response to what it calls "extremely weak business conditions".

Although the company was already streamlining its operations, in the quarter ended March its revenue from selling deposition equipment to the LED and solar industry nearly halved year over year.

From \$42.1 million in the first quarter of 2008, this figure dropped to \$22.2 million for the same period in 2009. Orders received and booked for the same sector fell to \$28.5 million from \$38.7 million. Veeco's overall revenue for the period slumped to \$62.8 million from \$102.3 million a year ago, and its loss widened to \$20.9 million from \$2.3 million.

"Clearly this is a difficult time for Veeco," said CEO John Peeler. "However, our restructuring activities are on track."

The firm's worst-case outlook predicts another quarter of similar revenue and loss. This required temporary steps beyond existing measures, including moving the Emcore Somerset, NJ, MOCVD system pro-

duction site to a fully outsourced model.

The extra savings will not, though, be made by further reducing the company's target of employing less than 1000 people by the end of 2009. From 1318 at the end of September, Veeco had shrunk its headcount to 1091 at the end of March.

Although Veeco predicts more losses in the current quarter, Peeler cautiously suggests that the low point in its business cycle has passed. The level of usage of deposition equipment already owned by LED manufacturers is increasing and more quotes for extra systems are being received, he says. Furthermore, there are currently no extra signs of problems with existing orders.

RESEARCH AND DEVELOPMENT

III-V fabrication heads to the Middle East

Compound semiconductor research looks set to receive a boost in the unlikely Middle Eastern locations of Saudi Arabia and Turkey.

The King Abdullah University of Science and Technology (KAUST), located in Jeddah and backed to the tune of \$10 billion by the Arab state's leading crude oil producer Aramco, is investing heavily in semiconductor equipment.

KAUST is still under construction and due to open in time for the new academic year on September 5. Meanwhile, cleanrooms at Turkey's \$120 million Institute of Materials Science and Nanotechnology (UNAM), located at Bilkent University in Ankara, are scheduled to be "fully functional" this month.

KAUST's Advanced NanoFabrication Center will investigate nanoelectronics, photonics, LEDs and functional materials. Already set up with Class 1000 and Class 100 cleanroom capability, and instrumentation including nanoimprint lithography and an electron-beam writer, KAUST has ordered more high-end equipment from Oxford Instruments Plasma Technology.

The order included several reactive-ion-etch PlasmaLab systems, PECVD equipment and a FlexAL tool for atomic layer deposition. MOCVD equipment is also set to be installed, although there are no current plans to purchase an MBE system.

At UNAM in Turkey, two inductively coupled plasma etch tools from Surface Technology Systems (STS) are on order. One of the tools will use chlorine-based process gases to etch III-V materials, with the second using fluorine for work on silicon.

UNAM's 400m² cleanroom is part of the first such national user facility for III-V work in Turkey. Users will have access to



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B5 ☐ Manufacturer of systems/components using compound semiconductor devices
B6 ☐ Semiconductor equipment or semiconductor materials company
B7 ☐ Finance or investment firm or market research/analysis
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C3 ☐ III-Vs: nitrides
C4 ☐ III-Vs: antimonides
C5 ☐ II-VIs
C6 ☐ SiC
C7 ☐ SiGe, SOI, epitaxial oxides, other silicon heterostructures
C8 ☐ Other (please specify) _____

5. What types of semiconductor device are manufactured or developed at the place where you work? (tick all that apply)

- D1 ☐ GaAs ICs or discretes
D2 ☐ InP ICs or discretes
D3 ☐ Wide bandgap ICs or discretes
D4 ☐ Devices employing SiGe, SOI or other silicon heterostructures
D5 ☐ Telecom laser diodes
D6 ☐ Non-telecom laser diodes
D7 ☐ VCSELs
D8 ☐ LEDs
D9 ☐ Solar cells
D10 ☐ Detectors
D12 ☐ GaN laser diodes
D14 ☐ Power semiconductor devices
D11 ☐ Other (please specify) _____

6. Please tick other relevant publications you receive/read. (tick all that apply)

- E2 ☐ Semiconductor International
E3 ☐ Solid State Technology
E4 ☐ Laser Focus World
E5 ☐ Photonics Spectra
E7 ☐ EuroAsia Semiconductor
E8 ☐ Semiconductor Today
E6 ☐ Other (please specify) _____

7. How many employees are there at your site? (tick one box only)

- F1 ☐ 0-19
F2 ☐ 20-49
F3 ☐ 50-99
F4 ☐ 100-499
F5 ☐ 500-999
F6 ☐ More than 1000

8. Apart from you, how many people in your place of work are likely to read your copy of Compound Semiconductor? (tick one box only)

- G10 ☐ 0
G11 ☐ 1-3
G12 ☐ 4-10
G13 ☐ 11-20
G14 ☐ 21+

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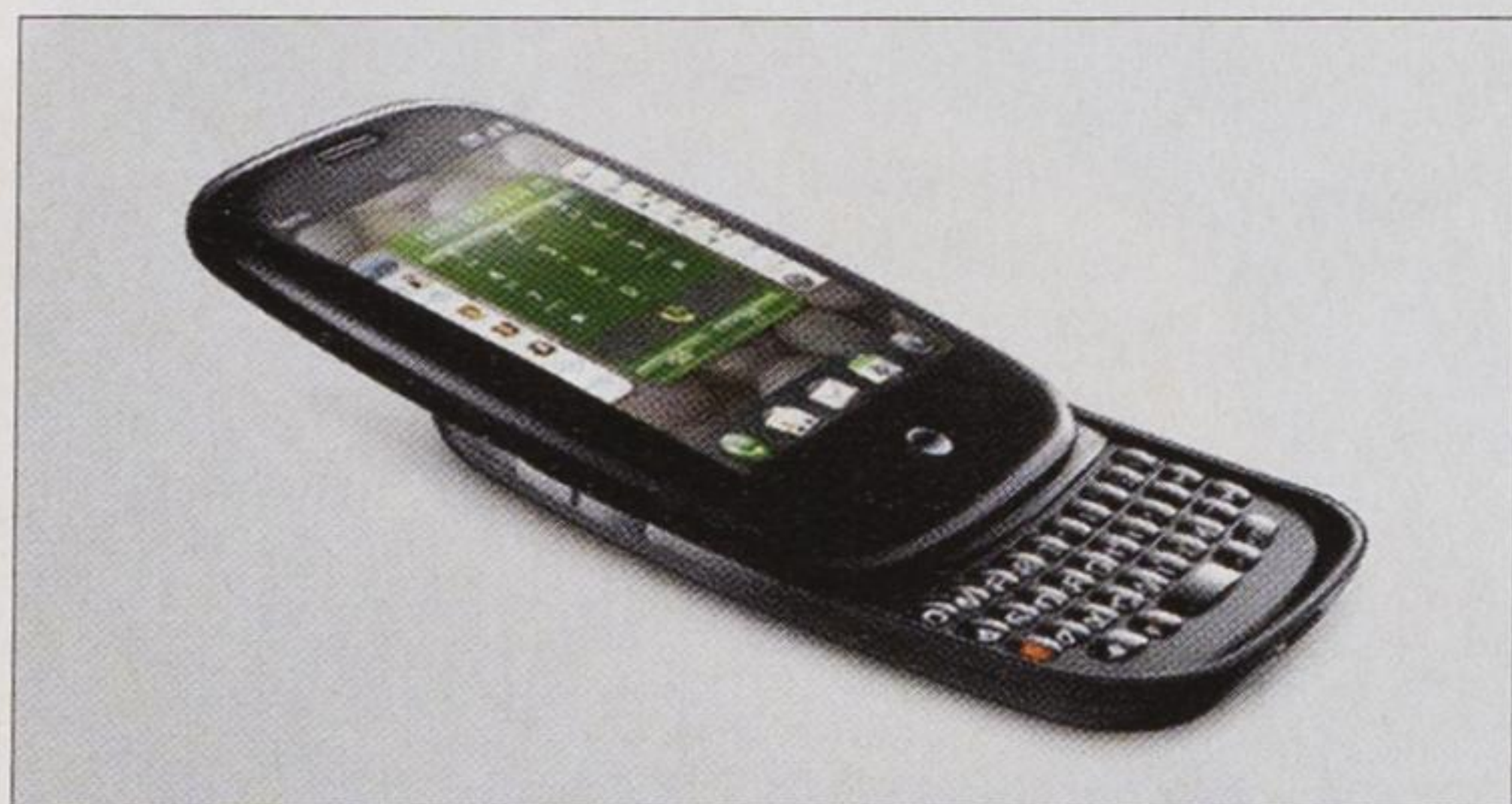
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a range of epitaxy equipment, including MOCVD, MBE and low-pressure CVD tools, as well as the latest STS kit, which will be one of the "workhorses" of the UNAM cleanroom.

GAAS MANUFACTURING

CEO charm offensive gives Anadigics hope



Anadigics says that a new flagship 3G Palm smartphone that is "getting rave reviews" – likely to be the Palm Pre – will include its GaAs PAs.

Anadigics' chips were successfully designed into 50 new wireless products in the first quarter of 2009, aiding the company's battle to stop its revenues shrinking any further.

Palm and Research in Motion have joined traditional key customers LG and Samsung in using Anadigics' power amplifiers (PAs) in 3G smartphones, supporting the company's claims of technology leadership.

CEO Mario Rivas has spent much of the time since arriving in February flying from the Warren, NJ, headquarters to rebuild relationships with the likes of Samsung. And while the Korean handset manufacturer no longer purchases the numbers of GaAs chips from Anadigics that it once did, Rivas believes that its downward trend is now reversing.

Despite these positives, the company's

\$30.5 million revenues for the three months ended March were far below the \$74.4 million that it achieved in 2008. However, this figure did beat its own expectations by approximately \$1 million. The bonus revenues arose from rush orders, which benefited from what Anadigics says is now its fastest production process ever.

This could be an important factor in reviving fortunes with companies like Samsung, who took their business away after Anadigics was unable to supply enough PAs. Although Rivas believes that the current economy will bring more rush orders, these cannot be relied on. Consequently, Anadigics predicts an 8–10% decline in sales for the current quarter, added to by a customer that is decreasing its inventory levels, that Rivas is disappointed with.

However, the firm foresees its quarterly loss falling from \$21.9 million in the March period, which itself is a drop from \$36.4 million in the December quarter. "Although I am not satisfied with our current financial results and second-quarter guidance, I believe that we are taking all of the necessary steps to manage costs and strengthen our business from the manufacturing and customer perspectives," Rivas said.

According to Mike Burton of investment banker ThinkEquity, even Anadigics' best efforts might not bring a turnaround. "We remain concerned that Anadigics' competitors are working hard to squash any attempts to stage a comeback," he wrote.

If the hybrid model cuts Anadigics' operating expenses enough, Burton says that some people might expect profitability in the second half of the year. However, that projection would be based on the kind of growth that Anadigics has seen in the past – and Burton says that this will be elusive. "We are not expecting a profitable second half," he concluded.



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...NEC Electronics and Renesas merge

Japanese component makers NEC Electronics and Renesas plan to sign an agreement at the end of July that will lead to the integration of its business operations on April 1, 2010. The companies are pursuing the move to strengthen their businesses "in light of global competition in the semiconductor market."

...TeliaSonera selects Infinera

Infinera's highly integrated InP chips will be exploited nationwide in the US by TeliaSonera, the largest Nordic telecommunications

provider. Its subsidiary, TeliaSonera International Carrier, is upgrading its US network and deploying the Sunnyvale, CA, company's technology to support its vision of becoming "the global IP carrier of choice."

...AXT's revenues halve sequentially in Q1

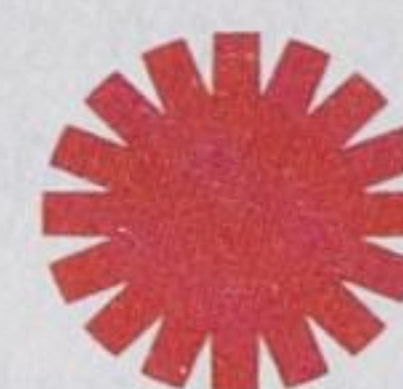
Substrate sales at AXT dropped to \$7.7 million in the first three months of 2009, from \$15.6 million in the previous quarter. GaAs substrate revenues dropped the most, falling to \$5 million. The company's net loss expanded to \$5.5 million from \$2.4 million sequentially.

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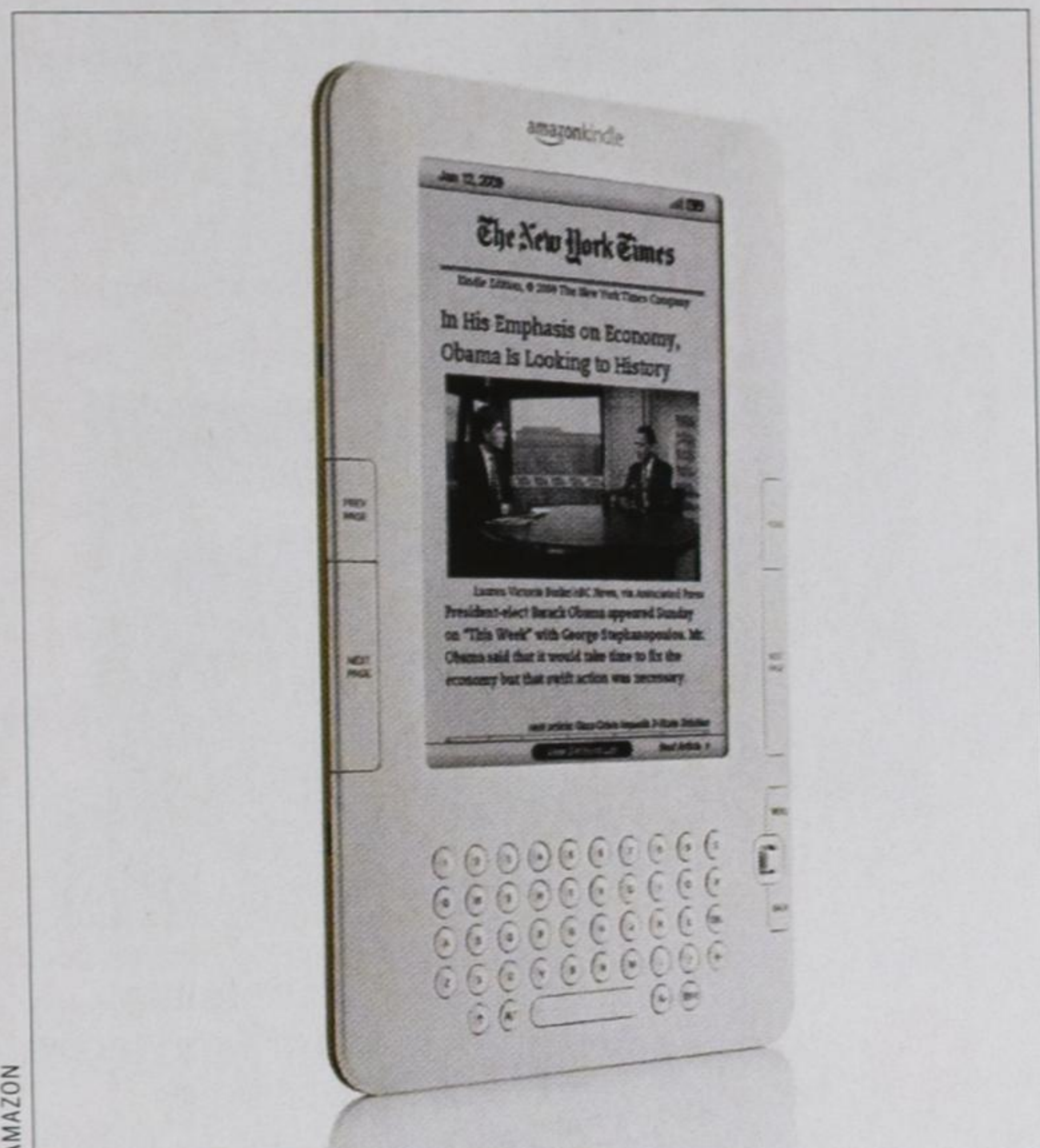


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RF ELECTRONICS

Steady Skyworks minimizes its losses



Amazon's Kindle is a prime suspect for the increasingly popular e-book reading platform "developed by one of the world's largest online retailers" that Skyworks says it is supplying chips for.

Skyworks Solutions, the Massachusetts-based manufacturer of GaAs devices, shrugged off the impact of the global recession in the opening quarter of 2009.

The company delivered revenues of \$173 million in the March quarter, \$5 million higher than previously forecast, swinging to a net loss of \$4.6 million. But in the context of the dramatic slowdown in the mobile handset market, which represents around three-quarters of Skyworks' sales, the firm's "fab-lite" manufacturing model appears to be paying dividends.

Skyworks CEO David Aldrich told investors that the company was gaining market share and, like other GaAs companies, benefiting from solid demand for high-end handsets that require better RF performance and therefore higher III-V content.

Samsung, Sony Ericsson and Motorola all accounted for more than 10% of Skyworks' sales in the March quarter, with LG and Nokia both close to the 10% figure.

Skyworks anticipates that its sales to Nokia will rise sharply over the next couple of years as the Finnish firm diversifies its supply chain to include Qualcomm and Broadcom chipsets.

With Skyworks also gaining a slot in "an increasingly popular e-book reading platform" – thought to be Amazon's Kindle – executives are confident of sailing through what Aldrich called the "choppy patch" that the handset market is experiencing.

Another possible source of high-volume demand for RF chips is "smart metering", which helps to improve power control across the electrical grid and already features Skyworks components.

Skyworks estimates that 150 million of these meters will be needed in the US by 2012, each with the potential to include \$3 to \$6 worth of its parts. Aldrich described the application, which offers healthy profit margins, as "recession proof".

Electricity meters that can be remotely read are a key element of "smart grid" technology that will benefit from a \$4.5 billion chunk of the American Recovery and Reinvestment Act. "The new federal funding will help to encourage and accelerate new smart grid plans, and reinforce those already in place," said Sam Lucero, senior analyst at ABI Research.

Skyworks' rival RF Micro Devices has also highlighted its sales of products for smart metering, which should ramp through the June quarter.

WIDE-BANDGAP SEMICONDUCTORS

II-VI wins \$5.2 m funding for SiC

II-VI Incorporated's Wide Bandgap Materials group has gained a US Department of Defense grant to drive its SiC substrate production towards industry-leading efficiency.

In the first quarter of 2009 \$5.2 million was awarded to help the crystal growth specialist manufacture state-of-the-art 100 mm wafers economically. The grant targets the production of 6H crystal polytype semi-insulating and 4H polytype n-type substrates at the division's Pine Brook, NJ, SiC manufacturing facility.

"We expect demand for 100 mm products to continue to grow as our customers complete their line qualifications with our products," said Francis Kramer, president and CEO of II-VI.

In preparation, the Saxonburg, Philadelphia, headquartered company has upgraded 90% of its SiC crystal growth equipment to a higher-output, larger-diameter design. "Work is also being funded to accelerate the development of next-generation substrates of up to 125 and 150 mm diameters," Kramer said in his company's financial results conference call.

The company's SiC substrate orders from US defense customers held steady in the quarter to March, even as its overall revenues fell by \$16.8 million year over year.

The demand for evaluation units of II-VI's 6H semi-insulating 100 mm substrates from the US and Japan for radio-frequency elec-

tronics continued at a steady rate. Orders from commercial customers in the US and Japan were "significantly lower than planned" by comparison.

SOLID-STATE LIGHTING

Cree pushes LED performance limits



Cree's XP-G XLamp LED boasts 139 lm output and 132 lm/W efficacy when it is driven at 350 mA.

With an LED that is capable of producing light with 132 lm/W efficacy at 350 mA, and a light fixture reaching 102 lm/W, Cree has thrown down the gauntlet to the solid-state lighting industry.

The Durham, NC, company showed off its XP-G XLamp LED and its prototype LR6 luminaire at New York's Lightfair show in early May. With the XP-G producing 345 lm when driven at 1 A current, Cree claims that it is the "industry's brightest and highest-efficiency lighting-class LED".

Cree remains on schedule with its moves to increase production efficiency of large, high-brightness LEDs by making its chips on 4 inch wafers. That move should be 50% completed by the end of June, says CEO Chuck Swoboda. By the end of 2009, conversion to the larger format should be finished.

The comments came after Cree delivered net earnings of \$4 million in the latest quarter, increasing liquid assets on its balance sheet to some \$405 million.

The company, which also produces SiC-based microelectronic devices, saw net revenues for its third quarter climb by 5% year on year to \$131 million.

Although sales in the three months to March were down on the quarter prior to that, Swoboda says that the growing demand for solid-state lighting has offset the predictably weak market for LED chips in automotive and consumer applications.

● Taking a slightly different tack, Philips Lumileds launched what it calls "the world's first high-efficacy power LED specified to deliver a minimum of 100 lm/W" at Light-

fair. The San Jose, CA, headquartered firm is targeting the Luxeon Rebel ES specifically at realizing the energy-saving capabilities of solid-state lighting.

LED COMMERCIALIZATION

SEMI: time for LED makers to collaborate

The president of SEMI, the worldwide microelectronics industry association, has warned LED makers that they must seek global standards and collaboration, or they will miss key targets in their bid to revolutionize the lighting industry.

Speaking at the US Department of Energy's (DOE's) solid-state lighting manufacturing workshop on April 21, Stan Myers said that the LED industry now reminds him of the silicon business in the mid-1970s.

"Wafers were two or three inches [in diameter] in 1975 and were posing tremendous challenges to manufacturing," Myers told delegates. "Throughput was only a fraction of what it is today, yield was approximately 50–60% and equipment utilization was in the mid-50% range."

To meet the long-standing cost-per-lumen targets set by the DOE, technological innovation alone will not be enough, Myers stresses. "Today's price for LEDs is more than \$25 per kilolumen – more than an order of magnitude greater than the [2015] goal."

While a doubling in device efficiency will contribute towards reaching that goal, Myers believes that a further eight- or ten-fold cost reduction must come from yield improvement, productivity gains and manufacturing efficiencies.

However, in stark contrast to the silicon business, the LED industry is largely

uncollaborative and may not welcome the prospect of sharing trade secrets built up through decades of research. "These companies see manufacturing as a source of competitive advantage and, naturally, are very secretive about their methods and processes," Myers said.

"But we do know that they are overwhelmingly using 3 inch wafers, that throughput is less than 50 wafers per hour, and yields and equipment utilization are low to moderate, at least compared with the 90–95% rates seen in [silicon] semiconductors."

There are three key ways to overcome these obstacles, Myers says. One is effective, ongoing collaboration at all levels of the industry, both between suppliers and vendors and among those who currently consider themselves rivals. The second is dissemination of the best-known practices in manufacturing. The third is introducing industry standards to reduce costs and allow research money to be spent on true innovation, rather than incremental improvements to chip fabrication techniques.

Myers went on to describe how SEMI's own international standards for silicon devices first came into being in 1973, before which there were a remarkable 2000 individual wafer specifications.

"Semiconductor device makers and their suppliers were opposed to the idea of standards because they would need to reveal 'proprietary' information to one another," Myers recalled. This changed when several wafer suppliers convened a standards meeting under SEMI oversight to make more efficient use of a restricted supply of silicon.

The SEMI president proposes the creation of a new alliance called the HB-LED Manufacturing Forum, through which a technology roadmap could be developed in open dialog with suppliers.



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...Microvision taps Corning for green lasers

Optics giant Corning has signed a deal to supply pocket-projector manufacturer Microvision with frequency-doubled green semiconductor lasers. Laser projection is less common than LEDs, and getting enough green light sources has delayed the Redmond, WA, based projector maker's production.

