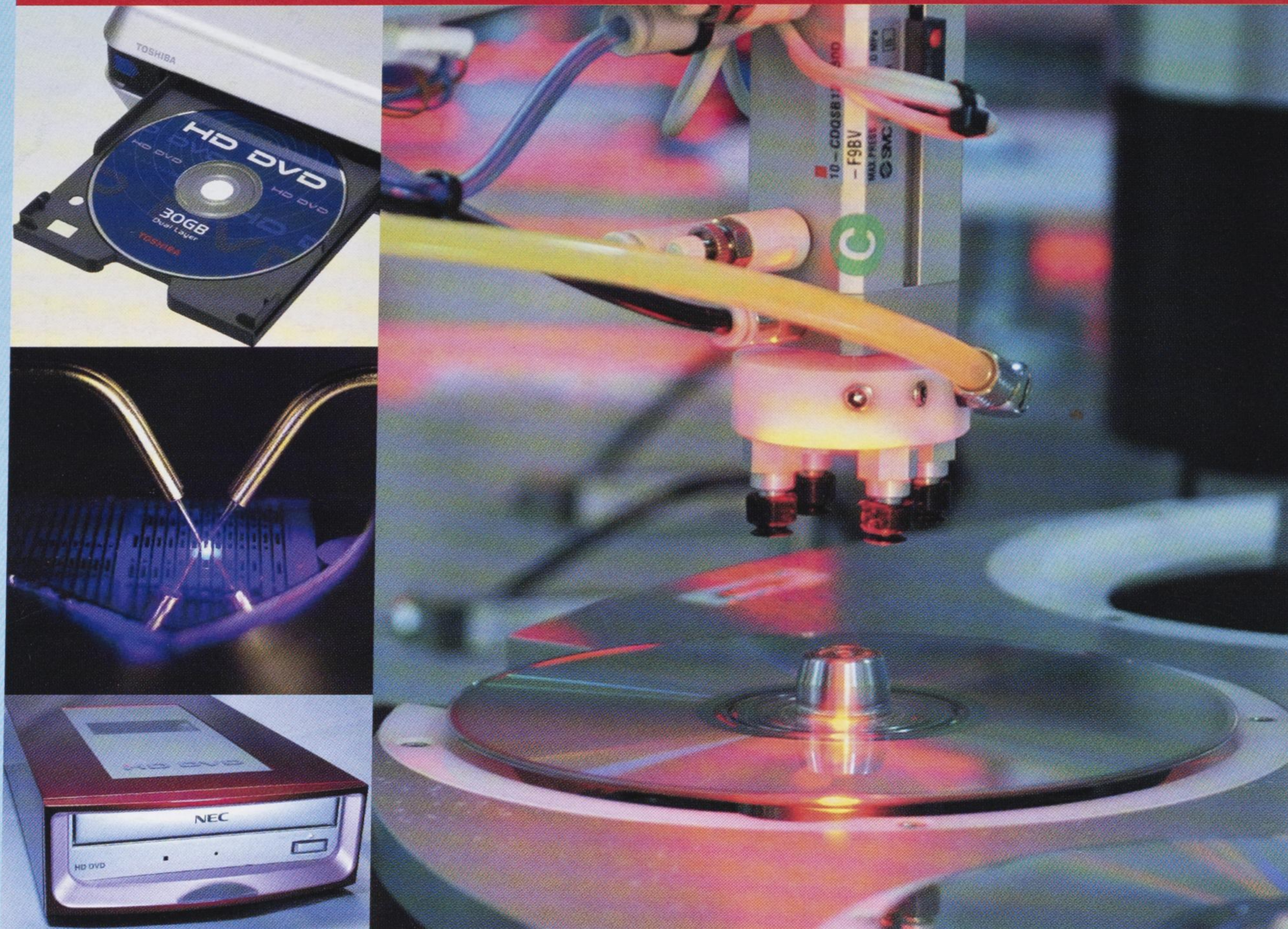


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Three-Fives and Silicon Heterostructures

January/February 2005 Volume 11 Number 1



HOT TOPICS 2005
**10 years after 'first light',
GaN lasers hit the big time**

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\$200 m Finisar deal**

**Nakamura gets \$8 m
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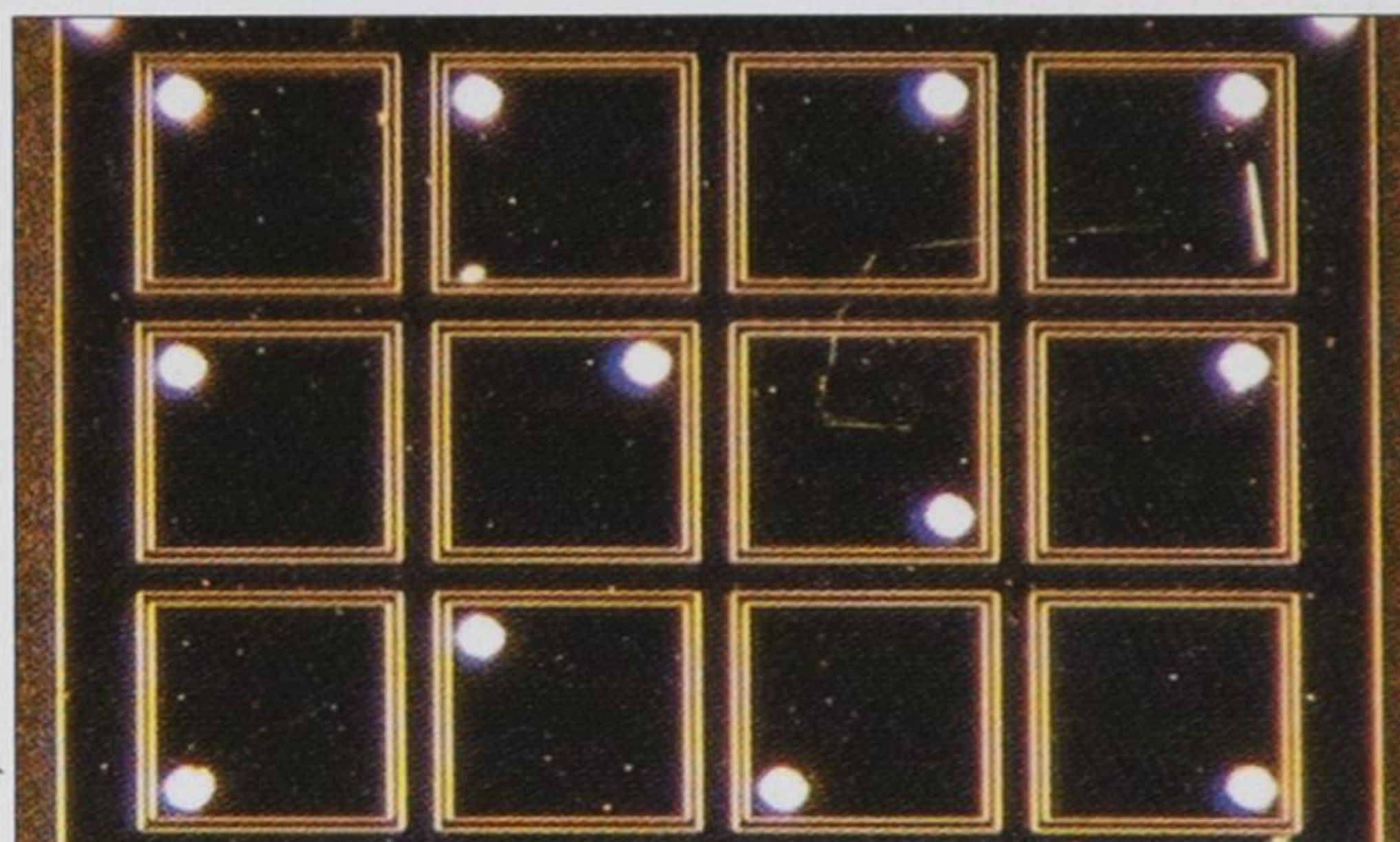
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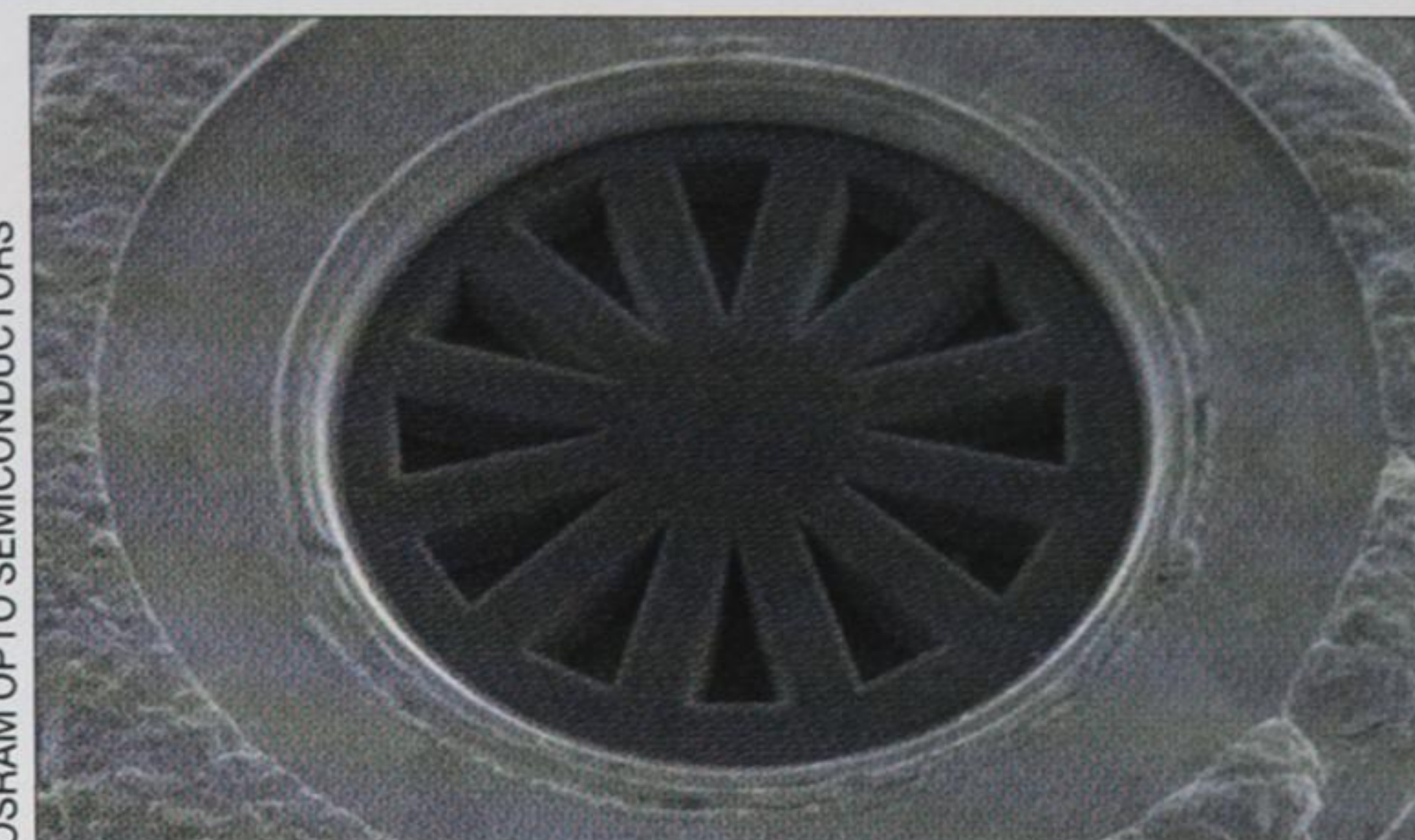
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III-V chipmakers stand to benefit significantly from a global 3G roll-out in 2005. **p16**



Scientists in Italy have developed radiation detectors based on silicon carbide. **p29**



VCSELs with triangular-shaped holes means high power and singlemode output. **p32**

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On the cover: 10 years after Nichia scientists produced a blue GaN laser operating at room temperature, 2005 will see the devices go into mass production as next-generation DVD comes of age. Credit: Toshiba, NEC, Sharp Laboratories Europe, Memory Tech.

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BPA 7979 total qualified circulation*
*June 2004 BPA audit statement

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

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Cree loses some sparkle



Despite the difficulties that have faced our industry over the past three years or so, US company Cree has shone out as one of the big success stories among III-V chipmakers. Every quarter, it seemed, another record was broken – soaring revenue, big profit margins and technological breakthroughs.

So the company's January trading report came as a bit of a shock. Cree said that it was only expecting revenue in the current quarter to be equal to that of December, at best.

Sure, the seasonal nature of the cell-phone handset market – which accounts for around half of Cree's chip sales – means that demand is weaker at this time of year. But something more than seasonal changes seems to be behind the slowdown. Increasing competition from low-cost Asian suppliers may be part of the explanation, as well as Cree's changing product mix, which has seen the firm introduce the competitively priced UT-230 LED for handset keypad backlights. It could also be that growth in the cell-phone handset market is, as predicted by Nokia and others, finally falling off.

Whatever the reason for the sluggish demand, the effect was to frighten investors and Cree's stock tanked by more than one-quarter after it released its update. Trading at around \$25 as this issue went to press, the stock is way off its late-2004 high of \$42. Cree's own senior managers certainly appear to have recognized the value of their assets during that period, between them selling off around \$40 million worth of stock in October and November. That even had an effect on the company's bottom-line performance in the most recent quarter, with earnings per share slightly reduced due to the stock options that were exercised.

Cree is set to remain a shining light in the industry – as well as a highly profitable enterprise – but it now looks to be facing a much trickier business environment than it has been used to.

Michael Hatcher

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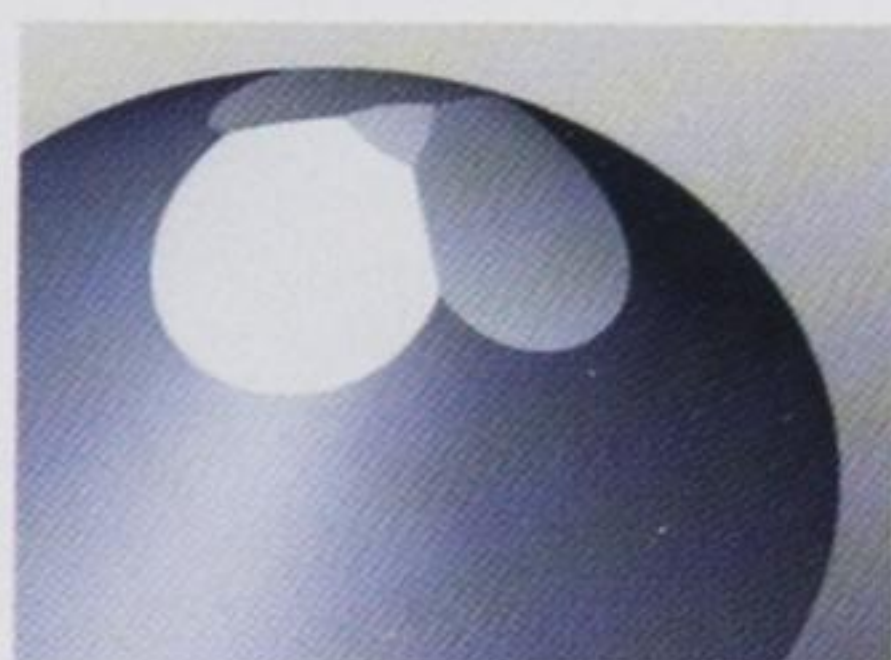
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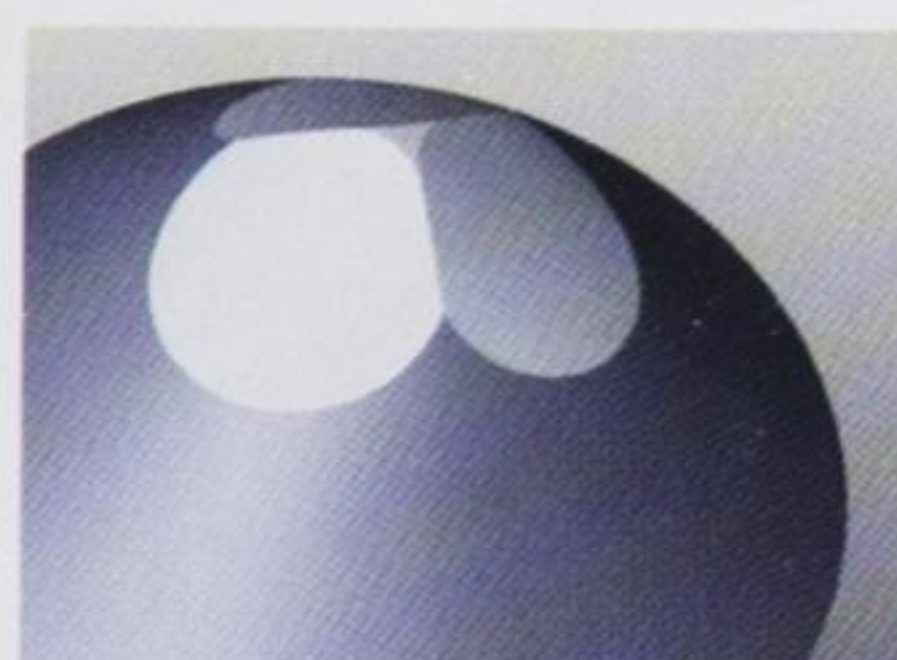
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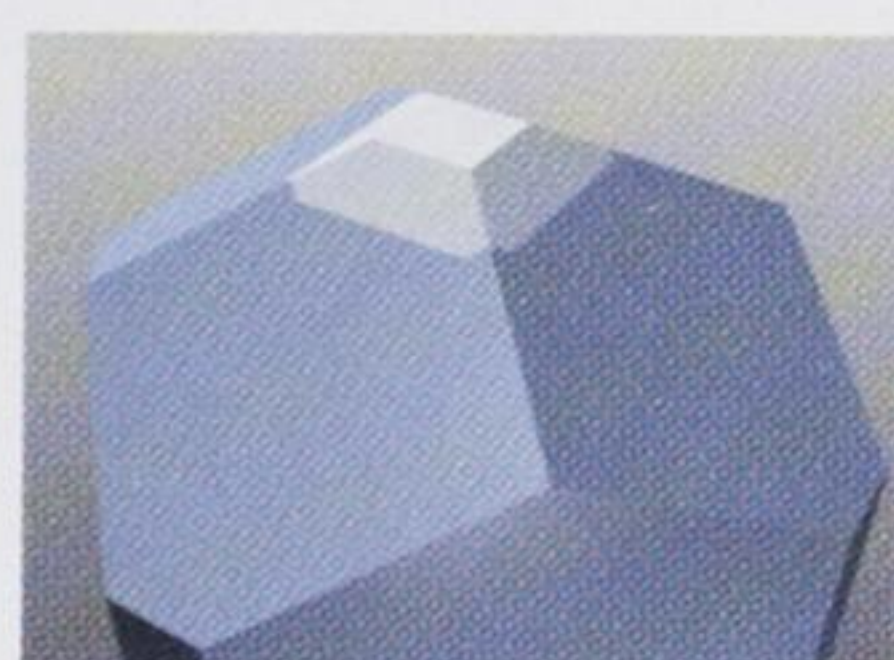
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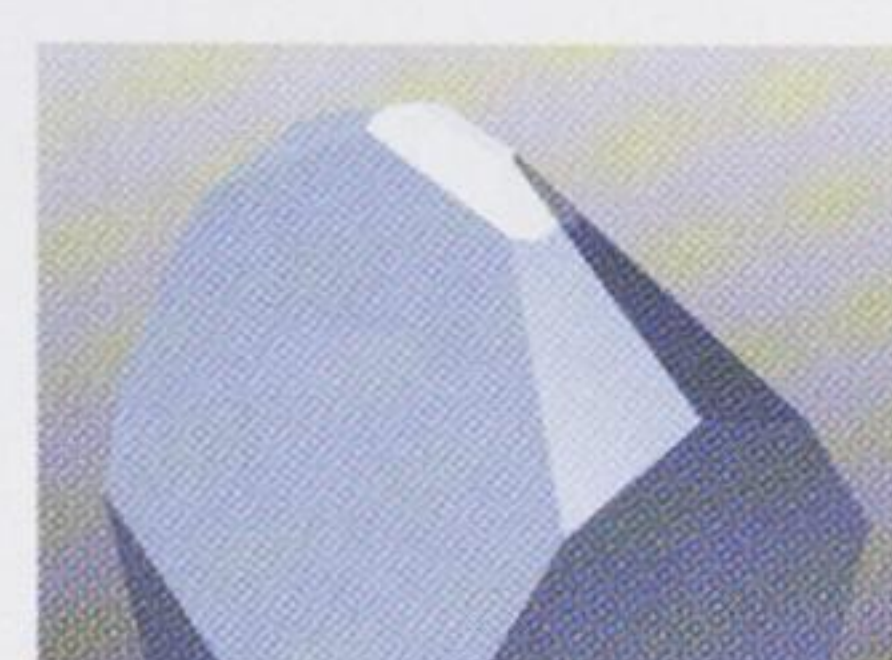
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Finisar and Infineon threaten to take legal action as \$200 m deal collapses

Infineon Technologies has called off the \$200 million deal that would have seen US-based Finisar acquire Infineon's fiber-optic business unit, which includes III-V chip fabrication facilities.

A substantial number of redundancies at the unit now seem inevitable, while both parties have raised the specter of potentially costly legal action against the other.

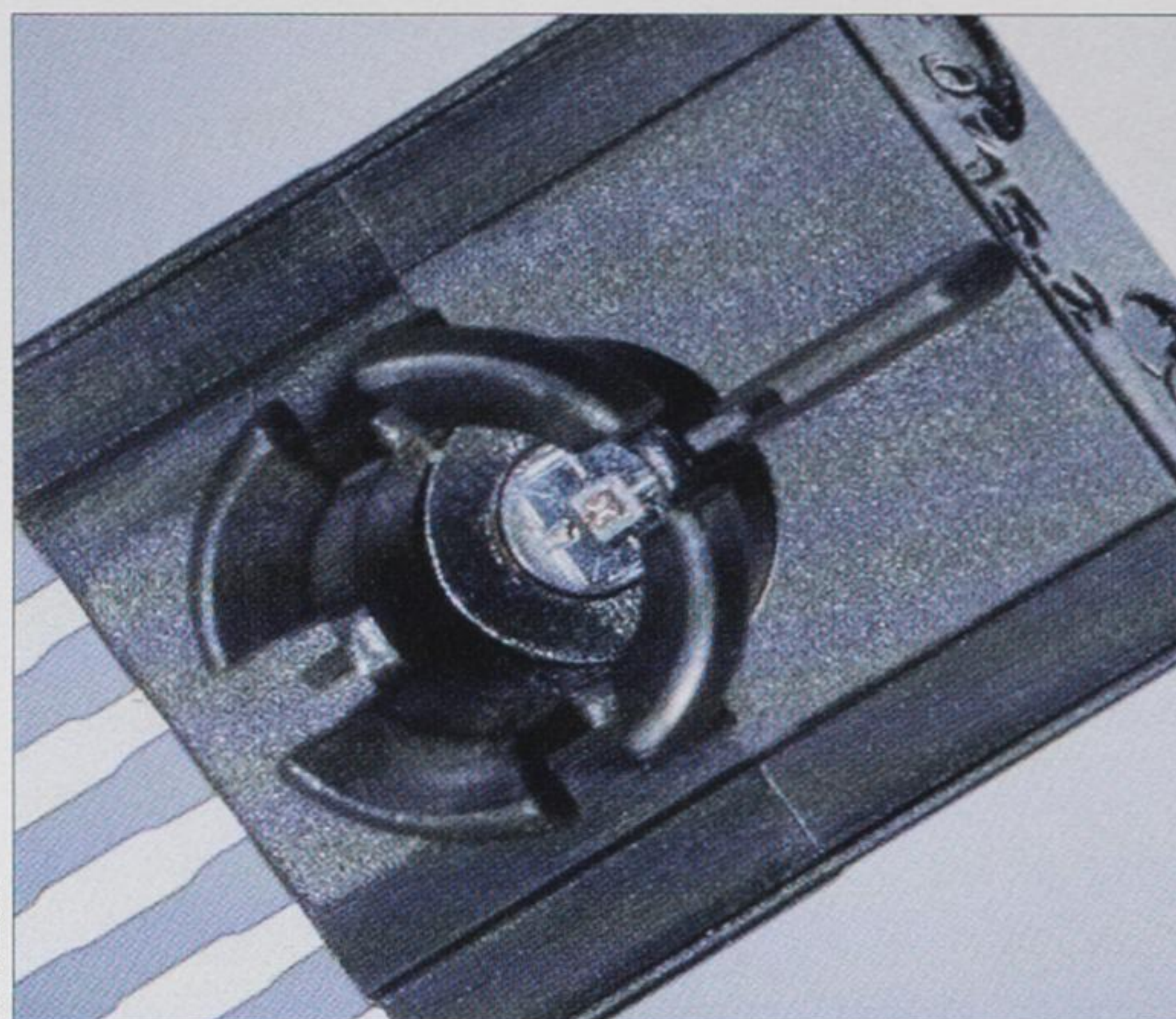
The Munich-based firm claims that Finisar's board had said that it was likely to withdraw its recommendation that shareholders vote in favor of the much-delayed acquisition.

"The significant delay and high uncertainty of closing are expected to result in deterioration of our fiber-optics business and in potential harm to our customers," explained Infineon. "[The firm] has therefore decided to terminate the agreement with Finisar."

Finisar denies Infineon's allegation that it was planning not to recommend the deal to its shareholders. "Infineon's notice alleges that the purported termination was based on Finisar's breach of the agreement," said the Sunnyvale, CA, company in a statement issued two days after Infineon terminated the deal. "No such breach has taken place."

Finisar claims to have told Infineon that its board was merely in the process of deciding whether or not it would recommend the deal "in light of a number of recent adverse developments" at the German company's fiber-optics business.

This re-examination was in compliance with the terms of the amended purchase agreement signed on October 11 last year, it claims.



Under the aborted \$200 million deal, Finisar had stood to gain access to Infineon developments such as this transceiver designed for in-vehicle optical communications via plastic optical fiber.

When the deal was first announced in April 2004, Infineon stood to hold a 38% equity share in Finisar on completion of the switch, then worth \$263 million. The October amendment reduced the value of the deal from 135 million Finisar shares to just 110 million, which would have been worth \$206 million on the day Infineon called off the acquisition.

In response to Infineon's claim that it would seek to recover damages incurred in the nine months since the aborted transaction was first announced, Finisar says that it will defend itself "vigorously" and possibly make a return damages claim of its own against Infineon.

Infineon's fiber-optic unit, which is headquartered in Berlin, includes a III-V chip

manufacturing facility at its Perlach fab in Munich, as well as a 56% holding in Taiwan-based Parolink, a joint venture with United Epitaxy Company. Both would have been transferred to Finisar.

The two firms had claimed that the combined entity would be "the largest pure-play optical-components company in the world".

But the poor financial performance of the Infineon unit, which has expertise in LEDs for vehicle communications systems and long-wavelength VCSELs among other technologies, since the deal was struck is undoubtedly a contributing factor to the collapse of the merger.

The Infineon unit made a loss of \$34 million on revenue of \$66.1 million in the six months ended March 2004, before the acquisition was renegotiated. Since then, Finisar made a loss of \$45 million in the six months until the end of October 2004. Holding cash and short-term investments of just over \$100 million, Finisar faced a mammoth task to make the combined business profitable.

Rather than seeking another buyer, Infineon will now concentrate on restructuring the unit – a move that the company admitted was likely to involve cost-cutting measures including lay-offs. The business has maintained a staff level of 1200 people since the Finisar deal was first announced.

With overcapacity still a big problem in the fiber-optic components sector, it is possible that Infineon will close the unit, although a spokesman says that the firm has "no intention" of taking such a drastic measure.

Nichia settles with Nakamura for \$8 m

Blue-LED pioneer Shuji Nakamura and his former employer Nichia have finally come to a compensation agreement over the invention of the GaN-based devices.

Tokyo High Court told Nichia to pay Nakamura ¥840 million (\$8.1 million), and the final outcome must be regarded as a victory for the company over the researcher.

The settlement is thought to be the most that a firm has ever paid an inventor in Japan, but it is far less than the ¥20 billion that Nakamura

was awarded by a Tokyo district court last year (*Compound Semiconductor* March 2004 p5).

A payment of that magnitude would have posed a big financial headache for Nichia, even though it has a huge share of the estimated \$4 billion high-brightness LED market. Nichia has said that it expects to make a ¥100 billion profit on sales of ¥220 billion in 2004, and it is investing heavily as it gears up for mass production of GaN-based blue lasers for next-generation DVD applications.

The high court estimated all Nakamura's inventions while the researcher was at Nichia to be worth ¥608 million to the company. The extra ¥230 million was awarded as compen-

sation for the delay in payment.

A clearly unhappy Nakamura told *Compound Semiconductor* that he was "very disappointed" with the settlement, while Nichia believes even the revised amount excessive.

Now working as a professor at the University of California in Santa Barbara and as a consultant for Nichia's US rival Cree, Nakamura had originally sued Nichia in 2001 as sales of the firm's nitride LEDs began to take off.

While the district court judge ruled that Nakamura's contribution to blue LED development was "not less than 50%", the final settlement has valued his work at Nichia to be worth just a fraction of that figure.

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RFMD invests \$75 m in increased wafer capacity

RF Micro Devices (RFMD) is to spend \$75 million on expanding its 6 inch-wafer processing capacity at its GaAs fabrication facility in North Carolina. The company is expected to add 75 jobs to its payroll as a result.

RFMD co-founder Jerry Neal says that this capacity expansion is necessary to keep driving down the cost of its products in line with the 15–10% annual price erosion demanded by cell-phone handset makers.

"We're adding cleanroom space and putting in the facilities, and the last stage will be moving in the processing equipment," said Neal. Around \$25 million will be spent on the building itself, with a further \$50 million earmarked for processing equipment. "We see

the coming year as one of major expansion of GaAs capacity, as well as reduction in cost and cycle time," he added.

The cell-phone handset sector, which is the primary market for RFMD's products, is expected to continue its rapid growth this year, albeit at a slower rate than has been seen over the past two years.

Nokia, the Finland-based market-leading maker of handsets and a key customer of RFMD, has forecast 10% growth in total unit shipments this year on top of the 630 million figure it estimated for 2004. Other estimates put the 2004 figure nearer 670 million. However, Nokia expects the dollar value of the cell-phone market to grow at a slower rate in 2005.

TriQuint purchases Oregon filter business

TriQuint Semiconductor is to acquire TFR Technologies, a company that makes thin-film resonator filters, for around \$3 million in cash.

Based in Bend, Oregon, TFR manufactures electronic filters based on bulk acoustic wave (BAW) or film bulk acoustic resonator technology. The company has 21 employees and stands to generate revenue of \$3 million–4 million in 2004, says TriQuint.

