

COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

September 2005 Volume 11 Number 8



ANNIVERSARY ISSUE

**A decade of compound
semiconductor coverage**

**A look back at the big stories from 1995 to 2005
The technologies that are set to shape the next decade**

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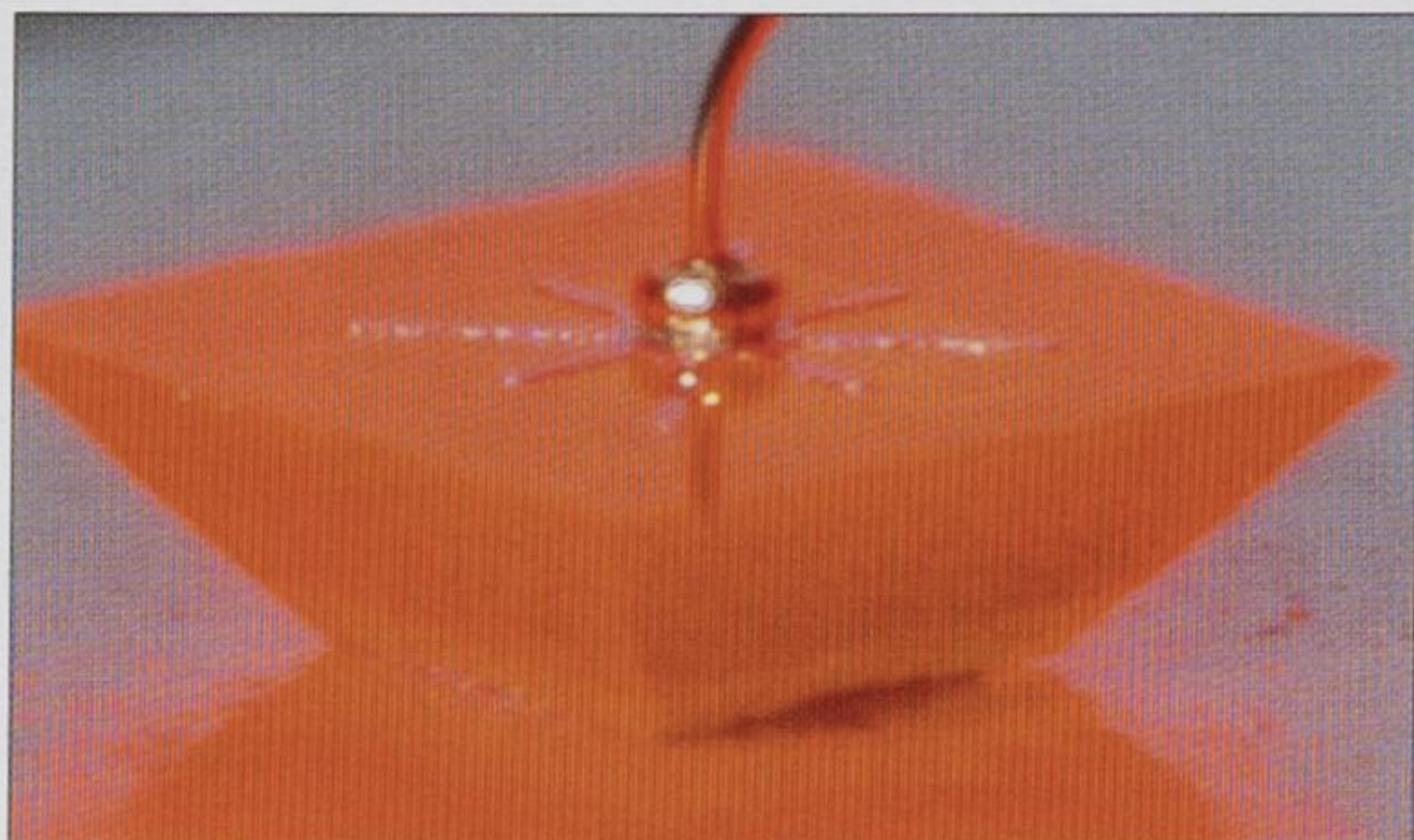
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COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