...Microsemi buys Endwave division

San Jose, CA, headquartered fabless GaAs specialist Endwave has sold its defense and security business to key defense electronics player Microsemi. The deal sees the Irvine,

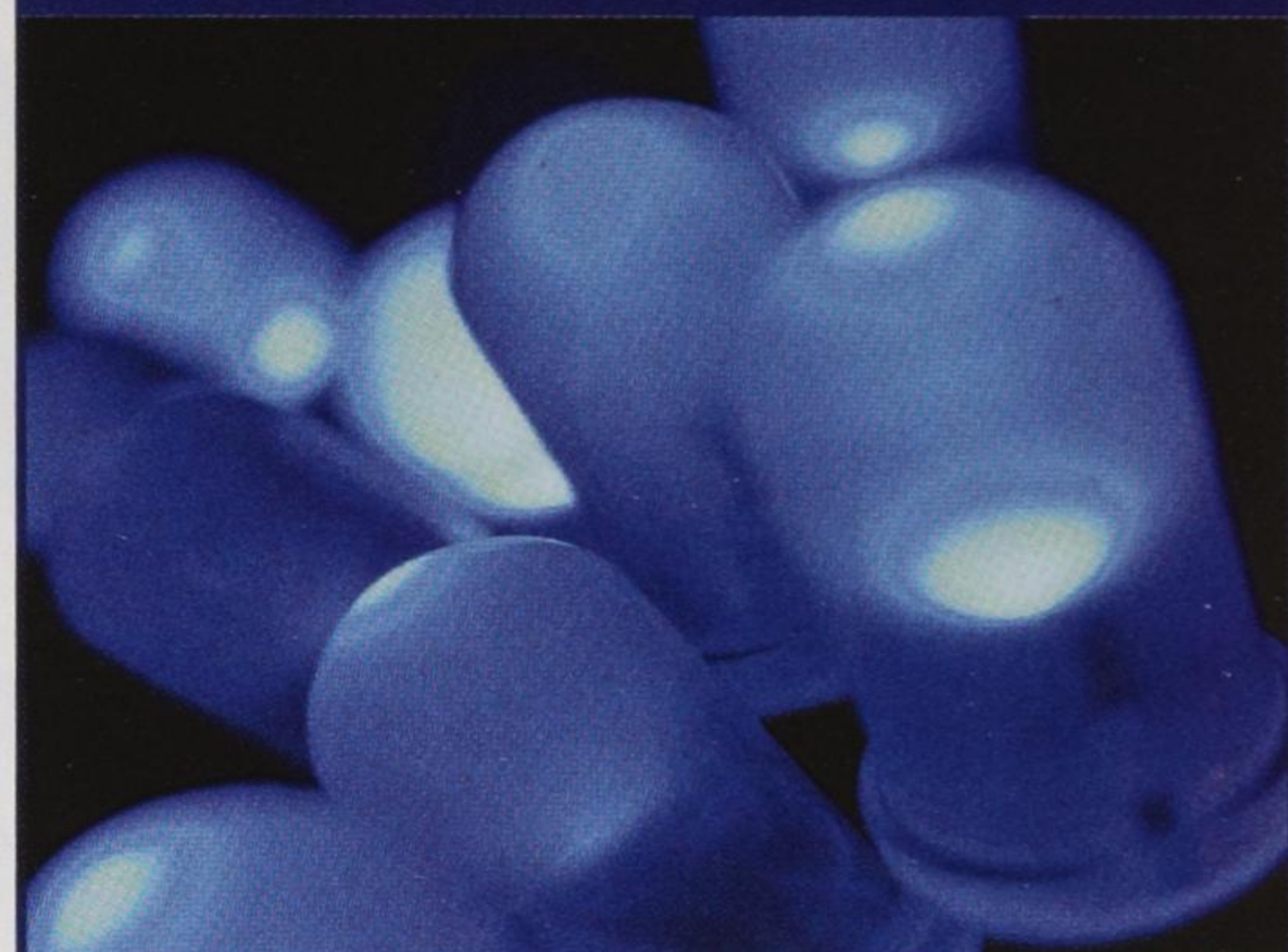
CA, firm acquire Endwave's "theater-wide" video and voice communication, advanced radar system, remote sensing and broadband transmission system technology. Microsemi paid \$28 million in cash and took on some related liabilities.

...Handset shipments suffer fastest fall

Market analyst Strategy Analytics says that global mobile handset shipments fell by a huge 13% year over year, to reach 245 million units in Q1 2009. This is the fastest decline in annual shipment growth since the modern cellphone industry began in 1983.

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LED MANUFACTURING

SemiLEDs reveals 6 inch LED progress

SemiLEDs has successfully produced blue LEDs on 6 inch diameter sapphire wafers for what it and deposition equipment supplier Aixtron say is the first time.

But despite the joint effort's promising results and significant yield benefits, SemiLEDs does not currently have any plans to upgrade its Taiwan production lines to the larger format. "We are in an R&D phase and will not plan for production until we can secure low-cost 6 inch sapphire," said Chuong Tran, president and chief operating officer of SemiLEDs.

"The price of 6 inch would have to drop down to about \$300 per wafer to be attractive," he told *Compound Semiconductor*.

Tran indicated that the 6 inch sapphire substrate market is still in an early stage. SemiLEDs will have to work hard with suppliers to guarantee enough wafers of sufficient quality to use in production. As SemiLEDs' production process involves removing the sapphire layer and replacing it with a copper substrate, Tran suggests that his company could recycle substrates to help solve this issue.

Converting an AIX 2800G4 MOCVD reactor like the one that SemiLEDs used to make the 6 inch wafers is extremely simple, Aixtron says, leaving general process conditions unchanged.

The Aachen, Germany, based company points out that larger wafers show a tendency to bow that must be controlled. "We have found ways to do this, including appropriate *in situ* monitoring," explained Rainer Beccard, Aixtron's vice-president of marketing.

Beccard says that the 6×6 inch configuration used in this joint demonstration is already well established in GaN electronics manufacturing, in particular for use with silicon substrates. "For LEDs, most of our customers are still using 2 inch, while they get prepared for 4 inch," he said. "6 inch is the next step."

- Aixtron is tentatively predicting a recovery in the LED market following increased interest from new customers in using its equipment for LED production.

Existing LED manufacturers' utilization of Aixtron's equipment has also surged to rates as high as 80%, although this has been volatile and liable to fall again quickly. To a certain extent both of these indicators are tied to a single continuing trend: LED backlighting of displays.

"We have seen backlights for laptops increase, and certainly there's been a lot

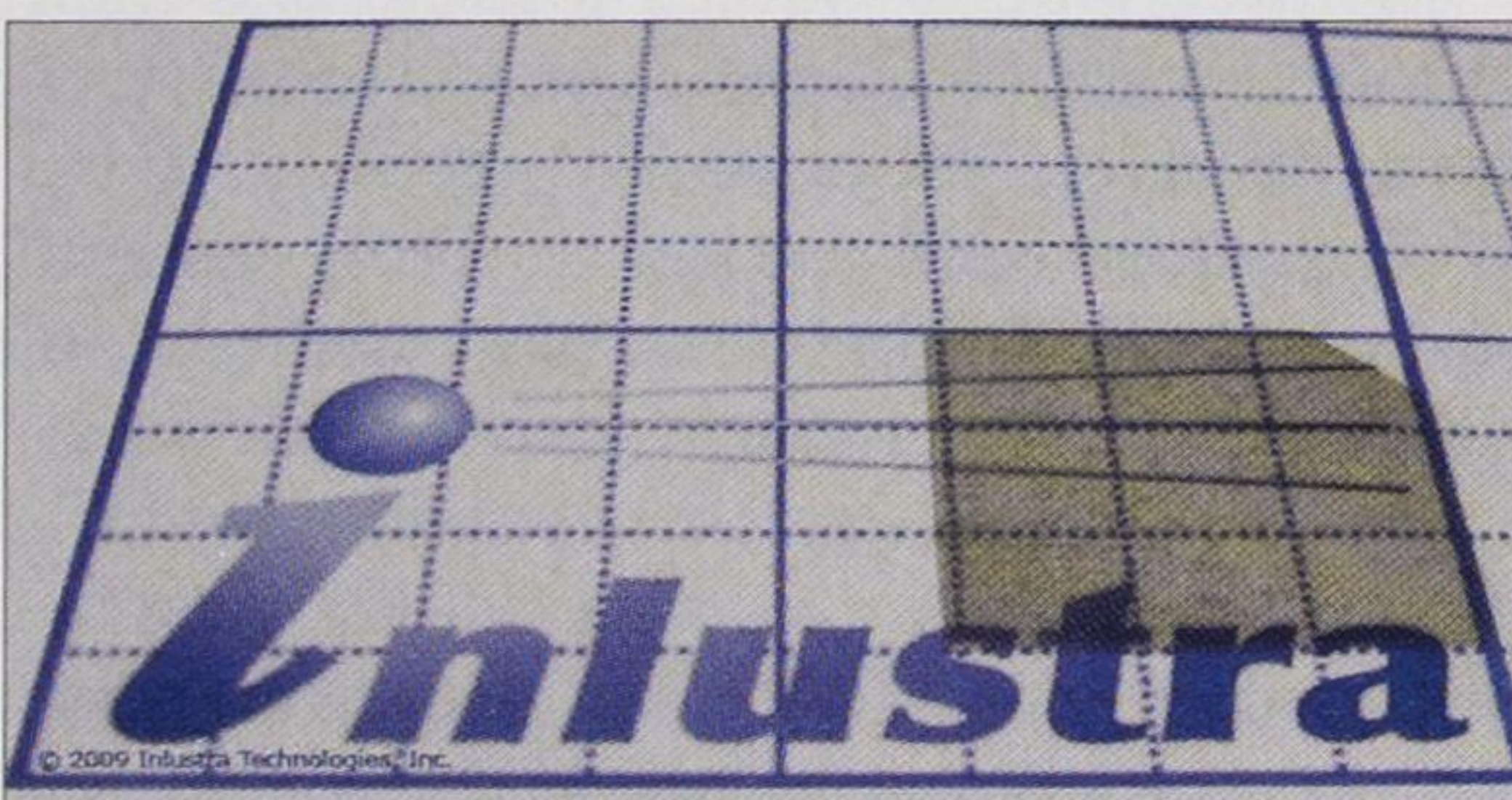
more activity on backlighting for televisions," said Aixtron CEO Paul Hyland. "This very difficult period has driven down the price of LEDs considerably. I suspect that's probably added a bit of momentum."

Aixtron is now seeing its traditional customers begin to order deposition tools again, as they benefit from this increased activity in displays. However, Hyland believes that the biggest impact in this application will be made by vertically integrated producers of consumer goods. "It's the new players coming in. All of the key players who are manufacturing TVs and monitors today are looking very closely and making investments," he said.

For the first quarter of 2009 the company recorded revenues of €46.2 million (\$62 million), down from €82.3 million in December, although net profit was up to €5.5 million from €4.1 million. Aixtron also issued financial guidance for fiscal year 2009, predicting revenues of €200 million to €220 million.

SUBSTRATES

Inlustra starts non-polar GaN production



Inlustra is now producing free-standing m-plane GaN substrates, like this one that measures slightly over three-quarters of an inch per side, in earnest.

Santa Barbara, CA, start-up Inlustra Technologies has begun selling a-plane and m-plane GaN substrates, which offer much improved performance for optoelectronic devices produced on them.

The company is currently offering non-polar GaN substrate sizes between 5×10 mm and 10×20 mm but will scale up its process to 2 inch diameter wafers within the next year. It also plans to treble its production capacity by the end of 2010.

CEO Ben Haskell says that users typically measure threading dislocation density less than $5 \times 10^5 \text{ cm}^{-2}$ in GaN films grown on Inlustra substrates. So far those customers include both academic and industrial researchers in the US working on LED and laser development.

"We believe that the dearth of high-quality, large-area non-polar GaN sub-

strates is proving to be a limiting factor in the development of robust and low-cost power-chip LEDs and laser diodes," Haskell told *Compound Semiconductor*. "Inlustra is focusing its efforts on remedying this substrate supply problem."

Haskell and fellow Inlustra founder Paul Fini worked with GaN LED pioneer Shuji Nakamura at the University of California at Santa Barbara. They have designed and constructed HVPE systems that they say take this experience in a new direction, allowing low-cost production of non-polar substrates.

PHOTOVOLTAICS

EPIR weds CdTe and multijunction solar

II-VI crystal grower EPIR Technologies is hoping to slash the cost of highly efficient multijunction solar cells to below \$2/cm².

The Bolingbrook, IL, company is using its expertise producing CdTe on silicon substrates to offer a low-cost alternative to depositing GaAs-based cells on germanium substrates. Nine months into the development of cells EPIR has expanded from 18 to 46 employees, most recently helped by a \$9 million US government grant in April.

Founded by Sivalingam Sivananthan, a professor at the University of Illinois Chicago and pioneer of CdTe-on-silicon deposition, EPIR is prototyping metamorphic multijunction II-VI cells.

While CdTe crystals are not rugged, and native substrates are extremely expensive, the EPIR president says the right know-how can replicate solar conversion efficiency record-holding III-V metamorphic designs.

"If you start looking at CdTe and also magnesium-based compounds, your choices for the bandgap are much bigger," Sivananthan told *Compound Semiconductor*. "If you go for the metamorphic then you're talking about 50% theoretical efficiency."

These cells are intended for use in concentrated photovoltaic systems at much lower cost than existing III-V offerings.

EPIR is developing cell production processes using an MBE system with a 9 inch diameter susceptor for holding wafers. Once the process has been developed, the company then plans to scale up the process, potentially as far as using 18 inch susceptors, which can hold six 6 inch wafers.

With cost a key issue, Sivananthan says that EPIR will be able to expand its CdTe wafer diameters beyond the current 5 inch maximum.

In 2008 EPIR and Sarasota, Florida "renewable energy and energy conservation company" Sunovia Energy Technologies

established a collaboration, which included each company investing in the other.

The partnership works because Sunovia has "access to the [solar] market" and to available private capital, Sivananthan says, while EPIR will focus on being the "chip house". They are working on a CPV system, which is scheduled for use in a 20MW deployment in the Dominican Republic in 2012.

WIDE-BANDGAP ELECTRONICS

TranSiC welcomes electric car plan



The Swedish government is hoping to accelerate sales of electric and hybrid electric vehicles, like this Volvo ReCharge concept plug-in hybrid automobile.

The Swedish government is planning to consign the nation's fuel-burning cars to the scrapheap by 2030, a move that suits SiC component manufacturer TranSiC.

By that date, according to a goal in the ambitious climate and energy strategy that Sweden announced on March 11, all cars in the country will be independent of fossil fuels. Based in Kista, just outside Stockholm, Volvo-funded TranSiC supplies SiC power electronic components for which electric vehicles are a key potential market.

"The 2030 goal certainly is of importance for TranSiC," said Bo Hammarlund, the company's outgoing vice-president of sales and marketing. "Despite the fact that it is 20 years ahead we can already see the Swedish automotive industry switching from combustion-only to hybrid and all-electrical vehicles."

Hammarlund says that, through its relationships with its compatriot car makers, TranSiC is involved in existing development programs intended to progress electric vehicle technology. SiC promises lower conduction and switching power losses than silicon electronics currently used in electric vehicles' power-train.

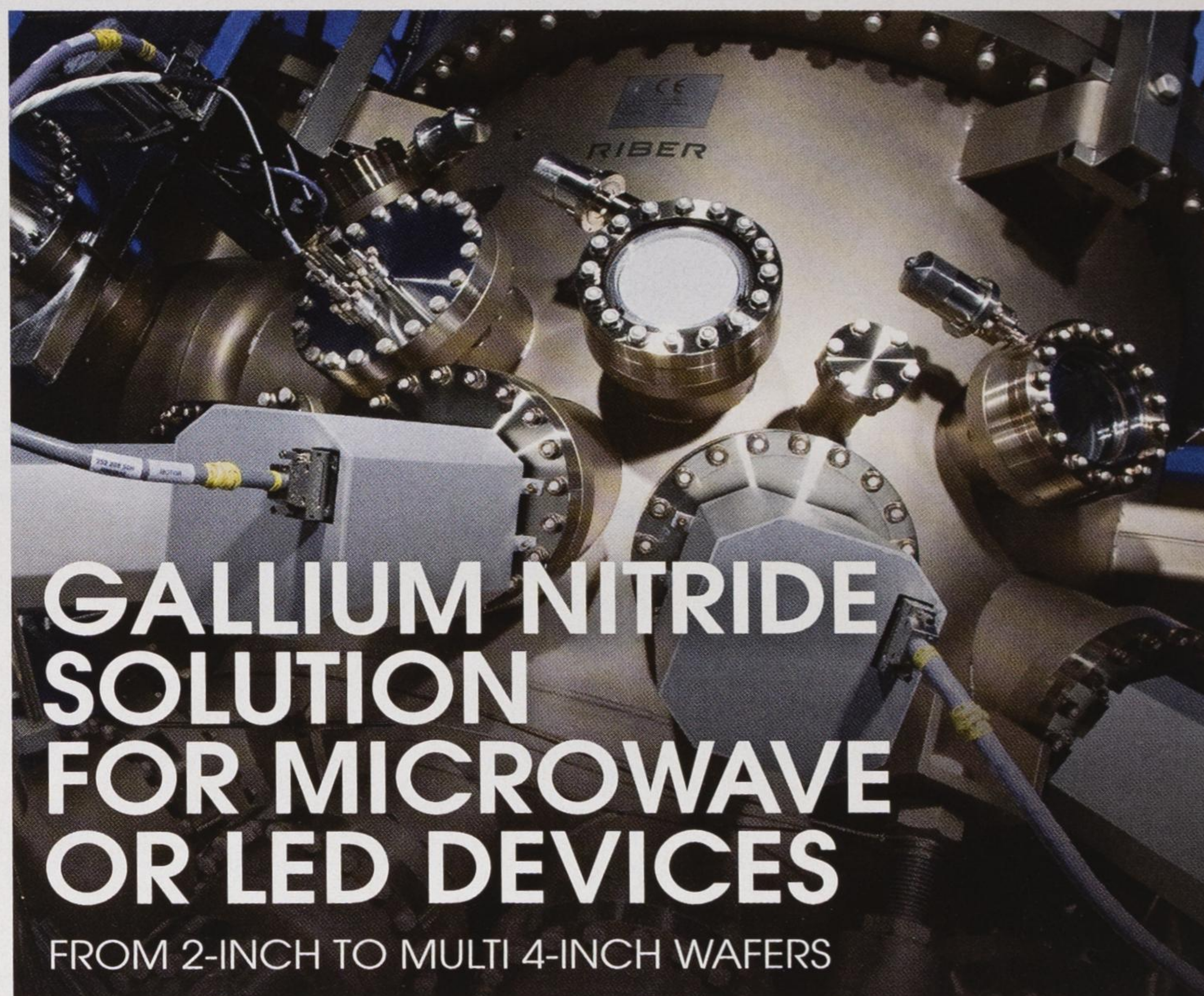
The recently announced energy strategy means that any such efforts could also be aided by government funding for vehicle energy efficiency.

As a next step in the strategy, the Swedish Energy Agency has been commissioned by the government to explore how the number of electric cars in the country can be increased. The agency was due to report back at the end of May, on subjects including possible measures for stimulating sales of electric and hybrid electric vehicles.

Sweden's climate and energy strategy developments come at a time of significant change at TranSiC. Hammarlund, one of

the firm's original founders, left his role on April 16 to pursue other entrepreneurial opportunities. On May 1, TranSiC welcomed a new CEO, Mats Reimark. He has many years of experience working for General Motors in developing power transmission for conventional and hybrid vehicles.

The company says that it has now left its start-up phase and is seeking to move from its current staffing level of 10 employees to full industrialization.



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SHARE-PRICE SURVEY

III-V industry stocks reach bottom?

The NASDAQ stock exchange has lost 40% of its value in the last 12 months, and the shares of most III-V players have fared worse. Well chosen acquisitions and manufacturing efficiency separate the winners and losers, finds **Andy Extance**.

Compound semiconductor share-price leaderboard

Rank	Company	Ticker	Share value May 1, 2008 (\$)	Share value April 30, 2009 (\$)	% appreciation	Change in rank
1	Riber (Paris)	RIB	1.26**	1.36**	8.42	+18
2	Cree	CREE	25.87	26.53	2.55	+2
3	Skyworks	SWKS	8.67	8.53	-1.61	+4
4	Kopin	KOPN	3.03	2.85	-5.94	+9
5	Hittite	HITT	39.75	36.89	-7.19	+9
6	RFMD	RFMD	3.39	2.49	-26.55	+14
7	IPG Photonics	IPGP	16.75	11.25	-32.84	+2
8	Infinera	INFN	12.66	8.22	-35.07	+10
9	NASDAQ composite	Index	2416.49	1732.47	-39.48	+3
10	TriQuint	TQNT	6.56	3.89	-40.70	-5
11	Aixtron (Frankfurt)	AIX	13.37**	7.65**	-42.79	-10
12	Finisar	FNSR	1.33	0.74	-44.36	+9
13	IQE (London)	IQE	0.23***	0.12***	-48.57	-5
14	Rubicon	RBCN	22.00	9.01	-59.05	-11
15	JDSU	JDSU	12.63	5.04	-60.10	+2
16	Endwave	ENWV	6.26	2.44	-61.02	-
17	Veeco	VECO	18.80	7.19	-61.76	-6
18	Bookham	BKHM	1.68	0.6*	-64.29	-3
19	Anadigics	ANAD	11.13	3.07	-72.42	-9
20	Emcore	EMKR	6.16	1.26	-79.55	-18
21	AXT	AXTI	5.11	0.85	-83.37	-15

*The share value for Bookham was taken on April 27, the day before it merged with Avanex to form Oclaro. **Converted to dollars using the exchange rate on April 30 (0.7568 USD to EUR).

***Converted to dollars using the exchange rate on April 30 (0.6796 USD to GBP).

Precipitous falls in stock market value dominate our annual share-price leaderboard. However, Riber, Cree and Skyworks Solutions have all performed exceptionally in comparison by ending the period with a similar price as they had at the start. This performance tallies well with the companies' sales growth and profitability, and gives credit to their manufacturing efficiency and merger and acquisition strategies.

The entire world has struggled against recession over the past year, and compound semiconductor companies were not immune. Across the community, management and employees have counted the cost of lost jobs, restructured operations and dramatic revaluations.

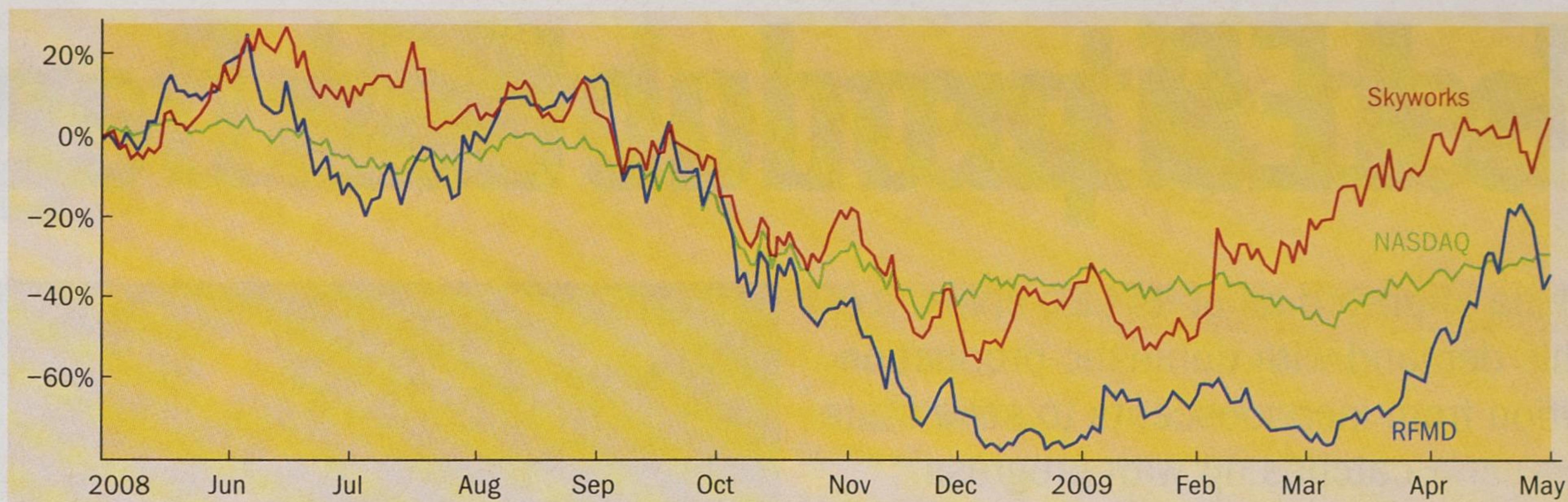
But the financial storm has not affected all equally. Some markets and companies have proven to be fitter than others and kept their head above the rising tide of trouble. Can they now emerge from the past 12 months of cost-cutting and sprint ahead of their rivals? If so, who are the likely winners? Despite the damage inflicted by the downturn on the confidence of the general public in investors, comparing share prices reveals a lot about who is poised to prosper.

That the share prices of just two companies in *Compound Semiconductor's* 20 key stocks have gone up over the past year reflects the level of the crisis. The NASDAQ composite stock market index fell by nearly 40% over the same period.

For those companies unfortunate enough to have been hit by additional complications the plunge has

been much greater. Three have lost more than 70% of their stock market value. At the very bottom, if you had put all of your savings into AXT in May 2008, you would now have less than 17% of your original investment. Since then, the three Chinese joint ventures that had previously boosted the Fremont, CA, company's business by providing cheap gallium, arsenic and germanium have presented difficulties.