Although TFR's products are used mostly by the US military, TriQuint CEO Ralph Quinsey is convinced that they are suited to the high-volume consumer sector in cell-phone, Wi-Fi and WiMax applications. The acoustic filters could be used in integrated front-end radio products sold by TriQuint.

TriQuint plans to integrate BAW manu-

facturing into its existing surface acoustic wave (SAW) filter production facility in Orlando, Florida. The transfer process is expected to take around 18 months, with high-volume production slated for 2006.

BAW filters can operate at higher frequencies than current SAW technology, which typically works at up to 2.5 GHz. In comparison, TFR's BAW filters can operate at more than 10 GHz.

Quinsey says that the wider potential of TFR's technology will be "unlocked" once BAW filter production has been transferred to its facility in Florida, allowing low-cost devices to be made in high volumes. TriQuint will then look to penetrate commercial markets with the technology.

Sumika expands its PHEMT-epiwafer production capability

Sumika Electronic Materials is to add GaAs PHEMT-epiwafer manufacturing capability at its Phoenix, AZ, site.

The Japanese firm, which is owned by Sumitomo Chemical Company, already makes GaAs HBT epiwafers in Phoenix. The addition of two new MOCVD systems means that Sumika now has two production sites for both PHEMT and HBT epiwafers.

Sumika says that epiwafer growth using the new equipment is expected to reach full-scale production in the current quarter. The company adds that it has plans to commercialize novel PHEMT technologies.

The extra capacity will also allow Sumika to add to its existing HBT and diode product lines in Phoenix.

Sumika was formed in 2003 when its parent company bought semiconductor-equipment-firm ATMI's GaAs epiwafer group, and formed two new businesses.

In the Japan-based wing of the operation, at Sumitomo's facility in Chiba, Sumika Epi-Solution makes HBT and PHEMT epiwafers.

Concept cars reveal LED potential at Detroit show

By Tim Whitaker

LEDs were very much in evidence at the North American International Auto Show in Detroit in mid-January. While many manufacturers have incorporated LEDs into their latest models, the exhibit itself also featured a vast array of LED displays.

Many of the cars at the show had made use of LEDs, notably the concept cars, including Acura's RDX and the Ford Shelby GR-1. Both sported LED headlamps, although this technology is not expected to reach the market-place for several years yet.

Kia Motors America (KMA) unveiled the KCD-II Mesa, a concept vehicle developed by Kia's California Design Center in Irvine. The SUV uses LEDs in all of its exterior lamps – namely headlamps, tail lamps, fog lights, brake lamps, front and rear turn signals, reverse lights and the center high-mounted stop lamp. The vehicle has one other distinc-



KIA MOTORS AMERICA

Kia Motors America's concept car, KCD-II Mesa, uses LEDs for all of its exterior lamps, including a roof-mounted LED searchlight.

tive and unique lighting feature: a large center-roof-mounted front LED searchlight, which the company describes as being "perfect for lighting up the waves at a night-time surfing session".

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

SET strives for mass-market penetration with deep-UV LED

Sensor Electronic Technology (SET), a US firm developing short-wavelength LED chips, is shipping deep-UV products. Its latest AlInGaN-based LEDs emit at 265–365 nm, and suppliers of test and sensing equipment have placed the first orders with the company.

However, SET president Remis Gaska is keen to expand the Columbia, SC, company's customer base: "We plan to penetrate very-high-volume markets for water and air purification and disinfection products."

SET uses a novel growth technique known as migration-enhanced MOCVD (ME-MOCVD) to fabricate its AlInGaN structures. The technique, which can be thought of as a combination of MBE and MOCVD growth, is said to be well-suited to the production of devices with a high aluminum content.

Gaska told *Compound Semiconductor* that its UV LEDs are grown on 2 inch substrates, and that SET has scaled up its ME-MOCVD reactors, with the first 3 × 2 inch production tool now operational.

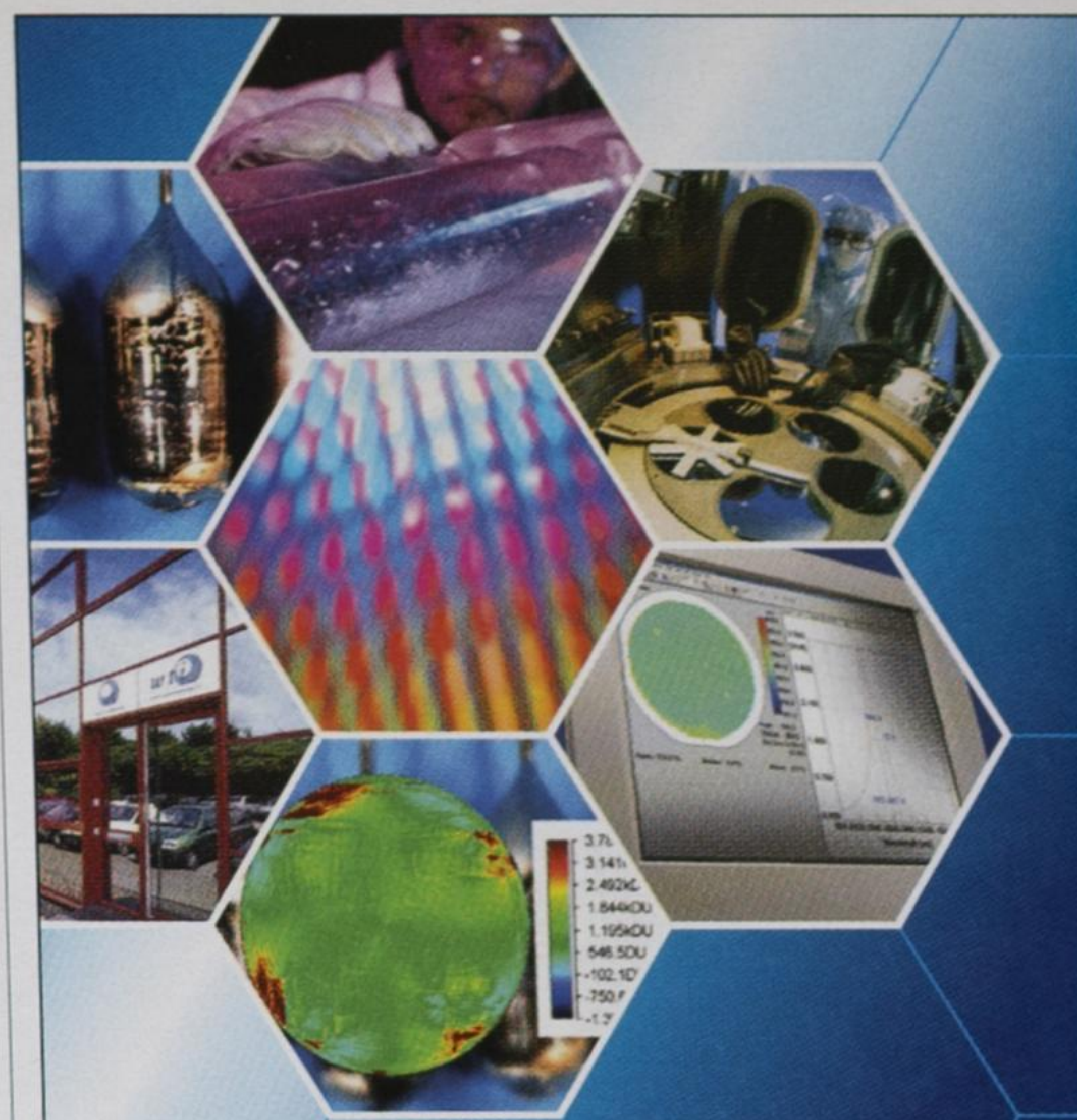
SET hopes that a range of other applications, such as food safety inspection, can also be penetrated in the future. The company already sells 340 nm LEDs and is also working on high-power RF electronic devices.

In brief

- **Lamina Ceramics**, the Westampton, NJ, company that makes high-brightness LED arrays, has halved prices on two of its major product lines. Cuts were possible because of the rapidly falling cost of LED die, which Lamina estimated at 20–30% per year. The price of its 570 and 108 lm white-light sources, known as the BL-3000 and BL-2000 respectively, have been cut by 54%.

- Korea-based **Seoul Semiconductor** has commenced production of its Z-Power LED series of high-power lamps, which includes a package containing three high-power red, green and blue chips.

The white Z-Power LED has a luminous flux of 140 lm at 1.4 A (5 W), corresponding to 28 lm/W, while its luminous efficacy is 40 lm/W at 350 mA.



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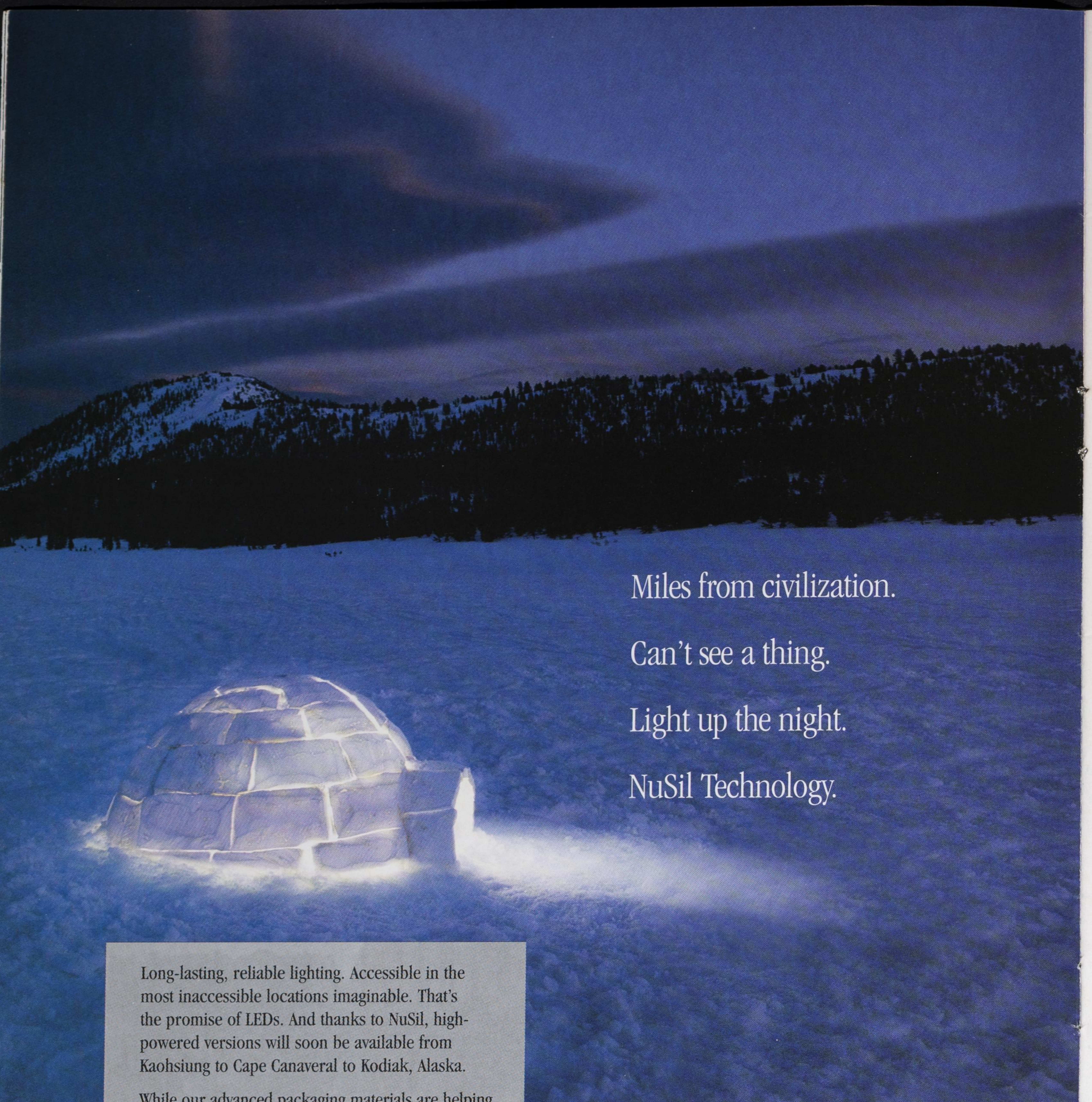
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Asia competition poses a problem for Cree as LED demand begins to wane

By Michael Hatcher

Competition from low-cost Asian manufacturers may be causing US-based LED chip-maker Cree more difficulty than had been expected in the cell-phone handset market. The Durham, NC, company saw its share value drop by more than 25% after releasing its latest trading figures.

According to a research note issued by an analyst at investment bank Adams Harkness, Cree, which has enjoyed rapidly rising revenue and profit in the past few years, will find it increasingly difficult to challenge Nichia and other rivals as competition grows and intellectual property barriers begin to crumble.

Around 50% of Cree's LED revenue comes from cell-phone-handset applications of its chips, and in May 2004 the company introduced its low-cost UT-230 LED for keypad backlighting. Cree has long held a strong position in handset keypads and maintained relatively high profit margins, but that now looks to be changing, with more sapphire-based die from Asian suppliers appearing in phones.

"Unless the company can move out of keypads and penetrate the display portion of the handset, which may take time, we feel Cree may face a dilemma [due to] increasing competition and commoditizing chip prices," said Adams Harkness analyst Jed Dorsheimer.

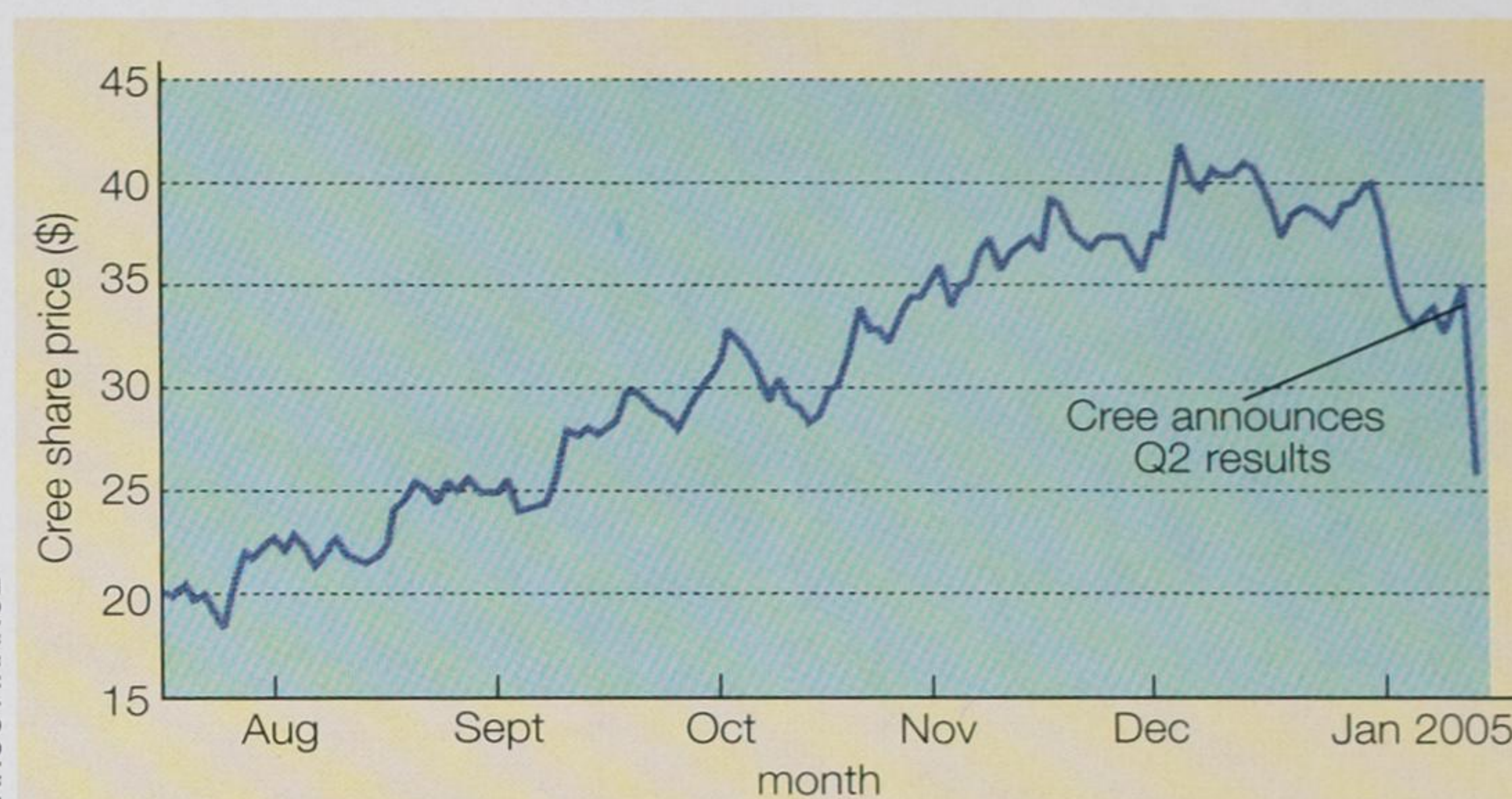
But this strategy poses its own problems: "While Cree believes it can displace Nichia in the display portion of the handset, our recent tear-down research suggests this strategy may be more difficult than Cree initially anticipated," continued Dorsheimer.

Spooked investors

His assessment came after Cree posted revenue of \$97.5 million for its financial quarter ended 26 December 2004, which was slightly lower than it had predicted in earlier guidance.

Although that figure represented a 34% increase on the same period a year ago, it was only slightly higher than revenue in the prior quarter. "Overall LED chip demand has slowed," admitted Cree CEO Chuck Swoboda.

As a result, Cree now expects revenue in the current quarter to be flat or slightly down, in the \$94 million–98 million range. That guidance spooked investors who were hoping that Cree would break through the \$100 million fig-



ure, and the company's share price tumbled on January 14, the day after the quarterly results were announced. The day of the fall saw very heavy trading, with more than 10 times the average volume of Cree shares changing hands, and around \$670 million wiped off the firm's market capitalization.

Prior to that sudden drop, Cree's share price had performed strongly through the second half of 2004, almost doubling in value to more than \$40 between June and mid-December. Some of Cree's senior executives sold large quantities of shares in that time. According to data supplied by financial information company EDGAR Online, Cree chairman Neal Hunter sold \$10.9 million worth of company stock over two days in late November, while in October and November, the company's chief financial officer Cynthia Merrell sold shares to the value of around \$20 million.

Swoboda admitted that the cost of the ongoing conversion from 2 to 3 inch wafer production had so far outweighed the benefits of manufacturing on the larger wafer size.

Around 15% of Cree's LED wafers are now made on 3 inch wafers, with Swoboda expecting this figure to rise to more than 50% by the end of the current fiscal year in June.

Dorsheimer had sounded a lone note of caution over the long-term effect of increased competition from Asian firms in June 2004 when he slapped a "reduce" notice on Cree's stock. Responding specifically to Nichia's move to license its InGaN technology to Taiwanese manufacturers, the analyst said: "We believe the competition landscape may not be as straightforward as we had thought."

The analyst believes that with other high-volume applications such as LED backlight-

ing for televisions still a couple of years away, Cree may face a difficult period.

In a conference call to discuss Cree's quarterly results, Swoboda was keen to identify the use of LEDs in LCD television backlighting as "probably the single biggest business opportunity for Cree and the industry".

Revealing that Cree had supplied LEDs to backlight a 40 inch LCD television demonstrated at the recent International Consumer Electronics Show held in Las Vegas, Swoboda believes that the application could prove to be a company-changing growth catalyst. Cree's rival Lumileds currently has the only commercial design win in this application area, supplying the LED backlights for large, expensive, Sony televisions.

Critical period

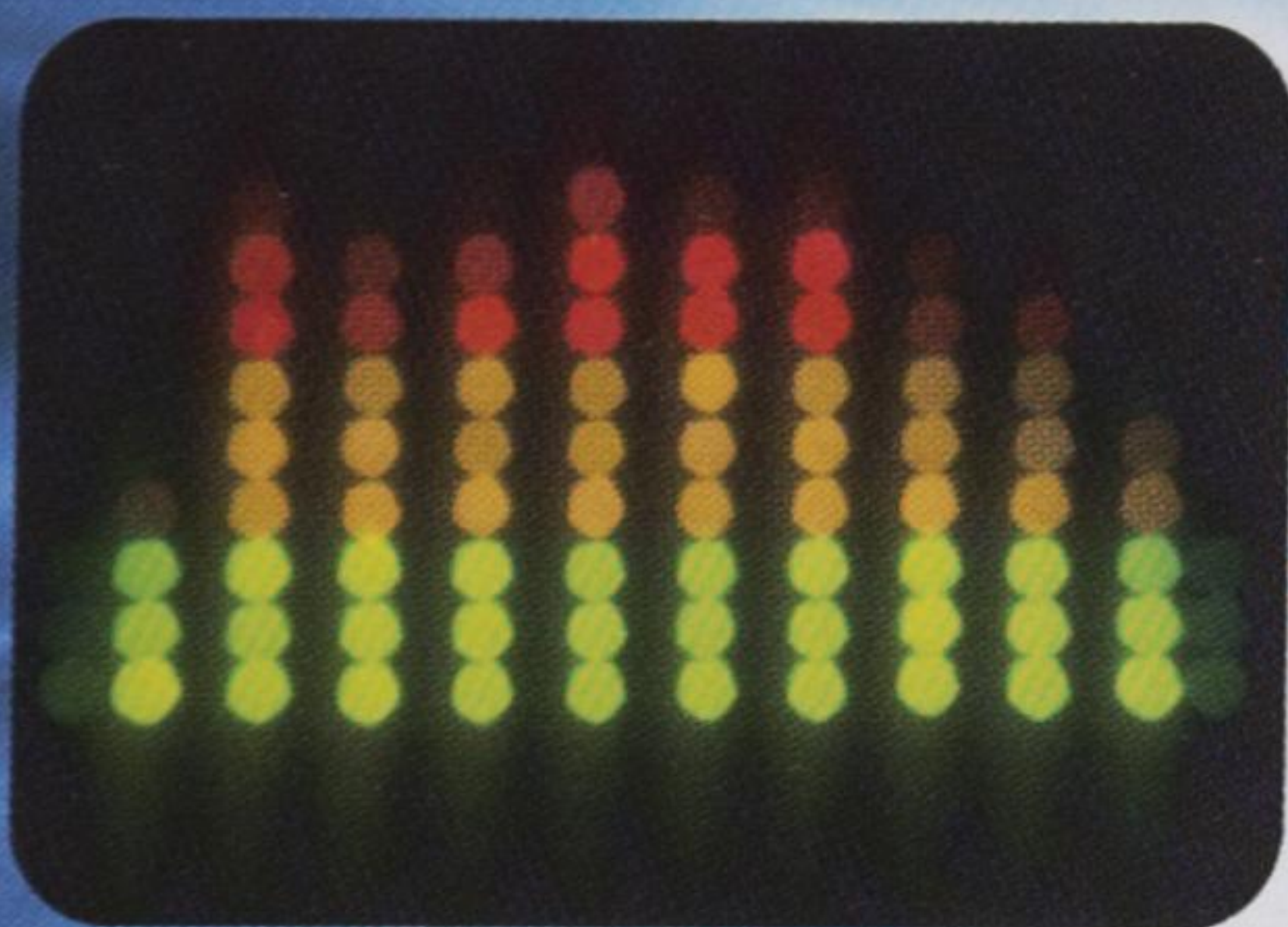
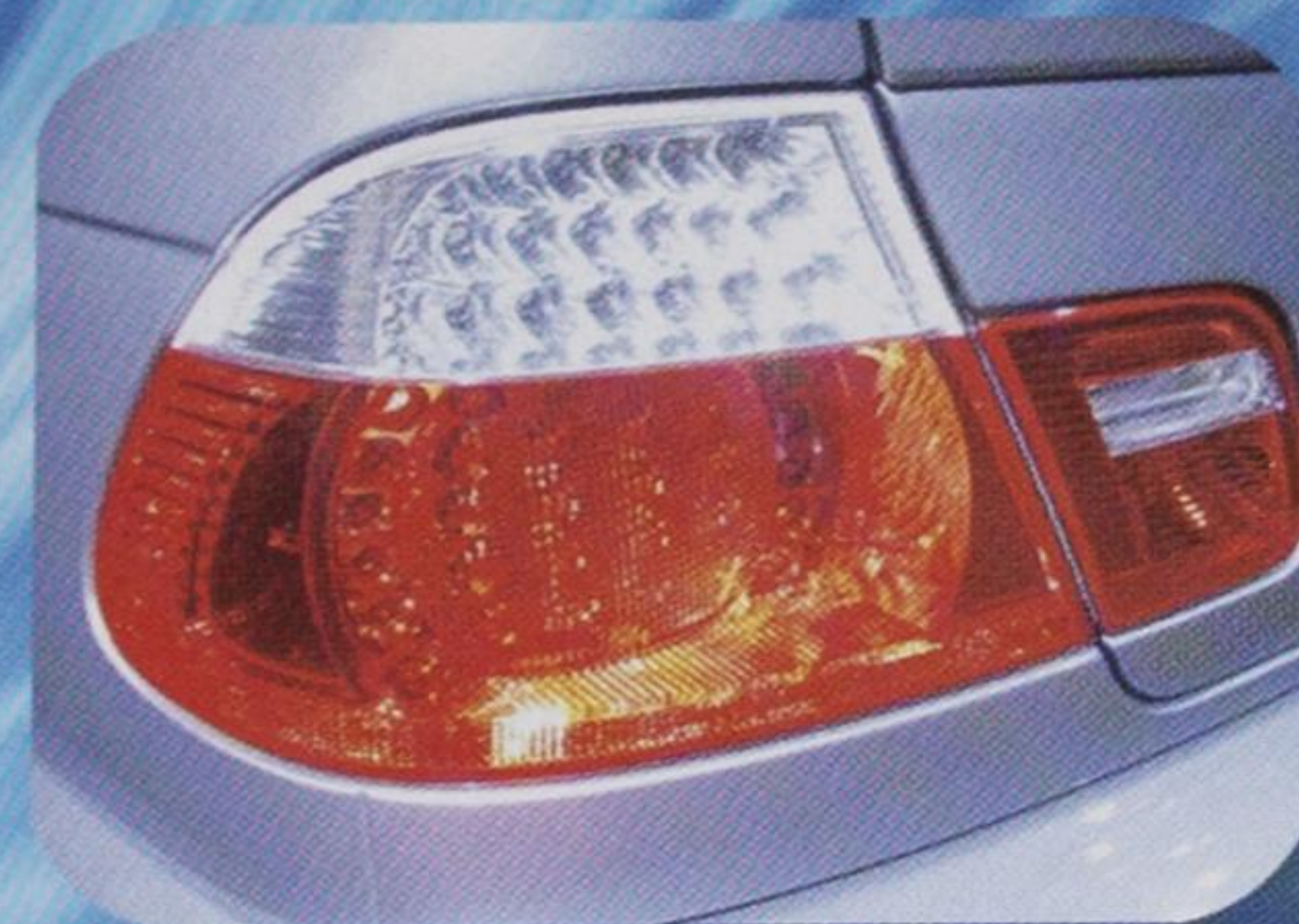
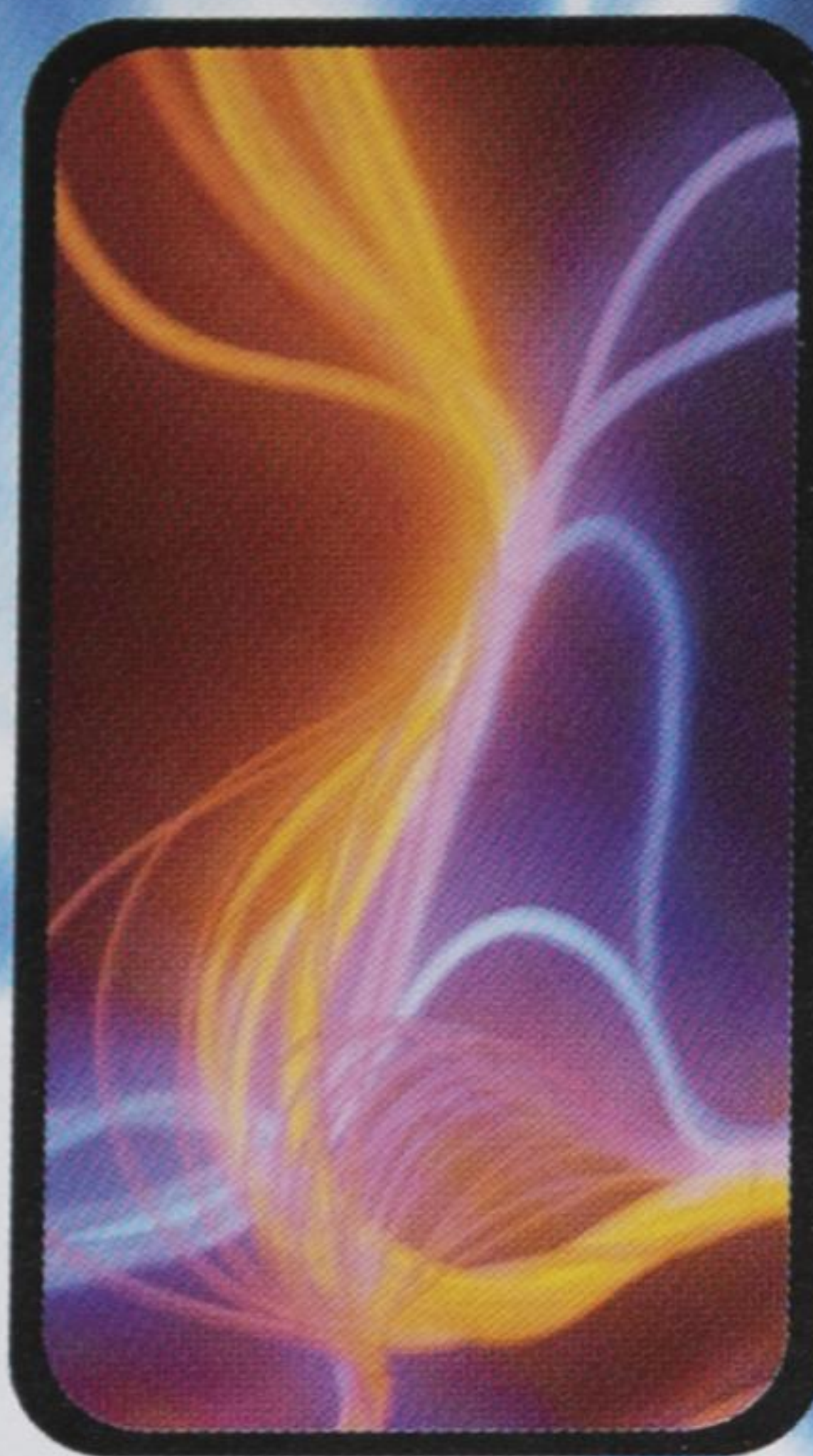
Swoboda forecasts that the next 6–9 months will be the critical period during which designs will be won and lost, with television makers preparing to launch new products in time for the 2005 holiday season.