SEPTEMBER 2005 VOLUME 11 NUMBER 8

PHILIPS LIGHTING



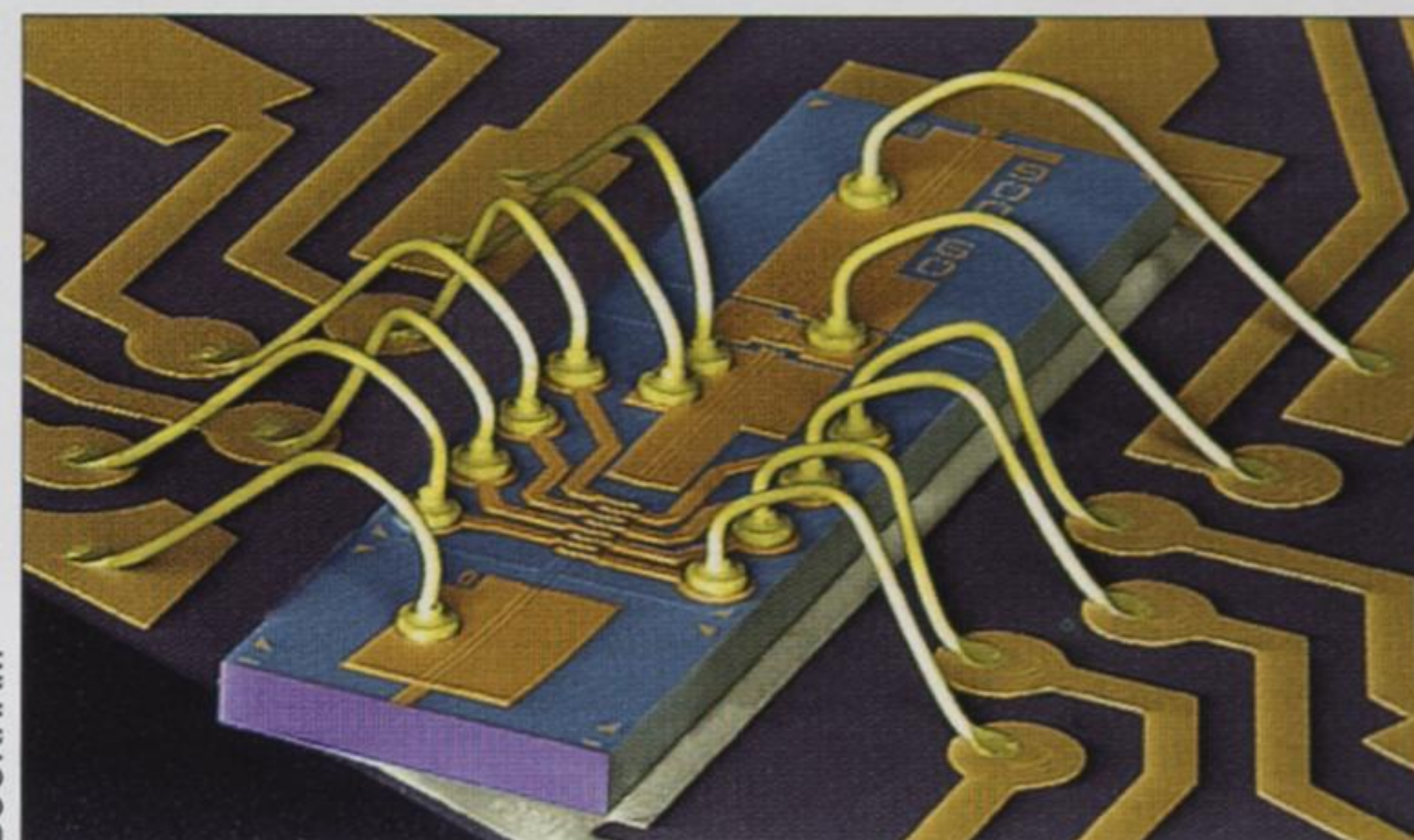
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BOOKHAM



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High-speed MMICs with lower turn-on voltages can be built by switching GaAs-HBTs for GAIN-HBTs with a dilute nitride base, say Matt Micci and Roger Welser. The advancement could allow mobile phone designers to build more reliable handsets operating at higher data-rates.
- 29** **Infinera moves in for the long haul as fiber recovers**
At the height of the photonics boom, Dave Welch helped orchestrate the merger of SDL and JDS Uniphase. Now chief technology officer at start-up Infinera, he's led the development of a digital optical network system based on massively integrated InP chips. Michael Hatcher hears about Infinera's recipe for success as growth returns to the optical telecoms business.