While LED makers couldn't manufacture quickly enough for the eye-catching displays at the Beijing Olympics, AXT was paralyzed by material shipping restrictions imposed by the Chinese government during the games. More recently the global recession ground the aluminum plant that houses and supplies power to a gallium-producing joint venture to a halt. These events combined with the fall in demand from handsets that tumbled AXT's revenues from \$19.6 million in the first three months of 2008 to \$7.7 million for the same period in 2009. With this sales contraction it seems hardly surprising that AXT has seen the biggest drop in share price in the III-V sector this year,



While RF Micro Devices' (RFMD's) share price began recovering on March 9, in parallel with recovery in the NASDAQ stock exchange, Skyworks Solutions' recovery could be traced back as far as December. Skyworks' revenues have now been higher than RFMD's for two consecutive quarters, positioning it to emerge from the credit crunch as the leading GaAs manufacturer.

and former CEO Phil Yin left the company in March.

Although Emcore would have been almost as disastrous an investment, wiping nearly 80% off its May 2008 share price, the firm has enjoyed a comparatively quiet year. The extent of the Albuquerque, NM, company's fall in value is perhaps best understood by the phenomenal rise of its share price from a low of \$4.60 to a high of \$15.90 in the previous year. With shares sliding to \$1.26 on April 30 it looks like the III-V solar business that originally gained it attention from investors has continued to lose credibility.

Written off?

Wounded power amplifier (PA) maker Anadigics completes the industry's most troubled trio. Its problems began as far back as late 2007, when it was unable to fulfill customer orders. Handset manufacturers then built up buffers of stock before switching to other suppliers early in summer 2008.

Mario Rivas has since replaced Bami Bastani as CEO and tightened up production at the company's Warren, NJ, fab. Perhaps in response to this – and the company's boasts of industry-leading PAs that are winning business back – Anadigics' share price is now recovering after reaching a bottom on March 9. However, that date also marks the nadir for many of the other leaderboard companies.

Looking at the key GaAs PA makers, all but one firm's share price began rising on March 9. That company is Skyworks Solutions, whose stock began recovering in December. Skyworks outperformed the NASDAQ index by having essentially the same share price at the beginning of May 2008 and May 2009. But scrutinizing the share price of the Woburn, MA, company reveals that it has been subject to a similar rollercoaster ride of rises and falls in value as its rivals, except that it has fallen less and risen more.

Throughout the period, the chipmaker's manufacturing efficiency has garnered positive comments from investment analysts. "Skyworks has posted consistently strong results in recent quarters, significantly outperforming peers," pointed out Todd Koffman of financial services company Raymond James. Although Skyworks recorded a loss in the three months ended March, sales exceeded those of its rival RF Micro Devices (RFMD) for the second quarter in succession. With RFMD traditionally claiming the highest GaAs wireless chip sales by some way, this could mark a key turning point in the industry.

RFMD has failed to make a profit since its purchase of Sirenza in late 2007. Over recent months those losses have been worsened by the same deal. Sirenza initially cost RFMD \$300 million in cash and \$600 million worth of stock. However, RFMD was forced to cut its valuation of those assets by \$673 million, in line with how its own value on the stock market has fallen. \$768 million in total revaluation charges have been added to RFMD's losses over the past two quarters. The \$33.9 million hit taken by the last of the four leading US PA manufacturers, TriQuint Semiconductor, on its acquisitions of WJ Communications and Peak Devices, seems modest by comparison.

Other high-profile III-V manufacturers have also been forced to make similar eye-popping "write-down" and "goodwill impairment" charges as their share prices crumbled this year. Optoelectronic giant JDSU's finances were hit by \$745 million in the past two quarters. However, this year's troubles can be put in some context by reflecting that the Milpitas, CA, company suffered a \$44.8 billion charge when the optical communications bubble burst in 2001.

Dutch electronics conglomerate Philips revised its valuation of its LED manufacturing subsidiary Lumileds down by €233 million (\$317 million), showing that even the solid-state lighting industry is not immune to the credit crunch. However, fellow industry leader Cree's 2.5% share-price growth over the last year, albeit modest in absolute terms, marks it out as a clear winner in today's economy. The Durham, NC, company has spent lavishly on acquisitions of luminaire developer LED Lighting Fixtures and Taiwanese LED packager COTCO in recent years. However, in contrast to nearly all of the other firms, Cree's sales continue to grow year on year, making it appear that the additions have slotted in well.

A similar comment could be made about the company at the summit of our leaderboard – MBE system manufacturer Riber. At the end of 2008 it bought the rights to the Oxford Instruments MBE system business that was originally VG Semicon. The French company's rights to support existing installed reactors will further boost the spares and services business that helped increase its revenues to €19 million in 2008.

Since March 9, the stock market falls that we have seen appear to be reversing. But the dramatic price changes have exposed the differences between efficient firms, like Skyworks, and the hapless.

Andy Extance does not own or intend to purchase any of the stocks in this article.

LEDs

China's LED production begins

As recent as 2002, China imported all of its LED chips. It is now meeting half of this demand with domestic production and making the transition from incandescents to solid-state lighting. **Richard Stevenson** catches up with progress.

The Chinese government is determined to create a domestic LED industry to serve all of its lighting needs. The country currently uses 10–12% of the energy that it generates for lighting, which equates to 300 billion kilowatt-hours of electricity every year. But those in charge want these figures to fall substantially by replacing conventional, inefficient forms of lighting with LEDs.

To aid the development of an LED industry, China is investing heavily in this technology. During the current five-year plan, which runs from 2006 to 2010, the country is plowing RMB350 million (\$51 million) into LEDs, through the Ministry of Science and Technology.

So is this investment starting to pay dividends? Absolutely. According to Wu Ling, director of the China Solid State Lighting Program Office, LED sales have increased six-fold over the last five years, device efficacy is rocketing towards 100 lm/W and chips are serving a wide variety of applications.

In terms of domestic market revenue, sales have risen from RMB10 million in 2003 to more than RMB65 billion last year. LED applications accounted for the biggest slice in 2008 (RMB45 billion) with packaging and chip manufacture netting RMB18.5 billion and RMB1.9 billion, respectively.

Ling explains that these revenues are shared between 3000 companies: 2000 firms focusing on applications; 1000 LED packaging specialists; and about 50 companies involved in LED chip production. Many are located in one of the seven national LED industry parks in Dalian, Shijiazhuang (Hebei), Yangzhou, Shanghai, Xiamen, Nanchang and Shenzhen, but Ling says that other cities also have competitiveness in all sections of the industrial chain.

Imported and domestically produced LEDs now serve a wide variety of applications. Ling told *Compound Semiconductor* that the breakdown of the markets employing LEDs in 2008 was: 28% architectural lighting; 27% signs and displays; 22% mobile appliances; 7% illumination; 6% signals; 2% automotive lighting and 8% in other categories.

One area where China has shown massive improvement over the last few years is LED chip manufacture. Ling says that all of its chips had to be imported in 2002, but domestic production fulfilled 5% of the chip demand in 2003 and continues



The 2008 Olympic Games highlighted the widespread deployment of LEDs in China for example, in the Water Cube, which employed nearly 0.5 million Cree XLamps. As it improves the performance of its power chips, it will become less dependent on imports.

Table 1. China's LED demand and domestic production, 2008

Chip type	Demand (1B pcs)	Domestic production (1B pcs)	Demand met by domestic production (%)
AlGaInP LED	36	16	44
GaN LED	32	13	41
GaAs LED	26	17	65
Total	94	46	49

to increase year on year – in 2008 the figure was 49%. By then LED chip manufacture had soared to 46 billion LED units, which were predominantly GaN- and AlGaInP-based devices (table 1).

Although China's LED industry is going from strength to strength, the performance of its premium high-brightness products still lags behind that of the world's leading manufacturers. "Chinese companies are small-scale and a gap in product quality exists compared with overseas manufacturers," admitted Ling. She points out that most of the domestically produced LED chips are deployed in "medium-to-low end" applications and the country imports 85% of its power chips.

However, power chip efficacies are increasing fast. In 2005 the best packaged white LEDs made in China delivered 30–35 lm/W at 350 mA using imported power chips, and just 20–25 lm/W when employing a domestic equivalent. Now, packages with domestic LED chips are hitting 80–90 lm/W at 350 mA.

Progress has not just been spurred on by the current five-year plan, which has earmarked 33% of the funding for advanced research and development

ns to fulfill domestic demands



LEDs in China –
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LED chip manufacturing firms in China

Company	Location	Status	LED products
Aqualite	Wuhan	volume production	blue, green
BlueLight	Shanghai	not known	blue, green
Century Epitech	Shenzhen	R&D	all
Changelight	Xiamen	volume production	yellow, red
Fangda	Shenzhen	volume production	blue, green
HC SemiTek	Wuhan	volume production	blue, green
Huagang	Shangdong	volume production	yellow, red
Lattice Power	Nanchang	development	blue
Lumei	Dalian	volume production	blue, green
Meiming	Xiamen	volume production	all
Rainbow	Shanghai	not known	blue, green
San'an	Dalian	volume production	blue, green
Silan Azure	Hangzhou	volume production	all
Tonghui Electronic	Hebei	volume production	all



THE LIN



THE LIN

The Ling Long Tower was used to stream international broadcasts from the Olympic village during the games. This 132 m high LED-lit tower features seven pyramid structures.

(the rest has been divided into 29% for key applications, 29% for aiding the LED industry and 9% for funding efforts to improve standards and testing). Funding from the National Solid State Lighting program is also helping to drive up LED efficacy. “Its mission is to reach 130 lm/W for an R&D chip by 2010 for general lighting applications and to realize 100 lm/W in mass production,” said Ling. Additional goals are the promotion of technology innovation and development of industrial parks.

When domestic high-power LEDs are available they will start to penetrate solid-state lighting applications that are just starting to emerge. “There are already some showcase lighting projects in streets, underground parking lots, shopping malls, schools and metro systems,” explained Ling. “With the development of energy saving and the expansion of domestic demand, LED lighting is entering an important historical period for further development.”

As domestic LED performances improve, the

Chinese chipmakers go from strength to strength

The recent success of China's LED industry is mirrored in the fortunes of two of its chip manufacturers, Shanghai Rainbow Optoelectronics Material and Aqualite.

Rainbow, which was founded in 2000, was one of the first LED chipmakers in China. Its general manager, Gang (Alan) Li, claims that it is one of the country's top-five manufacturers, in terms of throughput and revenue. Sales and profits have increased by 30% year on year since 2003.

Li says that Rainbow is the only

member from mainland China of the Solid-State Lighting and Display Center (SSLDC) at the University of California, Santa Barbara. This relationship benefits the company in the form of IP licenses, R&D activities and staff training. Thanks to the support of the SSLDC, Rainbow has broken the 80 lm/W barrier at 350 mA.

"This year we are targeting 100 lm/W," said Li.

Aqualite, a producer of blue and green GaN-based chips, is a more recent addition to China's LED

industry. It was founded in 2006 with \$30 million of investment from Chinese and US venture capitalists. This was used to build a facility with a 20,000 m² cleanroom that includes three 30×2 inch MOCVD tools.

The company's president, Zhijiang (James) Dong, told *Compound Semiconductor* that Aqualite's product portfolio comprises 0.5, 1 and 2 W chips, and the company shipped the equivalent of 10 million 1 W chips last year. This should rise

to 30 million in 2009. Another firm converts the chips into white LEDs, which can produce a cool-white emission of up to 90 lm/W. These packages are deployed in torches and street lamps.

Rainbow and Aqualite both use domestic and overseas suppliers for substrates, metal organics and carrier gases. "I think that substrates and metal organic sources from mainland China, Taiwan and Korea offer the most competitive prices, and the quality is good enough," said Li.

threat of legal action from the established LED makers increases. However, it appears that the Chinese LED industry is taking the issue of patents and intellectual property seriously. Chipmakers are filing for Chinese and US patents, and Ling says that in some cases they are trying to obtain international patents through mergers with foreign firms. The country is carrying out LED research in several universities and Ling's organization is trying to

ensure that any breakthroughs will be converted into intellectual property for LED chip manufacturers.

There is no doubt that China is quickly evolving into a major force within the global LED industry, with technology that is catching up the leading chipmakers. This has to be good news as competition from China will help to drive down prices, make a more compelling case for solid-state lighting and help to cut greenhouse gas emissions around the world. ●

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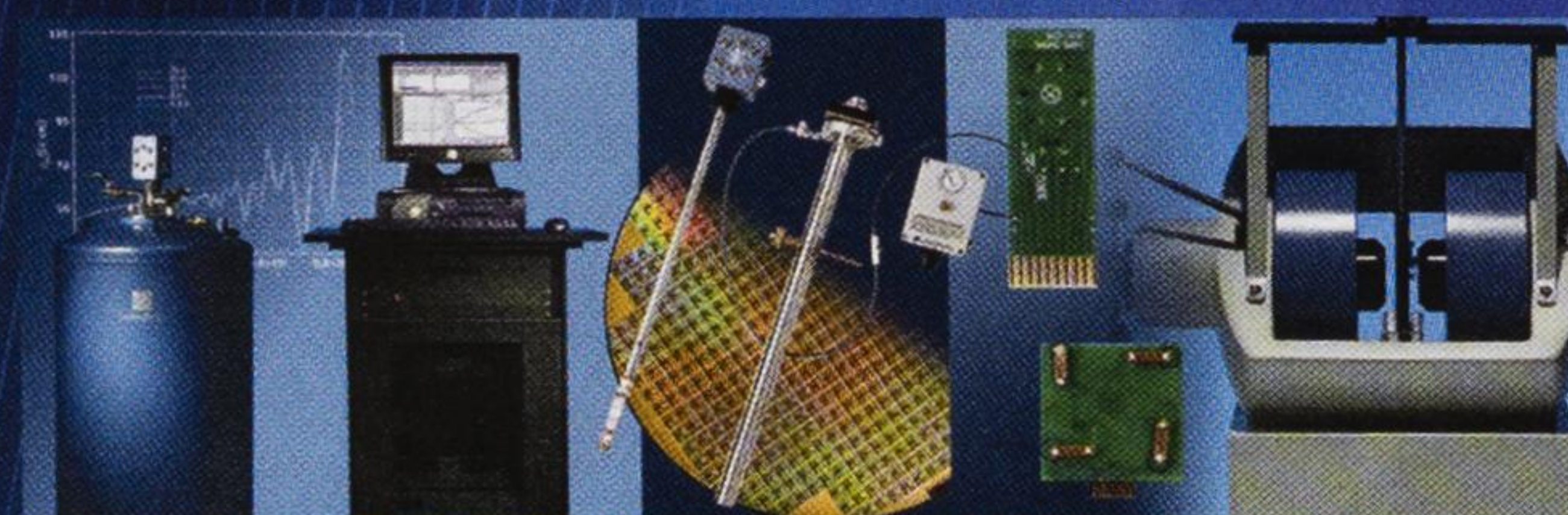
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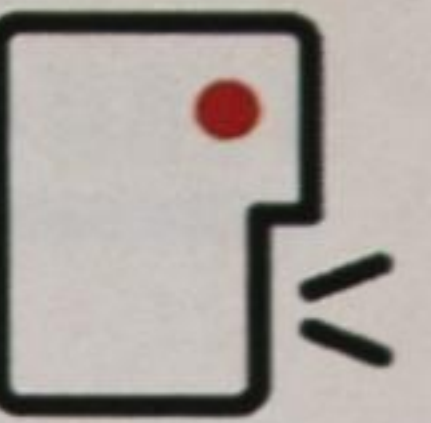
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SOLAR CELLS

Unsettled outlook hangs over CPV

Typically based on III-V solar cells, concentrated photovoltaics has the potential to be a fantastic source of renewable energy. But in a world where private finance has all but disappeared, **Michael Hatcher** wonders whether this fledgling industry has a future.

Spain makes a natural test-bed for concentrated photovoltaics (CPV), the solar energy technology that relies on high-efficiency converters.

The Instituto de Sistemas Fotovoltaicos de Concentración (ISFOC) installation near Puertollano, smack bang in the middle of the country, is there to do just that, hosting a selection of CPV systems built by the emerging leaders of this new sector.

Unfortunately, even in central Spain, it is not always sunny. When the sun doesn't shine, CPV systems produce no energy. On an organized trip to the site in late April as part of the CPV Today event in Toledo, wind turbines on the local hilltops would have made more effective use of the blustery conditions.

The contradictory weather highlighted the paradoxical state that this fledgling industry is in. One paradox inevitably centers on finance. While the ISFOC installations are up and running, the facility's headquarters is still under construction, and only a small amount of data have been collected on live systems.

Until those data look solid, any large-scale private investment appears risky to financiers chastened by the recession. "Now is not the time to go to the financial markets with 'unproved' technology," said Pablo Valera from the investment advisor ASTROM. In the current climate, even the solar industry's darling, First Solar, would have been deemed too risky, he adds.

The irony is that on a large scale and in a sunny climate, CPV has enormous scope to produce solar energy at a very low cost, perhaps as low as \$0.10/kWh in a best-case scenario including higher cell efficiencies, cheaper cells and a favorable location.

But until CPV companies can demonstrate low-cost production in volume, "regular" PV based on thin-film or silicon cells looks like a far less risky option. CPV has no long-term track record right now.

Another paradox surrounds the supply of high-efficiency cells, the components that account for a high proportion of the total system cost. Currently, supply is dominated by Boeing's Spectrolab subsidiary and this is keeping cell prices high. Systems firms want to see those prices brought down, either by increased competition or more availability.

The trouble is that without a guaranteed large order, cell makers don't want to risk the substantial investment needed to scale up. In a stalemate situation, systems firms can't place those large orders until they can be guaranteed a supply of low-cost cells.

Despite the problems, a remarkable degree of optimism permeates this emerging application. And there are some clear signs that the supply of cells is going to increase, particularly with Spectrolab's investment in a high-volume Veeco E475 MOCVD reactor, the likes of RF Micro Devices beginning to tackle solar-cell manufacturing in collaboration with the National Renewable Energy Laboratory, and III-V foundry



Solar farm: the design of most concentrated photovoltaics trackers allows mixed use of land, as this image from Concentrix Solar's power plant in Puertollano, Spain, clearly demonstrates.

companies, including IQE, Kopin and Spire Semiconductor, all taking an interest.

Russ Jones recently joined Spectrolab's senior management team and is heading up the cell maker's terrestrial PV applications business. According to him, the company's investment in capacity will enable it to fabricate cells capable of generating 300 MW of power in 2010, at an average efficiency of 40%.

Beyond that, Jones told CPV Today delegates that Boeing is committed to supporting a much larger expansion, to between 2 and 5 GW of cell production, in the coming years.

All of this sounds like good news for systems companies. Except that Spectrolab's expansion will do nothing to solve the problem of its dominance. As a result, some systems companies have decided to make their own cells; others may turn to foundry companies, although without any very large orders forthcoming, it is difficult for foundries to justify the spending to support production.

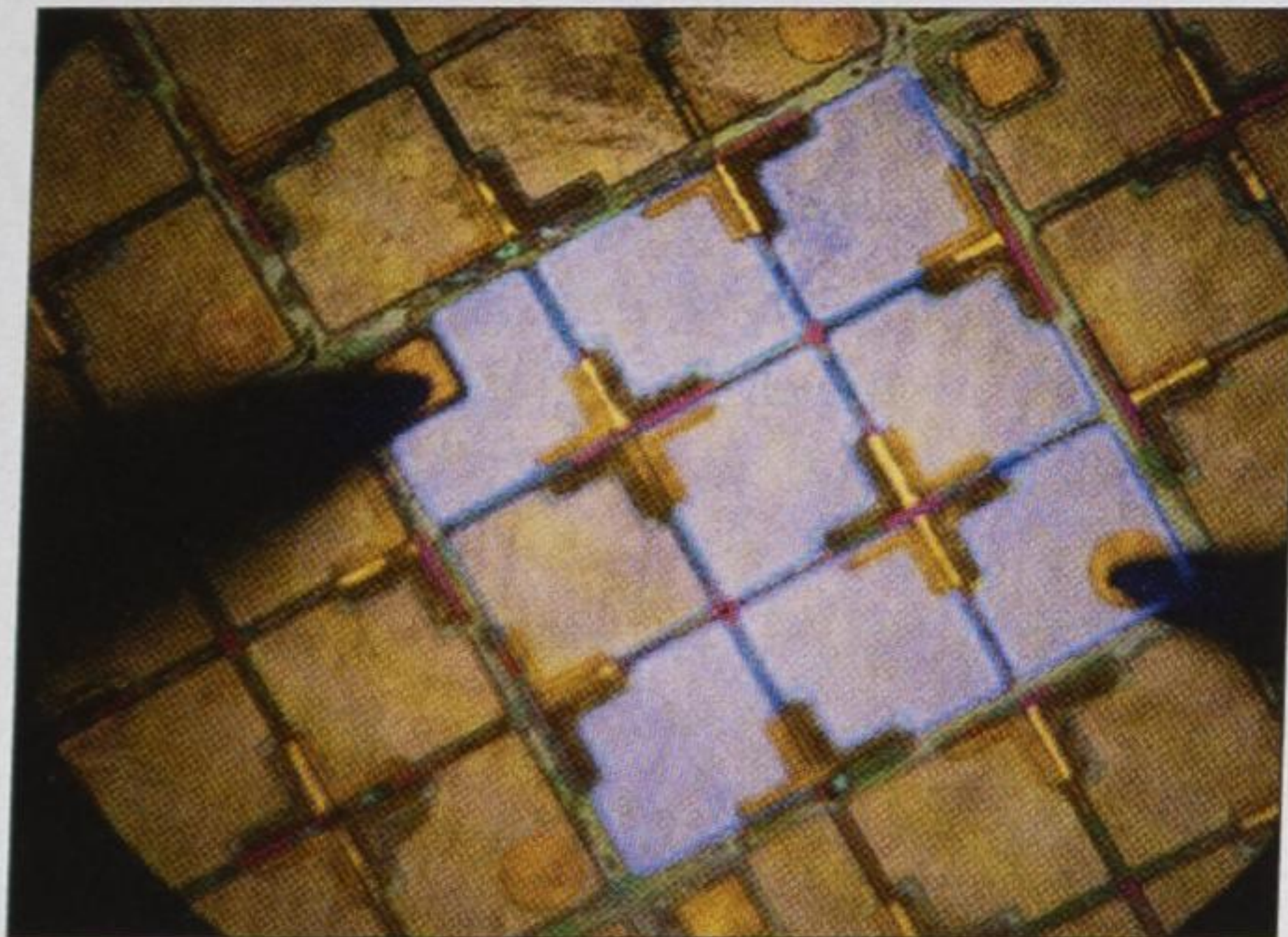
Clearly a number of issues must be solved. Key among them will be ISFOC securing the estimated €27 million (\$36 million) required to fund the second phase of the project, scheduled to begin in 2010. Standards must be developed, while more effective group action will be crucial to compete with the more powerful PV and thermal solar lobbies.

There is a need for more test-bed projects like ISFOC, to foster CPV technology development to the point where it becomes an attractive investment.