However, according to market analyst firm iSuppli, the television-backlight market for LEDs is not expected to take off significantly before 2007. Its recent market forecast (*Compound Semiconductor* December 2004 p27) predicts that after reaching \$40 million in 2006, the total value of the sector will rise to \$115 million in 2007 as the technology trickles down into in less-expensive sets.

With Cree facing increased competition from Asia, and iSuppli forecasting the dollar value of the keypad backlight segment to be in decline, the company may need alternative markets to emerge faster than expected if it is to regain its previous momentum.

Cree's "black" Friday: After doubling in value to more than \$40 in recent months, Cree's share price dropped by 25% the day after the release of its latest financial report. In heavy trading on January 14, around \$670 million was wiped off the company's market capitalization.

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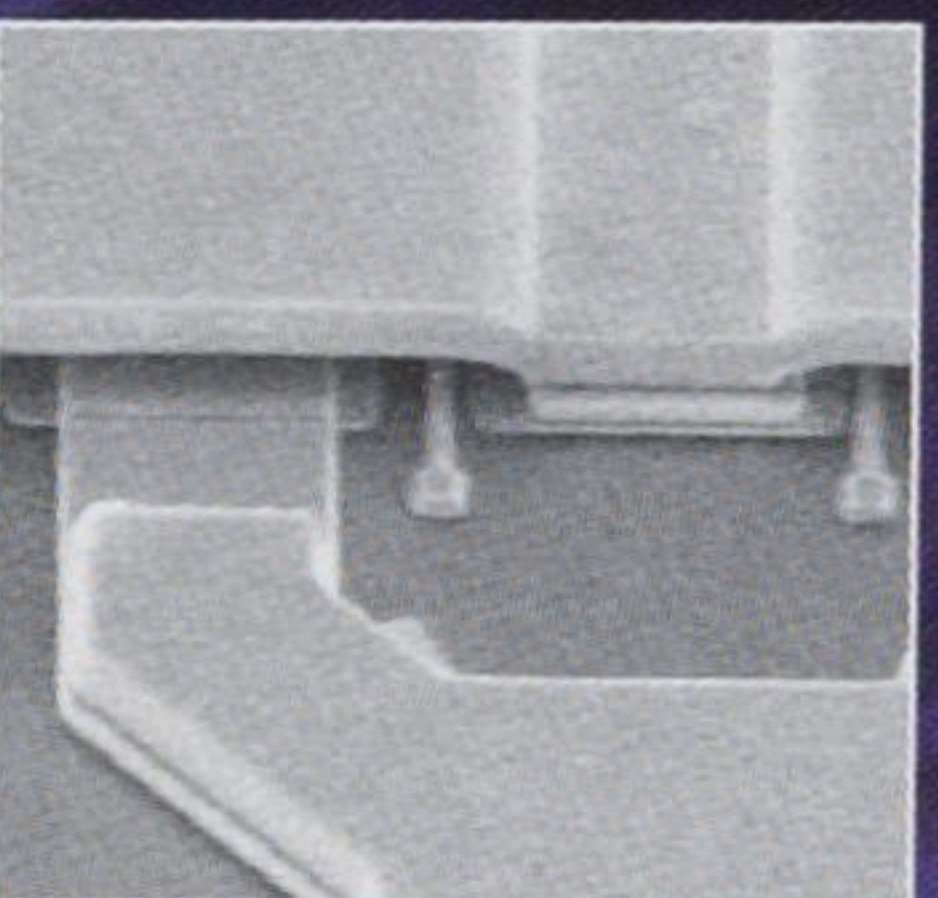
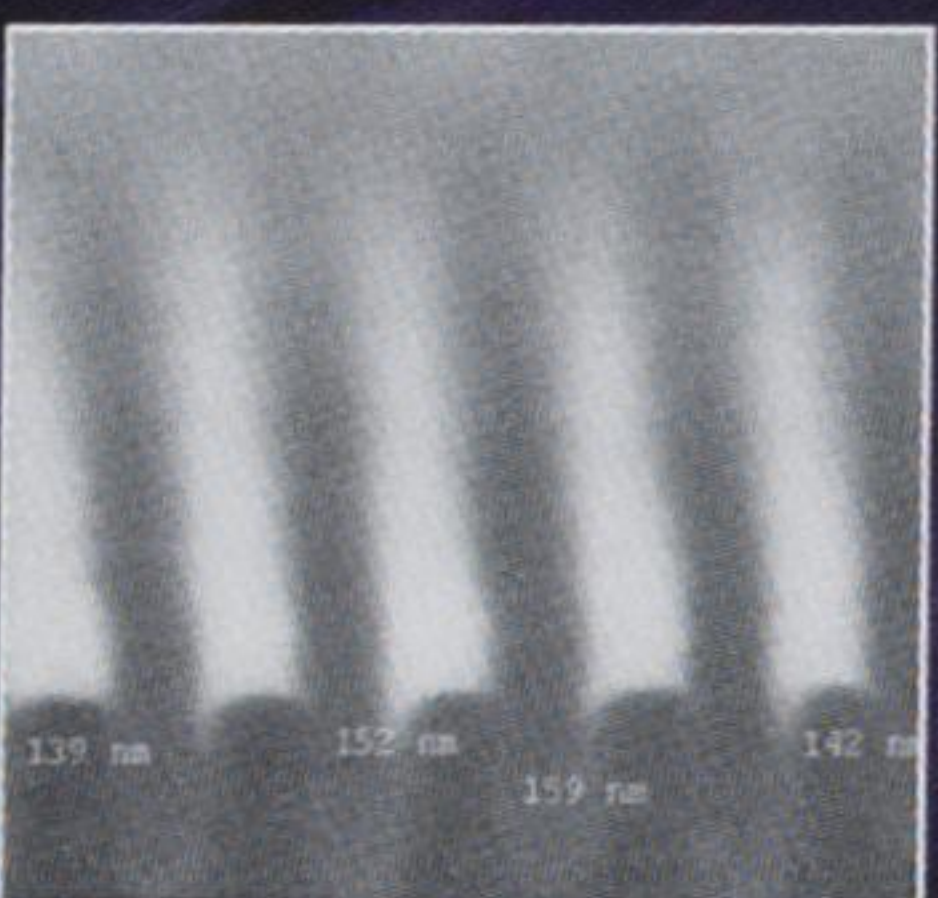
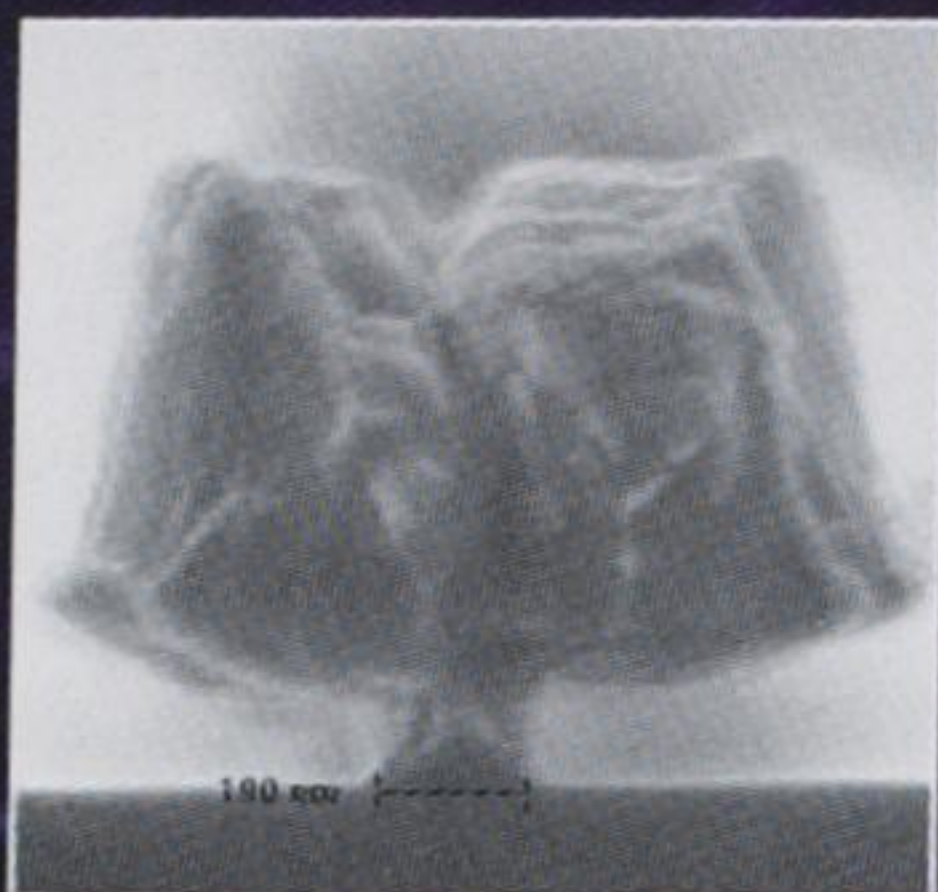
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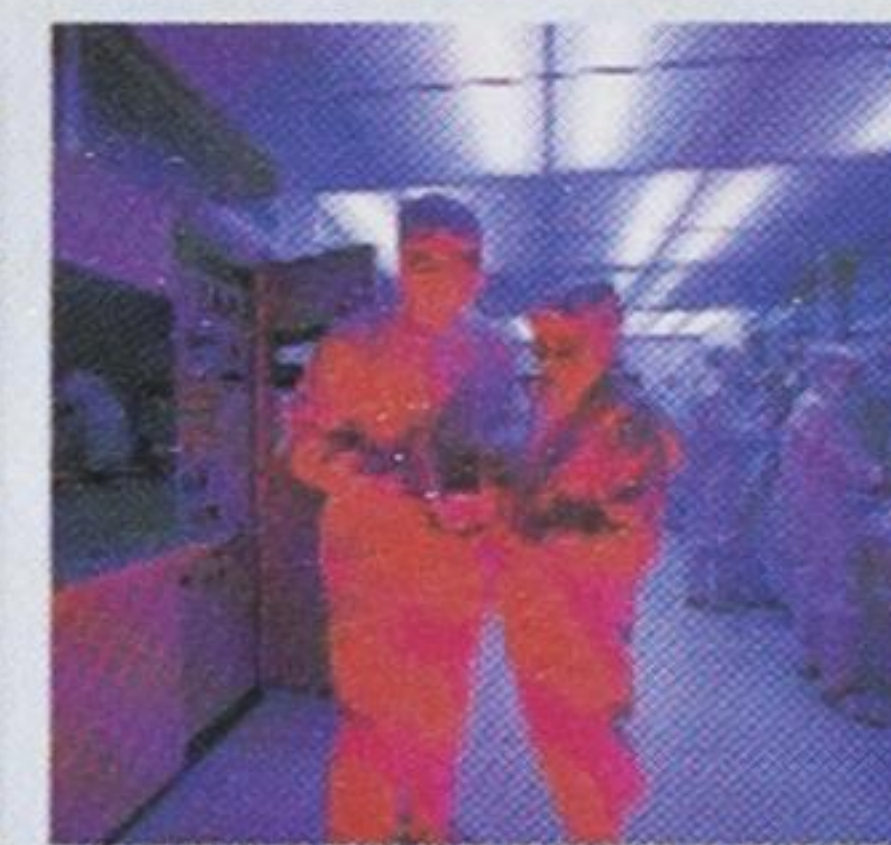
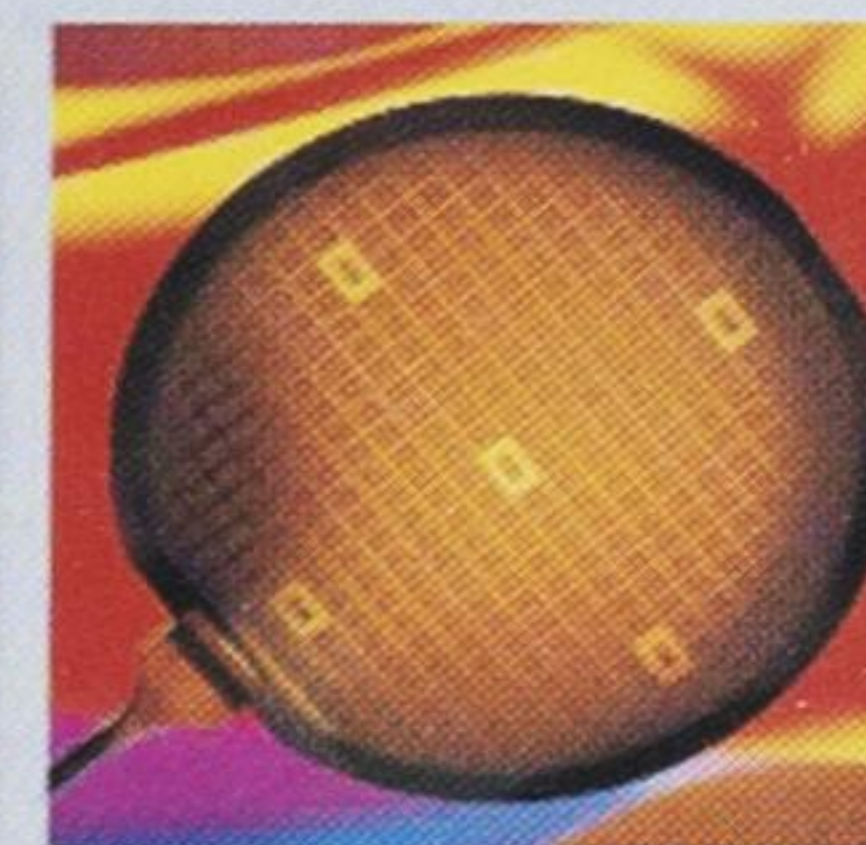
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Japanese businesses talk up GaN transistors

Three Japanese microelectronics producers have made recent progress in GaN-based transistors for wireless infrastructure applications.

Fujitsu Laboratories, a company that has spearheaded the development of the technology, says that it has perfected a low-cost manufacturing process that could propel GaN HEMTs into commercial applications.

By using conducting substrates that are normally only used for LED production, Fujitsu says that the devices can now be made at one-third of the conventional cost.

The company made a big splash a year ago when it revealed a GaN HEMT amplifier that emitted 174 W at 63 V and had a record drain efficiency (see *Compound Semiconductor* January/February 2004 p5).

Fujitsu now claims that it can make the HEMTs on a conducting SiC substrate rather than the more conventional – and much more expensive – semi-insulating SiC.

The manufacturing process uses hydride vapor-phase epitaxy to deposit a 10 μm layer of AlN on n-SiC. The GaN HEMT layer is then grown by MOCVD.

Devices made this way have a maximum output power of 101 W, a power-added efficiency of 50% and a gain of 15.5 dB.

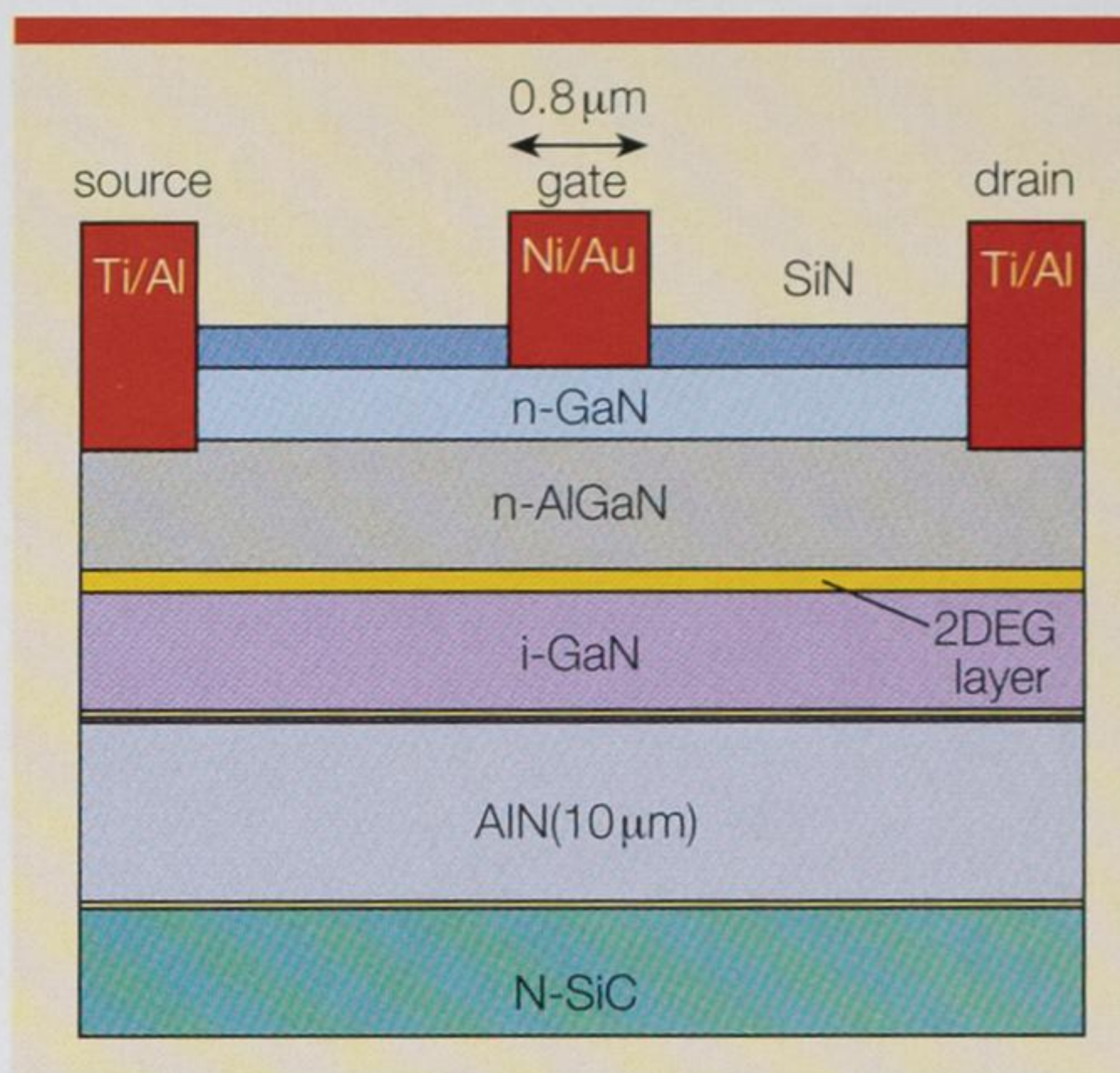
Fujitsu discovered that parasitic capacitance drops as the thickness of the AlN epilayer increases. According to the company, the wider bandgap of AlN compared with GaN also helps to suppress leakage current to the conductive substrate.

Meanwhile, Matsushita Electric has developed AlGaIn/GaN-on-silicon field effect transistors (FETs) that it claims could penetrate a range of high-volume applications.

Featuring so-called source-via-grounding (SVG) technology, the transistor's source electrode can be connected to the silicon substrate through holes formed on the surface side. This approach eliminates source wires, bonding and pads from the substrate surface, thereby reducing chip size and wire inductance.

Matsushita's FETs, which were fabricated on 4 inch silicon substrates, have a breakdown voltage of 350 V and can handle currents of up to 150 A. By using its SVG technology Matsushita also claims to have reduced the on-resistance of its FETs from 53 to 14 m Ω .

The GaN-based FETs could be used as



Fujitsu researchers presented details of their new AlGaIn/GaN HEMT at the recent International Electron Devices Meeting. The transistor was made on a conducting SiC substrate, which Fujitsu says could reduce the cost of the technology by two-thirds.

low-loss power switching devices in invertors for electrical appliances, hybrid cars and power supplies, says the company. According to Matsushita, using a silicon substrate means that its FET material is one-hundredth the cost of comparable SiC power MOSFETs.

The third Japanese firm to target GaN is Oki Electric, which is making available an early version of its GaN-based HEMTs for wireless base-station applications.

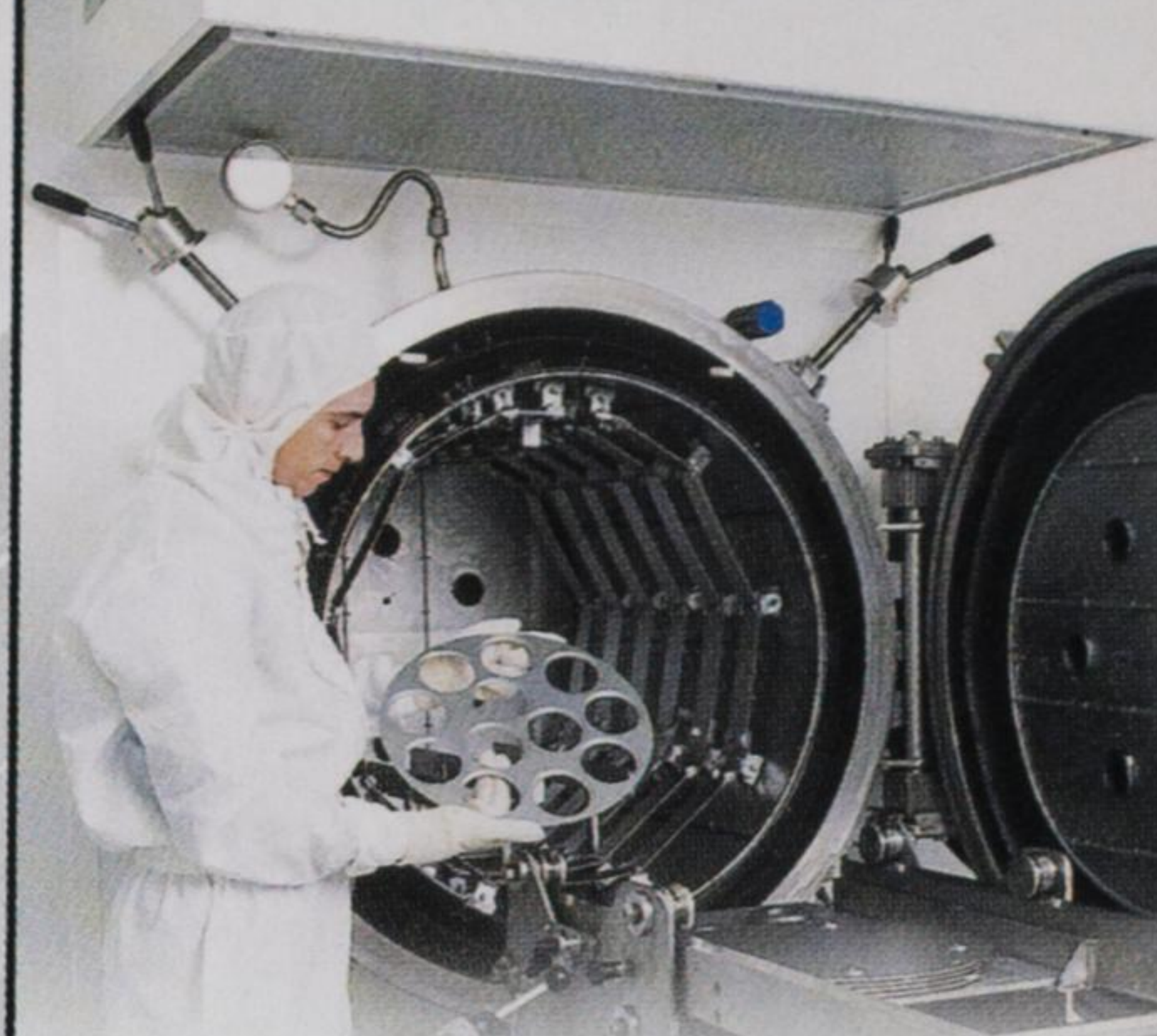
Measuring 15 $\times$ 5.4 $\times$ 3.1 mm, Oki's HEMTs have an output power density of 7.8 W/mm, and a maximum output power of 50.2 W.

Oki expects sample shipments to begin in early 2006, followed by volume production later that year. The company says it is aiming for a 30% share of the global GaN high-frequency power device market by 2008.

Although GaN HEMTs are regarded as the superior chip technology for use in the power-amplifier stage of 3G base-stations, the high cost and relative immaturity means that silicon LDMOS currently dominates the field.

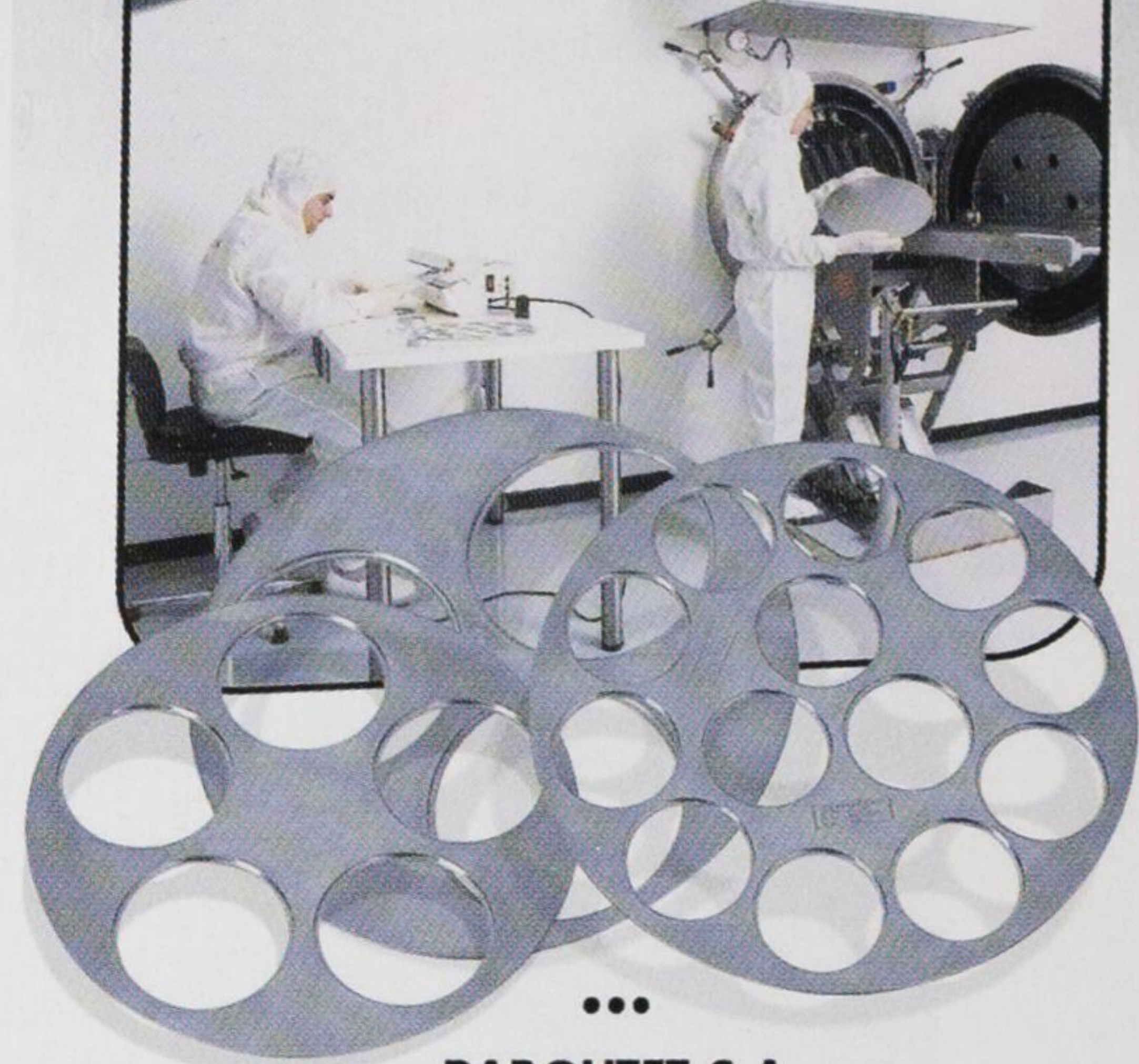
Japan looks to be the most likely place for GaN microelectronics to catch on. Fujitsu says that with its new production technology, commercial devices can be expected within two years. With two other Japanese contenders preparing to compete, as well as US-based RF Micro Devices saying that it plans to launch a commercial device in 2005, the race is on.

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IBM manufactures strained-germanium transistors via CMOS-compatible route

IBM researchers claim to have made strained-germanium transistors using a technique compatible with conventional CMOS processing. The PMOSFET devices, which were manufactured using two different methods, showed a three-fold improvement in drive current compared with standard silicon transistors.

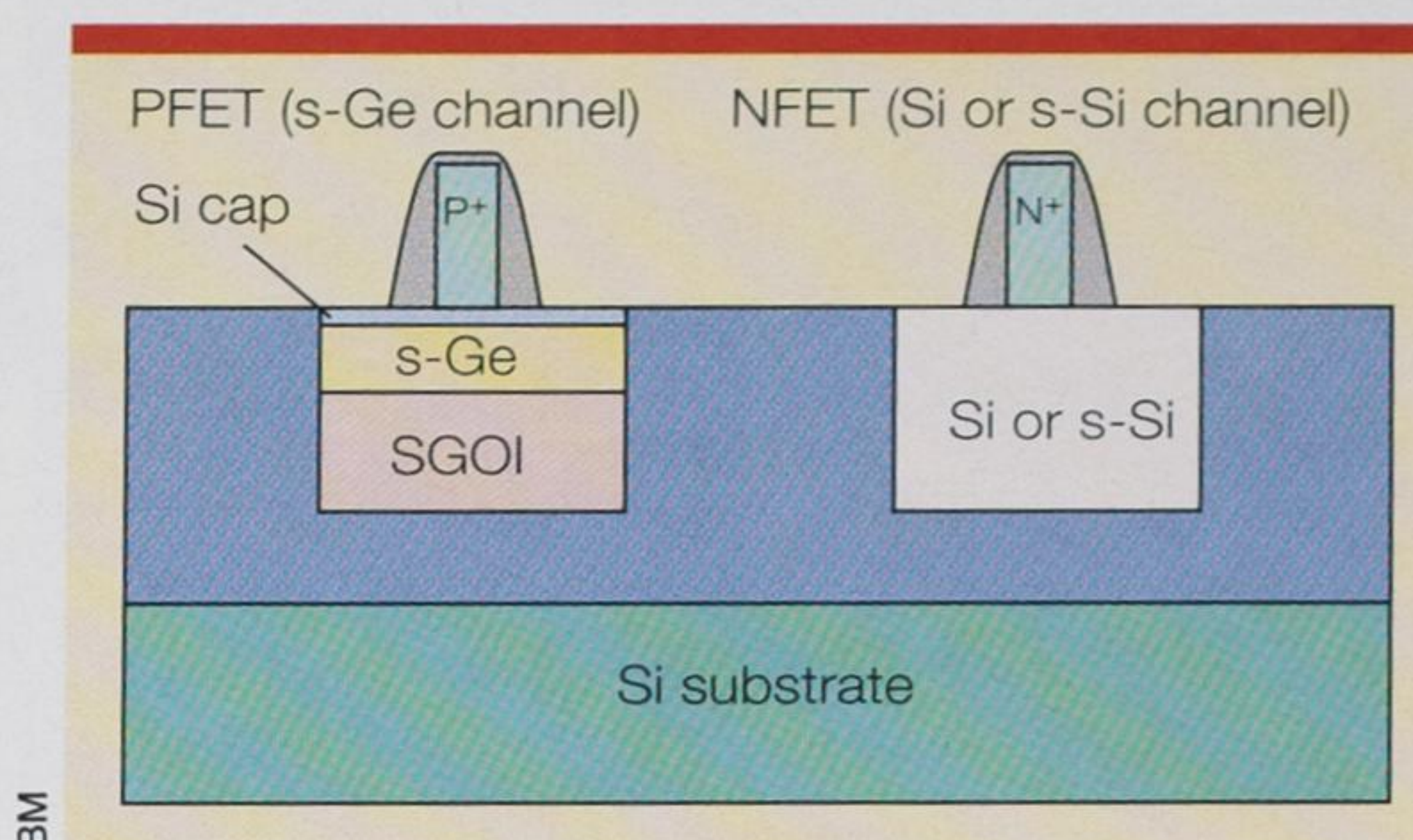
Using either local thermal mixing (TM) or selective ultrahigh vacuum CVD processing, strained-germanium channels were realized on pre-patterned SiGe-on-insulator regions.