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- 33** **Bookham targets integration sweet spot for metro network**
A tunable laser and a broadband modulator provide the best option for next-generation metro networks, according to Bookham. This combination can ease the transition from fixed-wavelength components to broadband monolithic transmitters. Richard Stevenson reports.



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On the cover: It's 10 years since *Compound Semiconductor* magazine launched. The "10" on our cover features detail from a GaN transistor wafer made by TriQuint Semiconductor.

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Editorial

Ten years on...



Ten years on from the first edition of *Compound Semiconductor* and the more things change, the more some other things just seem to stay the same. In issue one of this magazine, the focus was on short-wavelength light emitters. Emcore had just demonstrated that GaN-based blue devices could be made in one of its multi-wafer MOCVD tools, Nichia was ramping up LED production in Japan and Shuji Nakamura would shortly astonish everybody with a GaN-on-sapphire laser.

Since then, we've moved on in leaps and bounds technologically, and some of the applications hinted at back in 1995 – high-density optical data storage, green LED traffic signals and solid-state white-light illumination – have become a reality. The LED industry is now worth \$5 billion annually and is consistently hitting the headlines. This month's big news is that Philips is to take full control of Lumileds, its joint venture with Agilent, while two of Taiwan's top chip suppliers are merging to create a company with formidable manufacturing capacity.

The general illumination market is the ultimate prize for these companies, and having a light-bulb producer controlling Lumileds ought to help that drive. But according to both the Philips CEO Gerard Kleisterlee and the latest reports, the days of the humble bulb are far from over. LEDs will have to deliver a significantly brighter output at a much lower cost per lumen before that happens. Perhaps our 15th anniversary will mark that occasion.

There is another, sadder, parallel between 1995 and 2005. Both years saw the MANTECH conference (back then known as the US Conference on GaAs Manufacturing Technology) held in the incomparable surroundings of New Orleans.

As I write, a helpless "Big Easy" is drowning in floodwaters after taking a direct hit from angry Hurricane Katrina. The city will take years to recover. And while most of the compound semiconductor industry in the US can be found on the East and West coasts, some of our community is based near the Gulf of Mexico – companies such as the Mississippi State University spin-out SemiSouth. We wish them well.

Michael Hatcher

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Philips acquires Lumileds as Agilent cashes in on semiconductor group

By Michael Hatcher

Agilent Technologies, one of the compound semiconductor industry's biggest players, is exiting the chip manufacturing business.

The lighting and consumer electronics giant Philips has bought out the company's stake in Lumileds in a deal worth around \$1 billion (see box), and the remainder of the Silicon Valley company's chip operation will be snapped up by two private equity firms.

Kohlberg Kravis Roberts (KKR) and Silver Lake Partners will take control of Agilent's semiconductor products group (SPG) after sealing the \$2.66 billion cash acquisition.

That cash will be returned to Agilent investors through a \$4 billion share repurchase program and Agilent will become a "pure-play" measurement company.

Speculation has surrounded Agilent's SPG for months, with hints that the group would be auctioned off, enabling Agilent to benefit from the higher margins it makes in the test and measurement and life science sectors. CEO Bill Sullivan said of the sale: "We believe that the SPG can best realize its full potential as an independent company."

"This is good news for our customers and employees," said the SPG's CEO, Dick Chang, who will continue in his role despite the switch.

Agilent is probably best known in the III-V community for the expertise in LEDs and fiber-optic components that it inherited from its parent company, Hewlett-Packard. However, it also manufactured E-mode PHEMTs at a 6 inch GaAs wafer fab in Fort Collins, CO.