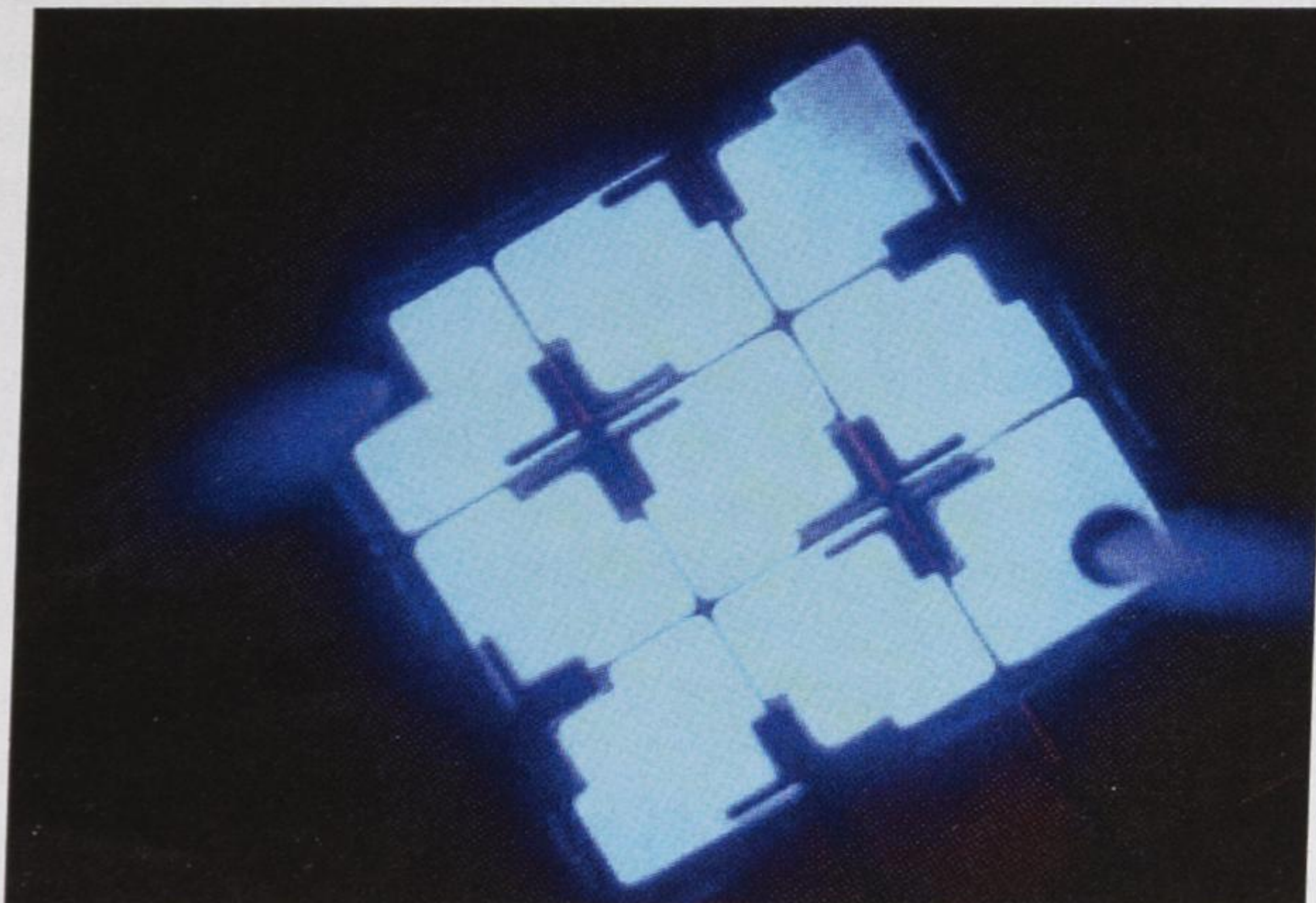
Without that, CPV will remain a cottage industry, reliant on sporadic small-scale deployments in sunny locations with generous subsidies, rather than a serious new application for III-Vs. Gary Conley, the co-founder of systems firm SolFocus, summed it up in a CPV Today panel session: "There is no CPV market; no CPV industry, yet. We have to create it."

Epistar's chips plug and play

Conventional LEDs that are used for solid-state lighting have to be connected to an AC-to-DC converter. But this bulky power supply impacts efficiency and reliability, and can be discarded by turning to Epistar's AC-LEDs that feature on-chip rectification circuits, says **Carson Hsieh**.



Epistar has developed LEDs that can be powered by an AC source. They incorporate rectification circuits based on diodes within the chip. Increasing the voltage between the two metallic contacts increases the brightness of this blue LED.



The LED business is changing. This decade began with rocketing mobile phone sales that drove up the shipments of LEDs employed for keypad and screen backlighting, which helped to create a multibillion dollar device market with a compound annual growth rate of 45%, according to Strategies Unlimited. But revenue growth had plummeted to single digits by 2006, due to strong downward pressures on LED prices, and now remains at similar levels.

New markets are now needed to reinvigorate LED sales growth. Automotive, architectural and general lighting all offer exciting opportunities, and the latter promises the greatest potential – it's a market that could be worth \$100 billion in 2010, in terms of lamps, lighting fixtures and components, according to Global Industry Analysts. However, taking a significant share of this market will require improvements in LED luminosity, alongside a reduction in the overall costs of these lighting systems.

The general public is not buying LED lighting

systems today because they are too expensive. AC-to-DC converting systems are needed in addition to the LEDs, because these unidirectional devices cannot be powered directly from the mains.

AC-to-DC converter systems introduce other problems, such as a reduction in overall lighting efficiency. LED driver-IC companies claim that their product's efficiency is as high as 90%, but this is only the DC-to-DC conversion figure, and overall efficiency is much lower. Converters also diminish the lifetime of the LED lighting system, particularly if they are built with short-lifetime electronic devices. In addition, they negate one of the most attractive features of LED illumination – its compact size.

At times it seems that the LED is destined to be driven by DC power. But there is another way. At Epistar Corporation in Taiwan, we have developed an LED chip that can be plugged directly into the wall socket. Thanks to the elimination of complicated electronic power supplies, our approach promises to slash the costs of an LED lighting system, while making it more compact and reliable.

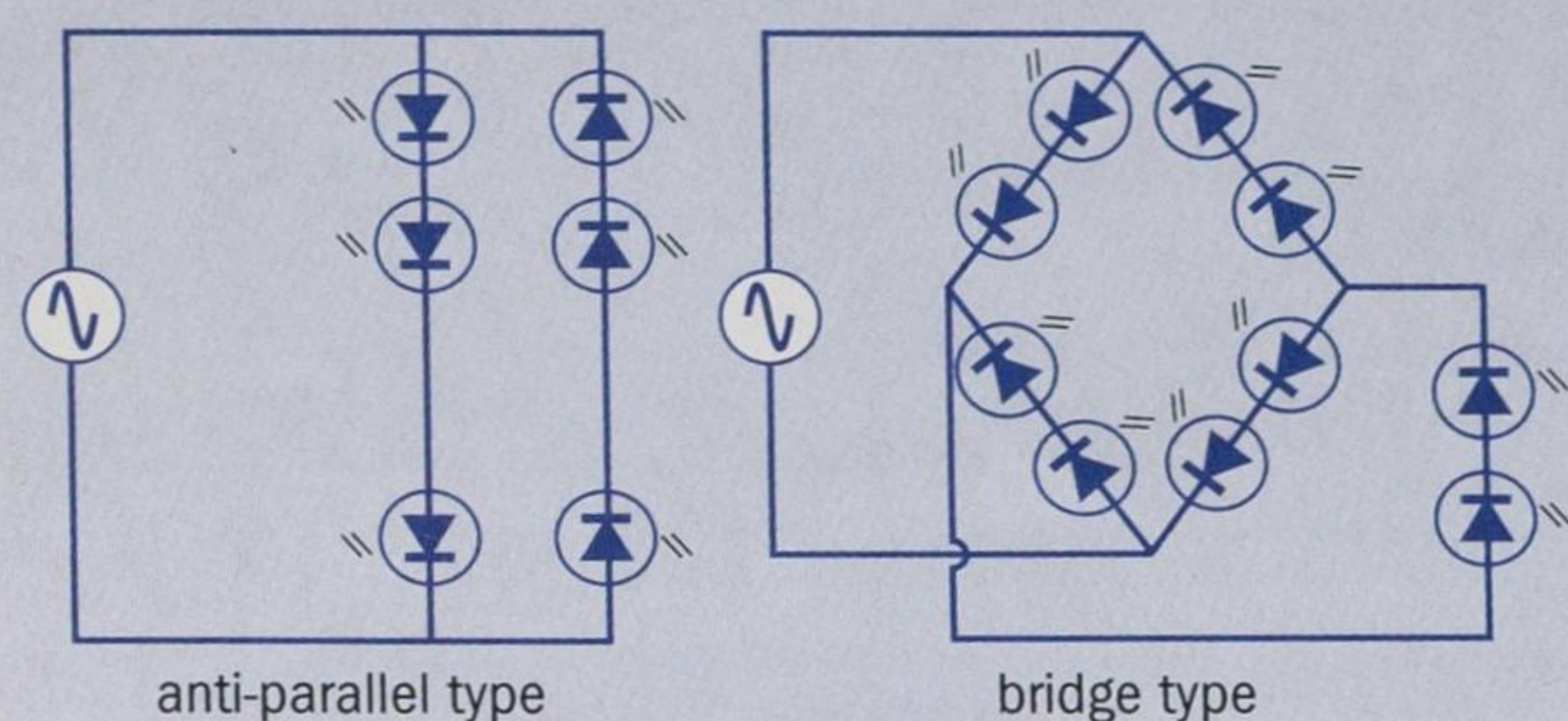
On-chip rectification

Although moving from an LED powered by a DC source to one driven by AC mains is a radical leap forwards, the technology required to make this jump is actually rather simple. It is centered on the construction of diode-based rectification circuits, and will be familiar to anyone with a basic grasp of standard circuit layouts.

We have focused our attention on the development of two types of AC-LED: those that employ an anti-parallel circuit for rectification and those that use a bridge circuit (an overview of both circuits is provided in the box "Rectifying circuits for LEDs"). A simpler chip design and layout are realized with the anti-parallel approach, but these benefits have to be weighed against a smaller illuminated area per cycle, compared with a bridge-type circuit. The challenge associated with the latter type is optimization of the ratio of rectifying area to the central ever-illuminated area (figure 1, p20). The III-V diodes that are used to produce these rectifying circuits are very similar to silicon-based equivalents, but we have to modify our epitaxial process for LED production.

AC-LED manufacture can be divided into the pro-

Rectifying circuits for LEDs



The role of a rectifying circuit is to convert an AC source into a DC form. Two of the common approaches are the anti-parallel circuit and the bridge circuit, which both employ several diodes. Currents travel through one part of these circuits when the AC source is providing a positive signal, and the current takes a different route when the AC signal is negative.

duction of monolithic chips and packages. Packaged AC-LEDs are an assembly of multiple, individual LEDs, which are united to form a single unit. In comparison, the monolithic approach involves fabrication of an array of cells that are combined within a single chip. This has advantages over the packaged approach: it is far less laborious and it produces smaller chips via a lower-cost process. Devices can also be customized to meet specific demands by tailoring the number of cells and the chip size.

The monolithic AC-LED production process is very similar to that used to make conventional LEDs, but it employs three additional, subsequent steps: isolation, insulation and interconnection. Each of these plays a key role in device operation.

Isolation is needed to electrically separate the cells from one another. The isolation trench has to be deep enough to reach the insulating substrate, but thin enough to prevent a substantial reduction in the size of the emitting area. So a high-aspect-ratio trench is needed because a higher ratio boosts device efficiency.

The next step – insulation – is the most critical. The material selected for this process has to have good insulating properties, and also enable excellent step coverage so that good-quality films can be deposited on the walls of each cell (figure 2). A metallic coating interconnects these cells, with a yield that is governed by the degree of planarization of the insulation layer.

One distinguishing feature of our AC-LEDs is their variation in efficiency with time, due to variations in the driving voltages for each cell. Our devices are predominantly operated in a high current regime and suffer from droop, a decline in efficiency at high drive currents. The cause of droop is not clear in the LED community, but it is attracting intense debate between researchers. Future developments in chip design may be able to address this weakness without significantly complicating the

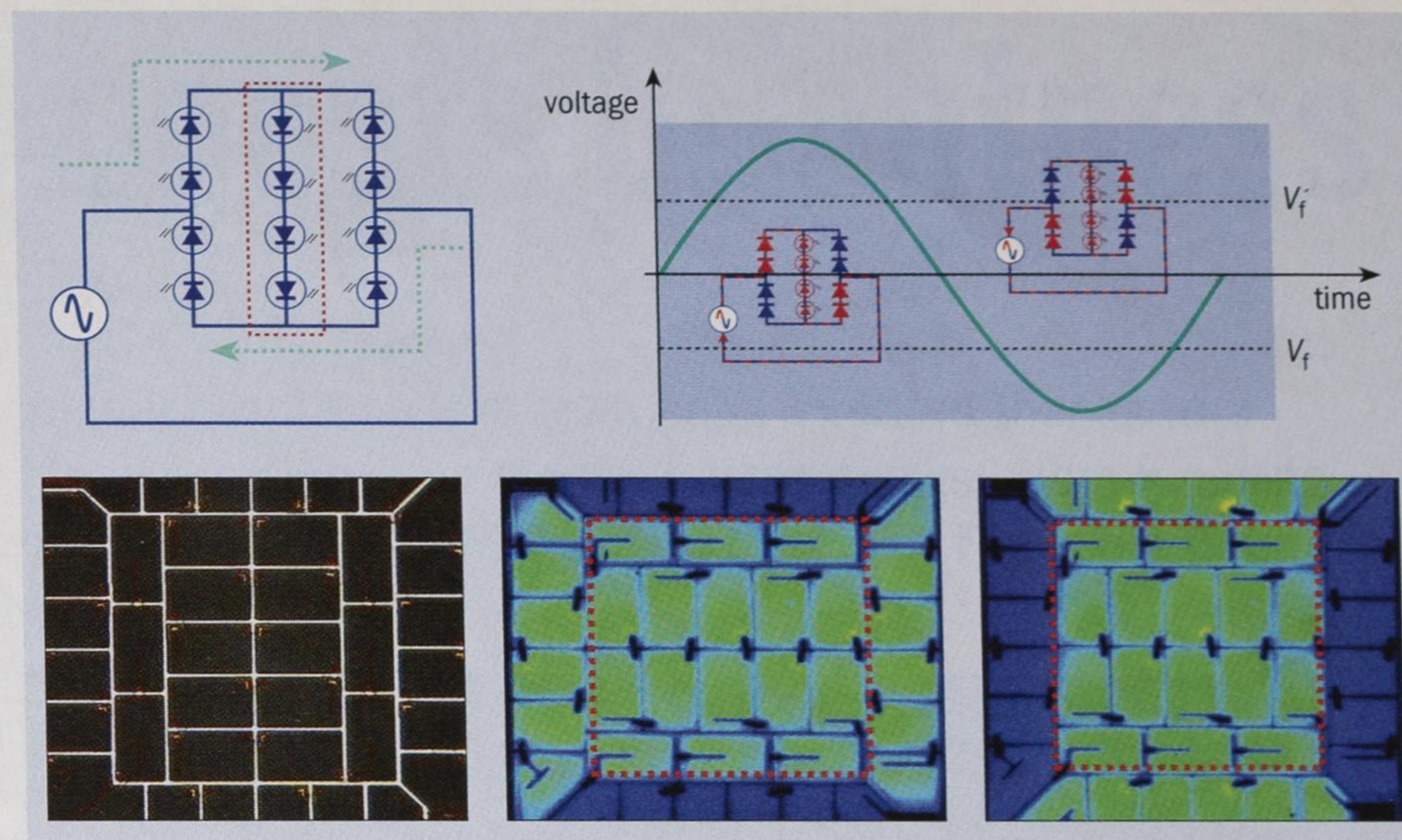


Fig. 1. The bridge circuit may lack the simplicity of the anti-parallel circuit, but it does increase the output from the chip, thanks to a central region of the device that is always emitting.

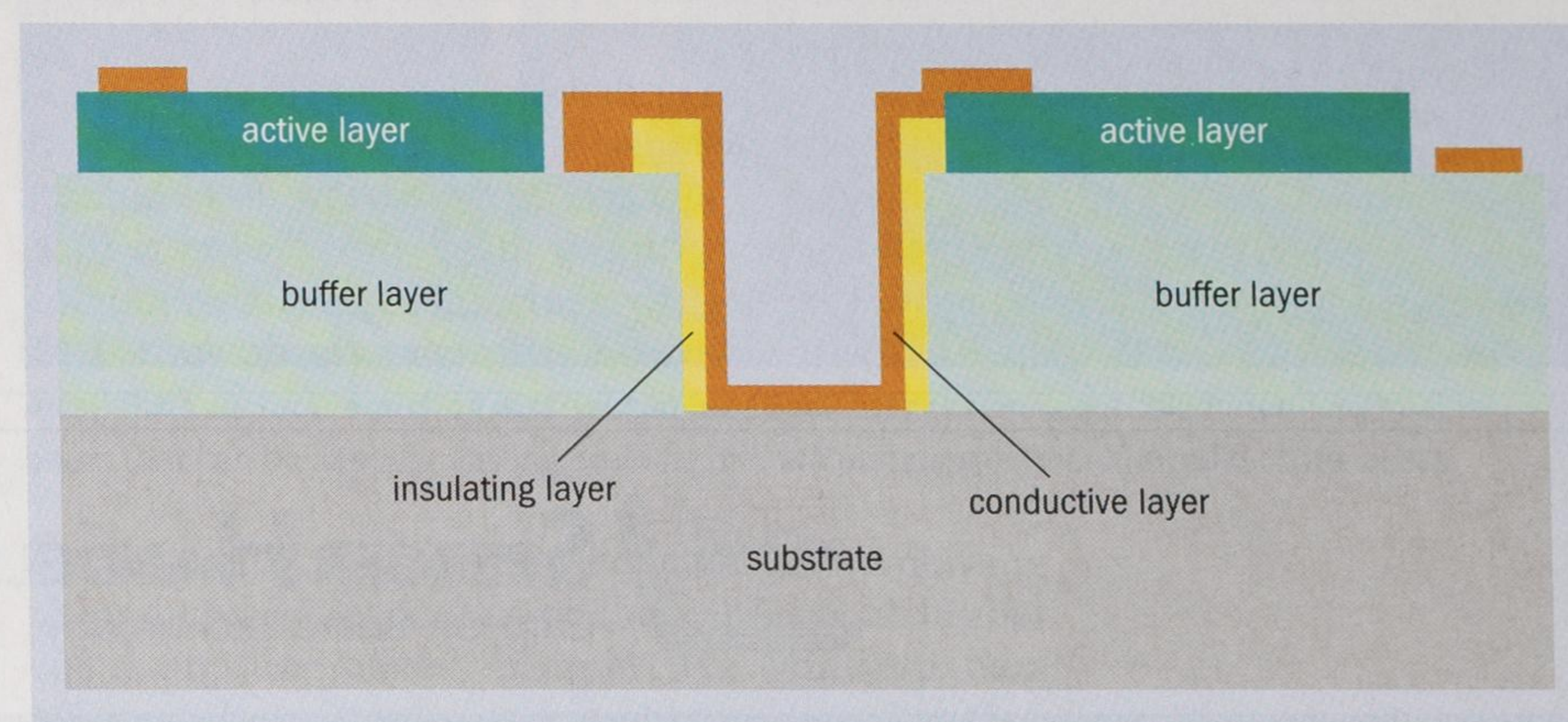


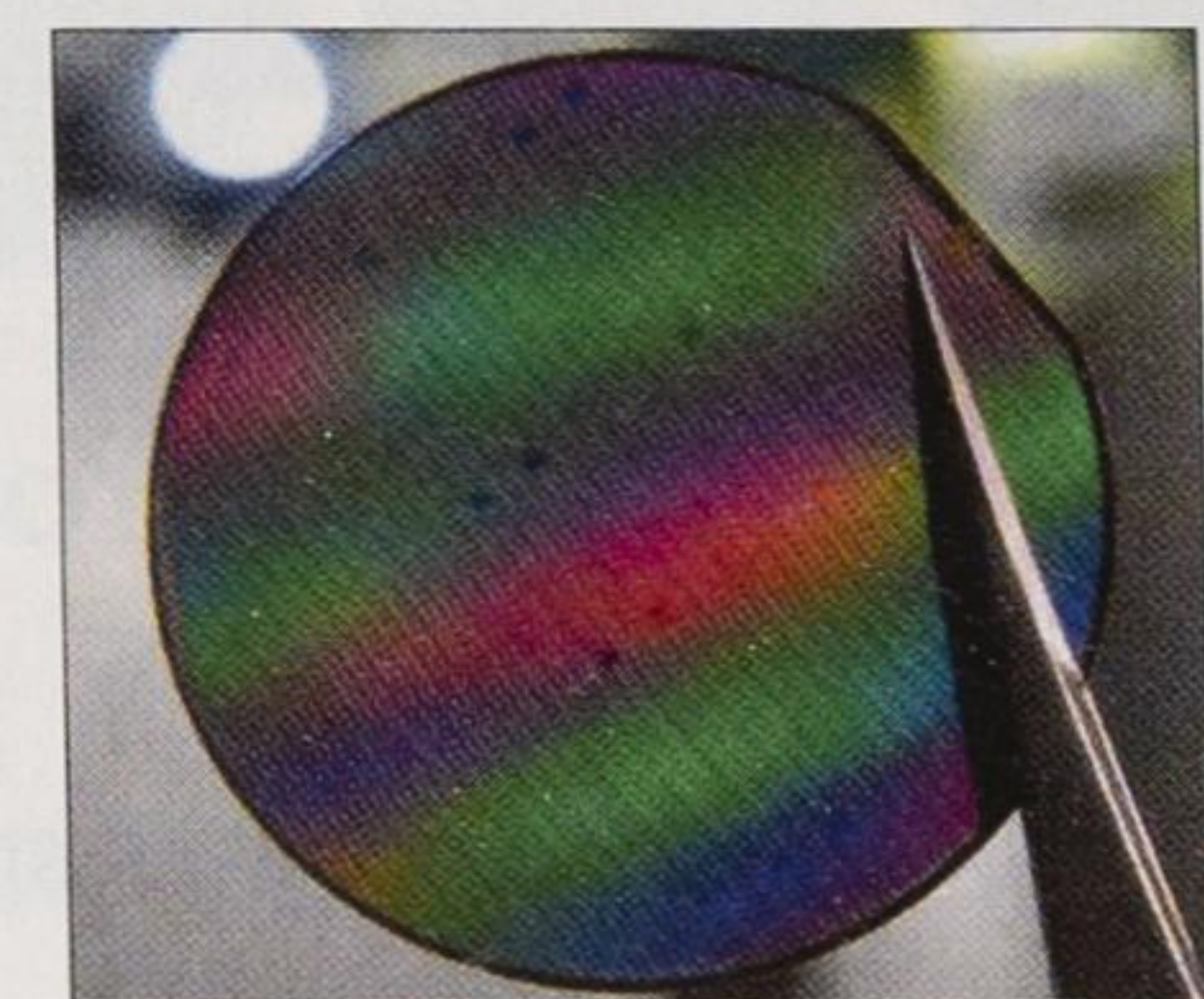
Fig. 2. AC-LED production begins by growing a conventional LED epitaxial structure. A trench is added to create individual cells before an insulating layer and metallic interconnects are added.

production process and this could lead to an increase in the efficiency of our AC-LEDs.

One downside of discarding the AC-to-DC converter is that it exposes the LED to variations in AC supply, including power surges. We have addressed this issue through the addition of an external resistor or capacitor, which prohibits the burn-out of our LEDs from a sudden power surge by diminishing the effects of voltage fluctuations (figure 3). However, this approach also cuts the overall lighting efficiency and it would be good to discover a better solution to improving the AC-LED's robustness to mains supplies.

The applications that we are targeting, such as solid-state lighting, require our AC-LEDs to operate at high powers. Heat dissipation is critical when LEDs are driven in this regime and our devices would benefit from a high thermal conductivity substrate. Sapphire, the substrate currently used for AC-LED production, has a relatively poor thermal conductivity, but improvements could result from the transfer of the epitaxial structure to a silicon or metal platform.

Even in its current form, our AC-LED promises to



AC-LEDs can be produced by growing the epitaxial structure on sapphire substrates before inserting trenches to define cells. Insulating material is deposited to cover the walls of this trench before metallic interconnects are added.



About the author

Carson Hsieh is the vice-president of the R&D center at Epistar. He joined the company in 1998 and has previously held the roles of fabrication manager, R&D director and R&D associate vice-president. Before this he worked at Highlight Optoelectronics and he has a doctorate from National Tsing Hua University.