After forming the germanium layer, the IBM team, based at the company's T J Watson Research Center in New York, used a standard CMOS process to complete the devices.

According to IBM, the development, which was detailed at December's International Electron Devices Meeting (IEDM), demonstrates for the first time that strained-germanium devices can be manufactured using conventional IC fabrication techniques. "IBM has demonstrated methods that can selectively place the strained germanium on the selected areas of a chip using a CMOS-compatible process," said the company.

As chip makers face an increasingly uphill struggle to keep pace with Moore's Law, the use of strain and alternative materials to conventional silicon in future ICs is becoming increasingly likely. "System performance depends on chip performance, and that will increasingly depend on new materials and design techniques rather than simple scaling," said T C Chen, IBM's vice-president of science and technology.

"With this work we've drawn on our experience [gained in] introducing technologies like



A schematic cross-section of IBM's ideal CMOS structure featuring strained-germanium device channels. Germanium is deposited in the PFET regions by selective growth and deposition by masking the NFET region with an oxide or nitride film.

SiGe, silicon-on-insulator and strained silicon," said IBM, adding that it believes that the strained-germanium technology could feature in future chip generations with feature sizes of 32 nm and smaller. According to current industry roadmaps, devices with these ICs are expected to emerge around 2010.

The company also says that the manufacturing technology it has developed improves the device without affecting other components or circuits on the same chip. "This dramatically reduces the risk of introducing a new material," it claimed.

IBM's TM-grown devices may also help the development of an alternative dielectric material to SiO₂. Some of the transistors fabricated featured a 3 nm HfO₂ gate dielectric deposited using MOCVD. IBM says that the use of germanium-based devices provides an "easier path" toward the introduction of so-

called high-k insulators.

In a late-news paper presented at IEDM, silicon giant Advanced Micro Devices (AMD) said that it has found a process technology for making strained-silicon devices that does not rely on SiGe epitaxy.

The AMD team, along with co-workers from IBM, Sony and Toshiba, has found a way to introduce strain without demanding significant changes to the current chip-manufacturing process.

The new process step, which is called "dual stress liner", enhances the performance of both n-channel and p-channel transistors. The silicon lattice is stretched in one transistor channel, while compressed in the other.

First, a highly tensile Si₃N₄ liner is deposited over the silicon-on-insulator wafer. The film is then patterned and etched from PFET regions. Next, a highly compressive Si₃N₄ liner is deposited, and this film is then patterned and etched from NFET regions.

Developed at IBM's research center in East Fishkill, New York, the new approach increased the transistor speed by 24% while using the same amount of power as similar devices that do not incorporate strain.

Intel has already developed and used a similar technology that uses SiGe to generate compressive strain in the PMOS channel.

AMD says that it will gradually integrate the newly developed technique into all of its 90 nm processor platforms, including future AMD64 chips. The US company adds that the first processors to be manufactured using the dual stress liner method will be shipped in the first half of 2005.

'Exceptional year' for WLAN market growth fuels SiGe sales surge

Annual revenue has quintupled in the past year at Canada-based SiGe Semiconductor, thanks to the rapid growth of the Wi-Fi market.

The company says it made \$20.1 million in revenue, although it did not reveal its bottom-line financial performance.

SiGe Semiconductor reckons that it has cornered around 45% of the global market for Wi-Fi power amplifiers, and recently sold its 30 millionth unit. Most of these products have been shipped to China to be integrated into consumer electronics such as notebook PCs,

digital cameras and other PC peripherals.

Central to the company's rapid expansion is its RangeCharger series of power amplifiers and its RF front-end modules for wireless LAN equipment.

"2004 was an exceptional year," said company CEO Jim Derbyshire. "We are focusing on research and development of innovative solutions that will improve integration, performance and reliability of Wi-Fi, Bluetooth, GPS and cellular-handset applications."

According to chief financial officer Steve

Bower, SiGe is investing heavily in research to expand opportunities in other markets for RF front-ends, with an initial public offering of SiGe shares earmarked for the future.

The company is particularly looking to expand its product offering in the traditionally GaAs-dominated sector of cell-phone handset power amplifiers, and is working on designs with lead customers.

ICs targeted at GSM/EDGE, CDMA, CDMA2000, W-CDMA and GPRS cellular services can all be expected in 2005.

Software giants favor Blu-ray option over HD DVD

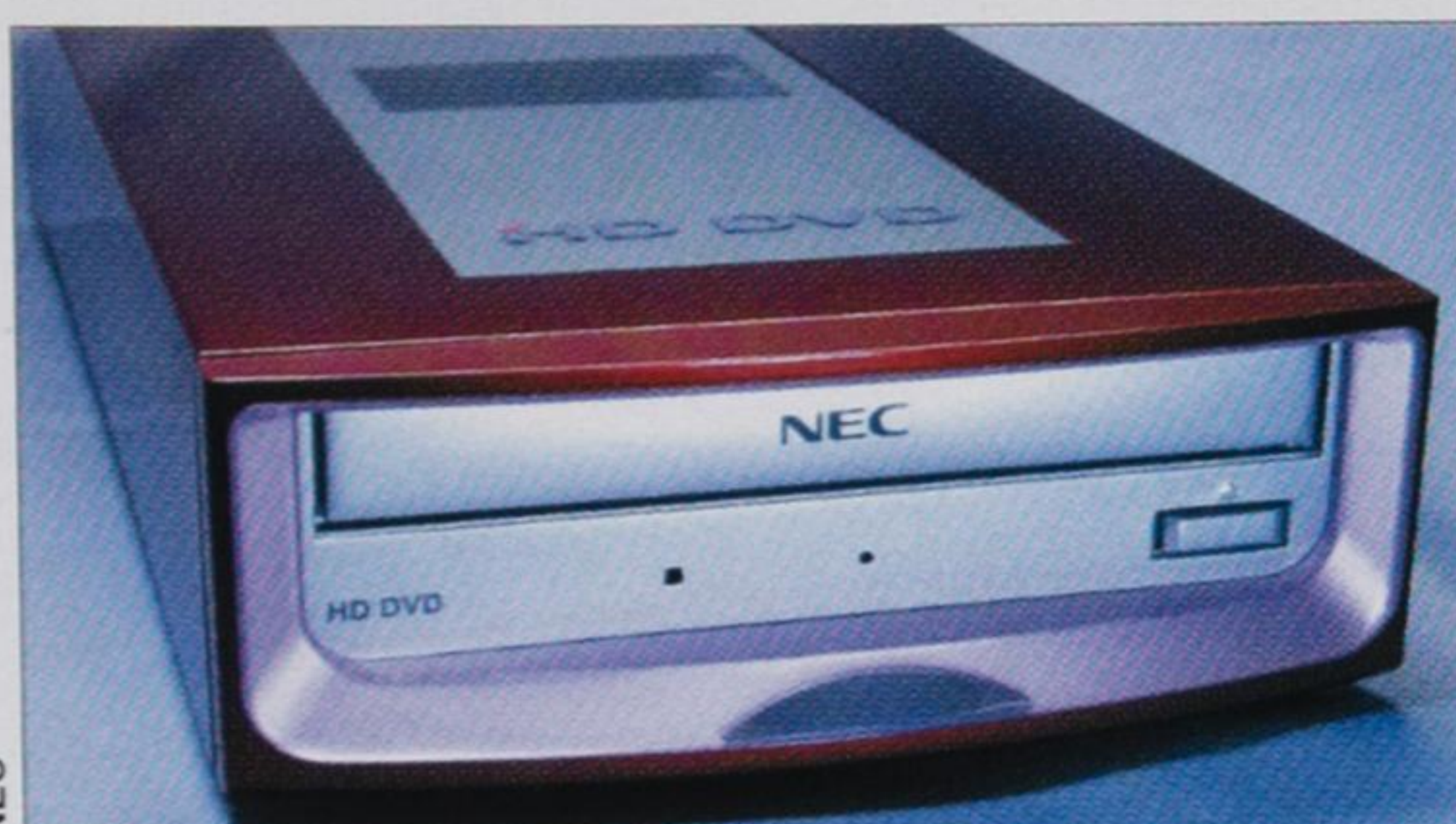
With Hollywood studios currently split over which of the next-generation DVD standards to endorse, it appears that the electronic gaming industry may favor the Blu-ray technology developed by Sony and Matsushita.

Software giant Sun Microsystems and leading games developers Electronic Arts and Vivendi Universal Games (VU Games) are the three latest companies to sign up to the Blu-ray Disc Association (BDA), joining businesses including Nichia.

Blu-ray technology and its high-definition (HD) DVD rival rely on a blue GaN laser diode chip, which is at the heart of every player and recorder.

According to the BDA, it is the extra capacity of the Sony format that is winning over games developers. Double-layer Blu-ray Discs hold up to 50 Gbyte of data, while Toshiba's dual-layer HD DVD format holds 30 Gbyte.

"These companies tell us they simply can't deliver the kinds of products they want to offer consumers with any other format," said chief



Using a single lens and three separate lasers, NEC's device is said to be the world's first optical disc drive to be CD, DVD and HD DVD compatible.

BDA spokesperson Maureen Weber. "Blu-ray offers the capacity, performance and high-speed Internet connectivity to take us into the future of gaming," added VU Games' chief technology officer Michael Heilemann.

Meanwhile, both next-generation technologies were a focal point at this year's International Consumer Electronics Show (CES), held in Las Vegas in January.

Samsung unveiled its Blu-ray Disc player and recorder at CES. The Korean company did not confirm the release date of the machine, but it is expected to hit the stores this fall.

Other key hardware on display included NEC's prototype three-laser optical drive for desktop computers. The drive is said to be the first to allow CD, DVD and HD DVD playback through a single optical head.

NEC has developed a control system that alters the numerical aperture of the objective lens according to which laser – blue, red or infrared – is required.

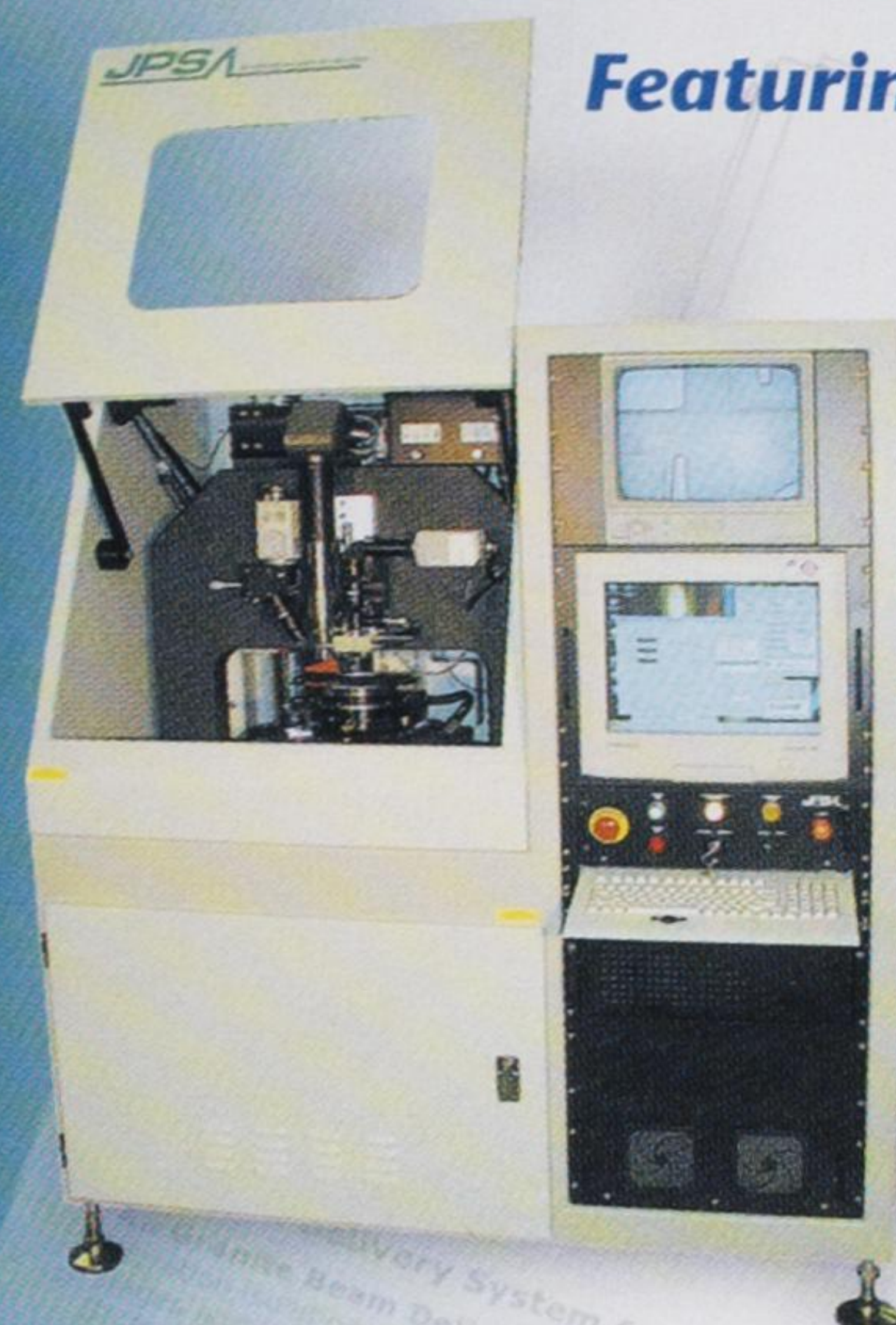
The Japanese company now says that it will deliver HD DVD read-only drives in September this year. Toshiba and Sanyo both have plans to supply HD DVD players in the fourth quarter, with Toshiba also due to deliver notebook PCs featuring the new technology.

In another boost for the HD DVD group, optical-disc manufacturer Memory-Tech says that it has six mass-production lines ready to make up to 50 million HD DVD discs per year.

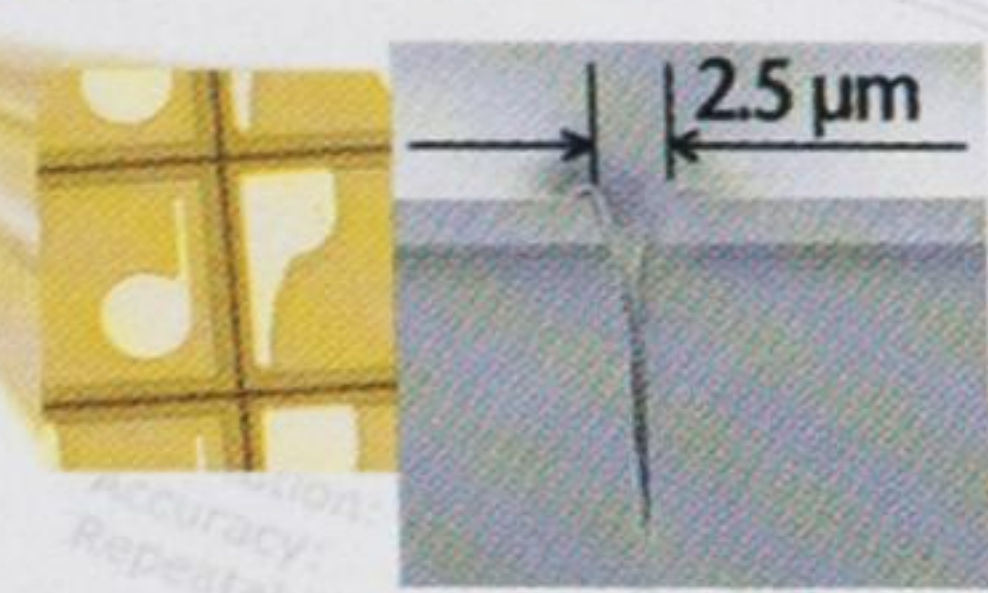
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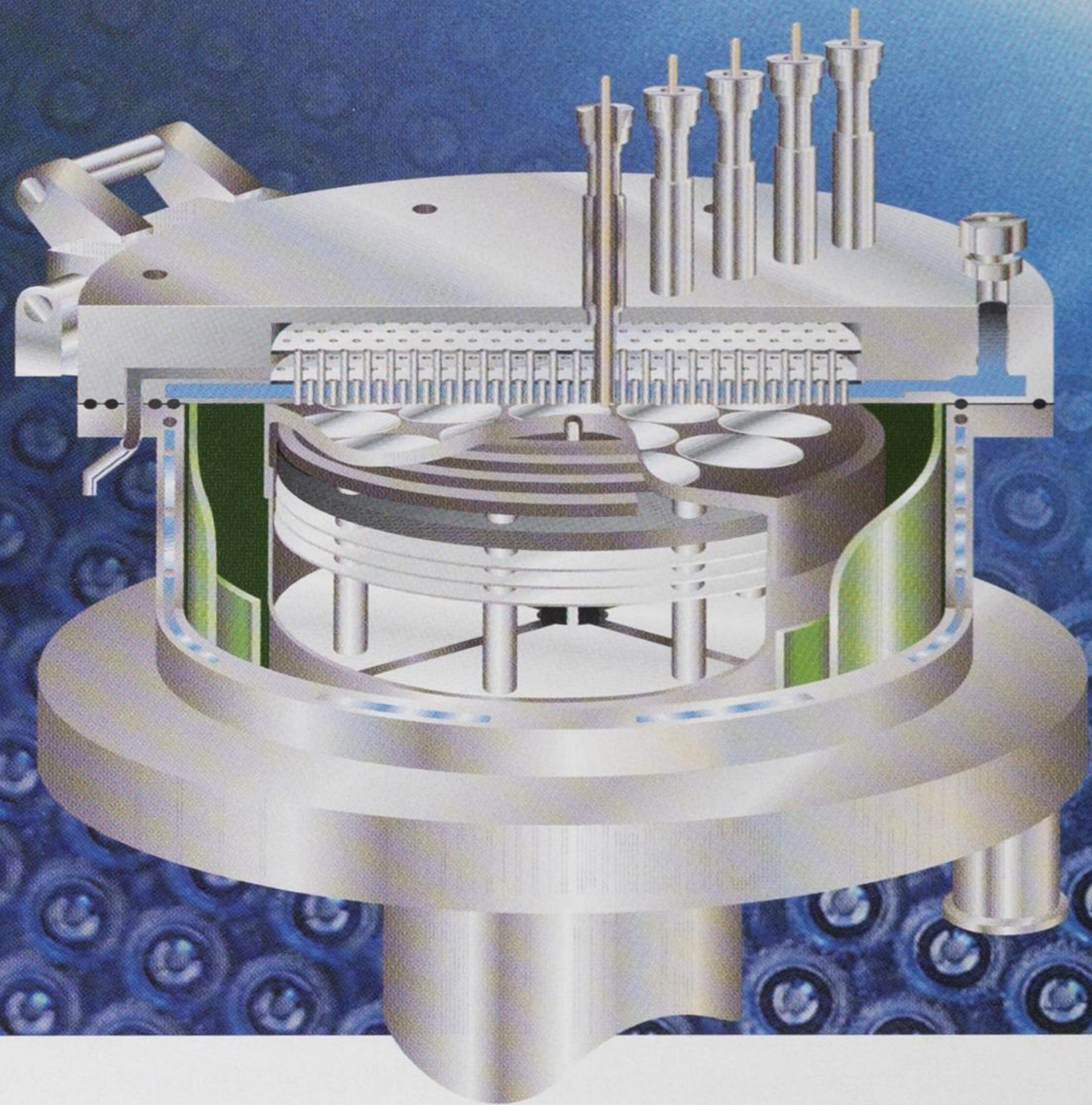
In brief

- Japanese company **Mitsubishi** plans to double its red-laser production capacity to 10 million units per month by September, claims a report in *Nihon Keizai Shimbun*. Said to already hold a 70% share of the red-laser market for DVD recorder applications, the company is set to invest \$20 million–30 million at its manufacturing base in Hyogo Prefecture.
- **Highwave Optical Technologies**, which is based in Brittany, France, says that it has signed a memorandum of agreement to acquire Sweden-based Northlight Optronics in a deal expected to be worth €16 million (\$21 million). Previously known as Ericsson's optoelectronics division, Northlight was set up in 2003 when its parent company decided to exit the flagging optical components sector. Along with two Swedish investment groups, Ericsson is one of the three major shareholders in Northlight.
- Optoelectronic device manufacturer **Exalos** has been awarded ISO 9001:2000 certification. The Zurich, Switzerland-based company specializes in making superluminescent LEDs based on both InP and GaAs technology.

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The long wait is over as 3G

3G cell phones and networks, next-generation DVD, and high-speed InP transistors are just some of the key applications that will shape the compound semiconductor industry in 2005, write **Michael Hatcher** and **Richard Stevenson**.

After what has seemed like an interminable wait, 3G mobile technology finally looks like fulfilling its promise on a global scale.

When Japan's NTT DoCoMo launched its 3G service back in 2001, the rest of the world was expected to follow its lead before long. But the slumping telecom and semiconductor markets put paid to that idea and 3G went on the back burner.

2004 and 2005 now look like being pivotal years in the global 3G roll-out. Some critical developments have taken place among US carriers recently, with major consolidation the story of 2004. This has been followed swiftly by the award of billion-dollar contracts to accelerate the deployment of upgraded networks across the US.

ABI Research – a New York-based technology research think tank and consultancy – says that the \$41 billion merger of US wireless telecom giants Cingular and AT&T Wireless (ATW) was a key development in 3G evolution. Prior to the merger, ATW had

already launched 3G services across its Universal Mobile Telecommunications System (UMTS) networks in six major US cities: Dallas, Detroit, Phoenix, San Diego, San Francisco and Seattle.

UMTS roll-out

Following the merger, Cingular (itself a joint venture between SBC Communications and BellSouth) said that it would use the spectrum acquired with ATW to roll out the UMTS services to carriers throughout the US. Some possible complications may arise from the frequency bands used. ATW's existing UMTS networks run at 1900 MHz, whereas the nationwide roll-out will operate at 850 MHz.

Nevertheless, Cingular says that it plans to be offering 3G services in "most" major markets by the end of 2006. "We expect to begin offering UMTS services in additional markets some time in the first half of 2005, with services available in the top 100 US markets by the end of 2006," the company told *Compound Semiconductor*. It expects to



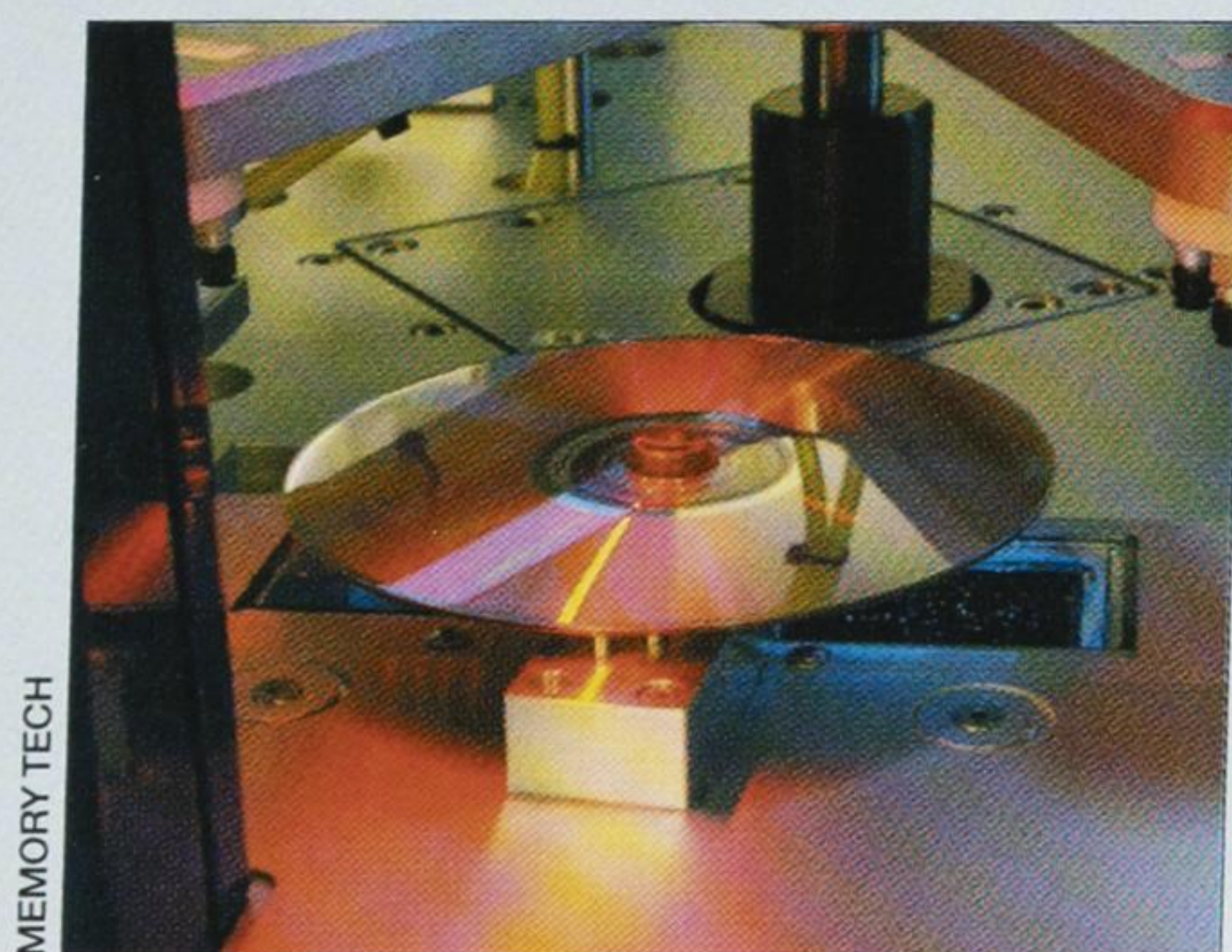
Left: 3G carriers are extending their networks, signing up for more spectrum, and will continue to develop new chips in 2005. The expected 15-20% price reduction in GaN-based devices will finally enable



GaN lasers

September marks key launch date for next-gen DVD

Just 10 years after Nichia researchers made the first, primitive GaN laser, high-volume manufacture of these devices is to begin this year as next-generation DVD players hit the big time. True, you can already buy a Blu-ray Disc player made by Sharp, Panasonic or Sony; but only if you're in Japan and willing to part with around \$3000. That will all change in September, which is set to be a key month as it marks the launch date of NEC's HD DVD drive and



HD DVD disc replicator Memory Tech says that it is ready to manufacture up to 50 million of the next-generation discs. Shown here is one of the discs on the Japanese company's in-line inspection machine.

(relatively) low-cost, high-volume application of the technology.

Despite Blu-ray having reached the market first with "early adopter" offerings, Toshiba's rival HD DVD group now appears to be making faster progress with lower-cost products. After NEC's September launch, look out for Hewlett-Packard's notebook computers featuring Toshiba HD DVD drives and HD DVD players from Sanyo.

Blu-ray Disc Association (BDA) member Samsung will provide some competition for NEC with its \$1000 player late this year.

For the compound semiconductor supply chain, this industry split is not a

good thing, as globally agreed standards are always preferable for their suppliers seeking to maximize manufacturing capacity. Success of GaN lasers for which ever succeeds will be another step forward for a sector that has prospered in the optoelectronic chip industry for years thanks to the phenomenal success of DVD players and recorders.

Upwards of 10 companies could end up manufacturing in volume, although the bulk of the devices are likely to come from Nichia initially. The two companies have shared huge amounts of intellectual property relating to device

3G technology goes global

3G services have been launched in Europe, and US carriers are among many now spending billions of dollars funding network upgrades around the world. As customers push for the advanced technology, cell-phone applications continue to represent the biggest market sector for III-V chips in 2005. The critical challenge for chipmakers is to meet expectations of handset OEMs demanding price cuts of 10% per annum through increased manufacturing efficiency. Below: With RFMD planning to launch commercial silicon-based power amplifier chips in 2005, the technology is expected to give silicon LDMOS a run for its money.



spend around \$1 billion upgrading to both UMTS and higher-specification mobile standards in the next couple of years.

Ericsson, which will be building the Cingular network along with Lucent and Siemens, says that the existing GSM base-stations will require new RF hardware for UMTS operation. The company is currently evaluating its power amplifier (PA) technology and is considering silicon LDMOS and GaAs-based solutions.

A marketing success

In Europe, where the wireless networks are generally more advanced than in the US, companies such as Vodafone and Orange have put their considerable marketing muscle behind 3G services, and shops were full of the high-specification handsets over the recent holiday period. Handset maker Motorola has launched a raft of 3G products to meet the expected demand and the company is to add around 16 new wideband code division multiple-access (W-CDMA) models in 2005. Although the advanced handsets accounted for only around 5% of Motorola's phone sales in 2004, the company is expecting this percentage to increase dramatically in 2005.

Meanwhile, Vodafone plans to buy a 3G network from Nokia for deployment across

"The thing we're addressing every day, what's really driving our business, is the issue of cost."

RFMD CO-FOUNDER JERRY NEAL IDENTIFIES THE KEY ISSUE FACING III-V CHIPMAKERS IN 2005.

Australia and New Zealand. Nokia, which already has nearly 50 W-CDMA customers and 31 roll-outs in progress, also has big plans for its 3G handset portfolio, with 10 new terminals planned for launch in 2005.

III-V chipmakers stand to profit from the 3G roll-out in two ways: through continued network upgrades, and handset applications. And it won't be just RFIC manufacturers feeling the benefit. Phones that transmit video clips and allow video messaging need display screens with high-quality backlighting provided by high-brightness white LEDs.

According to Strategy Analytics, an international market research and consulting firm, the value of 3G base-station shipments will grow at a compound rate of 31% overall through 2009. But growth in the base-station

ally agreed standards for chipmakers and ing to hit the right apacity. Still, the uptake hever format that othor shot in the arm s propped up the industry in recent phenomenal impact recorders. companies in the BDA manufacturing GaN lasers the bulk of the come from Sony and wo companies have nts of intellectual device manufacture

and Sony tends to produce "cutting edge" laser diodes in-house before outsourcing "older" technology to its industry partners. Sony may also spring a surprise by employing GaN substrates for volume laser manufacture, although perhaps not immediately.