But Agilent has struggled against the incumbent GaAs power amplifier suppliers in the cell-phone handset sector, according to Stephen Entwistle from the market analyst firm Strategy Analytics. And the new owners of Agilent's GaAs business will not be able to rely on a parent company as a potential customer for these products, unlike Freescale, Motorola's semiconductor-manufacturing spin-out.

With the SPG supplying such a diverse set of products to a wide range of customers, the new owners face the challenge of generating a coherent strategy, said Entwistle. Both of the equity firms stress that they take a long-term view towards their investments, and a KKR spokesperson confirmed that the new owners have no current plans to sell portions

of the SPG, stating: "We intend to maximize growth for the company as a whole." Although the world-leading fiber-optic and LED divisions would prove highly attractive to prospective buyers, the GaAs division may not be so desirable in what is already a crowded marketplace.

The acquisition sees the SPG, which the new management team plans to rename before the expected close of the deal on October 31, become the world's largest privately held, independent semiconductor company. It represents the new owners' first direct foray into the III-V industry. As well as having a large stake in the retailer Toys R Us and bed spe-

cialist Sealy, KKR's investment portfolio includes several technology companies, such as Austria-based lighting specialist, Zumtobel. Zumtobel's subsidiary, TridonicActo, recently signed a joint-venture deal with LED maker Toyoda Gosei (see *Compound Semiconductor* May 2005 p9).

Silver Lake's investments are focused solely on technology companies, and it lists disk-drive maker Seagate in its portfolio.

In Agilent's most recent financial quarter, the SPG saw a 2% drop in revenue year-on-year to \$458 million. But orders were up 25% from last year, something that will undoubtedly please the new owners of the business.

Philips takes control of Lumileds

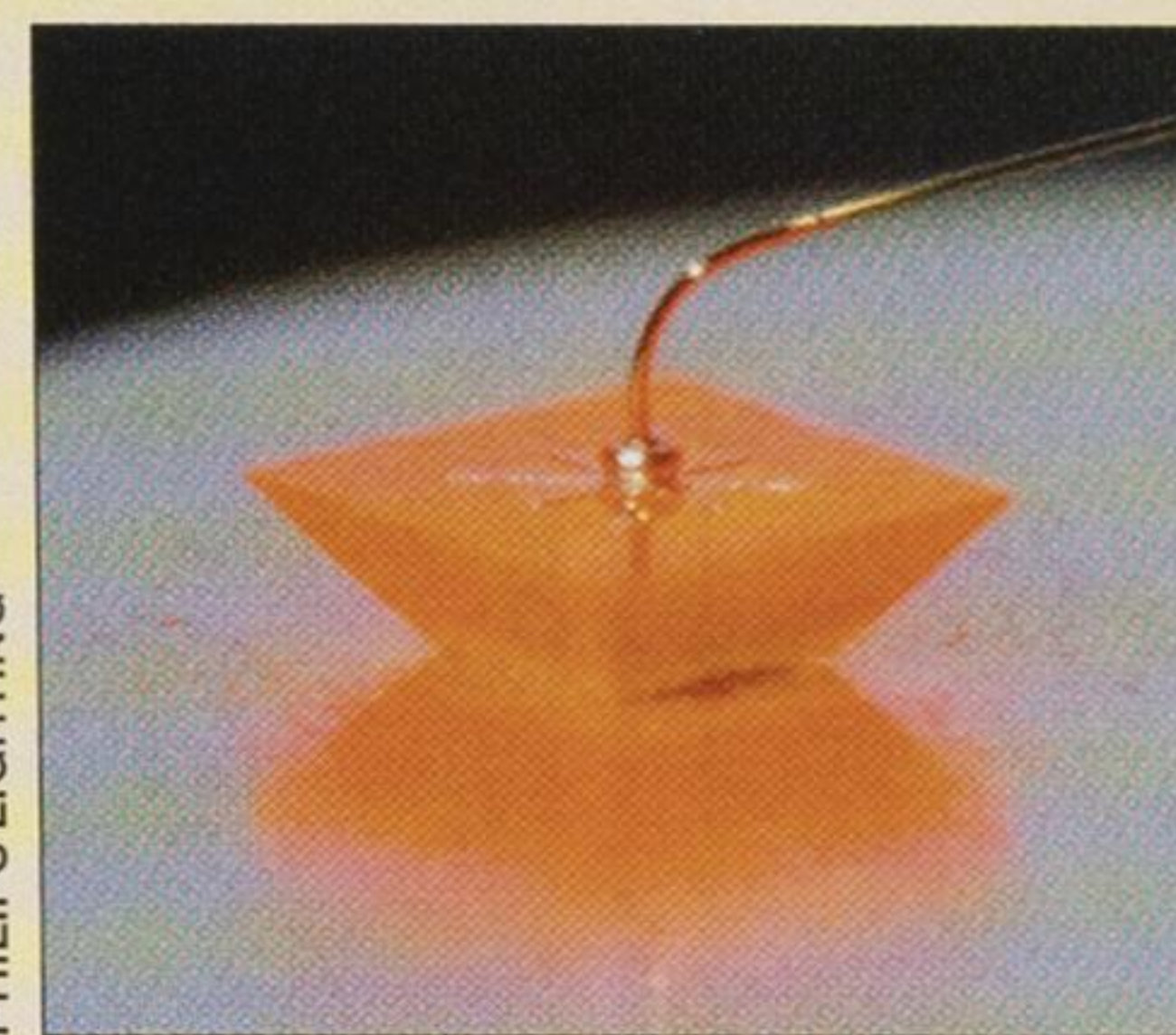
Lighting pioneer Royal Philips Electronics is to buy Agilent Technologies' 47% share in LED manufacturer Lumileds for €765 million (\$948 million) in cash.