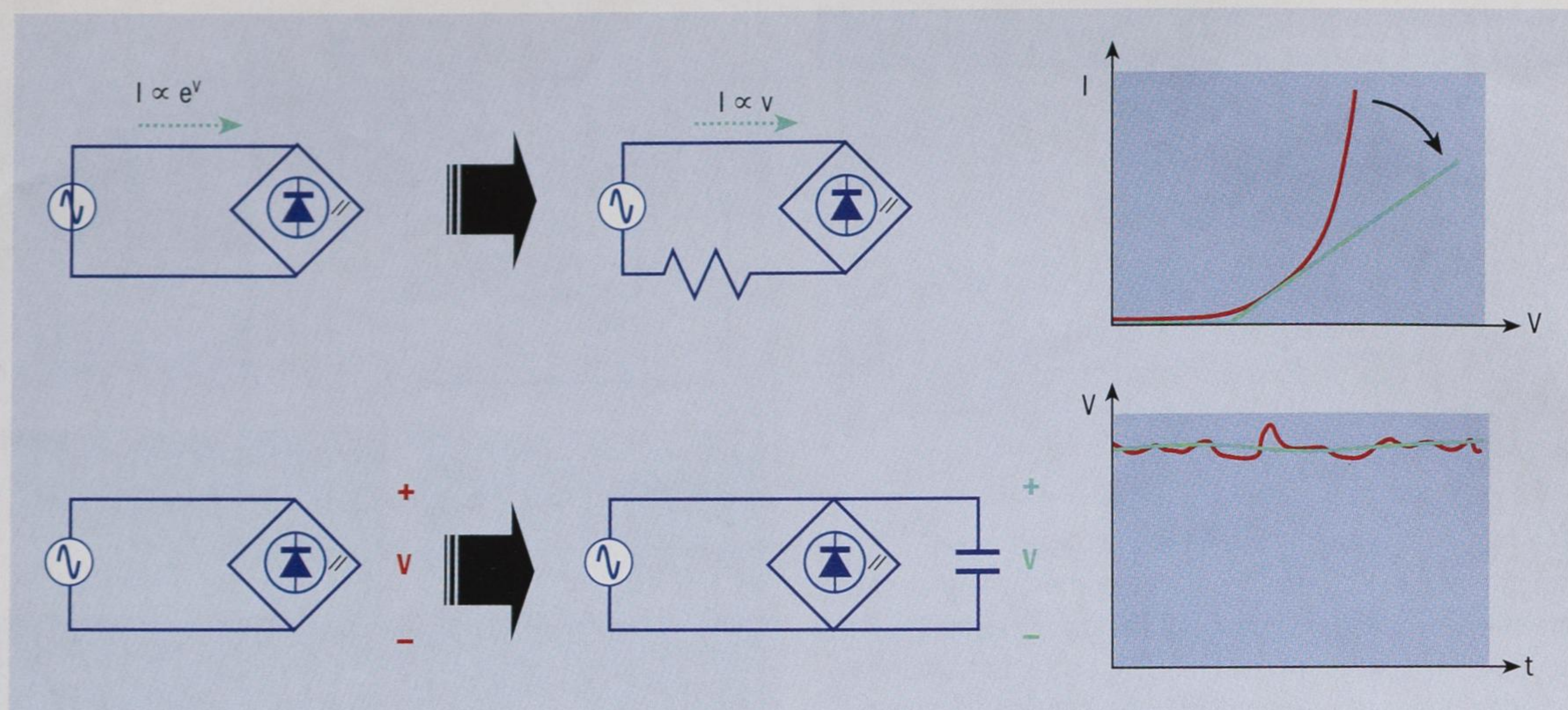


Fig. 3. Voltage surges and spikes could degrade the performance of Epistar's LEDs. To combat these concerns, an external resistor (top) or capacitor (bottom) can be used to protect the device. Adding a resistor in series changes the dependence of current on voltage from an exponential relationship to a linear one, and ultimately reduces the changes in current that are driven by voltage fluctuations. Inserting a capacitor across the LED dampens sharp rises and falls in the supply voltage.

play a major role in driving the transition to solid-state lighting because it addresses the need for a fully integrated system. It majors on its compactness and the opportunity that it provides to reduce the cost of lighting systems, through elimination of the AC-to-DC converter. However, the device is still

in its infancy and its efficacy lags behind that of the leading conventional LEDs. But this gap will shrink through improvements to the device, such as better designs for the epitaxial structure and the cell, and this should propel the fortunes of our AC-LED in the lucrative lighting market. ●



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Novel grating boosts brightness

Alfalight's top-emitting laser produces far higher output powers than edge-emitters thanks to a curved grating that runs along the underside of the chip. This radical design allows beam-focusing with simple optics and is ideal for pumping fiber lasers, say **Manoj Kanskar** and **François Brunet**.

High-power laser diodes serve many tasks. These include cutting metals, welding plastics and solders, and pumping solid-state lasers, fiber lasers and amplifiers, which can all be accomplished with single emitters, bars and arrays.

Many applications prefer to employ a circular beam emitted from the end of a fiber, rather than the more complex emission profile that comes from an edge-emitting laser. However, the costs of fiber-coupled laser diode manufacturing are high – almost an order of magnitude more than those for laser diode chips and bars, in terms of dollars per watt.

The increased cost of the fiber-based laser stems from the inferior beam quality of edge-emitting broad-area diode lasers and bars. Expensive beam-formatting optics with tight tolerances are needed to transform the output from these emitters into a form that can be coupled into a fiber, and this propels the dollar-per-watt figure to a level that is unattractive for many applications. But the packaging costs can be driven down with bright diodes built with low-cost manufacturing techniques that produce an output that is easy to couple into a fiber. At Alfalight, which is based in Madison, WI, we have developed a design that does this – a curved-grating surface-emitting distributed feedback (SE-DFB) laser (figure 1, p22).

Empowering the fiber

Coupling substantial power into a small-core fiber requires a laser with high spatial brightness. This means that the device has to produce a high power in a given entendue (a metric that reflects the size of the source and the spread of the beam, in terms of the solid angle).

One way to generate a high-power source is to couple the emission from several single-mode lasers into a single fiber. But this approach is impractical because each diode produces no more than 1 W of useful power, and an unwieldy number of lasers would have to be coupled together for power-hungry industrial applications. So numerous 100 μm wide, multimode broad-stripe lasers in bar and stack forms are used instead, which can deliver the hundreds to thousands of watts needed for pumping applications.

By utilizing a relatively simple coupling scheme, about 10 W of power can be launched into a 100 μm diameter, 0.15 numerical aperture fiber. However,



Alfalight's surface-emitting distributed feedback laser produces a collimated longitudinal beam that can be used for cutting, welding and the pumping of fiber and solid-state lasers.

power scaling is a significant challenge. Combining chips boosts power, but at the expense of higher costs and increased complexity. Multiple bars offer an alternative route to power scaling, but they require expensive micro-optics for collimation and complex, high-tolerance configurations for beam transformation. Once again, costs are an issue.

A far better source for fiber coupling is our SE-DFB laser, a novel emitter with a curved grating that is analogous to an unstable resonator. This design draws on a well known approach to establishing good lateral-beam quality over a large area, and enables fabrication of high-power, high-brightness lasers that can form an ideal source for power scaling, particularly in the form of arrays.

Our SE-DFB lasers have several advantages over their edge-emitting cousins: the absence of facet coatings; greater tolerances for bonding to a heat sink; better array yields; and simplified coupling optics. These four strengths create a laser with lower manufacturing costs than an edge-emitter, whether it is in the form of a single chip or an array.

Edge-emitters require a facet coating, which is a time-consuming, cumbersome step. SE-DFB production avoids this. It employs a wafer-level batch process to add an anti-reflection coating to the device's output window. Out-of-spec dies can then be discarded with wafer mapping techniques, leading to minimal yield losses at expensive downstream steps.

The SE-DFB design also simplifies bonding of

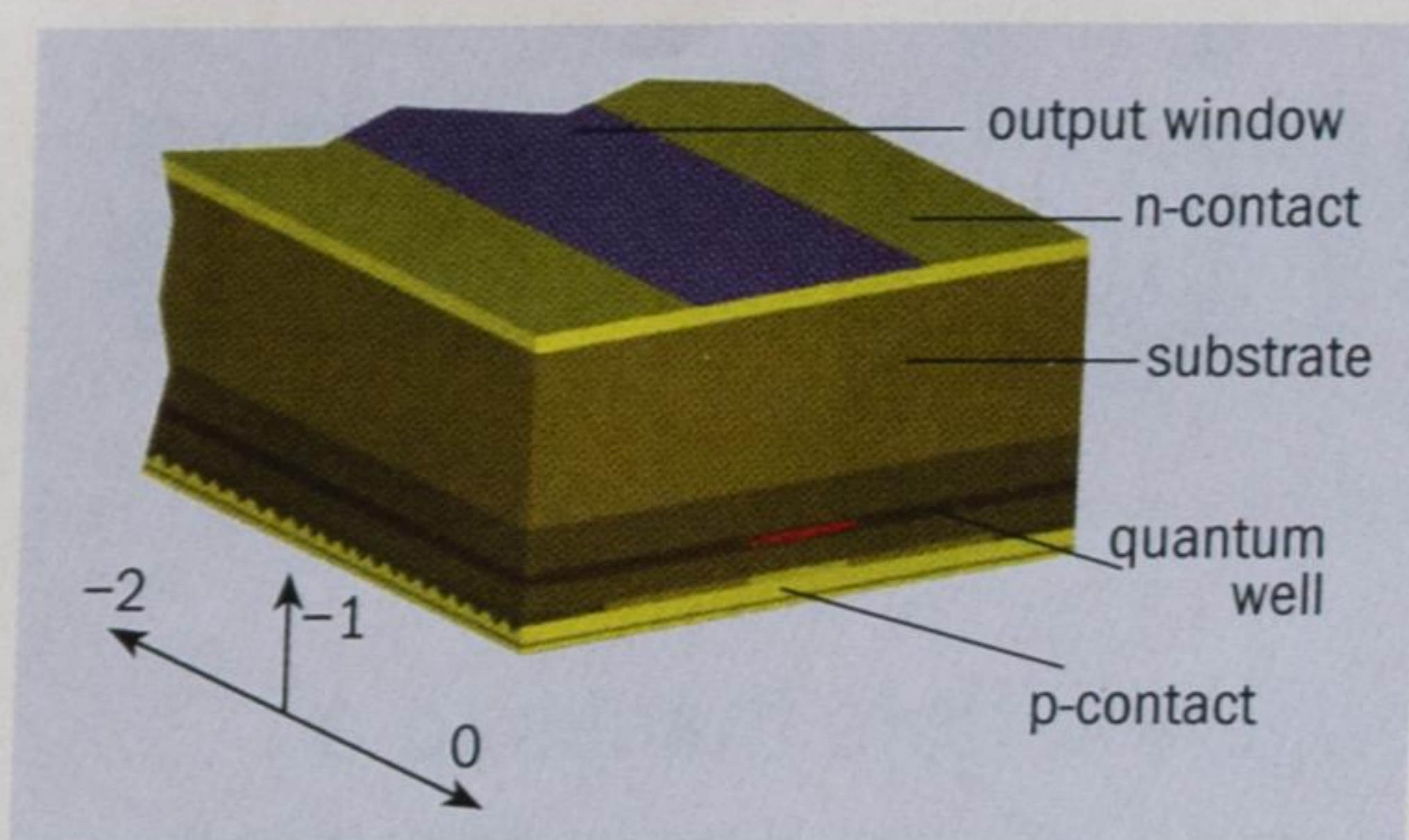


Fig. 1. The SE-DFB laser produces emission through the substrate via the surface-normal mode (-1). The fundamental (0) and feedback (-2) modes propagate along the length of the waveguide.

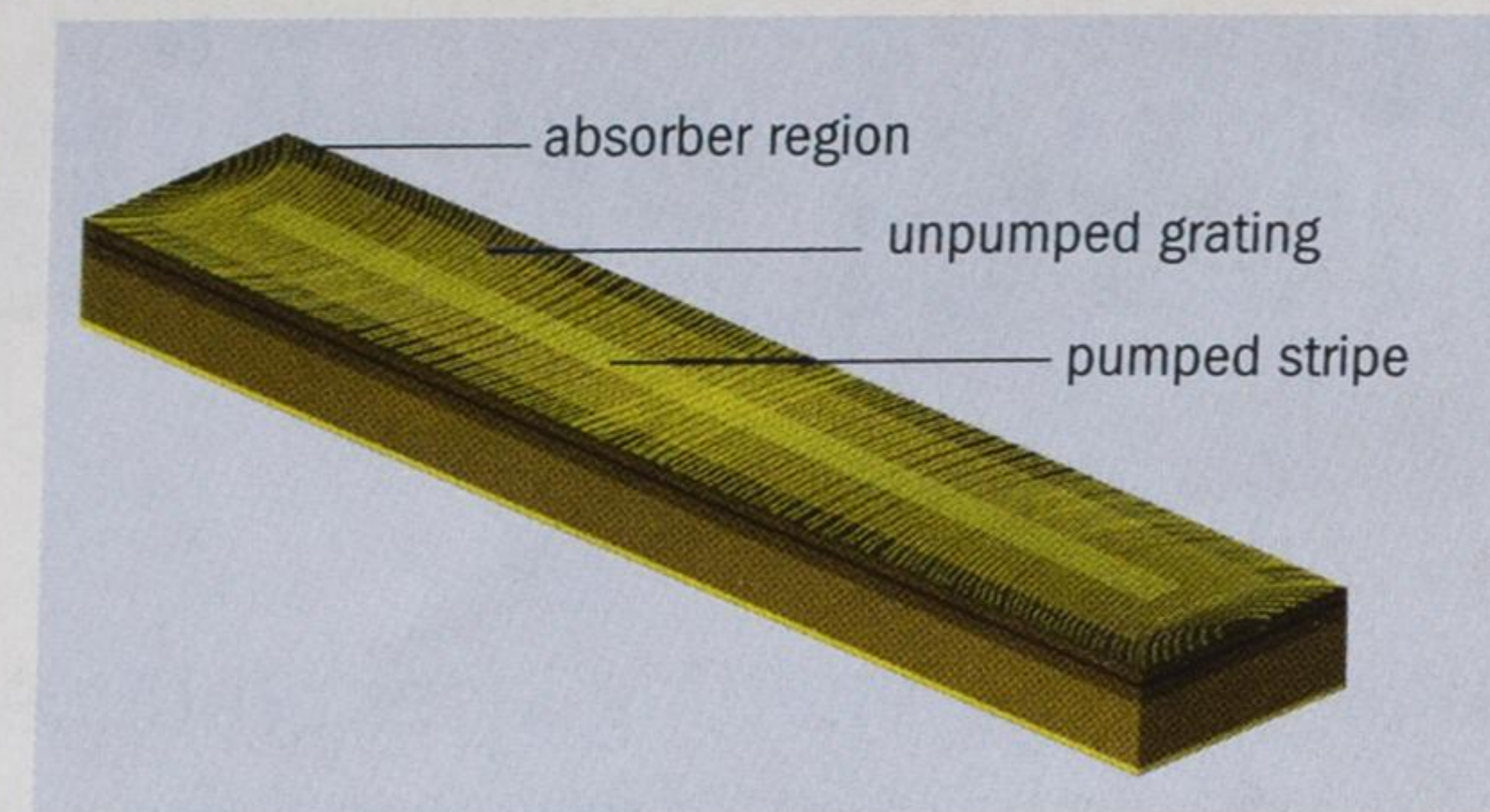
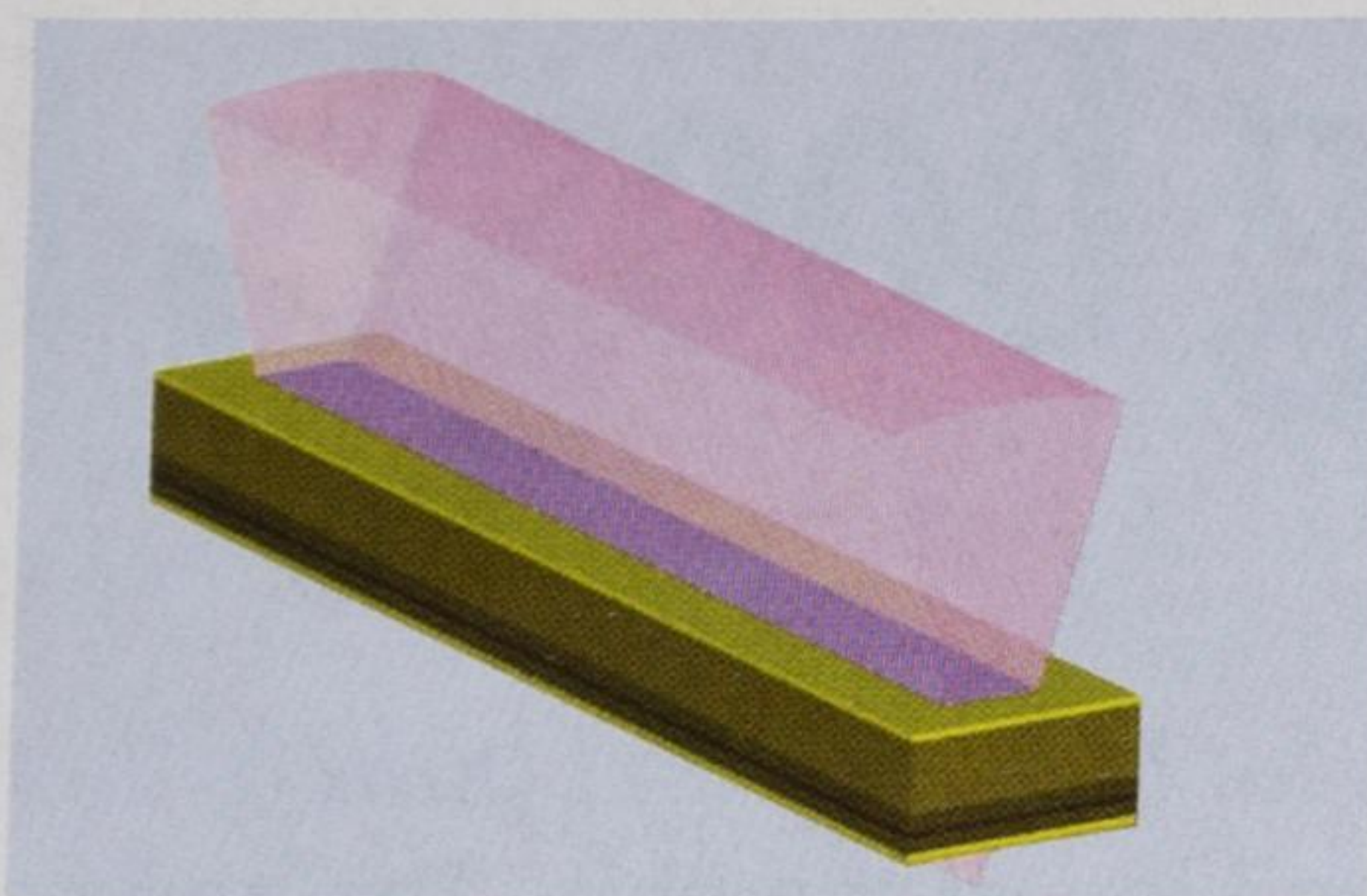


Fig. 2. The underside of a curved-grating SE-DFB laser has a central pumped stripe, grating and absorber regions.

the chip to a heat sink. Edge-emitters have to be precisely placed at the knife-edge of an expensive heat sink, whereas SE-DFB lasers can simply be picked and placed on an inexpensive flat heat-sink surface, using far higher alignment tolerances.

Fabricating arrays is more successful with SE-DFBs because failure can be eliminated by selecting burned-in, pre-tested, known-good devices. In comparison, entire stacks of edge-emitting arrays have to be scrapped after most of the value-adding has occurred if a handful of faulty elements are found.

Lastly, SE-DFBs simplify fiber coupling. Output can be collimated straight out of the chip in one direction, eliminating the need for an expensive diffraction-limited, fast-axis microlens, which is an indispensable component for collimating edge-emitters. Collimation along the perpendicular optical axis can be realized with a relatively inexpensive cylindrical lens. In fact, one aspherical lens can focus the output of a two-dimensional array of SE-DFBs, which cuts the cost of focusing optics.

The strengths of the SE-DFB laser stem from the curved second-order grating that is etched into the p-cladding and subsequently coated with gold (figure 1). Adding a patterned p-contact defines the pumped stripe dimensions, and the parts of grating outside of this region remain unpumped (figure 2).

A zero-order mode propagates along the waveguide, which has two diffraction orders: one for feedback and another for surface emission. Feedback only occurs from the grating, thanks to suppression of Fresnel reflections from the ends and sides of the chip by an absorbing layer above this structure. Surface emission is produced from transmission through the substrate via an anti-reflection-coated window aperture in the n-side metallization. Laser output is emitted from the device's top surface, with the beam collimated in the longitudinal direction and diverging in the lateral direction, with a full angle of 8°.

The SE-DFB's curved grating produces an unstable resonator with modes that are governed by the phase of the grating (i.e. its shape). This phase-related information is incorporated into the SE-DFB laser by taking a glass plate and encoding an array of phase-height patterns on this surface. This information is transferred to the device with an interference pattern that follows the curved

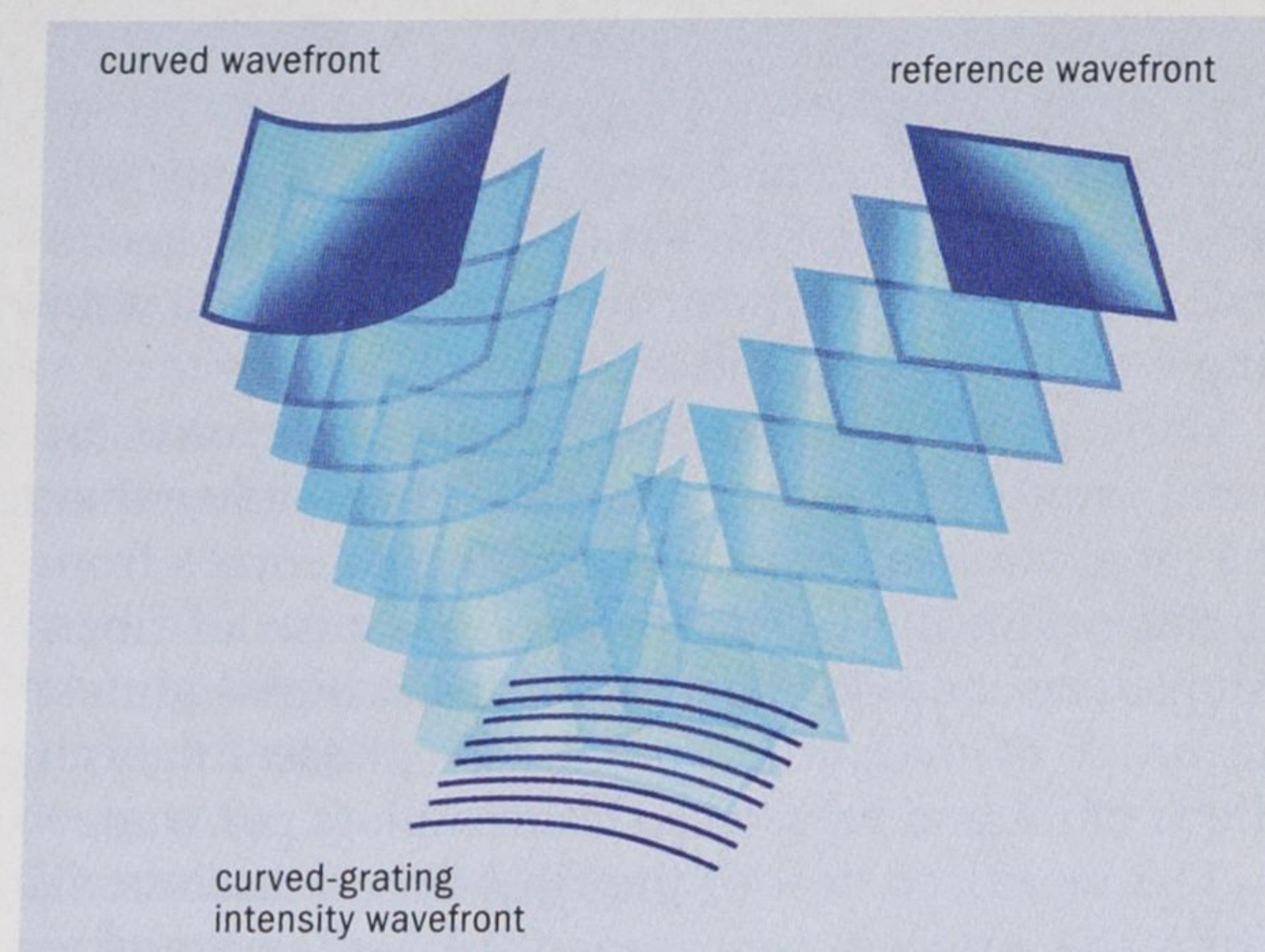


Fig. 3. Curved gratings that feature in the SE-DFB laser are formed by interference of a reference plane wavefront and curved wavefront. The reference wavefront comes from a collimated laser beam and the curved wavefront is generated by the collimated beam exiting the phase plate surface.

wavefront phase, which can be defined on a wafer that's coated with a photoresist using a holographic exposure system. High volume production is easy, because a single exposure can record the grating pattern over the whole wafer.

The curved grating is responsible for the SE-DFB's cylindrical wavefront in the output beam. This profile makes it appear that the beam emanates from a narrow virtual line source, even though a much wider stripe is pumped (figure 4). In fact, the ratio of the pump source width to that of this virtual line waist is approximately equal to the increase in brightness produced by the curved grating design. This grating also suppresses filamentation in the wavefront propagation – a common issue in broad stripe lasers – which stems from the combination of spatial-hole burning and carrier-index coupling.