While the BDA and the HD DVD Promotion Group have been falling over themselves recently to find favor at Hollywood studios, they have also been busy wooing Microsoft in a bid to get their technology implemented in the next Xbox gaming console.

Although not regarded as a key battleground, the gaming industry is an interesting market sector, as it pitches

key BDA member Sony in direct conflict with Microsoft as they fight to sell their PlayStations and Xbox consoles to the world's gamers.

That ought to favor the HD DVD group, but according to some reports Toshiba's format is not the first choice among software developers, who cite the extra capacity of Blu-ray as a key advantage of the technology. Sony is certain to use Blu-ray in its PlayStation 3 console, while two major developers (Electronic Arts and Vivendi Universal Games) have now joined the BDA.

According to Nichia, its research team observed the first laser pulse generated by a GaN laser operating at room

temperature in November 1995. Just 10 years on, the technology is the cornerstone of a global industry movement.

Potential GaN chipmakers in the two DVD camps

Blu-ray Disc	HD DVD
Sony	Toshiba
Nichia	NEC
Matsushita	Sanyo
Sharp	
Samsung	
Mitsubishi	
Hitachi	
LG Electronics	

Superfast transistors

InP set to break the speed limit

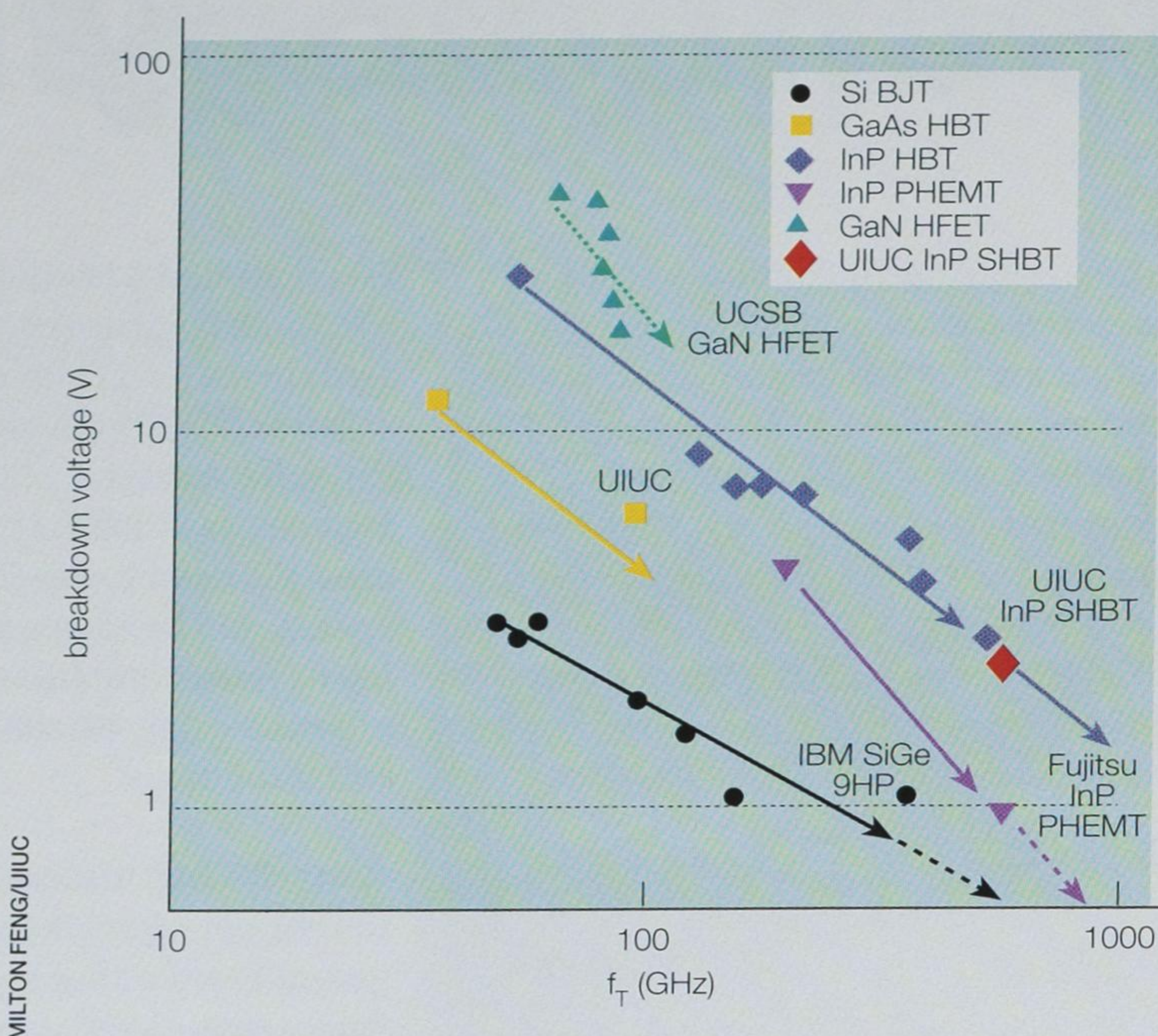
High-speed transistor development targeting the terahertz regime will be a strong research theme in 2005. The technology is wanted by the US military for a variety of applications, including analog-to-digital converters for digital-radar applications. One of the leading researchers in the field is Milton Feng of the University of Illinois at Urbana-Campaign. His team recently made a 550 GHz transistor, and Feng predicts that we will see a 700 GHz transistor before the year is out.

The UIUC group is busy refining InP HBTs, structures that Feng considers best-suited to very-high-frequency operation due to a combination of their inherent speed coupled with a reasonable breakdown voltage. The advantage of such devices over competing structures can be clearly seen in the graph. "If you were going to make a terahertz transistor with SiGe you'd run out of

breakdown voltage," explained Feng. "With PHEMTs you would have the same problem. In our case [HBTs], we actually have [a breakdown voltage] of more than 2 V at over 550 GHz."

Feng suggests that InP HBTs will operate above 1 THz, but that SiGe HBTs and InP PHEMTs are limited to 500 and 700 GHz, respectively. He points out that bipolar transistors have better I-V characteristics, such as output conductance, than FETs: "When FETs shrink down to 20 nm, their output conductance starts leaking between the source and the drain."

The problem with current GaAs HBT technology is power consumption, which limits high-level integration. "If you make a 5000 to 10,000 transistor converter chip with GaAs, it would consume more than 10 W, and that burns the chip out," said Feng. "With InP you can increase the transistor level



While transistors based on silicon, SiGe, GaAs and GaN will be limited by breakdown voltage at very high speeds, the trend lines suggest that terahertz operation will be possible with InP-based devices.

from MSI [medium-scale integration] to VLSI [very-large-scale integration], because each transistor consumes less power at a higher speed."

The research groups

developing high-speed InP HBTs fall into two camps; those using a single-heterostructure design, such as Feng, and those fabricating double-heterostructure devices

PA market specifically, which is where GaAs (and potentially GaN) chips fit in, is expected to peak in 2007 as demand for GSM and EDGE infrastructure declines and average selling prices are eroded.

The positive effects are already being felt by GaAs chip and RF module manufacturers, with Skyworks Solutions ramping up PA module production for W-CDMA phones, and TriQuint, Agilent and RF Micro Devices (RFMD) all launching either new PAs or RF transceivers.

Cautiously optimistic

Skyworks and RFMD – the market leaders in GaAs-based handset products – are cautiously optimistic about the opportunities presented by 3G technology in 2005. Steve Machuga, Skyworks' vice-president of technology development, said, "In 2005, we will indeed see growth in 3G handset sales. As the 3G infrastructure continues to develop, most OEMs will offer multimode handsets to enable users

to access both 3G and existing networks."

According to Machuga, that means handsets will need two radios and more complex RF switches, both of which are likely to mean higher GaAs content per handset. He expects "substantially more" HBT amplifiers and PHEMT switches on the market in 2005.

And despite the range of device designs required for different wireless protocols and the need for backwards-compatible handsets with multimode radios, Machuga says that the manufacturing processes are similar, and that these more complex PAs will ultimately become solitary devices.

As far as the networks are concerned, Machuga also sees increasing GaAs content as the build-out accelerates. "Some of the technical demands for 3G, such as improved linearity, will provide opportunities for higher-performance PAs, such as those based on GaAs," he said.

Over at RFMD, where the company is investing \$75 million in an expansion of

wafer-processing capacity, Jerry Neal and colleagues are seeing the benefits of advanced wireless communication at first hand. Neal himself has an RFMD-powered cell-phone handset that receives 32 television channels over the "2.5G" EDGE network in Greensboro, NC, while company employees use phones to transmit short video clips and high-resolution images in their everyday work.

Greater sophistication

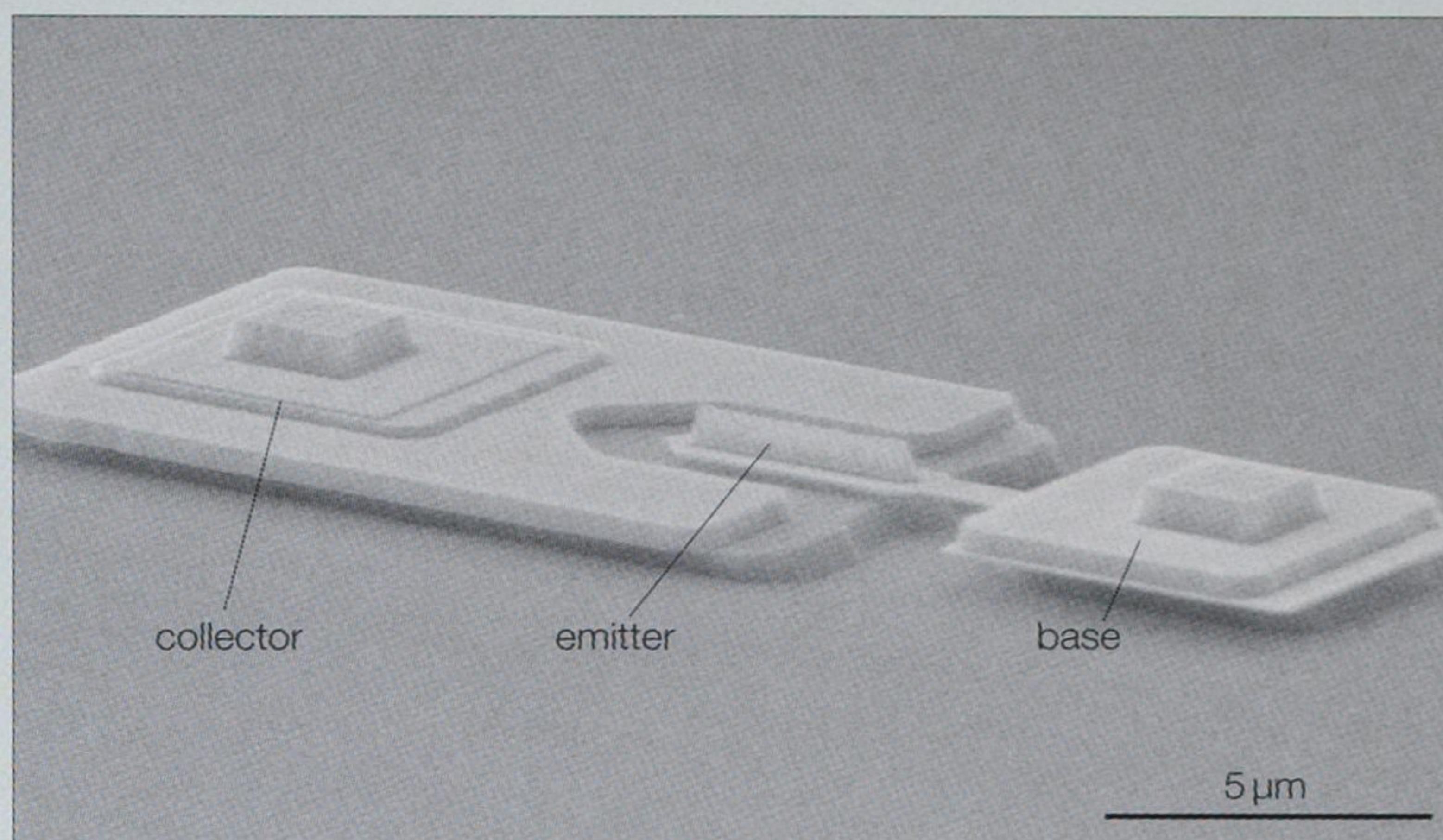
Neal's feeling is that firms like RFMD will inevitably benefit as cell phones draw together more and more applications. "All of the [new] functions and the higher data rates are driving enhanced power in the phone," he said. This extra functionality must be handled while the power budget decreases, meaning that increasingly sophisticated PAs are required.

"We're going to a whole new level of sophistication when it comes to maintaining the efficiency at all power levels," Neal said. While he believes that demand will acceler-

Superfast transistors continued

(DHBTs), such as HRL Laboratories. DHBTs fall into type I and type II categories. In type I structures the conduction band and valence band energies of the lower bandgap material both fall between the conduction and valence band energies of the higher bandgap material. However, in type II structures the conduction band of the narrower bandgap material may, for example, be positioned below the valence-band energy of the wider bandgap material.

Feng says that type I InP DHBT designs require a transition layer of 30–60 nm between the base and collector to address issues associated with bandgap discontinuity: “We choose SHBTs, because if you’re going to shrink the collector to 500–600 Å, then the advantage of the DHBT disappears. Fundamentally, a type I DHBT will be slower than a SHBT.” He concedes that while type II DHBTs have a great potential to provide the ultimate



Transistor speed can be improved by reducing the width of the emitter. This SHBT made by Milton Feng and colleagues (denoted by the red diamond in the figure opposite), has an emitter width of 0.25 μm, an f_T of 550 GHz and a breakdown voltage in excess of 2 V.

terahertz source, the development of such structures is still in its infancy.

Whichever type of HBT design that the researchers use, one universal goal is to reduce the emitter size, thereby increasing the base current. State-of-the-art high-speed transistors have emitter widths of around 0.25 μm, and are several microns long. Feng

acknowledges that although reducing the dimensions only yields a small improvement in the current gain cut-off frequency (f_T), it significantly improves f_{max} , the maximum oscillation frequency. f_T is the more fundamentally important figure as it depends on the transport characteristics of the device, rather than its geometry.

Reducing the dimensions of

the emitter also reduces power consumption. IBM is currently producing SiGe-based transistors with emitter dimensions of $0.1 \times 2.5 \mu\text{m}$: “If a three-five guy can shrink [an InP HBT] down to that scale by improving the doping concentration and doing some bandgap engineering, then I predict that the device will be close to terahertz operation,” said Feng. He cites achieving sufficient doping in the base region while maintaining crystal quality, and refinement of device design to reduce emitter current density, as two key hurdles to overcome as the device dimensions are reduced.

MBE appears to be the preferred growth method used by researchers fabricating high-speed InP HBTs, which Feng puts down to the greater time taken to develop MOCVD processes providing high-quality interfaces. While type I InP structures favor MBE growth, type II structures appear better-suited to MOCVD.

ate the use of high-performance 90 nm silicon circuitry, the RFMD co-founder says that GaAs-based PAs will remain the technology of choice for the next few years. That said, Neal thinks that the drive toward all-silicon PAs will gather momentum. “We have a lot of research and development going on in that area,” he admitted. Cost is not the issue, however, as the widespread use of 6 inch wafers and the shorter processing times (compared with silicon) of GaAs devices means that the III-V technology is now very cost-competitive. “The move to integration is going to drive opportunities for silicon PAs.”

Incredible performance

On the network side, Neal says that RFMD will introduce GaN-based PAs for base-stations in 2005. “We have those amplifiers now, and the power-density performance we are getting is incredible,” Neal enthused. “We’re talking about a voltage breakdown in excess of 50 V, and a power density of 100 W/mm,

“We think that GaN will give LDMOS a real run for its money.”

RFMD PLANS TO INTRODUCE GAN PAs IN 2005.

which is just incredible.”

With reliability tests in progress, Neal believes that the real technological battle in the base-station field will be between LDMOS and GaN in the final amplifier stage, with GaAs remaining in driver amplifier applications. “We think that GaN will give LDMOS a real run for its money.”

Neal wouldn’t confirm exactly when the GaN-based PAs would be launched, but he did indicate that RFMD had customers ready to implement the technology.

RFMD will face stiff competition from local rival Nitronex, plus the Japanese trio of Fujitsu, Matsushita and Oki Electric.

For Neal, however, one issue above all others will dominate 2005: “The thing we’re addressing every day, what’s really driving our business, is the issue of cost.” With customers demanding a 15–20% price reduction annually, efficiencies must be driven up along with manufacturing volumes just to maintain current revenue, hence the \$75 million Greensboro expansion.

Breaking China

China promises huge volumes, but it is one place where 3G networks have yet to take shape. Rumors abound that 2005 may see a breakthrough, with network trials in progress and local manufacturer Huawei launching its first 3G handsets. But the key development is the issue of 3G licenses, something that happened in Europe five years ago. For now, the jury is out on whether the Chinese government will issue the expected four licenses this year. If it does, 2005 ought to be remembered as the year 3G really did go global. ●



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Low-cost packaging is priority for millimeter-wave MMICs

Suppliers of millimeter-wave MMICs must cut their packaging and assembly costs if the technology is to achieve mass-market success. **Susan Curtis** reports on the emerging sector.

Extending MMIC technology to millimeter-wave (MW) frequencies has emerged as a crucial strategy for MMIC suppliers to achieve better profit margins and drive future business growth. Although mass-market demand for low-frequency MMICs operating at 1–2 GHz has been driven by the mobile-communications industry, manufacturers operating in this highly commoditized market are under continual pressure to cut unit prices. What's more, there are signs that the demand for microwave devices may be starting to level off as the cell-phone industry matures.

Driving down prices

Figures released by ABI Research – a New York-based technology research think tank and consultancy – reveal that power amplifiers for wireless networks represented 68% of the total RF market at the end of 2003, valued at almost \$2 billion, but that proportion is set to fall to 49% by 2008. According to Lance Wilson, senior analyst for ABI, the only option for RF-device manufacturers is to diversify: “No matter whether the [cellular] business goes up or down, the price pressure on [the device manufacturers] is so great that their problem is one of revenue. Their average selling price is falling, and they are converting to lower-cost packaging that will drive prices down even further.”

These challenging market conditions are prompting many MMIC suppliers to apply their existing know-how to MW frequencies at 20–100 GHz. A number of applications exist, but only a few commercial products are currently available. Indeed, TriQuint of the US – one of the world's leading MMIC suppliers – estimates that the market for commercial MW MMICs based on GaAs technologies is set to grow from \$163 million in 2003 to \$400 million in 2007.

MMICs operating in the MW spectrum offer several major benefits over their low-frequency counterparts. For a start, the higher operating frequencies enable more informa-

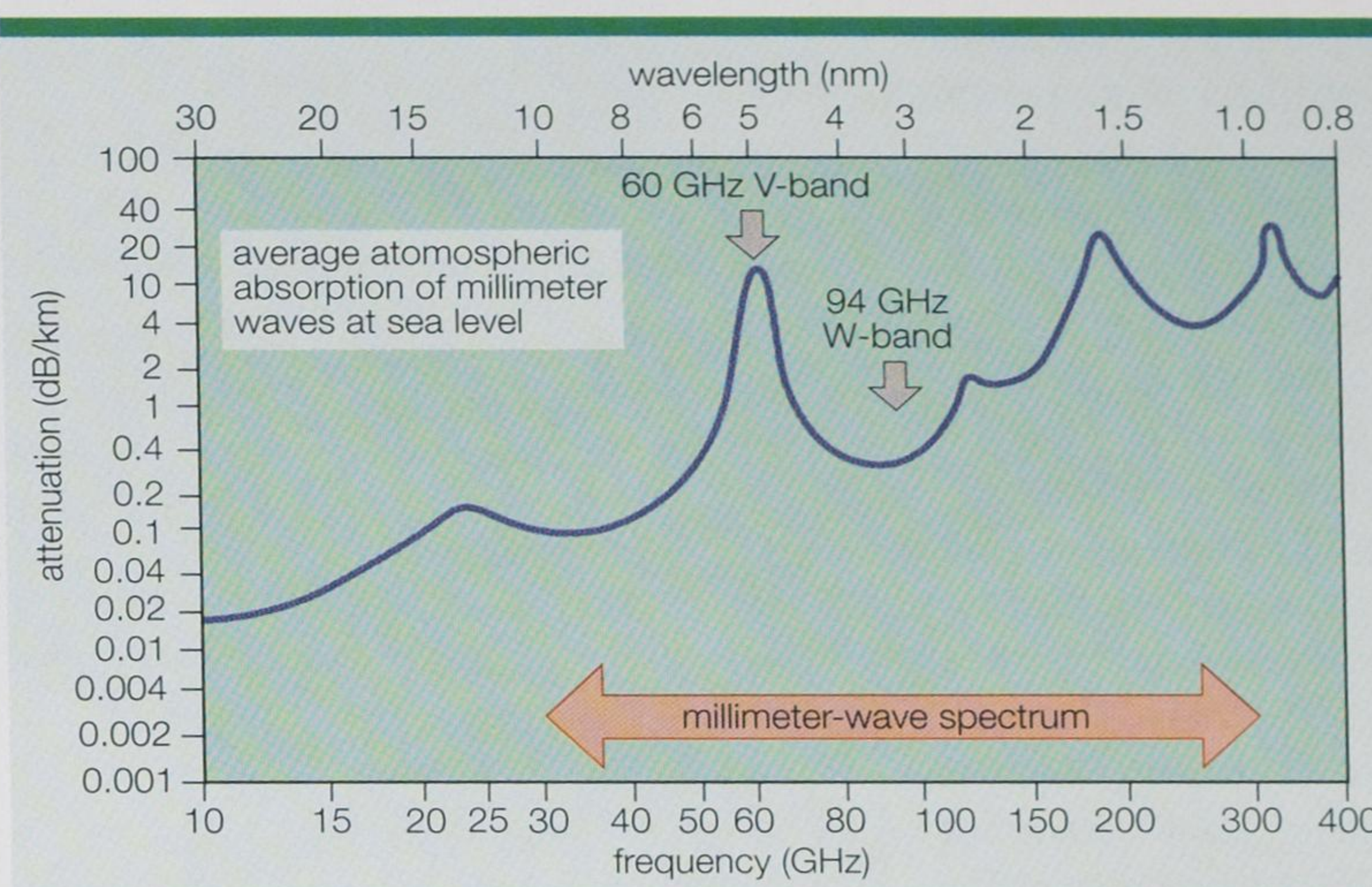


Fig. 1. Variations in the atmospheric attenuation of millimeter-waves at sea level caused by water and oxygen molecules provide windows for short-range and long-range transmission.

Applications using the millimeter-wave spectrum

Field	Sample application	Desired frequency (GHz)
Wireless communication	terrestrial broadband	59–64 (US)
		54–66 (Europe)
Satellite communication	two-way link	12–18 (Ku-band)
		26–40 (Ka-band)
Road transport telematics	vehicle–vehicle	63–64
	auto radar	76–77
Military	millimeter-wave imaging	94

tion to be encoded in the signal, which make MW solutions ideal for high-bandwidth, high-capacity communications systems. High-frequency MMICs also work for applications requiring narrow antenna beams or high spatial resolution in a compact size, since the shorter wavelengths of MWs enable the use of smaller receiver and transmitter elements.

These advantages have already been put to good use in the space and defense sectors, but continuing advances in circuit design are enabling smaller and cheaper components to be developed for commercial end-users. For example, vendors of fixed-wireless equipment, such as Terabeam Wireless, Ceragon Networks and Bridgewave, are exploiting MW MMICs in 60 GHz communications links that support data rates in excess of 1 Gbit/s – enough for enterprise customers to

connect their internal Ethernet networks to the fiber infrastructure. Systems operating beyond 70 GHz are now being developed to provide data rates of up to 10 Gbit/s with a range of up to one mile.

Satellite network operators are also eager to harness the benefits of higher frequencies. Two-way communications based on very-small-aperture terminal satellite technology at 12–18 GHz already represents a significant commercial market for microwave MMICs, while next-generation systems at 26–40 GHz are set to be deployed in 2005 and 2006. These deployments, which will offer better services at lower cost by enabling smaller antennas, dynamic bandwidth allocation and narrower beams, are likely to fuel strong demand for MW MMICs through 2008.

For true mass-market success, however, MW

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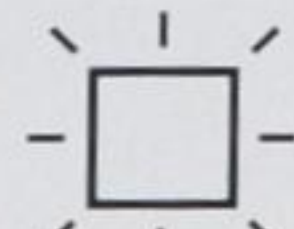
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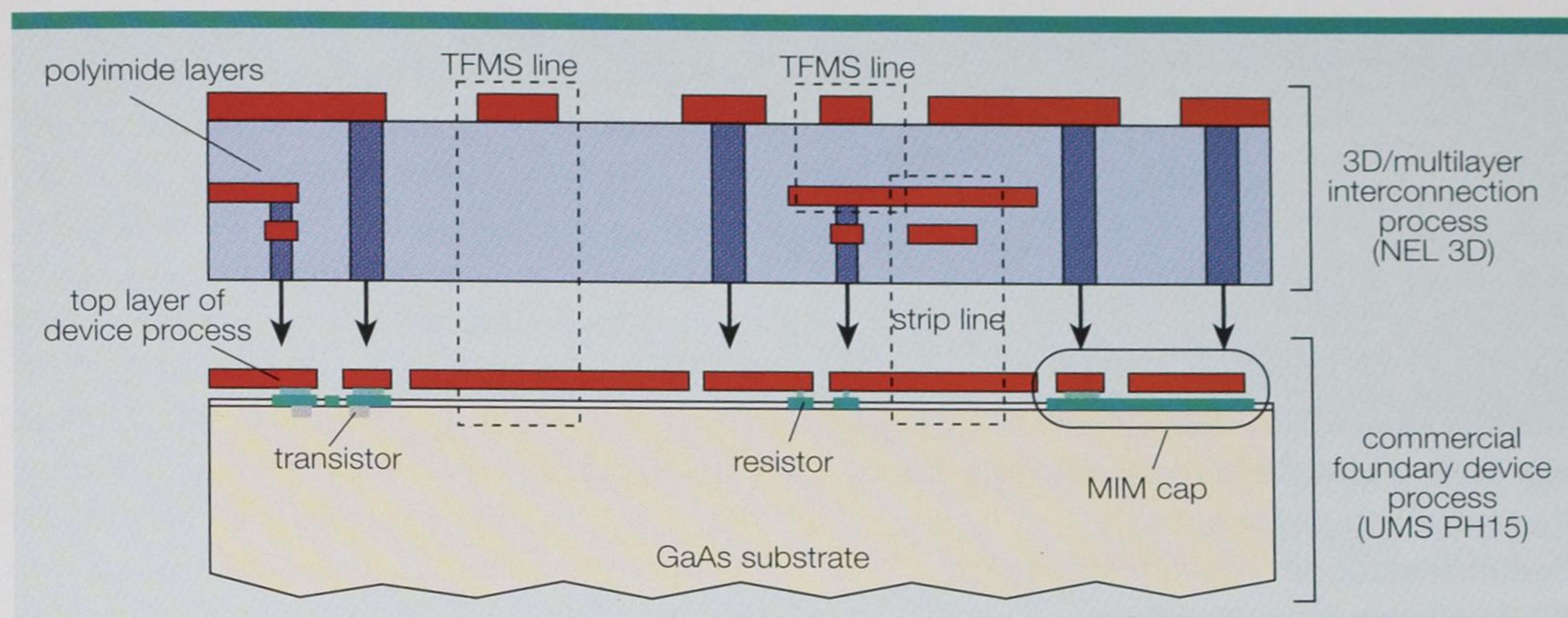
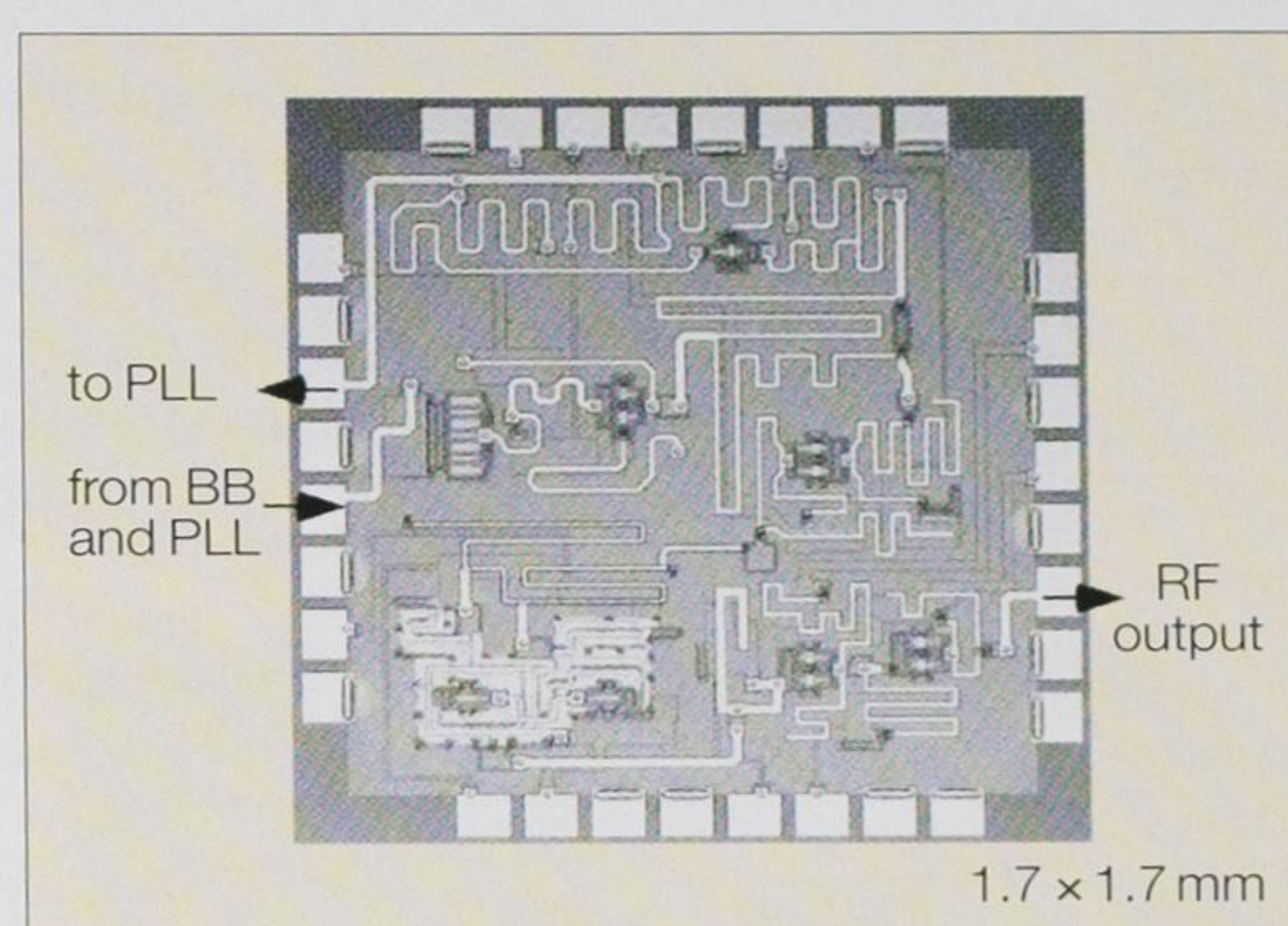
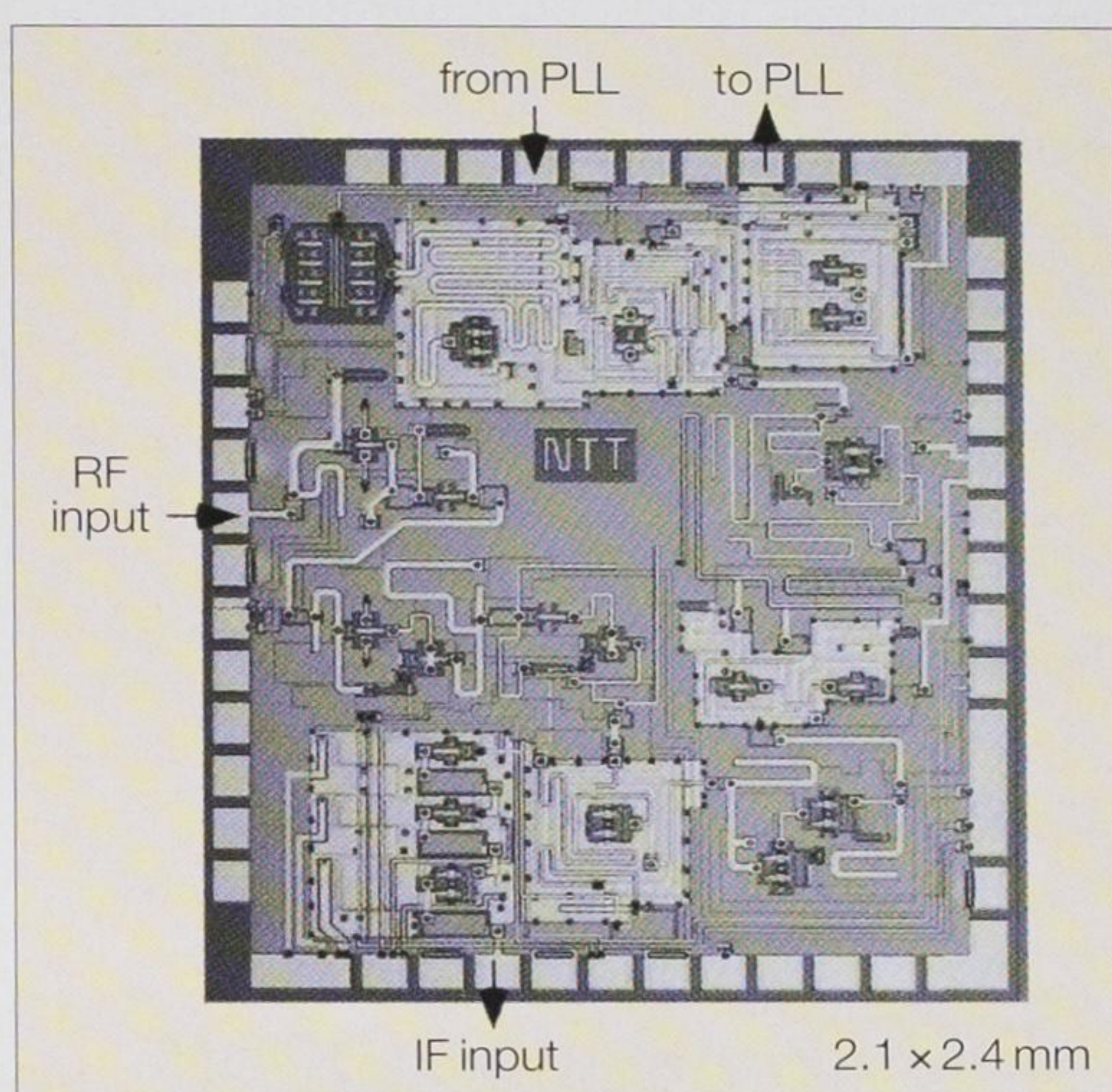