Netherlands-based Philips will now own 96.5% of Lumileds, and the remaining 3.5% will be held by an employee trust company. Even so, Agilent says that Lumileds will remain a "strategic partner" and supplier to Agilent.

The change in ownership means that two of the world's lighting industry powerhouses, Philips and Germany-based Osram, now have controlling shares in LED chip-manufacturing subsidiaries. This appears to shift the center of gravity of the solid-state lighting industry towards Europe.

Lumileds, which was founded in 1999 as a joint venture, makes LED chips, packaged LEDs, and is best known for its high-power Luxeon light sources.

It is this high-power



PHILIPS LIGHTING

Lumileds is well known for its AlInGaP-based red and orange HB-LEDs. Philips aims to capitalize on consumer applications of the technology, such as photonic textiles.

segment for lighting applications that Philips is primarily interested in. "This extends our involvement across the LED value chain," said Gerard Kleisterlee, the president and CEO of Philips. "[We now] have the full value chain under our control."

Theo van Deursen, the CEO of Philips Lighting, said that acquiring Lumileds was of "huge strategic importance" to the Dutch company, and he extolled the virtues of LED lighting for tempting shoppers and in medical applications.

But it is the general



illumination market that is critical for Philips. "We see this as a long-term growth market and we are going to invest in innovation," said Kleisterlee.

Lumileds' history is rooted in Hewlett-Packard (HP), where it began life as HP's optoelectronics division. That division became part of Agilent when HP split into two businesses in 1999.

Now headquartered in San Jose, CA, Lumileds employs 1760 people globally. Company sales grew 28% in the fiscal year ending July 2005 to reach \$324 million, says Philips.

Ask the Expert



Rajiv K. Agarwal, Ph.D.

Lead Research Engineer

Q

I am experiencing high n type background doping levels in my MOCVD process when I grow GaAs and AlGaAs devices. I think the problem is in the arsine I use. I'm buying the best grade available. What can I do?

A

Higher background levels of n type dopants in GaAs and AlGaAs structures are caused by trace levels of germanium, silicon and sulfur species present in the arsine. As customer applications evolve, the purity requirements for arsine must as well. Until recently, background doping levels of $10^{15}/\text{cm}^3$ were considered acceptable in most applications. In general, most currently available high-purity grades of arsine can satisfy these requirements. However, process changes and demand for more sophisticated devices have resulted in the need for lower background doping levels. To address these more stringent requirements, Air Products is introducing Megabit™ III arsine, our purest grade available. Our new Megabit III arsine has significantly reduced the amounts of germanium, silicon and sulfur species. Testing done at an independent laboratory proved the effectiveness of Megabit III on thick gallium arsenide films, with excellent results. In all cases, the background doping level was $<<10^{14}/\text{cm}^3$. Our research has shown that Air Products' Megabit III arsine will perform more consistently and produce fewer defects in our customers' finished products.