We have demonstrated that the theoretical strengths of the SE-DFB design can be realized in real devices, such as a single stripe emitter with a $7500 \times 500 \mu\text{m}$ active area. This chip produces a record power of 73 W from a single laser diode, thanks to the freedom to scale the pumped stripe area while maintaining the current density at a relatively low, constant value. With a well designed grating it is possible to suppress filamentation and control the lateral mode for a much larger size of



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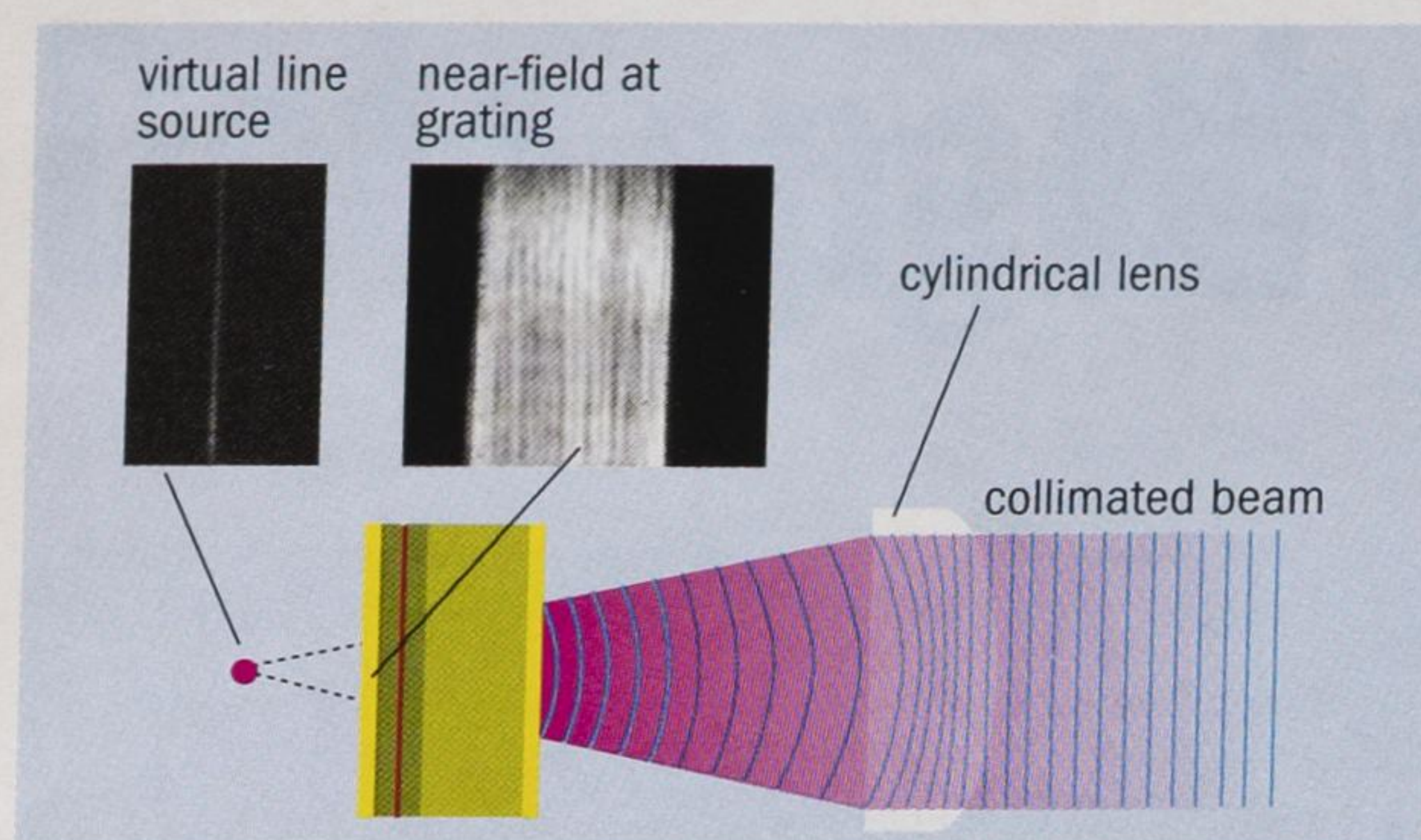


Fig. 4. The SE-DFB laser produces a lateral beam with a cylindrical wavefront that appears to emanate from a narrow virtual line source behind the grating surface. The wide stripe is an image captured at the grating surface and the narrow stripe is a virtual line source formed at the focus behind the chip.

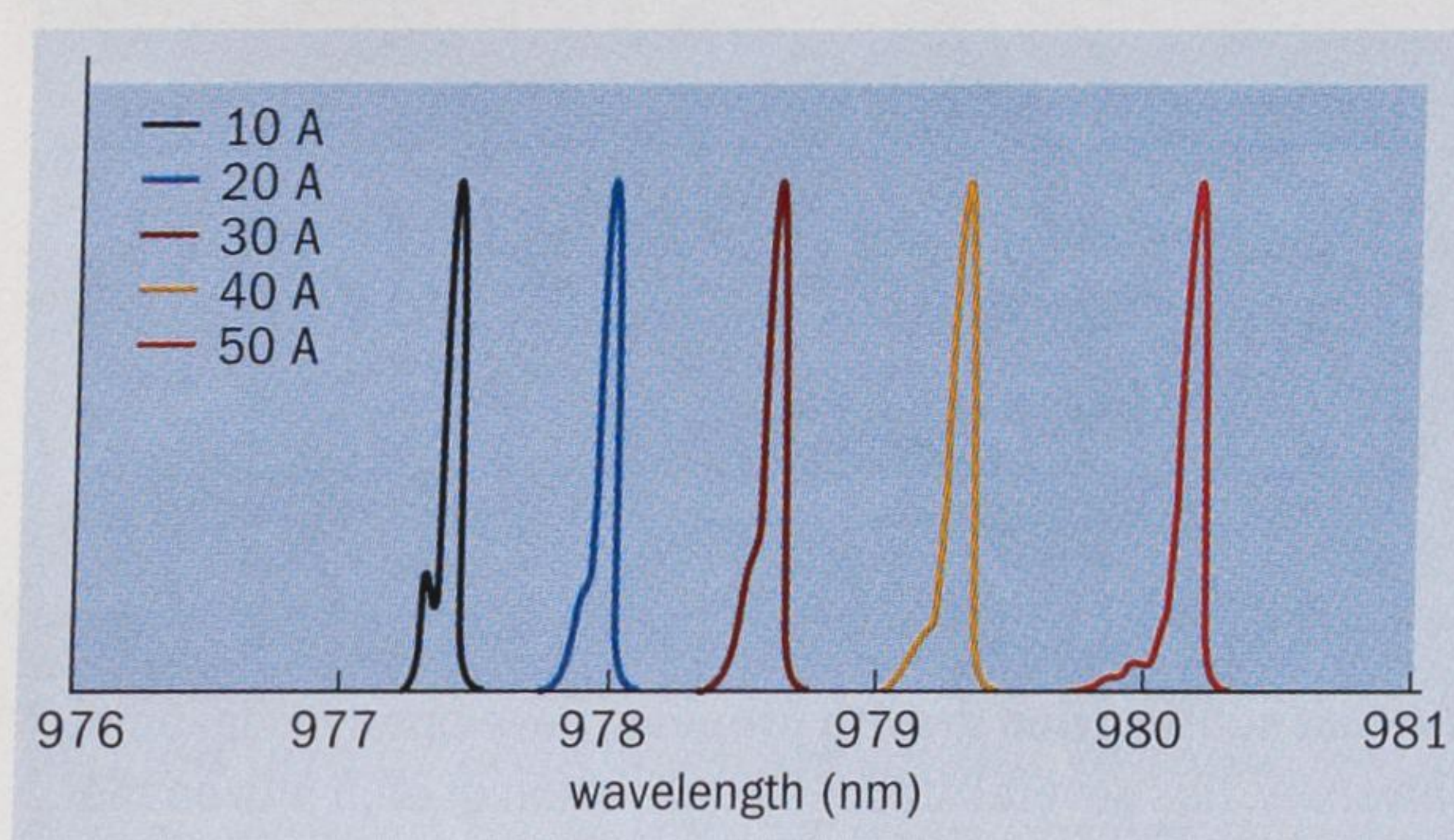


Fig. 6. Wavelength shifts with temperature for the SE-DFB laser are just 0.07 nm/°C, which makes this an ideal source for pumping narrow absorption lines of fiber and solid-state lasers.

gain stripe compared with edge-emitters.

The emission bandwidth of this SE-DFB laser is just 0.3 nm, which makes it 10 times as bright as an edge-emitter (figure 5). Our chip also produces a five-fold reduction in wavelength shift with temperature to 0.07 nm/°C, removing the need for chip cooling in certain applications. Immunity to catastrophic optical mirror damage – a common failure mechanism for high-power edge-emitters – is another strength of our laser that results from the absence of any facet. Due to the relatively large emission area of our SE-DFBs, the output beam of our laser at the exit window is 1000 times less than that of an edge-emitter.

In some applications, edge-emitters suffer from a back reflection that damages the source. This is not an issue for SE-DFBs because coupling light back into the cavity would require precise matching of the wavelength and the incident angle, which is very unlikely. Instead, incident light is reflected by the chip, preventing damage from parasitic beams.

We are developing a two-dimensional tiling of SE-DFBs to realize multi-kilowatt arrays, through the interleaving and polarization combining of individual sources. Further power scaling should be possible with wavelength beam combining. A key advantage of the two-dimensional tiling approach is that it allows devices to be “voltage-added”, which

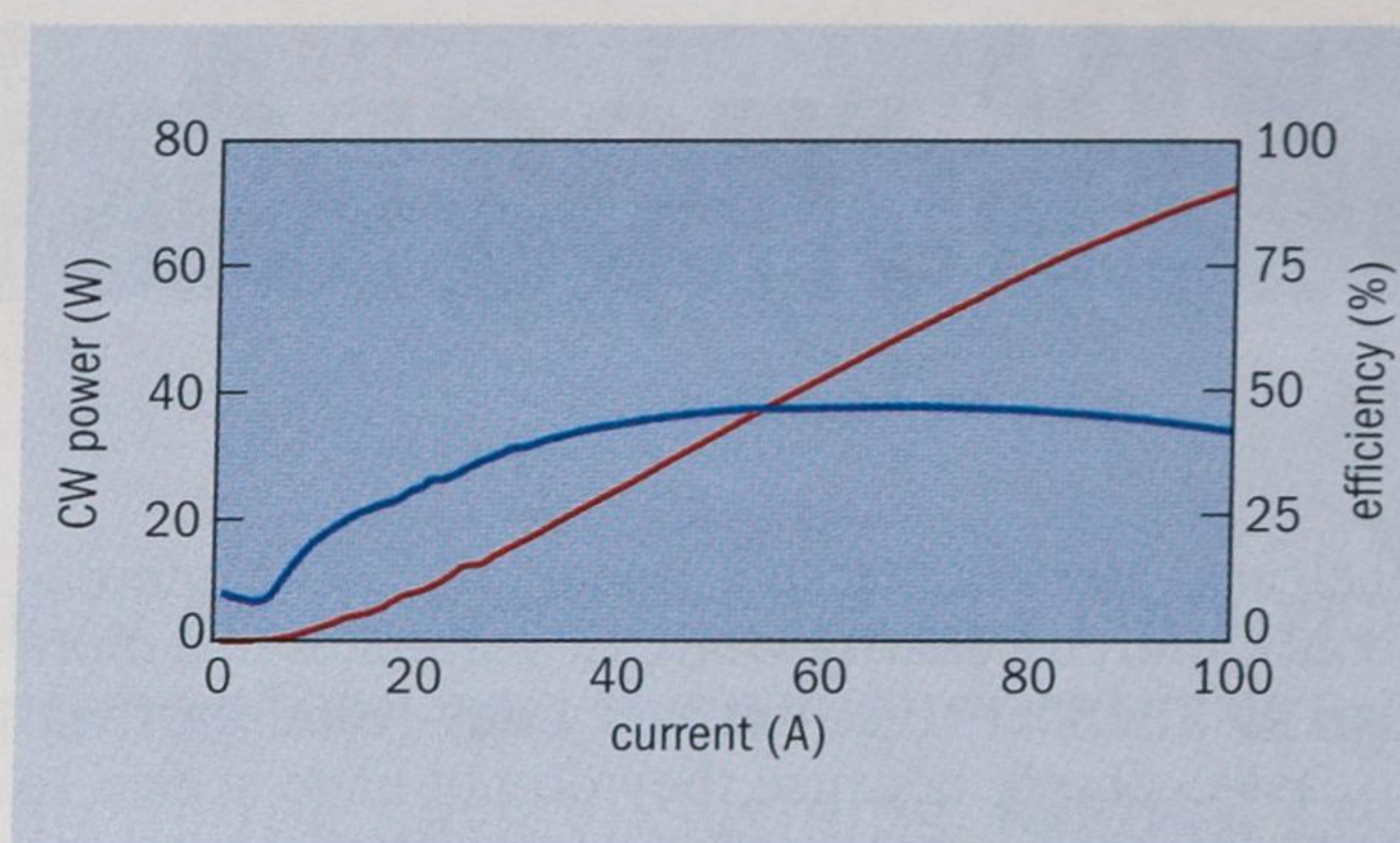


Fig. 5. Alfalight's SE-DFB laser can produce a continuous-wave output of 73 W, which is a record for a single chip. The efficiency of this source is 50%.

means that they can be driven with an inexpensive low current supply that cuts the overall system cost.

The SE-DFB's narrow spectral width and minimal shift in wavelength with temperature make it an ideal source for pumping narrow absorption peaks of solid-state gain media. This includes the 975 nm band of ytterbium-doped and ErYb co-doped fiber lasers, which has a relatively high absorption coefficient. Shorter fiber lengths can then be employed in the laser, which mitigate deleterious nonlinear effects, such as stimulated Brillouin scattering and stimulated Raman scattering. Another benefit of pumping at this wavelength is that it leads to a lowering of the quantum defect – the difference in photon energy between pump source and emitted light. Gain media can then run cooler, reducing the likelihood of thermal lensing. This is a significant benefit for solid-state lasers, such as slab and thin disc lasers.

It is impractical to use edge-emitting Fabry-Pérot lasers for pumping the 975 nm transition because their spectral width is too broad. In addition, the wavelength drift with temperature is too fast and expensive thermal management systems are needed to maintain the resonance wavelength. What's more, increases in pump current that detune the wavelength from resonance produce a substantial amount of power that is not absorbed, which has to be managed without causing failure to downstream components. This adds to the challenge of building reliable, kilowatt-class fiber lasers and amplifiers.

Our SE-DFB laser's desirable characteristics, such as incredibly high brightness and a very small shift in emission wavelength with temperature, make them great sources for pumping fiber-coupled arrays that generate kilowatt powers. However, they can also be employed as direct-diode sources for plastic welding, sintering, heat treatment, soldering, engraving and some cutting applications. Armed with bulk cylindrical optics, simple, low-cost collimation is possible and the SE-DFB can then be used as an inexpensive source for other applications, such as security illumination, sensing and designation. By operating this laser in pulsed mode, it can produce nanosecond pulses that have a five-fold increase in power, which makes this source a low-cost option for transmitters in range finders. With such a broad range of applications, it is clear that the SE-DFB laser has a bright future.



About the authors

Manoj Kanskar (left) is Alfalight's vice-president of research and development, and **François Brunet** (right) is product manager.



SUBSTRATES

SiC foundations assist AlN growth

Although AlN substrates have some great characteristics for UV-LED fabrication, it is very difficult to make this material. However, a fast sublimation growth process that deposits AlN onto SiC is producing very encouraging results, including incredibly low defect densities, say **Mikael Syväjärvi**, **Reza Yazdi** and **Rositza Yakimova** from Linköping University.

Unclean water is a massive global killer. The international children's charity UNICEF estimates that more than 4000 under-fives die every day from diarrheal diseases, simply because they do not have access to clean drinking water or adequate sanitation.

Water treatment could prevent many deaths. However, in some parts of the world the technique used for this task – ultraviolet (UV) irradiation with a mercury lamp – is too expensive for use in rural areas. That's because this source is inefficient, has a short lifetime and produces an emission peak that is a poor match for germicidal treatment. Mercury lamps emit at 254 nm, while water treatment has peaks in effectiveness at 185 and 265 nm.

Even water that is treated by mercury lamps can cause harm if it is then contaminated during transportation. So the ideal UV source is a small, robust, low-cost device that can target specific wavelengths and provide water purification at the point where it is needed. UV LEDs fit the bill, but their performance lags behind that of their visible-range cousins, primarily because of the lack of a suitable substrate.

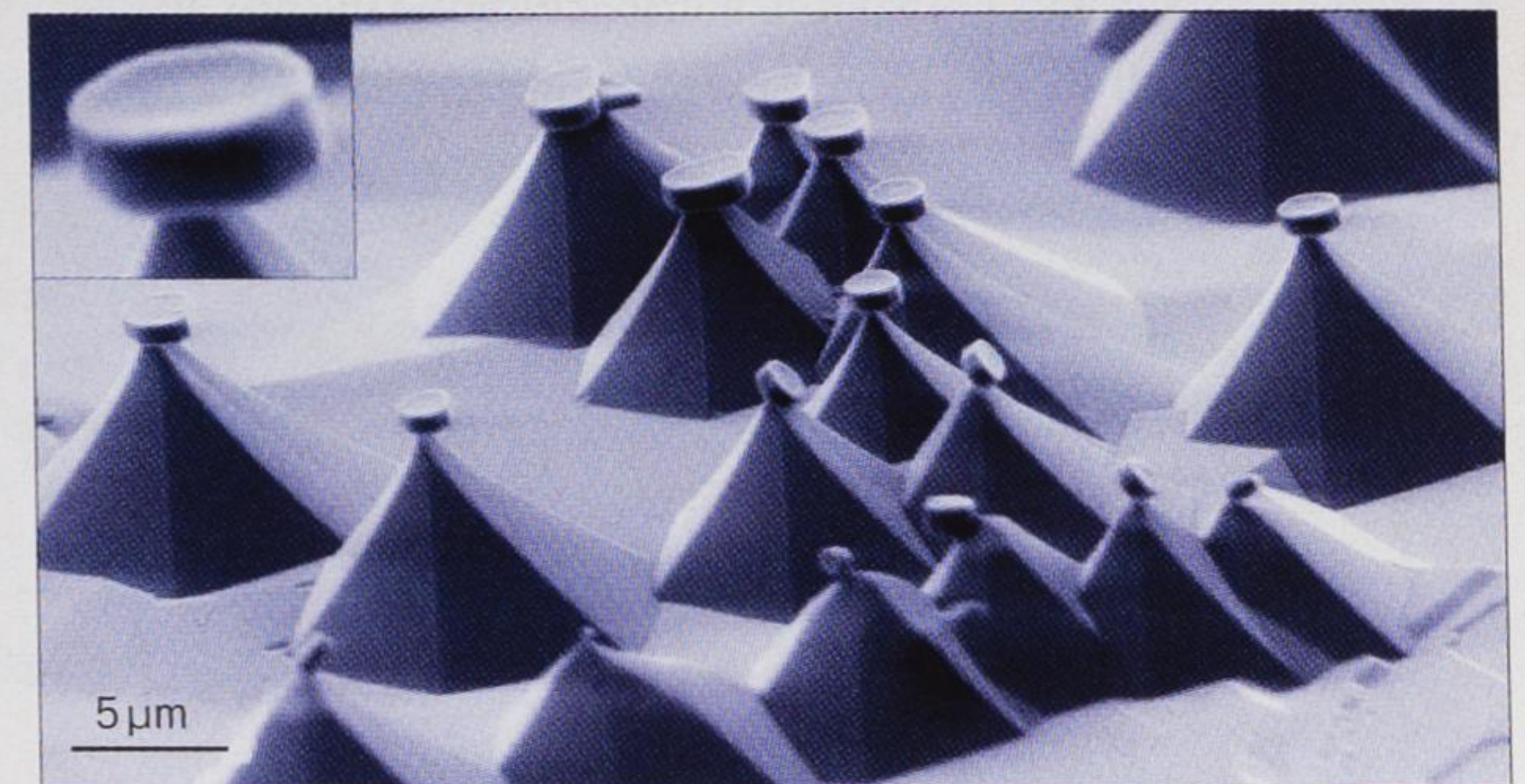
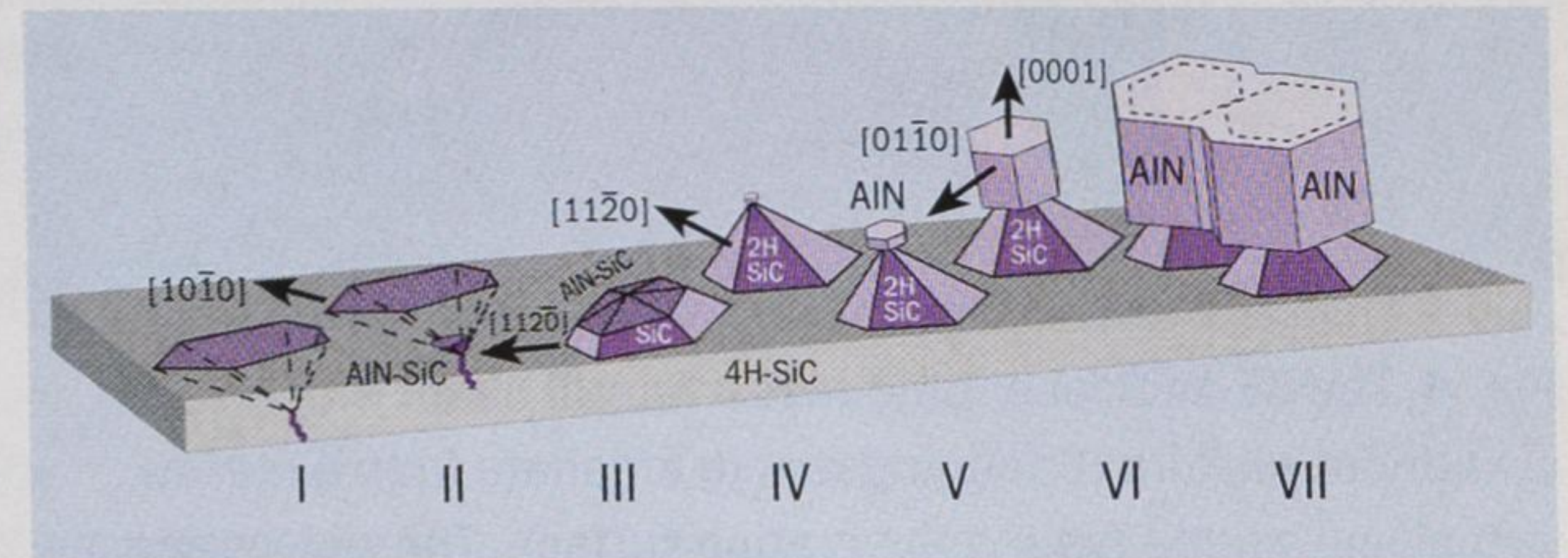
Sapphire and SiC, the common platforms for making blue LEDs, are not ideal for UV emitters. Growth on these platforms produces epilayers with a high defect density that degrades device output. GaN is an alternative base, but substrate prices are high, availability is limited and this platform absorbs below 360 nm, which prevents fabrication of flip-chip LEDs.

Benefits of AlN

A far better substrate candidate is AlN. This material is transparent down to 200 nm and provides better lattice and thermal expansion matches to the high-aluminum-percentage AlGaIn layers that are needed to produce 265 nm emitters. However, because AlN melts at 3200 °C, it is difficult to produce AlN substrates by conventional melt-based techniques.

Some progress has been made with a sublimation-recondensation technique, which involves evaporation of the AlN source that then cools on another platform. But defects tend to form in the seed crystal, which is typically SiC because of its better lattice and thermal match with the nitrides. The other major challenge is to realize a process temperature of more than 2100 °C, which is needed for growth rates of at least 0.1 mm/h. But there is another problem if this temperature is reached – aluminum starts to react with the surrounding materials.

At Linköping University, Sweden, we have developed a fast sublimation growth process that is suitable for AlN and employs a SiC seed. This approach can deposit material at speeds of 0.25 mm/h or more, at temperatures below 1900 °C, and ultimately produce free-standing substrates with dislocation densities of $2 \times 10^6 \text{ cm}^{-2}$, which is about two orders of magnitude



The fast sublimation growth process, developed at Linköping University, has several steps: the formation of etch pits on the SiC surface; the nucleation of AlN in the pits; the creation of AlN structures; pyramid formation; and the growth of discs that form microrods, which then coalesce to form a continuous AlN layer.

below that typically obtained by rival techniques.