Fig. 2. NTT has produced fully integrated transceivers (above) by combining a commercial foundry process offered by United Monolithic Semiconductor with 3D interconnection techniques. Below are photographs of the transmitter (left) and receiver (right) MMICs.



suppliers are looking to the emerging market for automotive anticollision radar at 76–77 GHz. Radar-based systems providing adaptive cruise control are now being fitted to luxury cars – such as the Mercedes-Benz S-Class and the Volkswagen Phaeton – and falling component costs look set to open up the mid-price car market. Dan Green, TriQuint's director of broadband technology, estimates that 4.5 million MW MMICs will be deployed for automotive radar applications by 2007, while total MW MMIC usage in this market could approach 100 million units by 2010.

Commercial opportunities

There is no doubt that MW MMICs offer serious potential in the commercial market-place, but the challenge for suppliers is to deliver packaged and tested parts that meet the performance, cost and size criteria demanded by commercial end-users.

These demands are already being addressed at the chip level by the major manufacturers of MW MMICs. "The latest generation of MMIC manufacturing processes can deliver

the gain and bandwidth performance required for applications at frequencies of up to 100 GHz, while further optimization of MW circuit designs are likely to reduce both the size and cost of MMIC solutions," said Jeff Powell and Dave Bannister of the MMICs and Millimeter-Wave Modules group at QinetiQ.

According to Powell and Bannister, the leading MMIC foundries are ready to introduce price structures that would allow significant rate reductions for high-volume orders, even with existing designs. But the big obstacle remains the cost of packaged MW transceivers, which are often about five to six times as expensive as bare MMIC die. "Only by reducing packaging and assembly costs can the MW community hope to achieve high-volume sales of MMIC devices and transceivers," said Powell and Bannister.

To tackle these issues, package designers are now investigating whether low-cost, lightweight materials could replace the milled-metal packages that have traditionally been employed for MW components. Most attention is focusing on laminates and low-temperature co-fired ceramic (LTCC) materials, which have already been exploited in MMIC technology at lower frequencies.

One crucial advantage of LTCC and lamin-

ate materials is their ability to be formed into multilayer packages that can replace a number of individual modules with a common substrate incorporating both passive components and active devices. This approach reduces the overall size of the MMIC subsystem, minimizes parasitic losses caused by electrical interconnections, lowers assembly costs and enables high-level integration of functions demanding different device technologies.

For example, Kenjiro Nishikawa and colleagues at NTT in Japan have exploited laminate multilayers to develop a fully integrated transmitter operating at 57–60 GHz and requiring a chip area of just 2.89 mm². The group has also built a 5.04 mm² integrated receiver, achieving a noise figure of less than 6 dB.

To build these devices, Nishikawa and colleagues form a 3D interconnection layer – consisting of four layers of 0.25 µm-thick polyimide film and 1 µm-thick metal (0.2 µm for the top-level metal) – on top of European MMIC foundry United Monolithic Semiconductor's (UMS's) commercial 0.15 µm PHEMT process technology (figure 2). Once the process is complete, the PHEMT has a cut-off frequency of 110 GHz.

This type of integration alleviates many of the headaches associated with interconnecting MW components, since traditional wire bonds lead to high parasitic reactances at these frequencies and often require labor-intensive assembly techniques. In contrast, multifunction modules enable low-loss interconnects to be made between the devices and the package as part of the fabrication process.

However, connecting the package to the next-level subsystem remains a major problem. One of the most promising solutions is flip-chip bonding, which allows low-loss interconnects to be achieved with automated pick-and-place machines that also ensure high throughput and yield.

For example, researchers at NEC in Japan have combined flip-chip bonding with an LTCC multilayer package to build 60 GHz MMIC modules for wireless applications. Eudyna Devices has also indicated that flip-chip modules might be used for automotive radar systems, while fellow Japanese companies Matsushita and NTT are investigating the potential of the technology for high-performance packages.

Other promising interconnect technologies include ball-grid arrays, which exploit an array of small metallic balls to provide a reliable and low-cost interconnect between a ceramic package and a circuit board. Meanwhile, UMS is

using coupled electromagnetic transitions between the chip and the substrate to provide W-band interconnects in a module designed for automotive radar at 77 GHz (*Compound Semiconductor* May 2003 p31).

These developments are certainly promising, but more work is needed to develop standard packaging solutions that are compatible with high-volume manufacturing techniques. One problem is that most module makers are aligned with their end-user market sectors, which reduces the opportunity for transferring new ideas between subsystem manufacturers serving different markets. It also creates a general lack of appreciation among the end-user community of the importance of packaging in low-cost MMIC solutions.

These issues are now being addressed by the International Wireless Packaging Consortium (IWPC), which aims to bring together MMIC suppliers and system manufacturers to close the "packaging knowledge gap". According to the IWPC, the introduction of cost-effective packaging technologies has been hampered by poor communication between the foundries, the component and module makers

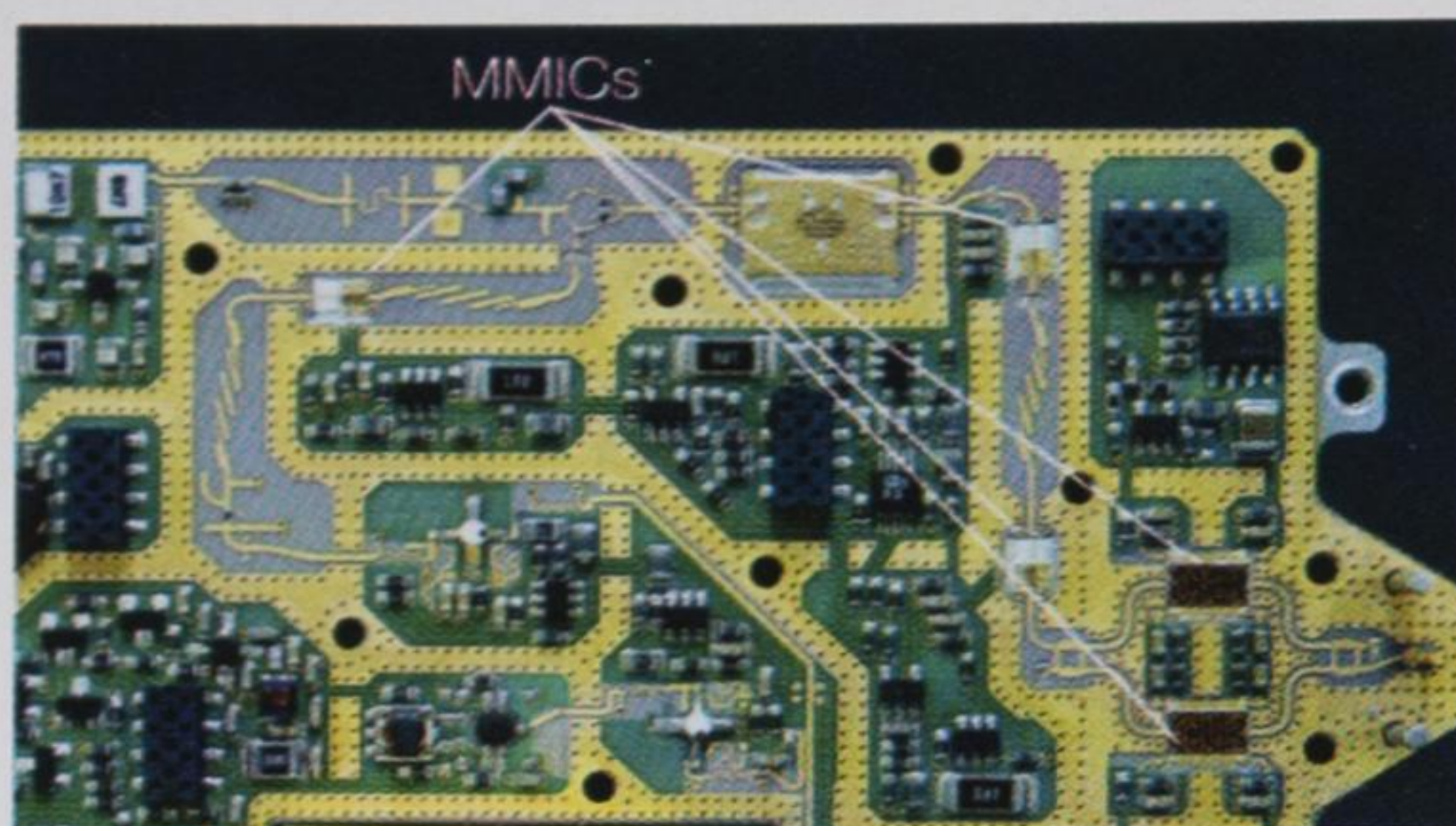


Fig. 3. Five MMICs feature in this Ka-band transmit module for satellite communications. They include two 27–32 GHz power amplifiers.

and the system manufacturers.

Although the organization covers all wireless technologies, the packaging challenges at MW frequencies have made this a crucial area of activity. For example, a recent workshop brought together device manufacturers, subsystem suppliers and end-users in the automotive industry to share ideas on the development of MW chips and modules for low-cost radar systems.

The IWPC is certainly attracting plenty of interest, with almost all the industry heavy-

weights appearing in its membership list. By raising the profile of packaging issues along the whole supply chain, it hopes that suppliers will better meet the needs of their customers and, in so doing, reduce unit costs, deliver the required performance and speed up the time to market.

These and other issues related to MW MMICs are explored in detail in a new report, *Commercial Applications for Millimeter-Wave MMICs*. The report is published by Technology Tracking, a partnership between QinetiQ, Europe's largest science and technology organization, and Institute of Physics Publishing, the publisher of *Compound Semiconductor* magazine. See www.technology-tracking.com for more details.

Further reading

K Nishikawa *et al.* *IEEE GaAs IC Digest* 2003 p97.

M Ito *et al.* *IEEE MTT-S Int. Microwave Symp. Digest* 2000 p57.

Susan Curtis is editor of the Technology Tracking reports.



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Wafer-fused VCSELS shape up for enterprise applications

Swiss start-up BeamExpress has developed a high-volume manufacturing process for long-wavelength singlemode VCSELS that combines the strengths of InP and GaAs technology. Company founder and chief scientist **Eli Kapon** outlines the wafer-fusion technique.

Vertical cavity surface-emitting lasers (VCSELS) offer numerous advantages over their edge-emitting counterparts for various different optoelectronics applications owing to their optical cavity configuration. In particular, VCSELS exhibit lower electrical power consumption, pure single-wavelength operation, easier coupling into singlemode optical fibers, compatibility with other optical elements for simpler packaging, and lower manufacturing costs thanks to the possibility of on-wafer testing.

In fact, short-wavelength ($<1\ \mu\text{m}$) VCSELS dominate very-short-haul ($<100\ \text{m}$) data-communication and optical-interconnect markets and are also increasingly being employed in sensor applications. This success results from a relatively simple fabrication technology, which relies on GaAs-based epitaxial wafers incorporating AlGaAs distributed Bragg reflectors (DBRs) and an (In)GaAs/AlGaAs quantum well (QW) active region.

Playing catch-up

VCSELS operating at longer wavelengths, particularly the 1310 and 1550 nm telecommunication wavebands, are attractive solutions for developing low-cost, wavelength-controlled sources in local-area and metropolitan optical fiber networks spanning transmission distances of between 100 m and 100 km. The development of these long-wavelength emitters, however, has lagged behind their shorter-wavelength counterparts. For best performance, these devices require GaAs/AlGaAs DBRs that offer a large refractive index contrast between their layers and a high thermal conductivity coefficient, and InP-based QW active regions with a high optical gain at up to 100°C .

Using such a combination of III-V semiconductor materials is particularly important when tackling the challenge of developing singlemode VCSELS that emit at least 1–2 mW at temperatures of $70\text{--}90^\circ\text{C}$. This performance is essential to ensure reliable

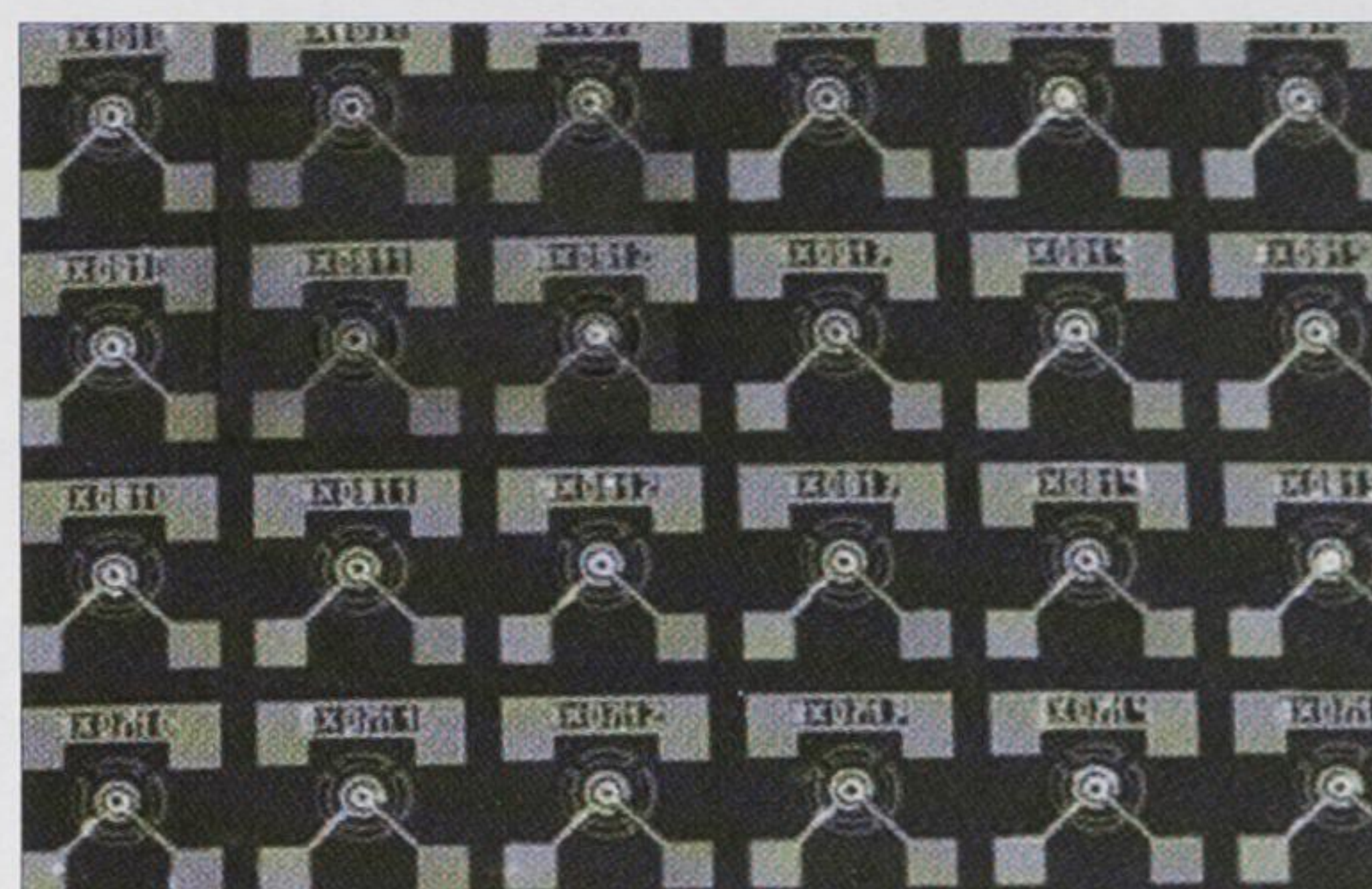


Fig. 1. BeamExpress's 2 inch locally fused wafers (top) combine GaAs-based DBRs and InP-based active regions. A micrograph (above) shows several VCSEL devices fabricated on a hybrid wafer.

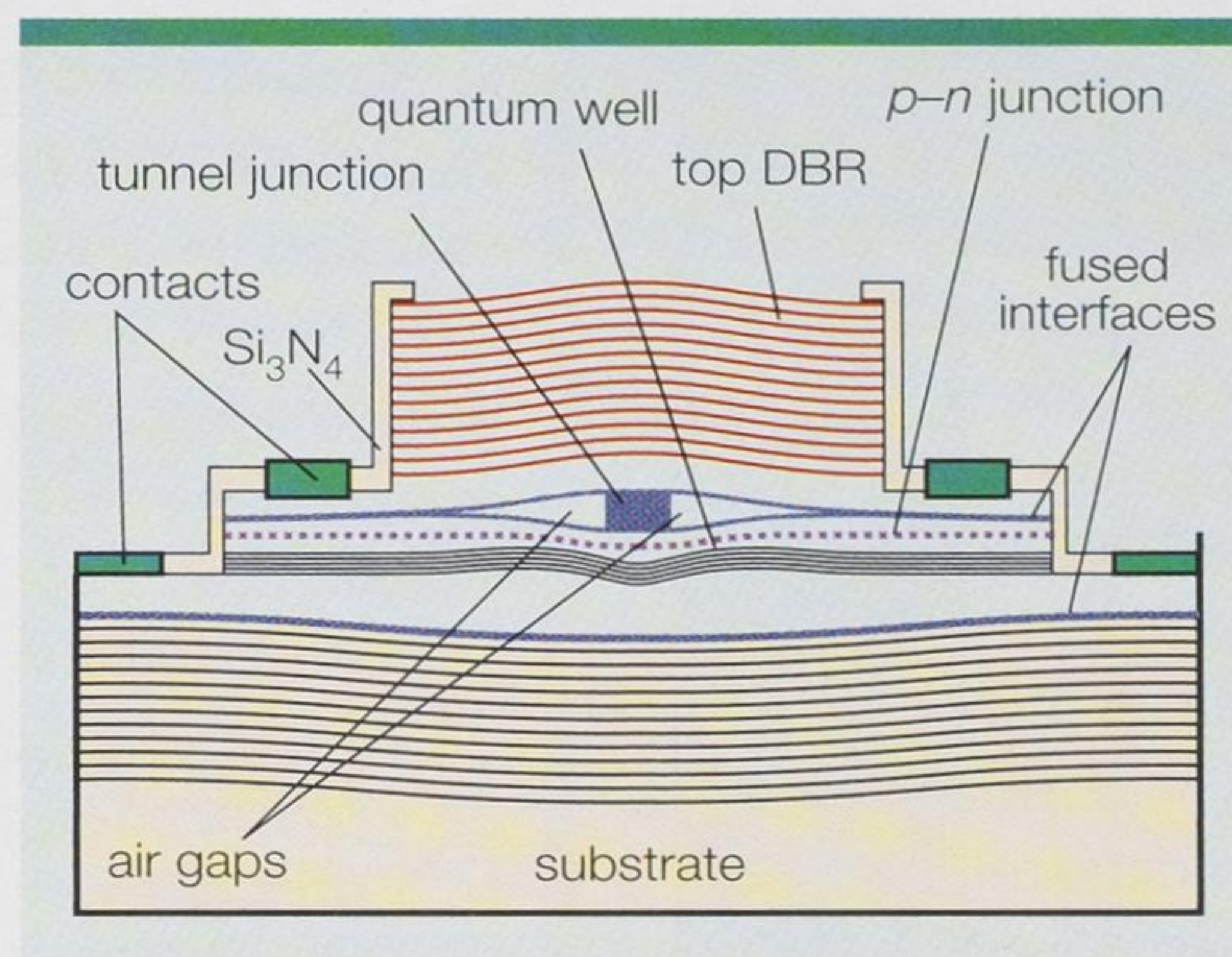


Fig. 2. A cross-section of BeamExpress's long-wavelength VCSEL, containing an InP-based active region with several strained InAlGaAs quantum wells and a heavily doped $p\text{--}n$ tunnel junction sandwiched between two GaAs-based DBRs.

operation of enterprise data and telecom networks, which represent the largest application sector for long-wavelength VCSELS.

The difficulties associated with mixing GaAs- and InP-based structures using conventional epitaxy has prompted exploration of alternative techniques for making such devices. Approaches include using highly strained QWs or quantum dot GaAs/InGaAs active regions; dilute-nitride GaInNAs/GaAs active regions; InP-based metamorphic DBRs; dielectric mirrors with InP-based active regions; and antimonide compounds. Although these techniques have made considerable progress, they still suffer limitations in terms of the choice of emission wavelengths and/or their singlemode output power.

A symbiotic relationship

An attractive alternative to single-substrate VCSEL technologies is wafer fusion, where the device is constructed by bonding together the separate components of the VCSEL cavity that are grown on their host substrates. This approach combines InP-based active regions with GaAs-based DBRs to give the best VCSEL performance.

A modified wafer-fusion technique, called localized wafer fusion, has been developed at the Laboratory of Physics of Nanostructures in the Swiss Federal Institute of Technology in Lausanne and is now being exploited by local start-up BeamExpress. In this technique, one or more wafer surfaces are structured using conventional lithography prior to the fusion step. This surface structuring defines the optical cavity and the carrier-confinement region inside the VCSEL. In particular, it permits precise adjustment of the laser's optical-cavity length, which in turn enables nanometer-scale precision when setting its emission wavelength. In addition, localized fusion helps to regulate the fusion process across the rest of the wafer, yielding reproducible high-quality fused interfaces.

BeamExpress has recently fabricated 2 inch

Photonic Device Fabrication – Glasgow, U.K.

Owing to recent new contract awards Compound Semiconductor Technologies is recruiting in the following areas:

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A senior level appointment to develop and expand III-V Process Engineering activities within the company. Relevant process experience includes photolithography, dielectric and metal deposition, wet and dry etching of InP and GaAs based materials.

- Develop device integration technologies to allow the fabrication of sophisticated integrated photonic components.
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Process Engineer

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- Support the implementation and enhancement of the wafer process library.
- Optimise processes to increase device yields.
- Experience of processing III-V materials and/or photonic devices would be an advantage.

Senior Device Engineer

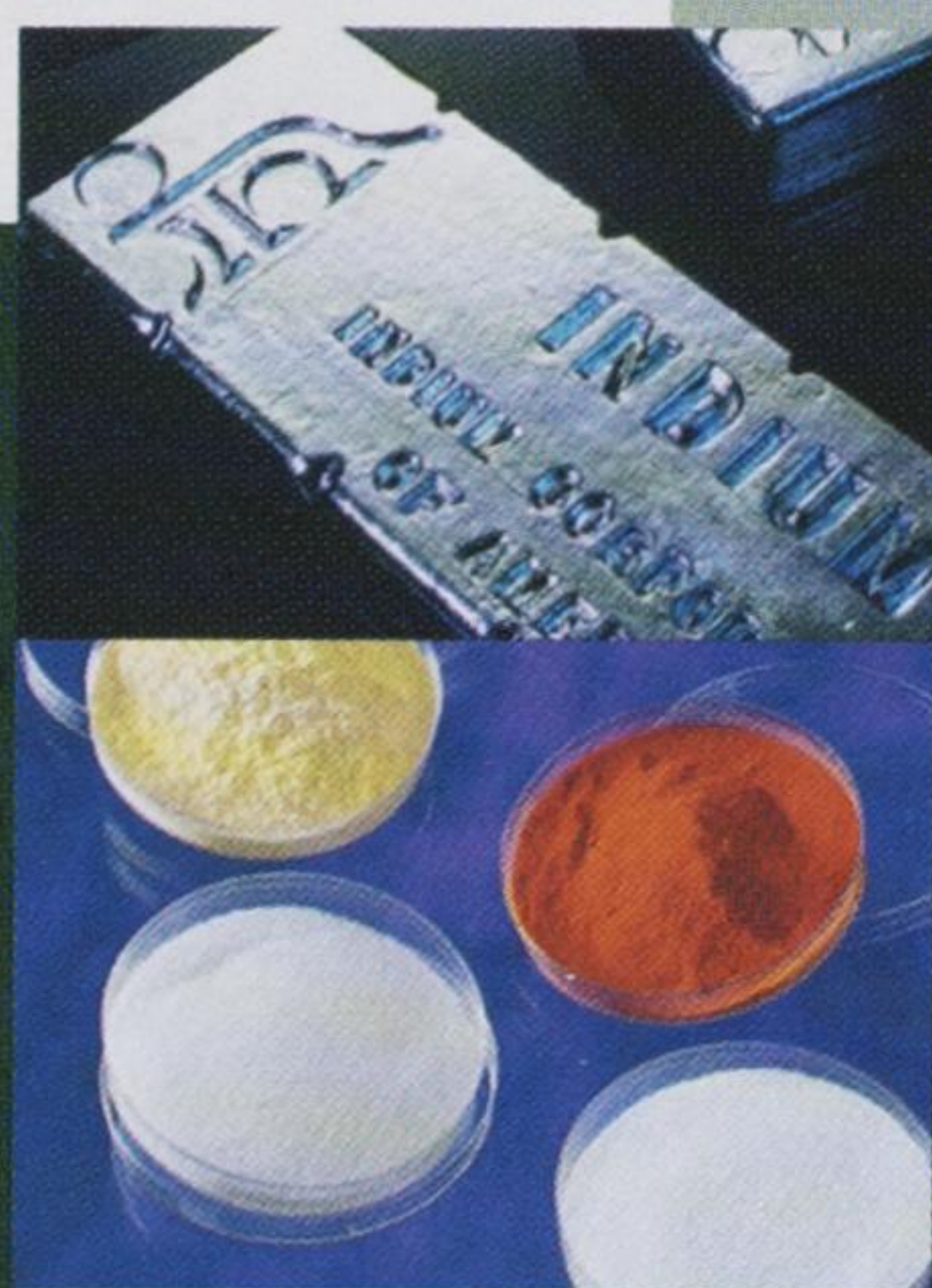
A Senior Level appointment to expand CST's optoelectronic design capability. Experience of semiconductor laser design would be a necessity.

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double-fused VCSEL wafers with high uniformity and excellent repeatability, thereby establishing localized wafer fusion as a viable mass-production technology (figure 1). Such wafers employ an industry-standard small die size, enabling production of a large number of devices per wafer.

Figure 2 shows a localized, double-wafer-fused VCSEL. The active region typically incorporates several InAlGaAs strained QWs and a heavily doped p - n tunnel junction, grown on an InP substrate by MOCVD using silicon and carbon dopants. Lateral electrical and optical confinement is obtained by etching mesas through the tunnel junction. The top and bottom DBRs, typically containing 21.5 and 35 periods of undoped $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{GaAs}$ quarter-wavelength layers grown on GaAs substrates, respectively, are fused to either side of the active cavity material.

Mesas at the fused interface are surrounded by lens-shaped nanogaps formed by plastic deformation of the fused wafers. Current is driven through the tunnel junction into the active region via n -type intracavity layers. A reverse-biased p - n junction around the mesa provides efficient lateral-current confinement.