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IBM and Infineon look to topple GaAs with SiGe

Silicon chip giants IBM and Infineon Technologies have targeted wireless applications that are traditionally served by GaAs technology with new processes based on SiGe.

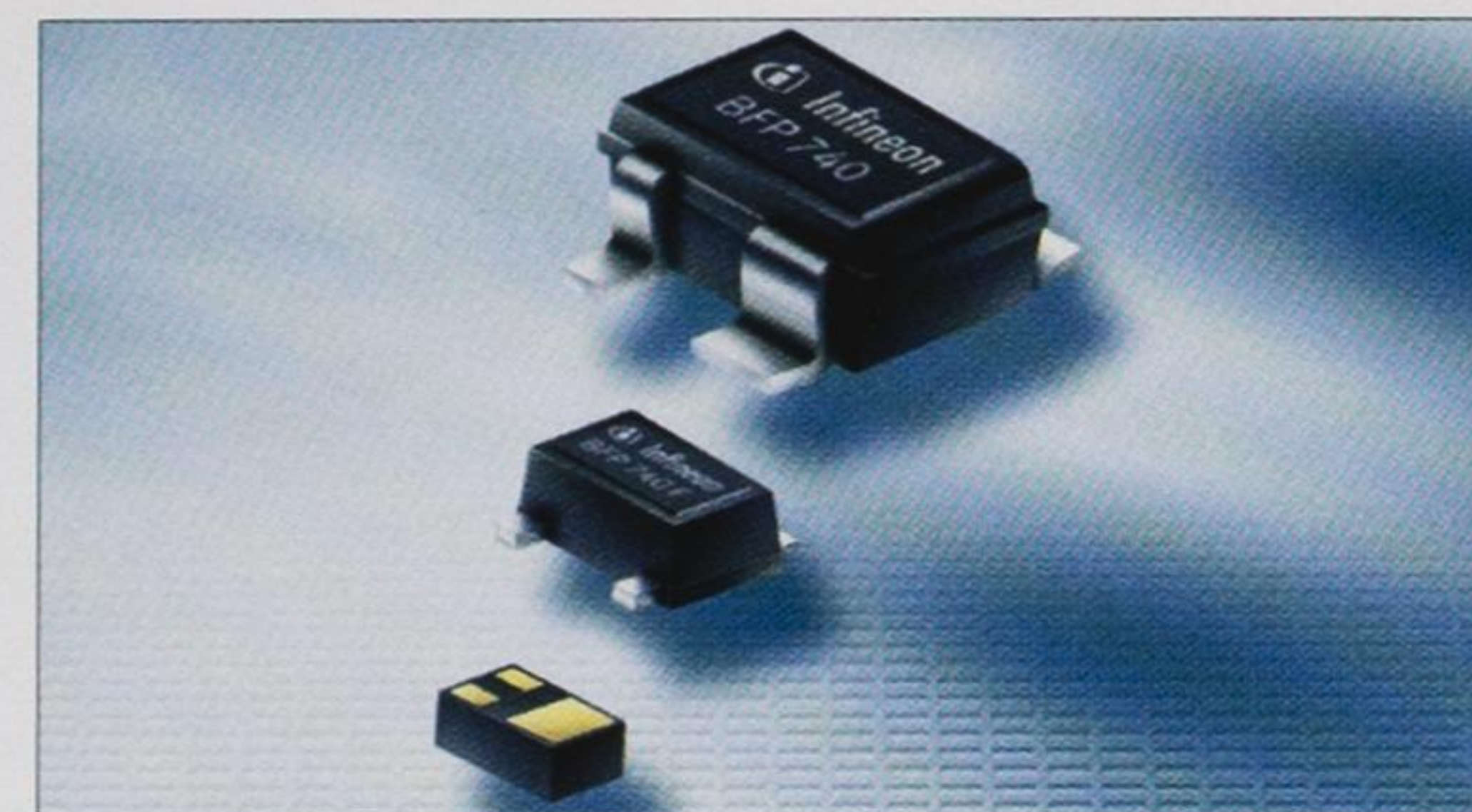
IBM has revealed a fourth-generation SiGe bipolar CMOS (BiCMOS) foundry process, which it says offers twice the performance of its previous incarnation.