The heart of our process is the transformation from a 4H-SiC seed to 2H-SiC through pyramids formed on the surface, which act as foundations for 2H-AlN. It begins by placing 4H-SiC and ceramic AlN plates in a TaC-coated crucible. As this is heated SiC sublimates before AlN, due to its higher vapor pressure, leading to the formation of etch pits on the SiC surface at 1400 °C. These are caused by thermal decomposition of SiC at surface intersections of threading dislocations.

As heating continues towards the growth temperature of 1700 °C, aluminum vapor is produced and nucleates with nitrogen in the etch pits. When the growth temperature is reached, hexagonal pyramids are created, followed by the formation of AlN discs on their apex. These discs grow into microrods, which coalesce to form a continuous AlN layer that can be easily separated from the 4H-SiC epilayer, thanks to the small contact area at the top of the pyramid and the stresses created between the two materials on cooling. In this way, free-standing AlN wafers more than 100 μm thick can be produced. Thanks to minimized interfacial strain, they are also crack-free.

We have produced free-standing AlN with a size of about 1 cm² and we have our sights on scaling to 2 inch diameter material. However, our ultimate focus is the development of processes to make UV LEDs on these substrates. Fabrication will not be trivial, but our ambition is to produce low-defect epistructures that can be processed into highly efficient devices.



About the authors

Mikael Syväjärvi (left) and **Reza Yazdi** (center) developed the basic SiC fast sublimation growth process and the AlN growth process, respectively.

Rositza Yakimova (right) heads the group.

Dots speed datacom VCSELS

Transmitters operating well beyond 10 Gbit/s are needed for emerging communication standards. Quantum-dot VCSELS can operate at four times this, and even higher rates are promised with a design incorporating a modulator in the top mirror, says VI Systems' **Nikolai Ledentsov**.

Serial transmission speeds in data communications undergo a four-fold hike every five years, which is driven by silicon scaling and increased demand on processor bandwidth. 3–8 Gbit/s transmission is becoming increasingly common in electrical interfaces for consumer and personal computer applications, and further upgrades are on the way.

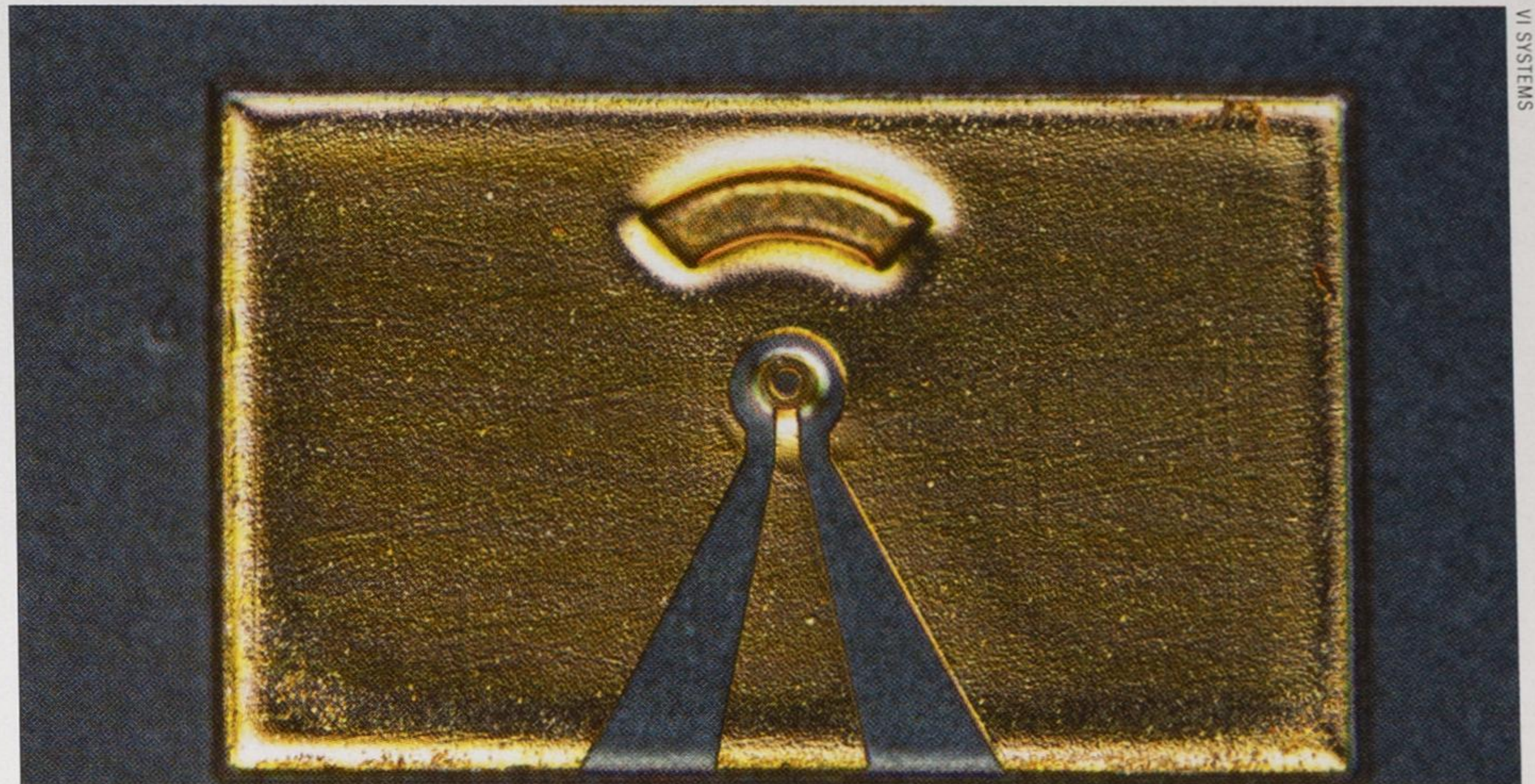
Copper is the traditional medium for routing the data, but it suffers from significant drawbacks. Links made from this material dissipate a lot of power and can cause unacceptable electromagnetic interference. At bit rates of 30 Gbit/s or more, copper links are limited to just a few centimeters on printed circuit boards. However, all of these issues can be avoided by switching from copper to optical fiber for signal delivery.

One option for the optical source is the 850 nm VCSEL, a reliable, low-cost, low-power-consuming laser that's suitable for short-distance data communication networks based on multimode optical fiber. This device can potentially produce transmission speeds of 40 Gbit/s or more when it is positioned on top of or embedded within a silicon chip, and directly merged and interconnected to the upper copper-based metal interconnecting layers.

Obstacles to faster speeds

However, if directly current-modulated 850 nm VCSELS are going to fulfill their promise, their producers will have to address significant reliability challenges that have impeded increases in data bit rates. At VI Systems, which is based in Berlin, Germany, we have found a route to higher speeds via quantum-dot (QD) VCSELS that can operate reliably at 40 Gbit/s. We are also developing another type of VCSEL with a radical design, which features a modulated top mirror that should be even faster.

At high excitation densities, current-modulated VCSELS, which are the most common form of the device, have a transmission speed limit that is governed by the stimulated radiative recombination rate. When the device is operated in this excitation regime, shorter radiative lifetimes produce a faster response to the changes in the input voltage that create the "1s" and "0s" of the binary code. If VCSEL data rates need to increase, then shorter radiative lifetimes are possible by injecting more carriers, but



VI Systems' 850 nm quantum-dot VCSELS are suitable for ultra-high-speed data communication.

a two-fold reduction in radiative lifetimes demands a quadrupling of the injected carriers.

Increasing the number of injected carriers also produces a dramatic hike in non-radiative recombination, alongside greater defect generation. Faster device degradation results, and even at speeds of 10 Gbit/s reliable operation demands significant compromises in design and overall efficiency.

Reliability can be improved at the expense of performance by increasing the size of the VCSEL's oxide-confined aperture. Higher injected current densities can then be realized, which lead to higher switching speeds without severe degradation. But if the current gets too high, this begins to limit the operating temperature range of the VCSEL. Higher currents also diminish spectral purity, shortening the maximum length of the optical fiber link.

Excessive output powers are another penalty that stems from the switch to higher current densities and larger apertures. Optical attenuators can reduce output power to the required level, but also diminish the power efficiency of the VCSEL and its driver IC. Reduced efficiency, combined with the weaknesses that we have highlighted, has led most current-modulated VCSEL manufacturers to conclude that this form of laser cannot provide degradation-free operation at data rates beyond 10 Gbit/s.

In contrast, single-mode 850 nm VCSELS driven under external intensity modulation can produce

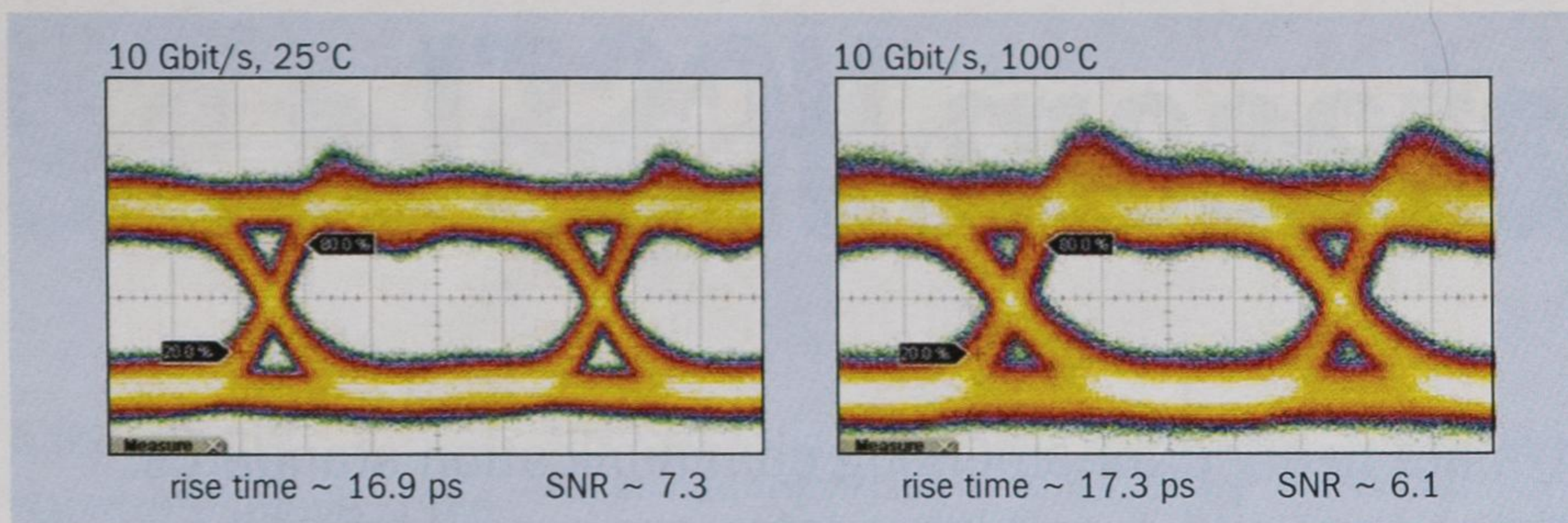


Fig. 1. Optical eye diagrams from an 850 nm VCSEL at room and high temperatures. The measured rise time (20–80%) is 16–17 ps and weakly dependent on temperature. The system-deconvoluted VCSEL rise time is below 9 ps at all of the temperatures studied. Open eyes are obtained from large signal modulation experiments using a non-return-to-zero data pattern with a 2^7-1 pseudorandom bit sequence at the given data bit rate. The resultant signal-to-noise ratios (SNRs) are greater than 6.

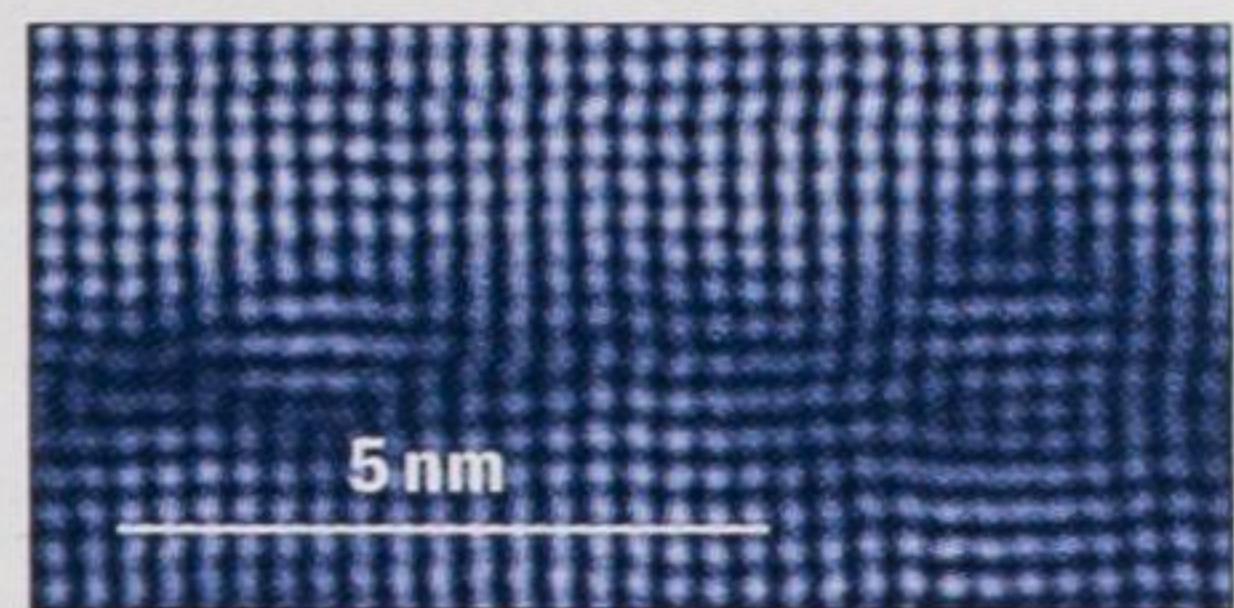
40 Gbit/s error-free transmission over 2 km lengths of photonic crystal fiber. Single-mode, degradation-robust devices are realized because the VCSEL is operated in continuous-wave mode at low current densities. However, there are downsides with this approach. Traditional external electro-optic modulation is power hungry and typically restricted to long-distance 1.3 and 1.55 μm telecom applications. In addition, modulators are bulky and modulated systems require complex coupling optics and optical isolation, which makes them rather expensive.

To improve VCSEL speed and reliability, researchers have turned to new materials for the active region. These include InGaAs strained quantum wells (QWs), which are widely used in edge-emitting lasers emitting in the 1 μm range and are well known for high degradation robustness, even at very high power levels. Larry Coldren's group at the University of California, Santa Barbara, has had success with this approach and fabricated 35 Gbit/s, 980 nm VCSELs operating at relatively small current densities (see *Compound Semiconductor* June 2008 p29).

The wavelength of these VCSELs is outside the range for multimode fiber (840–860 nm) and GaAs PIN photodetectors cannot operate above 0.9 μm . One way around this is to add small concentrations of indium to the QW of an 850 nm VCSEL, which push the emission to the required spectral range, but this reduces the benefits of the new active medium. For example, the confinement potential for the injected carriers is the same as that for GaAs QWs.

Our view is that it is far better to turn to an entirely different material system for the active region – InAs QDs. These nanostructures significantly increase material gain and differential gain, thanks to the switch from electron-hole plasma recombination that occurs in layered materials to inherently excitonic lasing. This in turn reduces the radiative lifetime at comparable current densities. QDs also have a secondary benefit – they improve reliability by localizing many carriers and preventing their diffusion towards defects where they could create dislocations in the material.

The first high-performance QD VCSELs were 1.0–1.3 μm devices that were fabricated by the Ioffe



The InAs-GaAs-AlGaAs submonolayer

(~0.9 monolayer thick) that is inserted in VI Systems' 850 nm VCSELs is revealed by atomic lattice transmission electron microscopy. Chemically sensitive conditions were chosen for the imaging. This produced a lattice contrast reversal at an average InAs composition above 20%. You can clearly see lattice contrast reversal in two regions of the image, with a height and a lateral size of 2 nm.

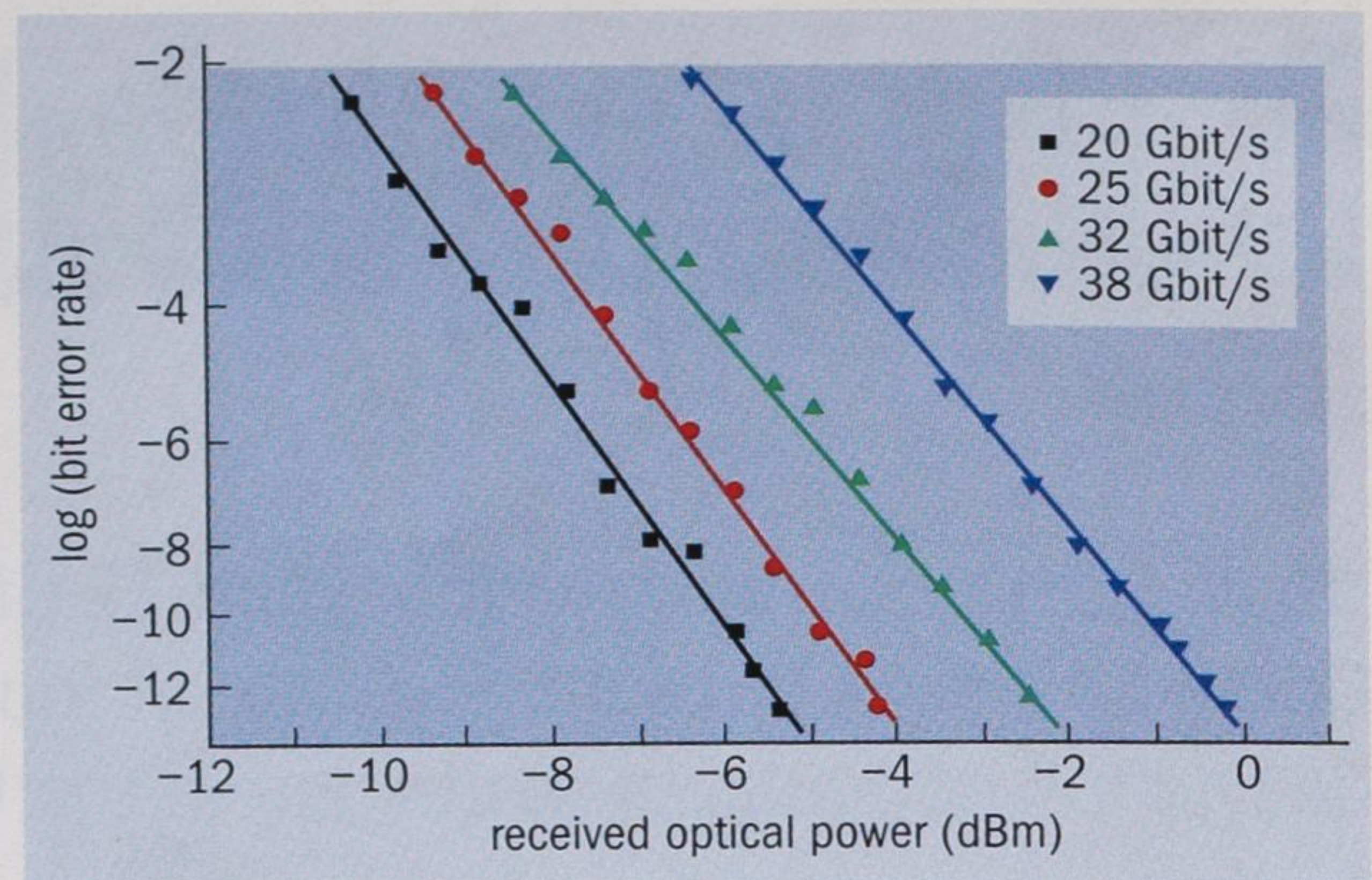


Fig. 2. Bit error ratio (BER) measurements as a function of received optical power show that error-free transmission, defined as $-\log(\text{BER}) < 1 \times 10^{12}$, is possible at low received optical powers. BER measurements were performed in a back-to-back configuration for a 9 μm diameter oxide-confined InGaAlAs VCSEL at 20, 25, 32 and 38 Gbit/s bit rates with a bias current of 9 mA and an operating temperature of 20°C. The current density is 10 kA/cm^2 and the root-mean-square spreading of the emission spectrum is less than 0.3 nm. True minimum power values can only be defined when amplifiers and drivers are optimized for the particular transmission speed measurement.

Institute in St Petersburg, the Technical University of Berlin and the Air Force Institute of Technology in Dayton. High-power single-mode operation at 1.25–1.30 μm has followed, and we have recently demonstrated 20 Gbit/s error-free operation up to 150°C.

Our latest efforts have focused on the development of the first 850 nm InAs QD VCSEL, which produces data bit rates in excess of 20 Gbit/s, has good temperature stability and has the potential for high degradation robustness.

High-speed VCSEL operation can be limited by parasitic impedance. Non-optimal mask design, an improper planarization process and an imperfect oxide-confined aperture design can all compress the electrical bandwidth. To compensate for the bandwidth deficiency in conventional VCSELs, excessive current density is applied to the device to maintain the modulation amplitude. However, this also accelerates the degradation process and often reduces the mean time to failure. A far better approach, which enhances electrical bandwidth and simplifies production of degradation-robust VCSELs, is to lower the device's intrinsic capacitance and resistance.

We used this approach to fabricate 850 nm VCSELs that operate over a wide temperature range. Eye diagrams at room temperature and 100°C show that the two signal levels, “0” and “1”, are well separated in intensity (figure 1). Measurements of bit error ratios as a function of the received optical power reveal that current-modulated 850 nm-range VCSELs, when driven at moderate current densities, are capable of high bit rates over a wide temperature range (figure 2).

Efforts have also been directed at developing a radically different modulation technology that promises to deliver incredibly high transmission

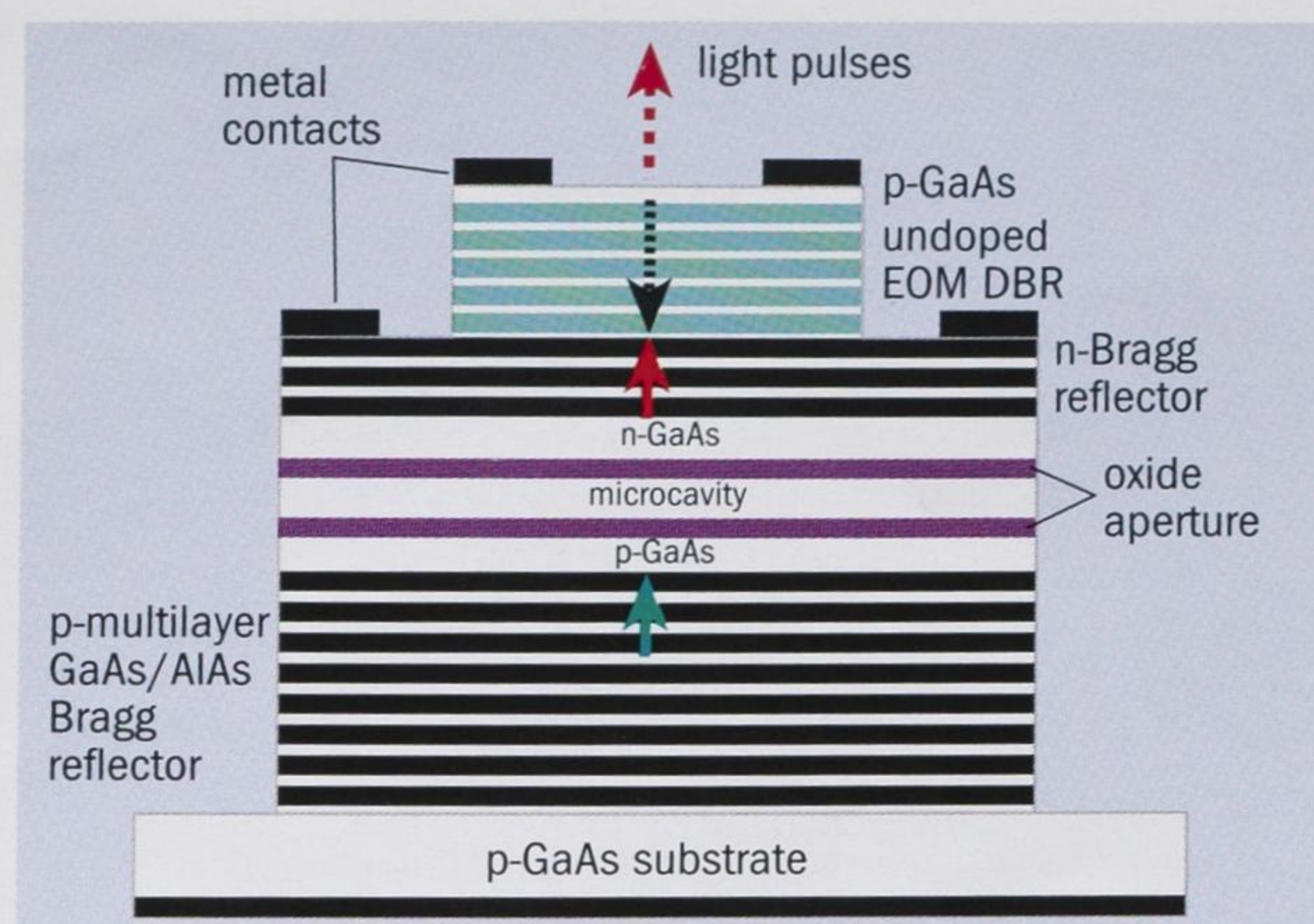


Fig. 3. Very fast bit rates could be realized with VI Systems' electro-optically modulated distributed Bragg reflector (DBR) VCSEL. Modulating the voltage across the upper DBR reflector makes it behave as a chopper (essentially a semi-transparent shutter) that interrupts the light from the microcavity. The laser is driven at a small steady-state current density.

speed. This approach, which could also enhance LED modulation speeds, involves modifying the upper VCSEL mirror – a distributed Bragg reflector (DBR) – so that it behaves like a beam chopper, interrupting the light exiting from the microcavity (figure 3). The principal changes to a standard VCSEL design include: the insertion of an active medium into several layers in the upper DBR; and the addition of a metal contact below this part of the upper mirror. Applying a modulated voltage between this contact and the one at the top of the mirror creates an electric field across the electro-optically active section of the DBR, which modifies the refractive index contrast. This in turn alters the reflectivity of the semi-transparent Bragg reflector mirror and the width of the DBR's reflectivity band, leading to adjustments in the output of the VCSEL.