Optimized operation

The light-current-voltage characteristics at different ambient temperatures for 1310 and 1550 nm-emitting devices are shown in figure 3. Optimizing the device design leads to threshold currents of less than 3 mA and a diode voltage of less than 2.5 V throughout the temperature range for both wavebands. At 85 °C, singlemode optical powers of 1.2 mW at 1340 nm and 1.6 mW at 1510 nm have been obtained, and a sidemode suppression ratio of better than 35 dB was achieved at all of the tested temperatures (figure 4).

Operation at selected wavelengths conforming to the standardized coarse wavelength-division multiplexing (CWDM) grid has been demonstrated with a mesa-trimming technique that involves setting the cavity length prior to the fusion step. Of equal importance, the high singlemode power of BeamExpress's localized wafer-fused VCSELs is obtained without compromising either beam shape or direct modulation speed.

By employing 7 μm diameter apertures, circularly symmetric fundamental-mode beams with full width at half maximum values in the region of 7.5 and 9.5° are obtained for 1310 and 1550 nm VCSELs, respectively. These beam shapes have a high coupling efficiency into singlemode fibers (80 and 70% with a

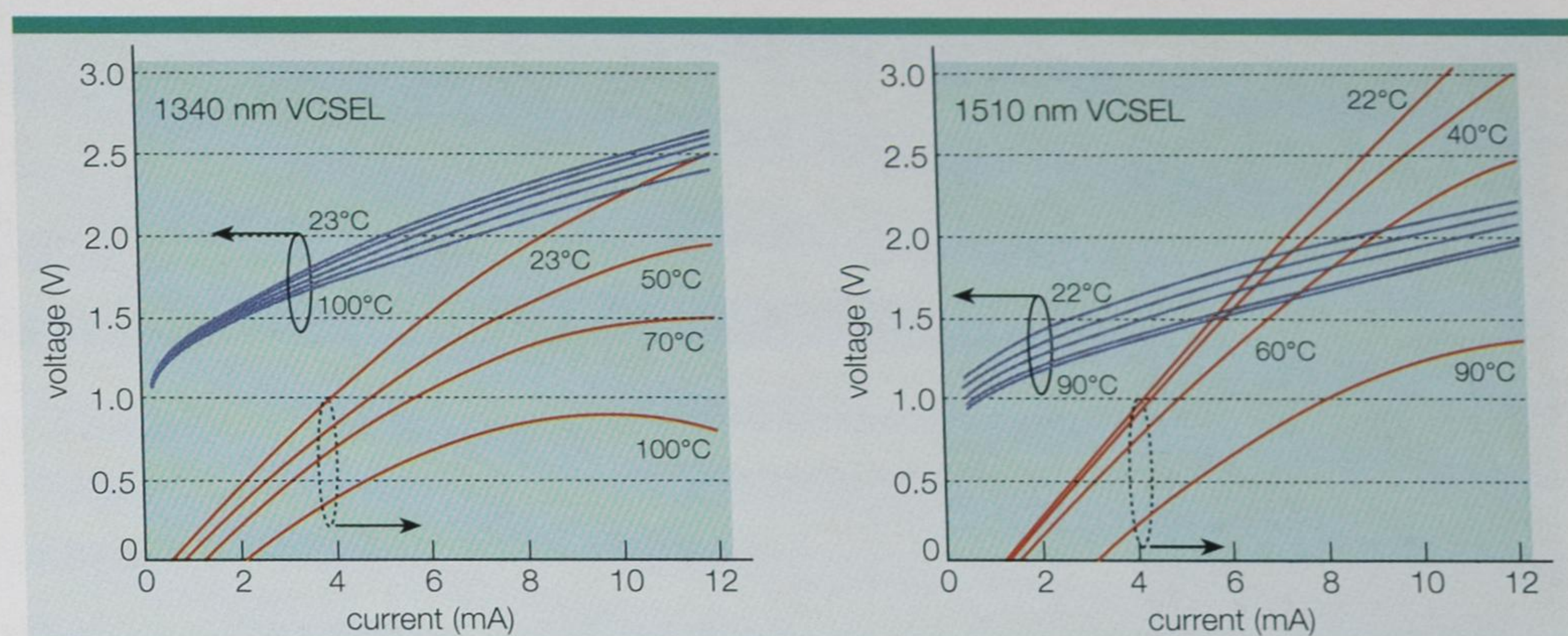


Fig. 3. The performance of BeamExpress's VCSELs at high-temperatures establishes the devices' credentials for deployment in enterprise data and telecom networks.

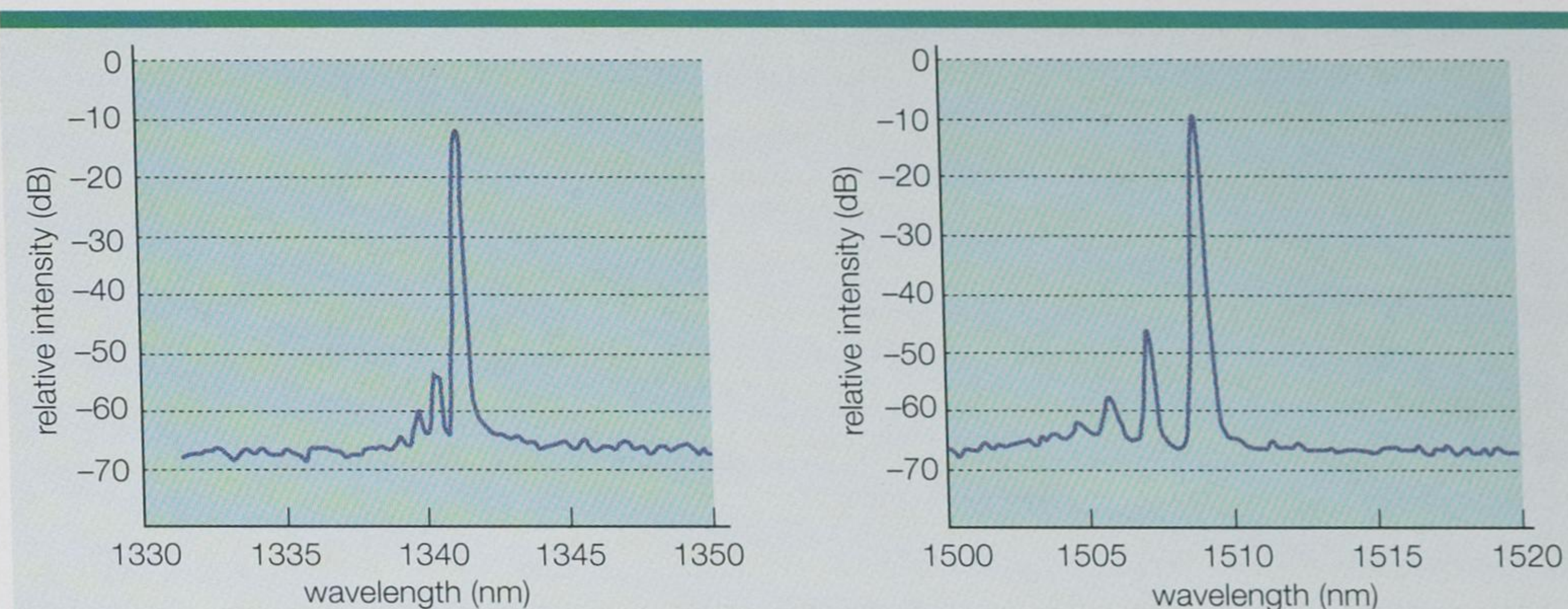


Fig. 4. With a sidemode suppression ratio of at least 35 dB and output powers of more than 1 mW, BeamExpress's VCSELs are potential candidates for use in 10 Gigabit Ethernet.

lens for 1300 and 1550 nm wavelengths, respectively, and 50% for butt-coupling at both wavelengths). Direct modulation at 3.125 Gbit/s is achieved with devices at both wavebands, and the extension of modulation speeds to 10 Gbit/s is under development.

BeamExpress's devices exhibit singlemode output powers at 85 °C that are two to three times as high as those of other 1310 and 1550 nm-emitting VCSELs. Due to the significantly improved coupling efficiency into singlemode optical fibers, these VCSELs can now effectively replace edge-emitting distributed feedback (DFB) lasers operating at much higher (>5 mW) singlemode powers. When operating at high temperatures (70–90 °C), the electrical power consumption of a BeamExpress VCSEL is one-tenth that of a comparable DFB edge-emitting laser.

This very low power consumption enables VCSELs to be packaged in far more compact modules, opening the way to new generations of low-cost, high-performance optical transceivers. Low power consumption is just one aspect of the ease of integration of these devices, which will play a major role in shrinking the footprint and the cost of

VCSEL-based optical modules.

One example is 10G-BASE-LX4 transceivers, the four-wavelength CWDM standard for 10 Gigabit Ethernet. Here, BeamExpress's VCSEL technology offers a substantial cost advantage in multiplexing the multiwavelength laser array, making it suitable for high-volume low-cost manufacturing. In addition, efficient VCSELs operating in the 1310 and 1550 nm telecommunication wavebands enable production of 8-channel CWDM VCSEL arrays, with yet more channels available if water-free fibers are introduced.

BeamExpress is now working with manufacturing partners to optimize future high-volume production of localized wafer-fused long-wavelength VCSELs. A fully automated wafer-fusion process allied to subsequent processing steps that resemble those established for short-wavelength VCSEL manufacturing indicates that competitive chip costs will be possible with this technology. The company is engaged in intensive reliability tests for all aspects of the technology, and encouraging results have already been obtained. Long-wavelength VCSEL prototypes are also being sampled by selected customers.



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- G: Advanced Gate Dielectric Stacks on High-Mobility Semiconductors
- H: Giant-Area Electronics on Nonconventional Substrates
- I: Organic Thin-Film Electronics
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BIOLOGICAL AND MOLECULAR MATERIALS

- K: Biological and Bio-Inspired Materials and Devices
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- P: *In-situ* Studies of Gas/Solid Surface Reaction Dynamics
- Q: "Smart" Surfaces and Interfaces
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NEW APPROACHES TO MATERIALS SYNTHESIS AND FABRICATION

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- Z: Chemistry of Nanomaterial Synthesis and Processing
- AA: Dynamic, Self-Organizing Systems in Multifunctional Nanomaterials and Nanostructures

MODELING AND COMPUTATION

- BB: Mechanical Properties of Nanostructured Materials—Experiments and Modeling
- CC: Coupled Nonlinear Phenomena—Modeling and Simulation for Smart, Ferroic, and Multiferroic Materials
- DD: Heat and Mass Transport at Nanoscale—From Fundamentals to Devices
- EE: Linking Length Scales in the Mechanical Behavior of Materials

GENERAL

- FF: Advanced Devices and Materials for Laser Remote Sensing
- GG: Materials and Technology for Hydrogen Storage and Generation
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SYMPOSIUM TUTORIAL PROGRAM

Available only to meeting registrants, the symposium tutorials will concentrate on new, rapidly breaking areas of research and are designed to encourage the exchange of information by meeting attendees during the symposium.

EXHIBIT

A major exhibit encompassing the full spectrum of equipment, instrumentation, products, software, publications, and services is scheduled for March 29-31 in Moscone West, convenient to the technical session rooms.

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Graduate students who are interested in assisting in the symposium rooms during the 2005 MRS Spring Meeting are encouraged to apply for a Symposium Assistant position. By assisting in a minimum of four half-day sessions, students will receive a complimentary student registration, a one-year MRS student membership commencing July 1, 2005, and a stipend to help defray expenses. Applications will be available on our Web site by November 1.

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A Career Center for MRS members and meeting attendees will be offered in Moscone West during the 2005 MRS Spring Meeting.

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Silicon carbide opens the door to radiation-detection market

Desirable properties such as low-noise performance at room temperature, radiation hardness and high-temperature operation could persuade manufacturers to invest in silicon carbide-based devices for radiation detectors. **Richard Stevenson** investigates.

Although silicon carbide (SiC) chips are largely viewed as a solution for next-generation high-power devices, the material's intrinsic properties are also suited to the detection of alpha, beta, ion and soft X-ray radiation. At present, SiC detectors – devices comprising one or more rectifying junctions operating in reverse bias – only exist in the research domain. However, SiC has attractive properties as a detector, including a low leakage current. This could allow chips based on the material to penetrate markets that are currently dominated by silicon and germanium devices, and compound semiconductors such as CdTe and CdZnTe.

SiC detectors are made up of a layer of SiC sandwiched between two metal contacts. Incident radiation generates several electron-hole pairs that are pulled apart under an applied electric field, creating a current that is amplified and recorded.

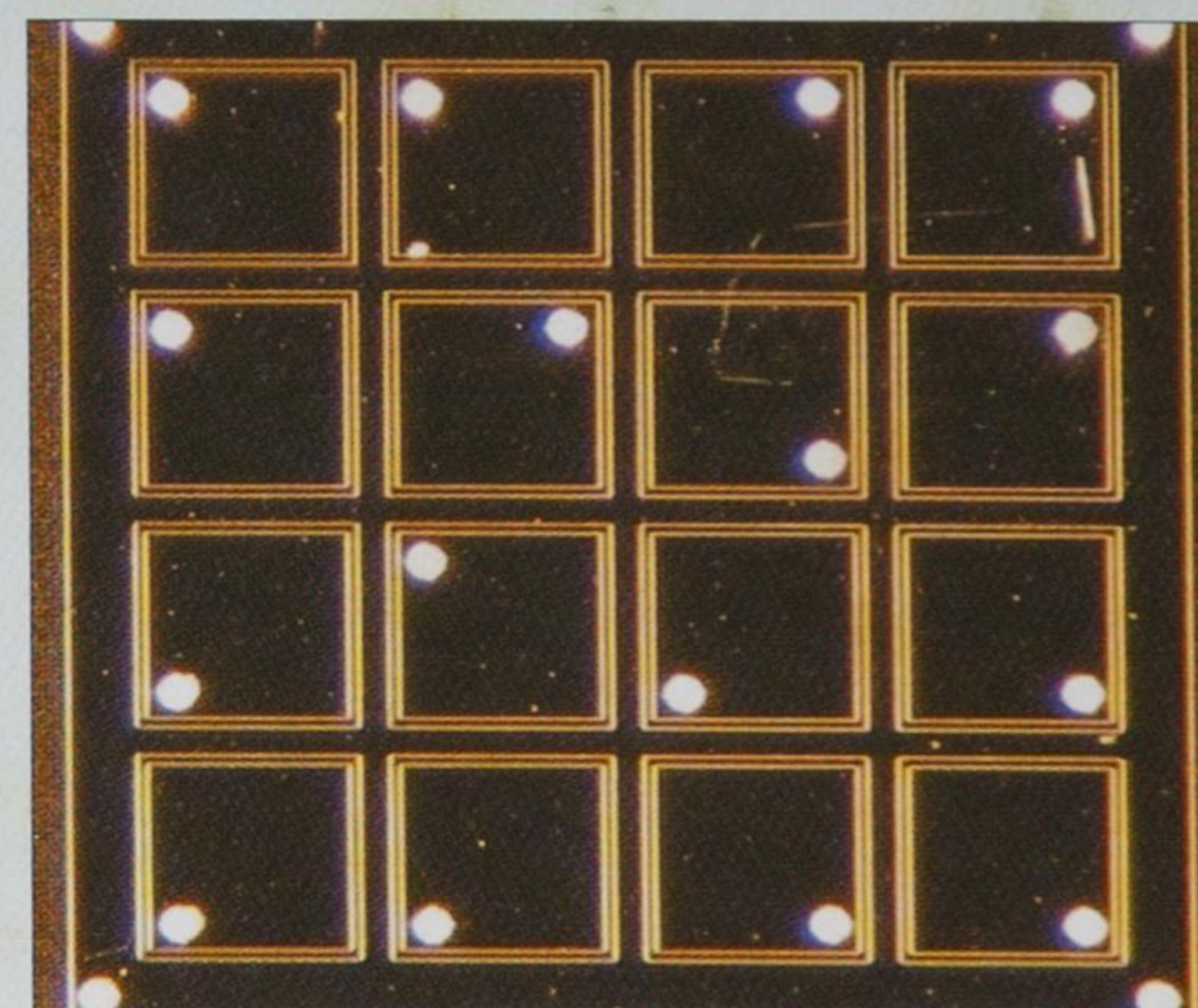
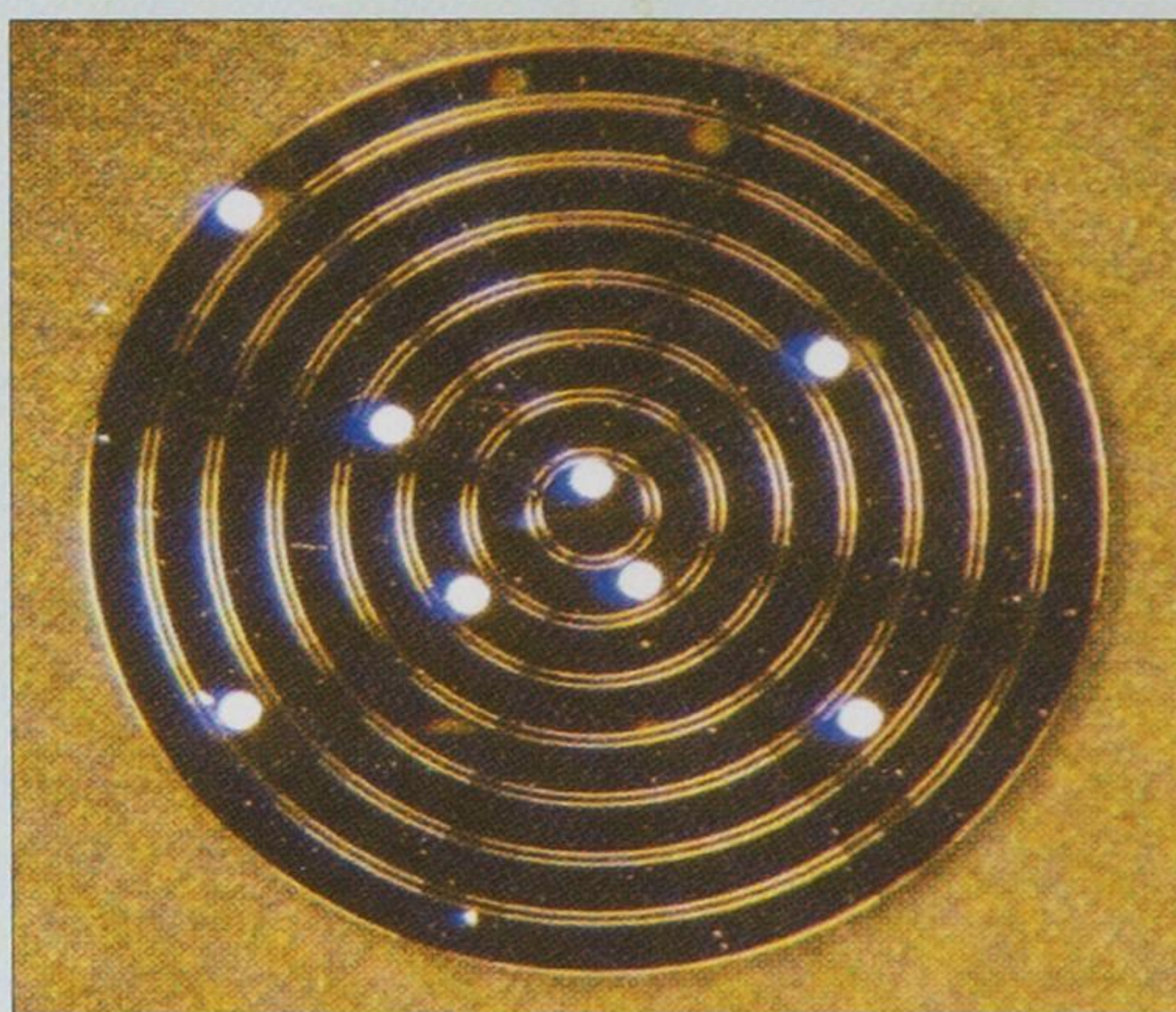
Beating the competition

These SiC devices will compete with established detectors for existing markets, including detectors for high-energy physics research, astronomical X-ray telescopes, and archeometry (the non-destructive identification of chemical elements in works of art).

Giuseppe Bertuccio, a researcher at Politecnico di Milano, believes that the advantages of SiC detectors include high-temperature operation, detection of a range of particles with various energies, and a potential for radiation hardness and high temporal resolution.

Bertuccio states that SiC detectors can distinguish between small differences in the energies of incident radiation even at room temperature, thanks to their negligible leakage current. In contrast, silicon and germanium detectors used for X-ray spectroscopy applications, which demand high-energy resolution, require cooling. "Typical leakage current densities of silicon detectors are of the order of 1 nA/cm², but SiC detectors have current densities of as little as 1 pA/cm², three

SiC detector development



INFN, SiCPOS AND COFIN-01

Circular SiC detectors (above, left) – designed for single-channel detection of any X-ray source – and square detectors (above, right) – suitable for X-ray spectroscopic imaging – were produced under SiCPOS, a National Institute of Nuclear Physics (INFN) funded program, and SiC-Cofin-01, an Italian Ministry of Education, University and Research-funded program that ran between 2002 and 2003. The detectors were built by Alenia Marconi Systems of Rome and the physical characterization of

the SiC material used in their manufacture was determined by the universities of Bologna and Milan - Bicocca. The design of the detectors and the associated electronics was undertaken by the Politecnico di Milano. The radiation hardness and the performance of the detectors were evaluated by the universities of Modena and Turin, and Florence University assessed the detectors' beta-radiation performance. Recent additional funding (provided by INFN and SiC-Cofin-04)

will enable the collaboration to investigate the manufacture of advanced radiation detectors. The Politecnico di Milano in collaboration with the University of Milan will develop detectors with integrated front-end transistors for signal amplification. A GaN HEMT will be added to a SiC detector to act as the first transistor of the preamplifier, thereby eliminating the need for external silicon devices, which exhibit a poorer performance at higher temperatures.

orders of magnitude lower," remarked Bertuccio. This particular feature means that SiC detectors can be made with a much larger detection area than their silicon counterparts.

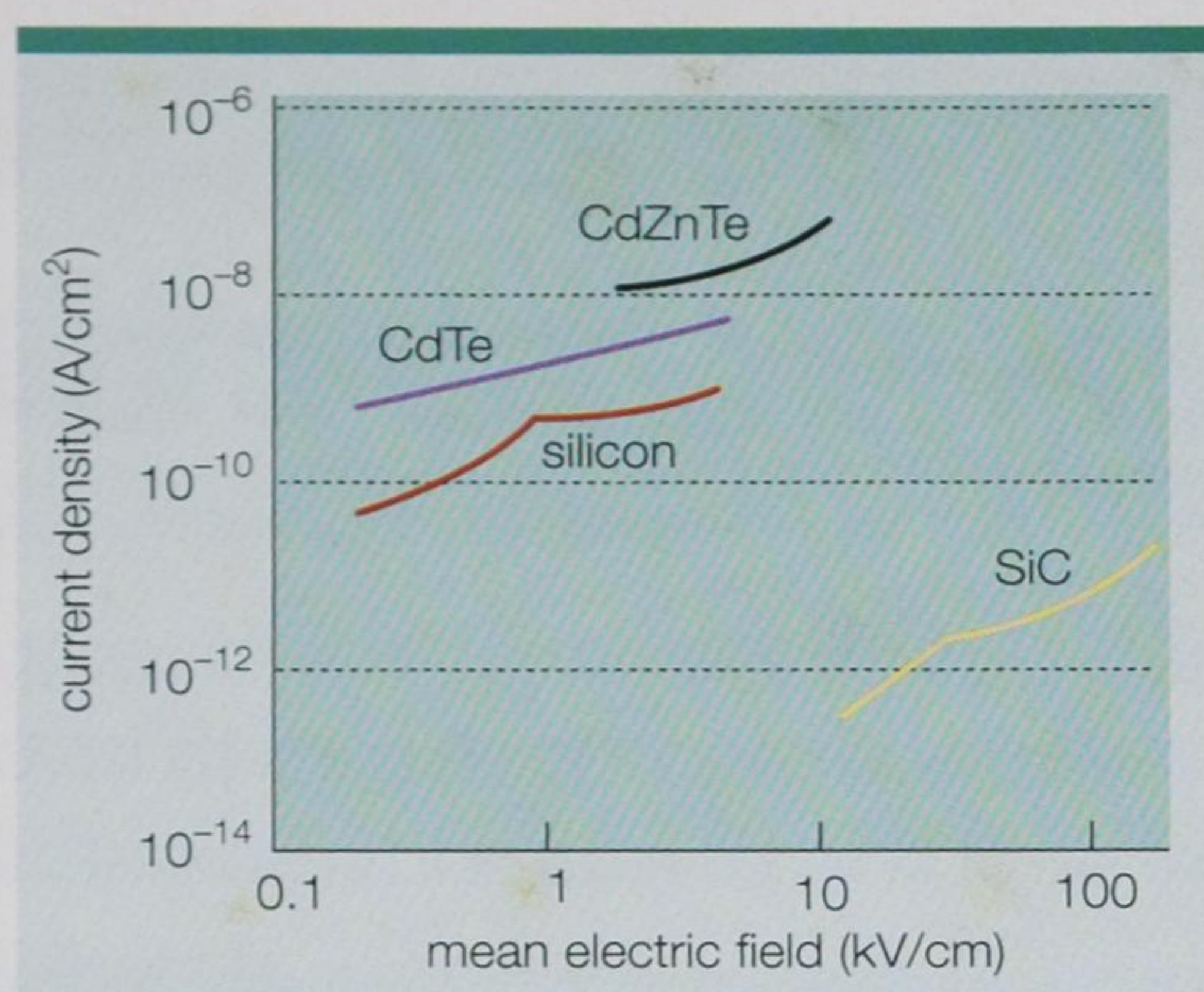
SiC is suitable for detecting various forms of radiation, including soft X-rays with energies of between 0.1 and 20 keV. "For X-rays with photon energies of greater than 2 keV, SiC has a similar stopping power to silicon,

because the interaction is predominantly a photoelectric effect that depends on the presence of silicon atoms," said Bertuccio. However, for energies of less than 2 keV, SiC is superior to silicon, thanks to its higher attenuation coefficient. SiC detectors can also detect relativistic particles and ionizing radiation such as alpha particles, protons and ions with energies of up to a few megaelectron-volts. →

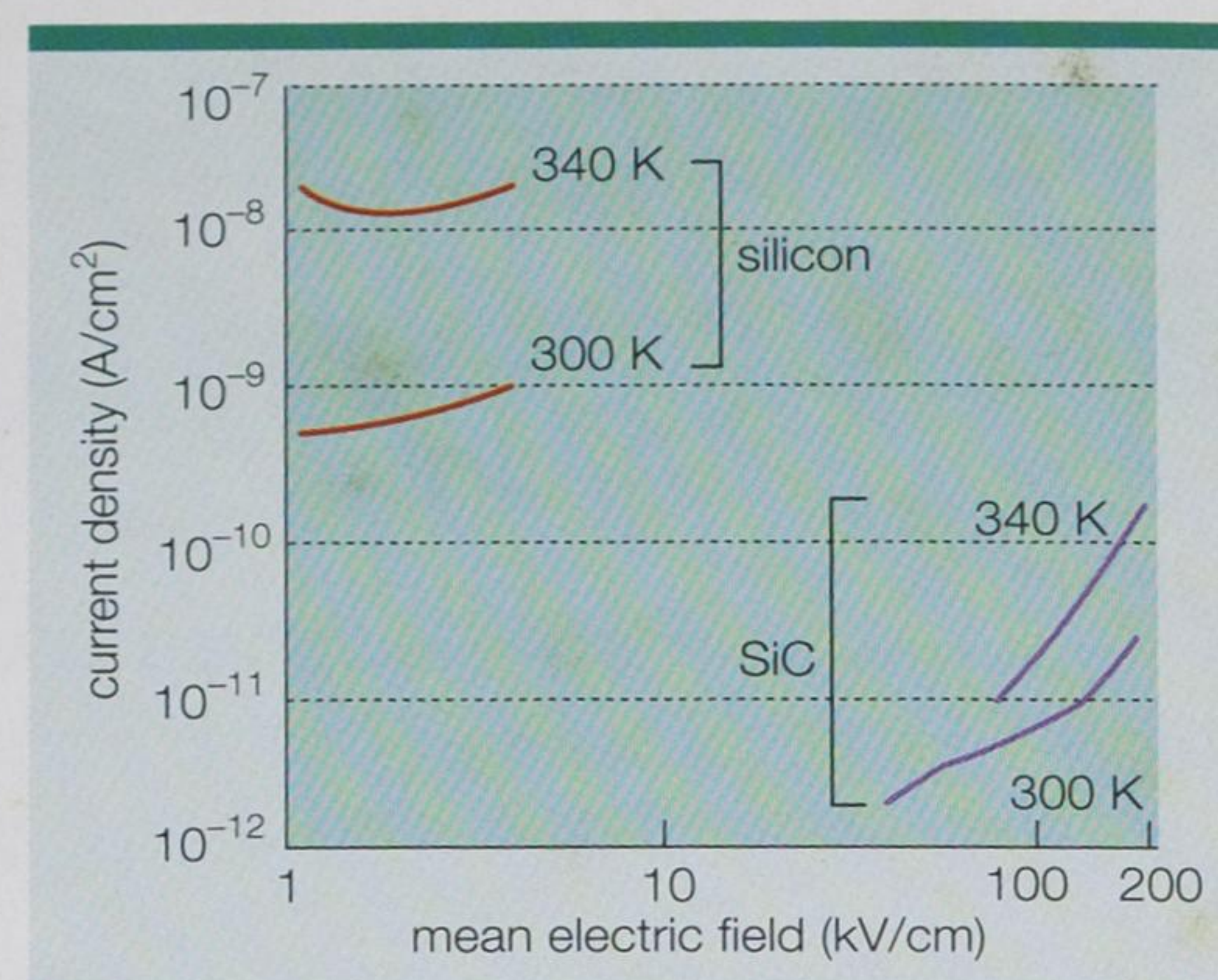
Bertuccio acknowledges one downside of SiC detectors: their relatively low detection signal, which is a direct consequence of SiC's wider bandgap. However, he points out that SiC detectors have the lowest noise figures of all semiconductor-based devices. This partly explains their highly desirable signal-to-noise ratio, which is ultimately limited by the performance of front-end electronics.

Today the scientific community's efforts are directed toward building large-area detectors with a finer energy resolution. Bertuccio believes that SiC and GaAs detectors will benefit from the techniques developed for their silicon predecessors that were used to form complex detection structures such as pixel arrays and microstrip detectors. The spatial resolution of these instruments should be comparable to multielement silicon detectors.

One potential advantage that SiC detectors have over other compound semiconductor detectors is a higher temporal resolution. SiC has a high breakdown field of more than 2 MeV/cm, allowing devices to be operated under a large applied electric field. "This implies that the charge carriers can move at



(Left.) Low leakage currents and the ability to withstand high electric-field strengths make SiC a strong candidate for next-generation radiation detectors. (Right.) The relatively small temperature dependence of leakage current for SiC detectors, when compared with those using silicon, makes them well-suited to high-temperature applications.



their saturation velocities, thus achieving very fast output current signals," said Bertuccio. The saturation velocity for electrons in SiC is roughly double that of electrons in GaAs and silicon. A further drawback of today's silicon and GaAs-based detectors, when used in high-energy physics or radiation-monitoring applications, is their limited radiation hardness.

Bertuccio believes that the unique characteristics of SiC detectors that allow them to operate at raised temperatures could spur their first commercial breakthrough. Other possible applications include detectors for X-ray spectrometers and in radiation-level monitors that are used in the nuclear industry.

Material quality is key

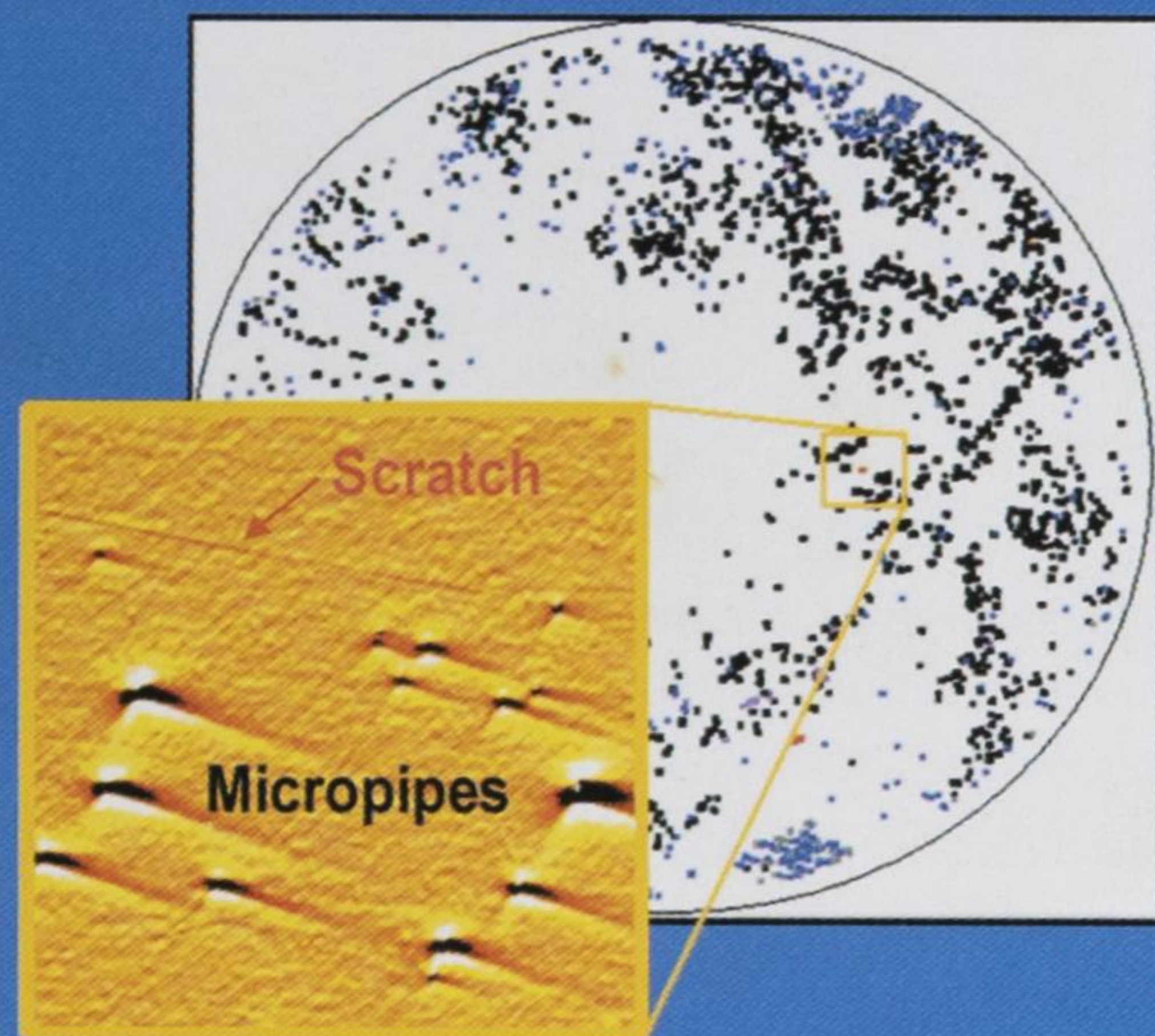
According to Bertuccio, three obstacles currently prevent the commercialization of SiC detectors: growing thick epitaxial layers; producing layers with a low dopant concentration; and the fabrication of ultrapure semi-insulating bulk SiC crystals.

Today's best efforts include SiC epitaxial layers of up to 70 μm thick, and dopant levels in the region of $5 \times 10^{14} \text{ cm}^{-3}$. However, Bertuccio believes that a layer of up to 300 μm thick and a dopant level of less than 10^{13} cm^{-3} will be required to deplete the whole detector at a reasonable voltage (100–500 V) and achieve detection efficiencies similar to those in silicon devices currently used in X-ray and high-energy particle detectors.

He also notes that although semi-insulating bulk SiC wafers of up to 400 μm thick are commercially available today, they exhibit impurity and defect densities well in excess of those present in epitaxial SiC. "This limits the performance of semi-insulating SiC radiation detectors due to the trapping of signal charges at deep levels, which degrades the signal-to-noise ratio," said Bertuccio.

Compared with other semiconductor detectors, a commercial SiC device would be expensive because of the greater cost of SiC wafers: "Nevertheless," said Bertuccio, "X-ray SiC detectors do not require cooling, so running expenses for a spectrometer are lower."

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IQE's 'smooth' approach increases carrier speed

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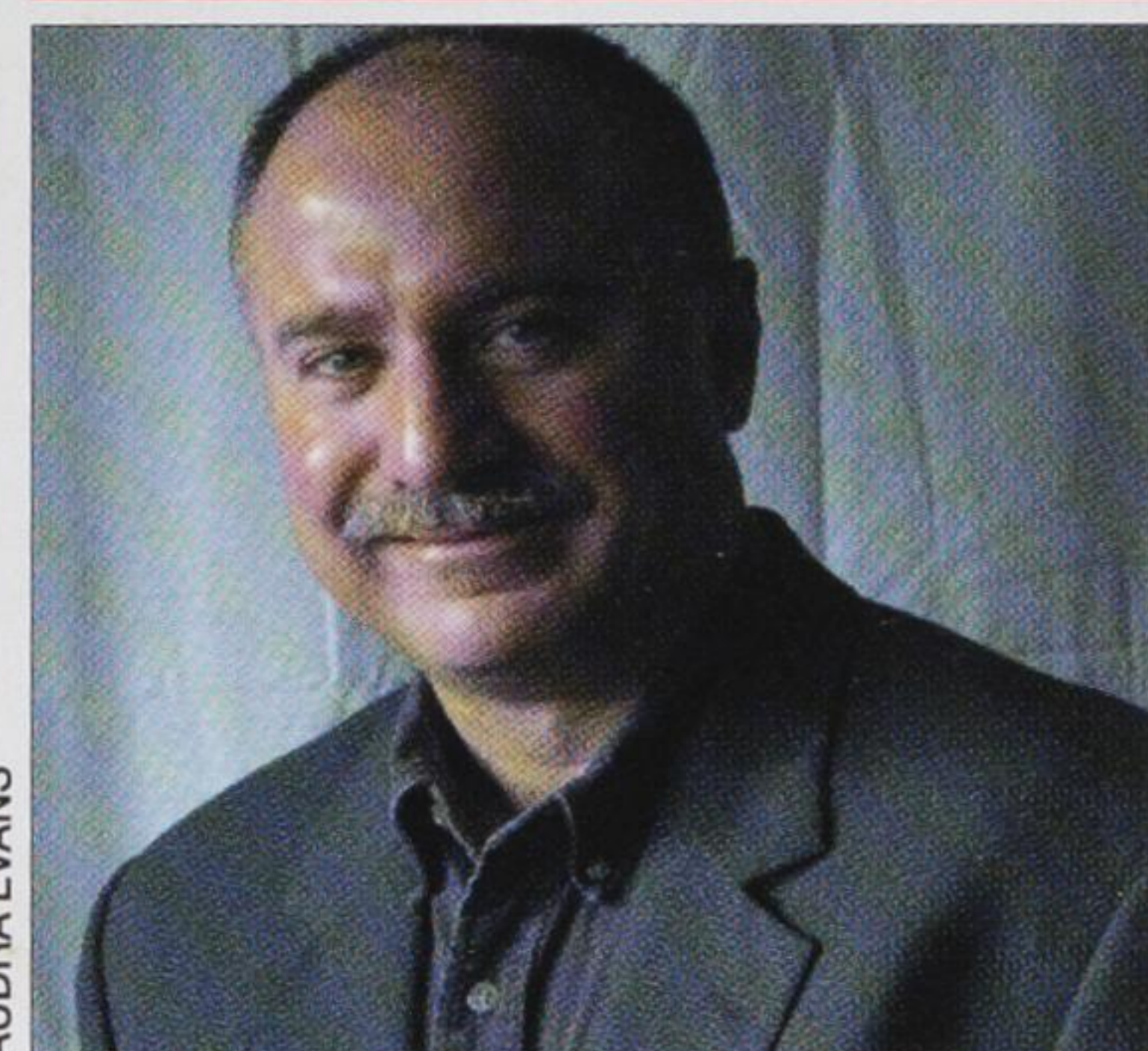
CMOS is a process technology that uses both NMOS and PMOS (negative- and positive-channel metal oxide semiconductor) devices. Improvements to NMOS device performance has resulted from using a strained active layer, but improving PMOS devices has proved more problematic.

According to IQE, although additional increases in strain should, in theory, improve PMOS device speed, in practice, material defects increase and hamper both

NMOS and PMOS performance.

IQE's alternative approach has been to develop a very low dislocation density strained silicon surface using what it describes as a "simple, cost-effective, single-stage epitaxial process".

Working with a silicon IC manufacturer, "significant performance enhancements" to p-type and n-type devices have been demonstrated with strained silicon deposited on a SiGe buffer layer with a 17% germanium content, says IQE. Increases in the mobility of carriers in PMOS and NMOS devices were 15 and 100%, respectively, compared with standard silicon.



AUDRA EVANS

Keith Evans, former vice-president of business development and chief marketing officer at Crystal IS, has become president and CEO of GaN-substrate supplier Kyma Technologies. Evans' new firm uses a fast-growth vapor-phase process to fabricate GaN substrates (*Compound Semiconductor* July 2004 p20).

In brief

● **Aixtron** has sold a Thomas Swan GaN Showerhead MOCVD production tool to Advanced Epitaxy Technology (AET) of Taiwan.

AET will use the reactor with the proprietary Close Coupled Showerhead (CCS) technology for high-volume production of GaN-based ultrahigh brightness LEDs. The German firm has also received an order for a Thomas Swan CCS 7 × 3 inch MOCVD system to be installed at Northrop Grumman's facility in Linthicum, MD, for research and development, and the production of

AlGaIn/GaN devices.

● France-based **Riber** has installed two MBE32P systems in Japanese research laboratories. The machine delivered to the Nanoscience Research Team at RIKEN, Wako, Saitama Prefecture, will be used to investigate nanometer-scale, high-tech devices. Another reactor has been installed at the Nanotechnology Research Center of Hokkaido University, Sapporo, where it will produce quantum dot heterostructures for electron-spin-based computing.

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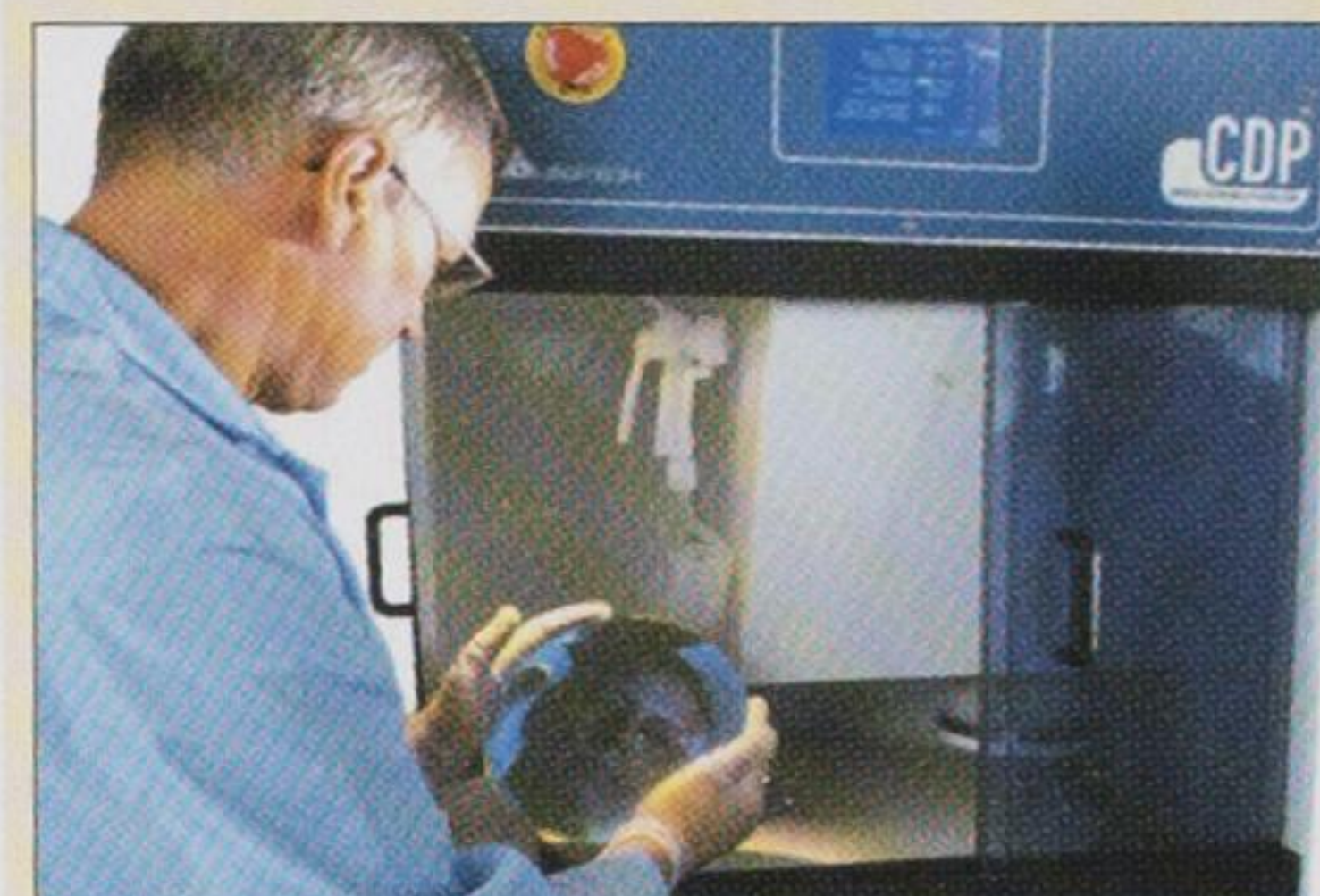
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VCSEL aids fiber transfer of RF signal

VCSELs could prove to be key components in future cellular networks. Although the devices are widely used today in fiber-optic digital communication, a Swedish team has now transmitted analog signals along fiber, in what could be a key technology for the deployment of next-generation wireless networks (*New J. Phys.* 6 176).

The researchers from Chalmers University of Technology, Gothenburg, used a VCSEL to transmit radio-frequency (RF) signals along a 500 m fiber-optic link. They say that the results of their experiment satisfied the requirements for mobile communication systems and wireless local-area networks (WLANs).

The team has also carried out successful trials with Ericsson, using the VCSEL to propagate wideband code-division multiple-access signals for 3G systems along optical fiber.

The analog data are generated by driving a VCSEL with an RF signal. Modulation of the optical intensity follows the RF-signal ampli-

tude, so that the signal received by a photodetector bears the hallmark of the original RF signal.

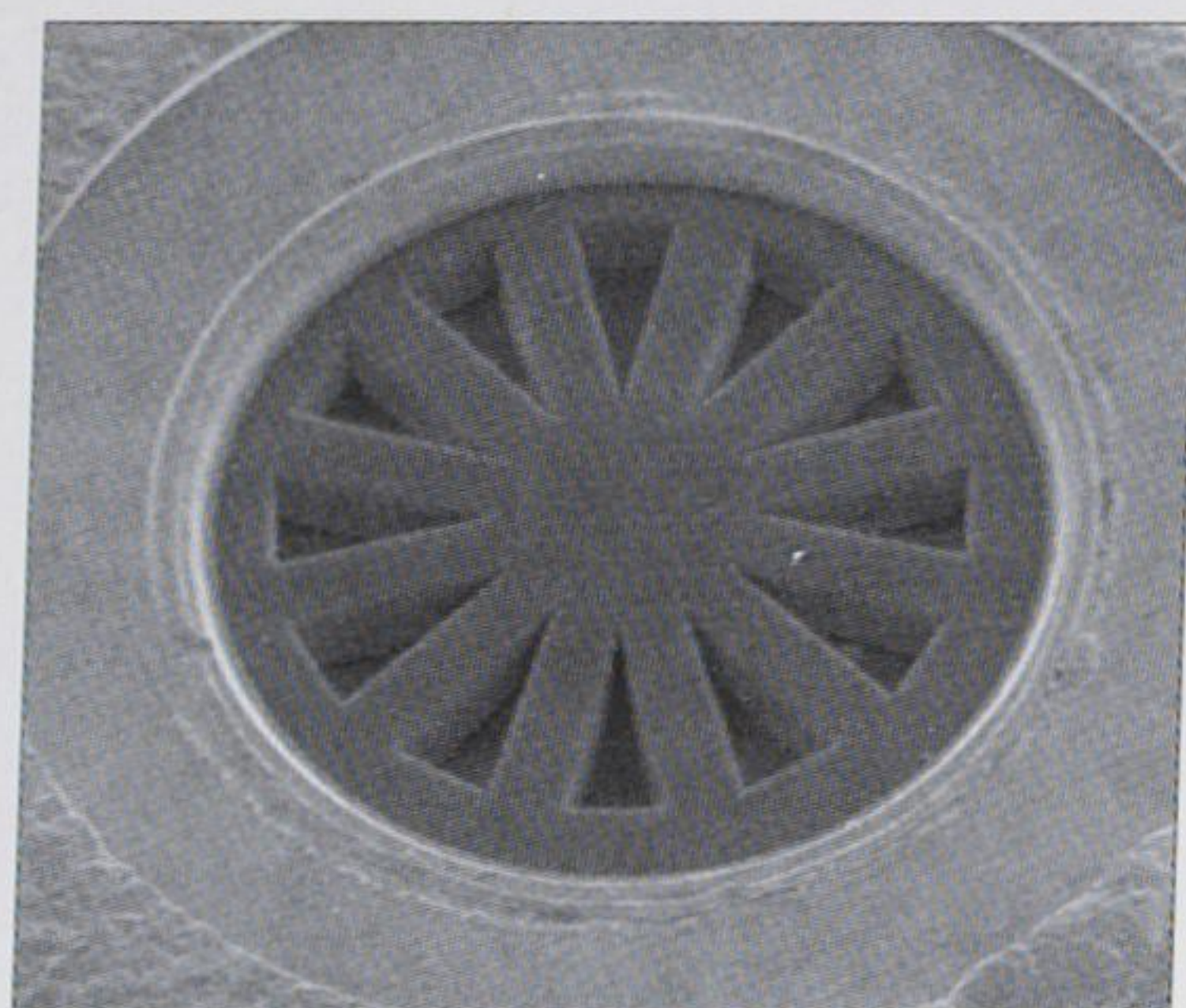
The optical signals are coupled to a multimode fiber, because this is significantly easier to align than a singlemode fiber. Anders Larsson, a member of the Chalmers team, believes that multimode fiber, in combination with the directly modulated VCSEL, should result in low-cost solutions for network infrastructure.

"We have targeted cost-sensitive applications like distributed-antenna systems within buildings in mobile-communication systems and WLANs," added Larsson.

The 850 nm VCSEL was engineered to exhibit performance characteristics appropriate for analog links. According to Larsson, the high-power singlemode VCSEL has a relatively low resistance, lower noise, and better linearity than multimode devices, an important consideration for analog applications, since nonlinearities produce distortion.

Triangular holes increase singlemode output power in lasers

Researchers in Japan have demonstrated an alternative approach to fabricating singlemode, high-power VCSELs, by using larger apertures containing triangular-shaped holes.



Triangular holes, made using electron-beam lithography and etching, allow large apertures and singlemode emission.

The partnership between Sony and Yokohama National University developed 850 nm triangular-holed-structure VCSELs with 15 μm diameter apertures that emit up to 7 mW (*Appl. Phys. Lett.* 85 5161). Although this singlemode power is similar to that of other devices using apertures of 5–8 μm , the Japanese team claims that lasers featuring larger apertures could produce 10 mW while maintaining singlemode output.

Comparable VCSELs fabricated with apertures of this increased diameter would instead generate multimode emission.

The team used electron-beam lithography and reactive-ion etching to define between four and 12 triangular holes with height, width and depth dimensions of 5, 1.25–3.75 and about 3 μm , respectively, on top of the VCSEL structure (see figure, left). One of the devices, containing nine 4 μm -deep triangular holes, emitted 2 mW with a sidemode suppression ratio (SMSR) of between 45 and 50 dB.

A second device containing eight, 2 μm -deep triangular holes produced an output power of 7 mW and an SMSR of 40 dB, although its emission profile was more complex: "The emission is not a multimode pattern or a higher-order singlemode, but is a deformed fundamental mode whose bright spots coherently oscillate by the same phase," commented the team.

According to one of the researchers involved, Akio Furukawa, applications that require high-power singlemode VCSELs include sensing, laser printing and mid-range passive optical networks.

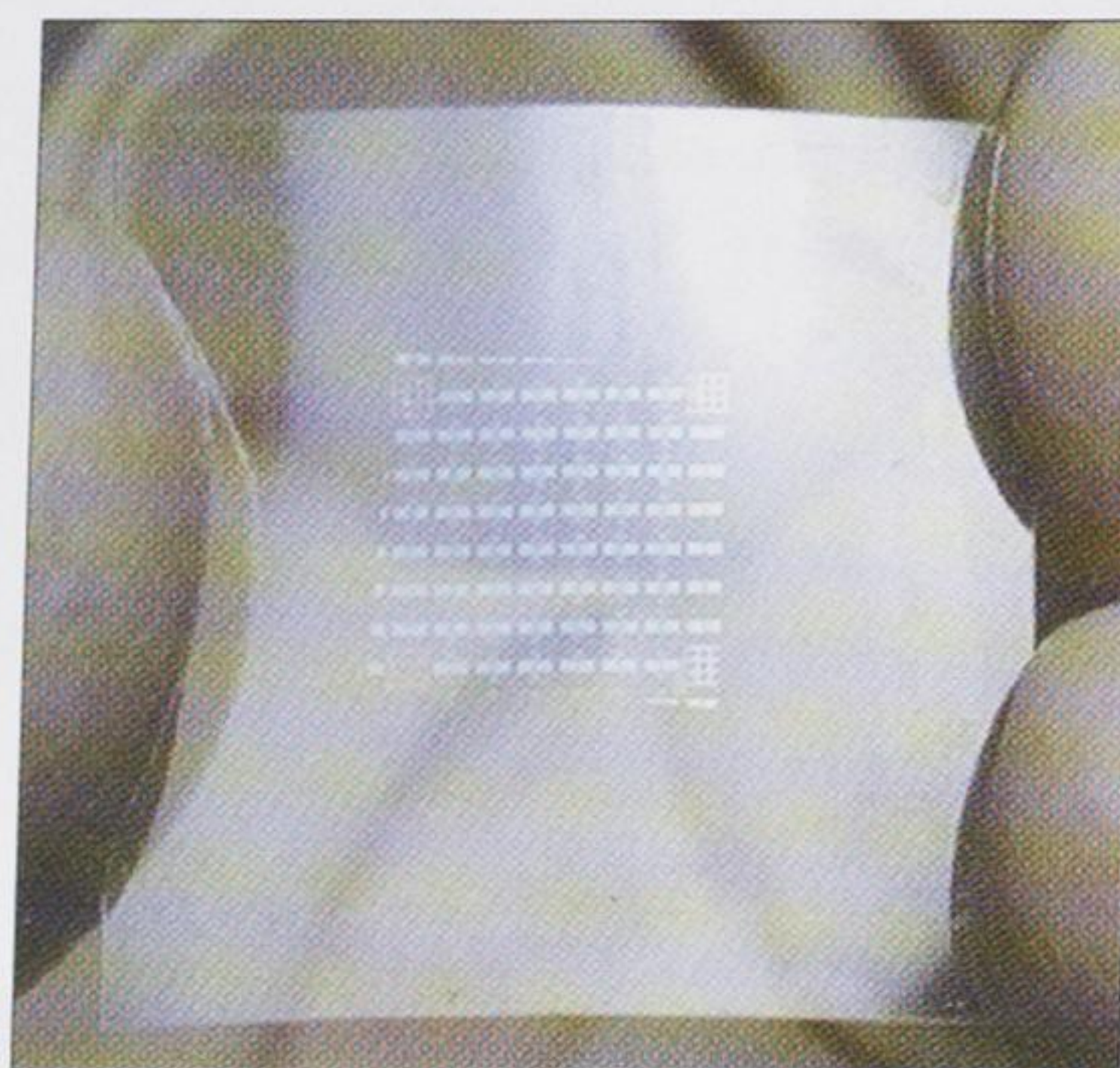
InGaZnO shows promise as a transparent transistor

Researchers at the Tokyo Institute of Technology have fabricated transparent flexible thin-film transistors (TFTs) containing an amorphous indium gallium zinc oxide (InGaZnO) active channel (*Nature* 432 488).

TFTs are fundamental building blocks for state-of-the-art microelectronics, such as flat-panel displays. The devices, when combined with transparent circuit technology, could be used to integrate display functions into car windscreens.

InGaZnO is not the first material to be investigated for flexible electronic applications, but its field-effect mobility of $5.6 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ is significantly higher than today's well-established alternatives: hydrogenated amorphous silicon (about $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) and pentacene ($1.5\text{--}2.7 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$). InGaZnO is also optically transparent between 390 and 3200 nm, and so, unlike silicon-based devices, it is suitable for fabrication of transparent circuits.

The Japanese team formed the active InGaZnO layer by pulsed laser deposition, but they believe that a sputtering or MOCVD method could be used for large-area uniform deposition and mass production.



InGaZnO-based transistors deposited on flexible substrates offer speed and versatility.

The top-gate flexible transparent TFTs contained an InGaZnO *n*-channel active layer deposited on a 200 μm thick polyethylene terephthalate substrate. Standard photolithography and lift-off techniques defined the source, gate and drain contacts.

The behavior of the TFT device concurred with transistor theory. The devices were then tested when flexed, by bending the TFT sheet into a curve with a radius of 30 mm. According to the researchers, the performance

of the transistor was "almost unaffected by bending, although a slight decrease is observed in the saturation current".

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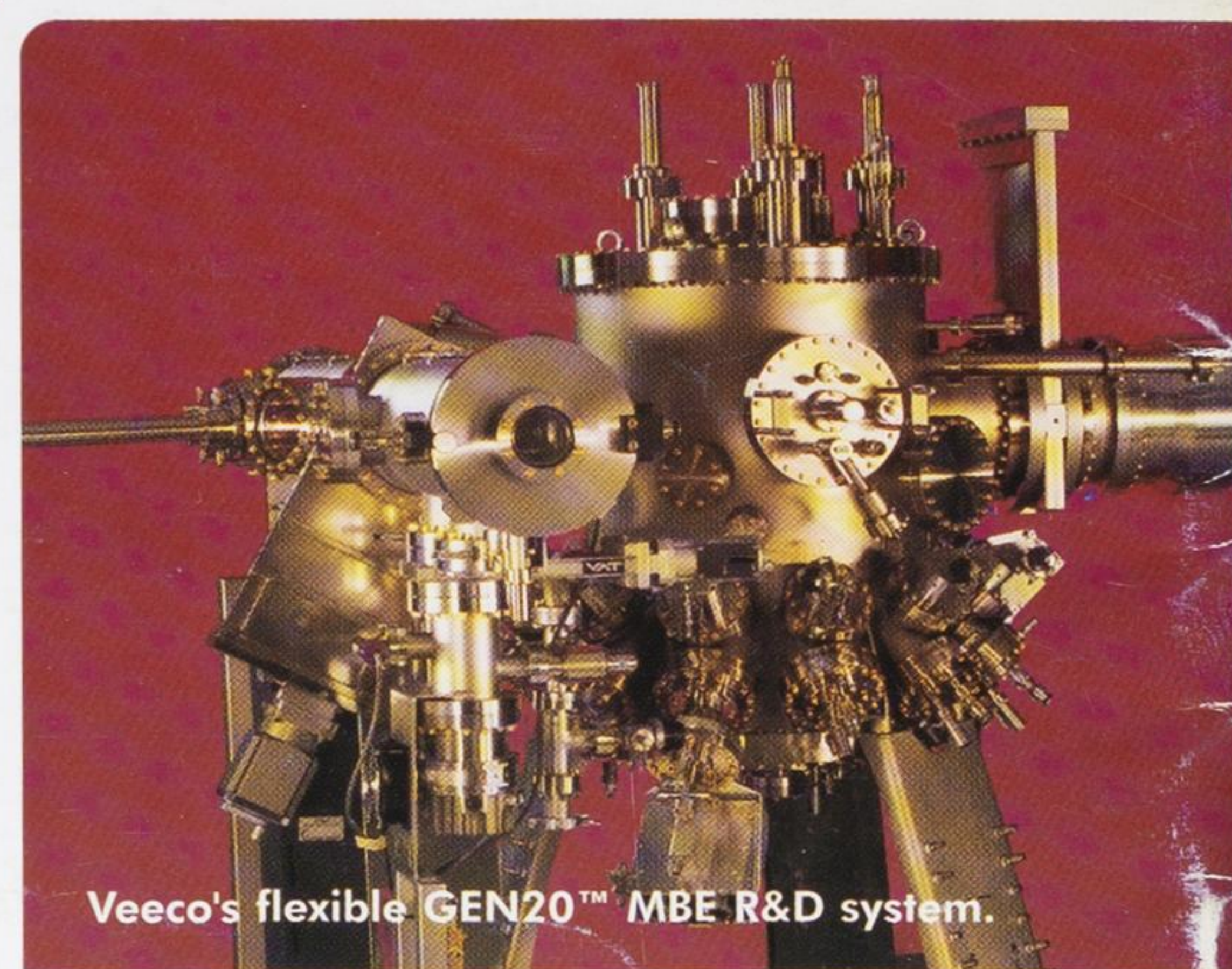
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