In the past, researchers at other institutions have attempted to build a high-bit-rate VCSEL by adding a modulator section based on absorbing QWs. In this case the application of an electric field can shift, enhance, reduce or broaden the strong exciton absorption peak, and ultimately lead to some absorption of light at the VCSEL lasing wavelength.

This electro-absorption effect is strong only in the vicinity of the exciton resonance. Changes in refractive index, however, occur over a broader spectral range. This means that any increases in temperature lead to an exciton absorption red-shift that tracks the change in bandgap, and a shift in VCSEL cavity wavelength that moves in the same direction, but at a much slower pace. Because the absorption peak must never match the lasing wavelength, even at the highest operation temperature, say 85°C, these features have to be well separated at lower temperatures. Consequently, the modulation effects are insufficient in this type of device unless a massive voltage is used. In addition, the VCSEL can suffer from overheating, lasing-induced transparency, self-pulsations and parasitic frequency resonances, due to a strong

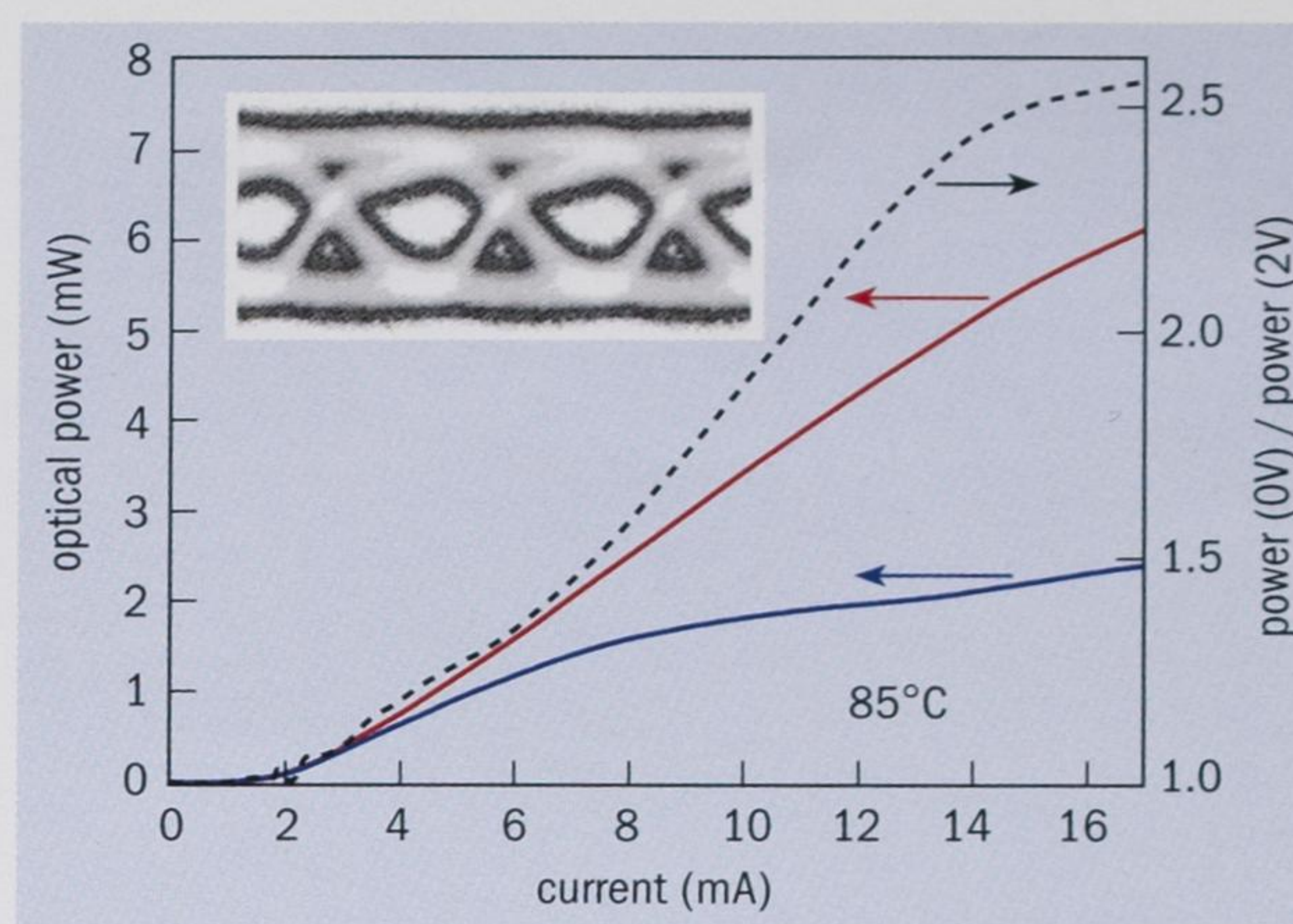


Fig. 4. VI Systems' electro-optically modulated VCSELs can deliver transmission speeds of 6 Gbit/s or more using a modulating voltage of 2 V. Devices feature 10 µm circular apertures and deliver similar performance from 25 to 100 °C.

absorption of carriers in the modulator section.

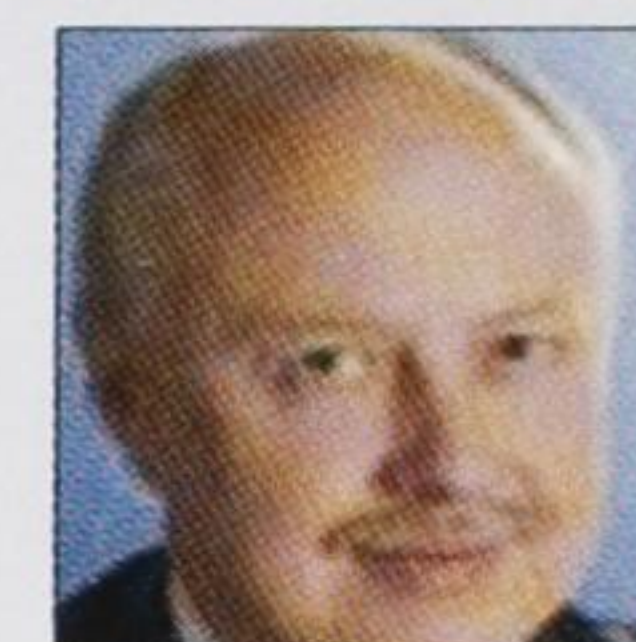
However, with our design – the electro-optically modulated DBR VCSEL – the changes in exciton oscillator strength affect the refractive index across a very broad spectral range. That's because the exciton absorption peak adds a resonance contribution to the refractive index that slowly decays away from the resonance and is superimposed on a background refractive index. Even when the exciton absorption peak is dramatically enhanced or reduced in intensity, the resonance contribution to refractive index is proportionally affected across the spectrum.

The upshot of this is that absorption does not significantly degrade the modulation characteristics of QD VCSELs with an electro-optically modulated DBR, and these devices can exhibit a smooth, featureless small signal modulation curve up to 100°C. We have recently built a prototype that can produce 50–70% modulation with a modulation voltage below 2 V and deliver error-free transmission beyond 6 Gbit/s. This enables our low-capacitance electro-optical modulator DBR to operate with a very low power consumption of the modulator driver IC.

One of the key strengths of our electro-optically modulated DBR VCSEL is that it allows the realization of devices with a uniform, robust performance. These lasers can be produced on 3 inch diameter wafers and feature active regions based on either QDs or QWs. Further optimization of our structure should produce VCSELs with operational data bit rates of 40 Gbit/s at 1.0–1.5 V modulation voltages, which will be strong contenders for filling the gap for on-chip optical input/output devices for new generations of multicore processors.

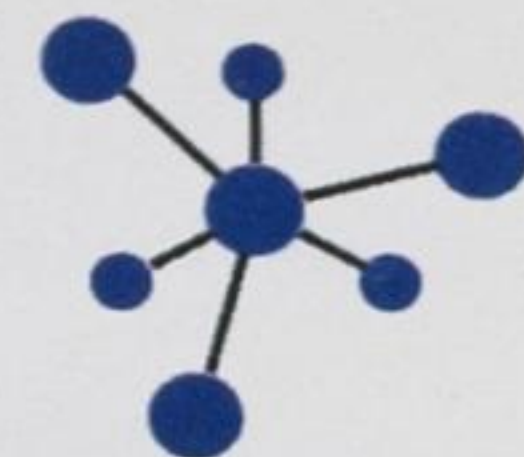
Further reading

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About the author

Nikolai Ledentsov is founder and CEO of VI Systems. He is the most cited active Russian scientist and is currently on leave from the Ioffe Institute in St Petersburg, Russia. This feature is written in co-operation with JA Lott, VA Shchukin, A Mutig, G Fiol, T Germann, SA Blokhin, AM Nadtochyi, LYa Karachinsky and D Bimberg. The team has enjoyed the support of the VISIT project – a Seventh Framework Program of the European Commission – the HiTrans project funded through the Program to Promote Research, Innovation and Technology of the Investitionsbank Berlin (IBB); the NanOp program of the German Ministry for Education and Research (BMBF); and the German Aerospace Center (DLR).



MBE

Nitrogen radicals repair InN epilayers

InN has the smallest bandgap and highest electron mobility of all of the nitrides, but its poor material quality is preventing it from being the key ingredient in infrared light emitters and high-speed electronic devices.

However, material quality can be improved by switching to an MBE growth method that eliminates indium droplets with a beam of nitrogen radicals, according to Tomohiro Yamaguchi and Yasushi Nanishi from Ritsumeikan University, Japan.

Yamaguchi says that MBE is the preferred technique for depositing InN. MOCVD is less attractive because very little ammonia decomposes into nitrogen and hydrogen at the temperatures needed for InN deposition.

The challenge for MBE growers is maintaining the optimal III-V ratio. If you add too much nitrogen, a poor-quality, rough film is produced, but add too little and indium drop-

lets are formed on the surface, which are difficult to remove.

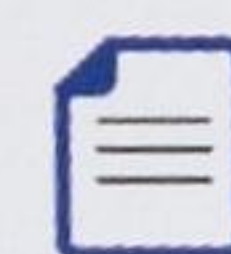
Striking the balance between too much and too little indium is hard, but this problem can be negated by a modified MBE technique that Yamaguchi stumbled on by accident: "I started to use a new MBE machine and I did not know the growth condition at all."

One day Yamaguchi unintentionally used very indium-rich growth conditions for depositing InN, and when he looked through the viewport he could see that the sample was actually metallic. At this point he wanted to stop the growth, but only turned off the indium supply, so the sample was still irradiated with nitrogen radicals. As this was taking place, the intensity measured by the *in situ* reflection high-energy electron diffraction tool shot up, indicating a massive improvement in material quality.

Yamaguchi deduced that a beam of nitrogen radicals substantially expands the width of the growth window for InN.

The Japanese researchers have produced a range of InN films on GaN-on-sapphire templates at a growth temperature of 450 °C. These InN films have a root-mean-square roughness of less than 1 nm, according to atomic force microscopy measurements, and have electron mobilities and carrier concentrations of $1700 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $1.5 \times 10^{18} \text{ cm}^{-3}$, respectively.

Yamaguchi says that crystal quality and electrical properties are improving "day by day". He is now turning his attention to InGaN growth.



Journal reference

T Yamaguchi et al. 2009 *Appl. Phys. Express* **2** 051001.

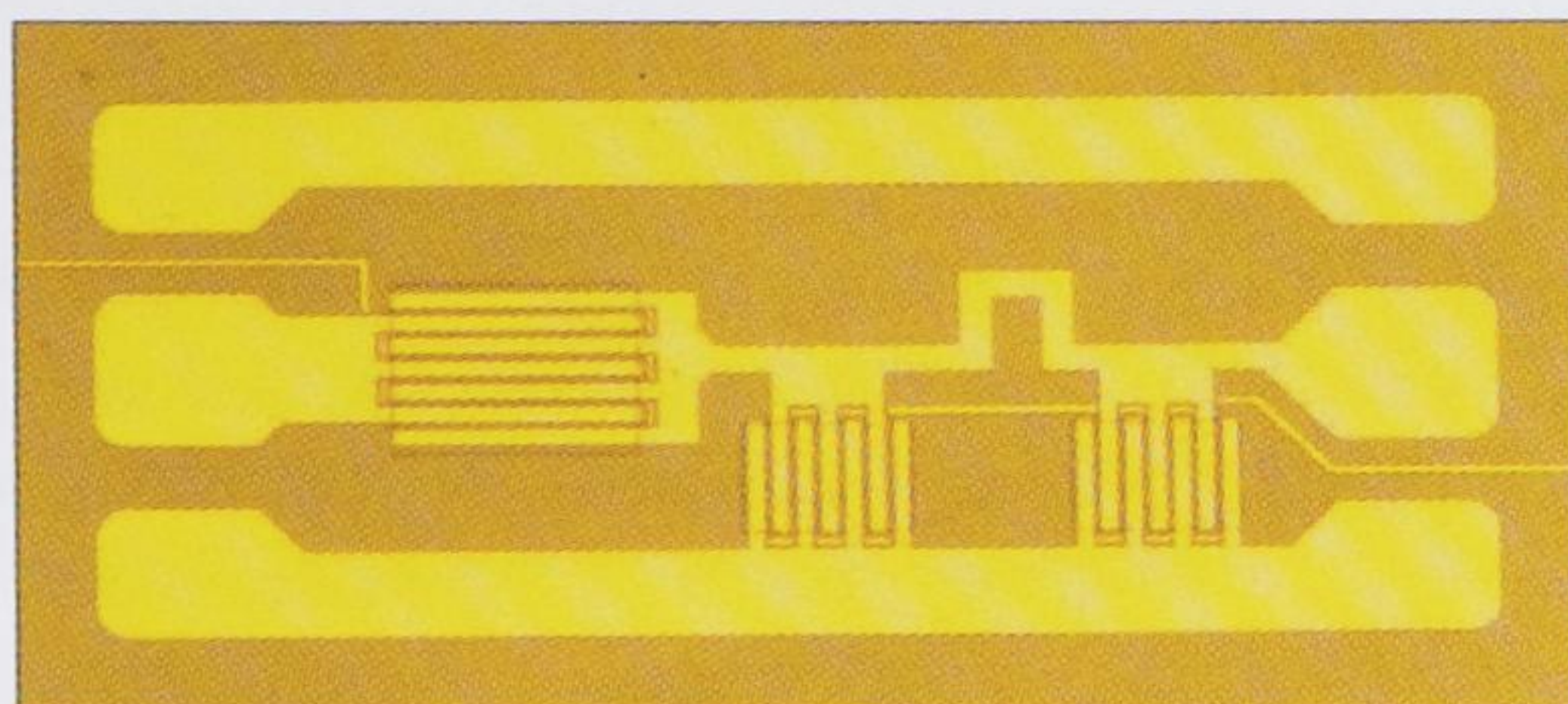
III-N HEMTs

HfO₂ dielectric layer increases output power

A US team has increased the power handling capability of switches made from AlGaIn/GaN HFETs by adding capacitively coupled contacts based on HfO₂.

Lead author Alexei Koudymov from Rensselaer Polytechnic Institute claims that these devices could be used for radar, telecommunication and satellite communication systems, along with novel types of software-defined radio. "Their biggest advantages appear at frequencies above 2 GHz, where the effective impedance of the capacitive coupled contacts becomes even lower than that of regularly annealed contacts."

The team – which includes researchers from Sensor Electronic Technology, the University of South Carolina, Princeton University and the State University of New



The first GaN-based HFET with capacitively coupled contacts and a HfO₂ layer has been built by a partnership between Rensselaer Polytechnic Institute, Sensor Electronic Technology, the University of South Carolina, Princeton University and the State University of New York at Albany.

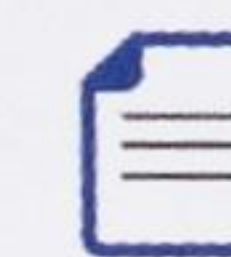
York at Albany – started developing microwave devices with capacitively coupled contacts back in 2005. "In capacitively coupled contact devices, the dielectric layer plays a crucial role, being responsible for the device turn-off voltage, control voltage, linearity and leakage," explained Koudymov. Turning to a HfO₂ dielectric has already aided the sili-

con industry, which is searching for superior alternatives to SiO₂ for the gate oxide, and it is now helping this US team to improve the performance of its HEMTs.

Transistors were produced by taking an AlGaIn/GaN heterostructure, etching this into a mesa and adding a HfO₂ film by reactive electron-beam evaporation. 250 nm long gates are defined by electron-beam lithography.

Compared with conventional HEMTs, these HfO₂-based devices have comparable insertion losses, DC leakage currents that are two orders of magnitude lower and a power-handling capacity that is four times higher in the on-state.

Koudymov says that the team plans to develop devices with significantly lower off-state capacitance, even lower insertion losses and higher linearity.



Journal reference

A Koudymov 2009 *IEEE Electron Device Lett.* **30** 478.

GaN VCSELS

Native platform extends emitter life

Replacing a sapphire substrate with a native one improves GaN VCSEL performance, according to researchers at Nichia.

Changing to the GaN platform led to a 4.5-fold increase in output power to 0.62 mW and lengthened device lifetime. Devices

grown on sapphire failed after 2 min, while those grown on sapphire operated for at least 10 min, and at this point the threshold current had only increased from 7 to 8 mA.

Although more improvement is needed before these devices can become commercial products, they are promising for high-density optical storage devices, laser printers and arrays, thanks to their single longitudinal-mode operation, circular emission profile and two-dimensional array capability.

The Japanese researchers carried out their study by growing identical epitaxial structures on sapphire and on a GaN substrate with a dislocation density of 10^6 cm^{-2} . These structures feature n- and p-type layers, and an active region with two 9 nm InGaN quantum wells and a 13 nm thick barrier.



Journal reference

K Omae et al. 2009 *Appl. Phys. Express* **2** 052101.



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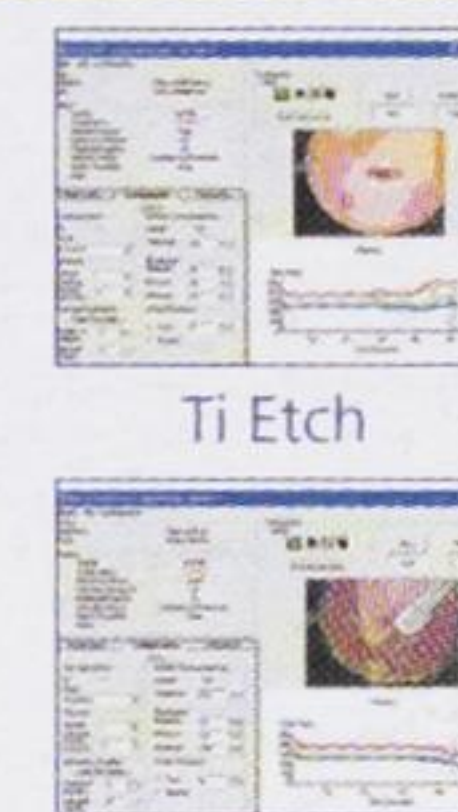
Backside Film Removal



Stream Etch for Films & Metals



In-situ Post-Etch Cleanup



Ti Etch

Cu Etch

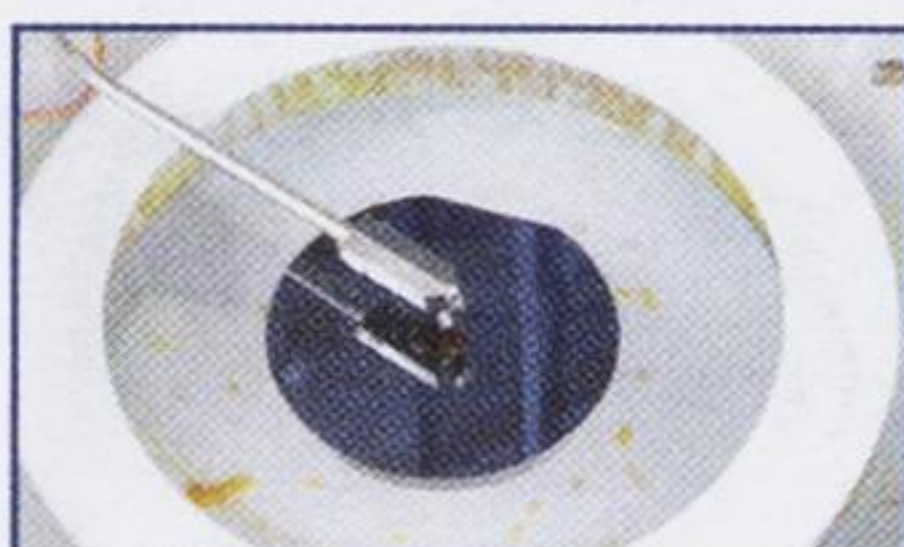


Poly Silicon

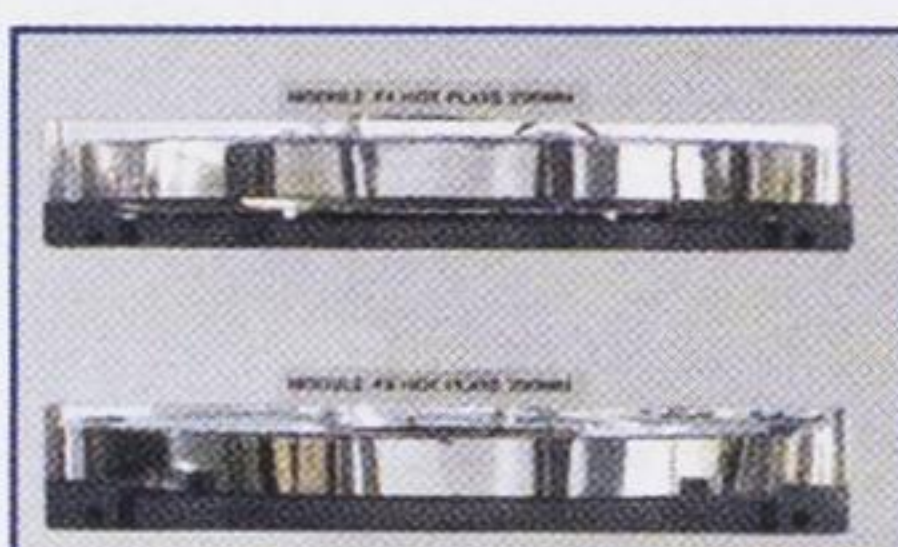
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