And Infineon has unveiled its new SiGe:C technology, which it says yields high-gain, low-noise HBTs for high-frequency applications.

Both companies have identified applications in wireless LAN and ultra-wideband communications as key markets for the new processes. IBM has also highlighted an opportunity in short- and long-range automotive radar.

"The fourth generation of SiGe will continue to enable wireless connectivity on an increasingly global scale," said Bernie Meyerson, IBM's chief technologist for its systems and technology group.

IBM's latest process, called 8HP, employs an advanced lithography stage. Devices are manufactured using 130 nm technology. This allows an emitter width of only 120 nm, which



Infineon hopes that its BFP740 series of SiGe:C bipolar transistors will displace GaAs devices in wireless applications.

gives the 8HP chips an f_t of 200 GHz. A low-cost variation of the technology, 8WL, operates with an f_t of 100 GHz.

Infineon is focusing on frequencies of 10 GHz and above. The key to its process technology is a very low base resistance, which produces transistors with what it claims to be the industry's lowest noise figures for silicon discretes. The BFP470 HBT series of devices also features a new method of reducing parasitic ground inductance that improves gain at high frequencies.

Letters

Sir,

Your article "Foundry model could be key to InP industry future" (August p17) points out that the OIDA is looking for a viable foundry model and it seems to be willing to put a lot of resources into finding a solution. If companies placed a high emphasis on CAD/CAM standards they could use existing technology and simply provide a factory interface where the processes and models are licensed as IP. This creates two recurring revenue streams at very little cost. The key (from my own frustrations) is to keep as few engineers involved as possible.

A small unit of about one or two technicians, a database administrator, a portal developer and a sales manager could create a customer-driven design flow. Simply put, it takes longer to create an engineer than to create a process. A highly promoted simple company interface makes the factory more accessible to a wider group of design houses. From there,

the OIDA could put resources behind new product development and promoting small, "fabless" design houses.

The technicians would have to be very knowledgeable with the recommended uses of design and simulation software. Their role would be to make the engineers/designers twice as productive. They would also benefit their company by providing free technical support to customers, and this support helps to build a foundation of standards within the industry. A company's reputation would be built on quality products, short cycle time and high-profile technology "evangelists". The better the technicians, the better the company image.

I'd like to be one of the technicians myself.
Bill Thayer, Dallas, Texas

We welcome feedback on any of the articles published in *Compound Semiconductor*. To have your say, e-mail comments to: michael.hatcher@iop.org.

3G phones present opportunity for rivals to gain on GaAs market leaders

RF Micro Devices (RFMD) and Skyworks Solutions are pulling away from rival companies in the GaAs device market, according to a recent report.

A market review by Strategy Analytics suggests that the two front-runners each have a market share of around 28%, with fellow US chip manufacturer TriQuint providing the main competition.

Despite the strong growth of the cell-phone handset market in 2004, this translated into only modest growth at the GaAs device level. Overall, the GaAs market was worth some \$2.4 billion in 2004, compared with

\$2.2 billion in 2002 and \$2.3 billion in 2003.

However, as Strategy Analytics' GaAs analyst Asif Anwar noted, the overall flatness of the sector masks some big fluctuations in the sale of different types of component.

For example, the market in GaAs MMICs grew by around 13% on the back of robust cell-phone sales, whereas the digital GaAs device market is now virtually non-existent. Sales of discrete GaAs devices also fell away in 2004, said Anwar.

In 2005 there may be a chance for second-tier GaAs MMIC vendors to take share from the two market leaders, as consumers in mature

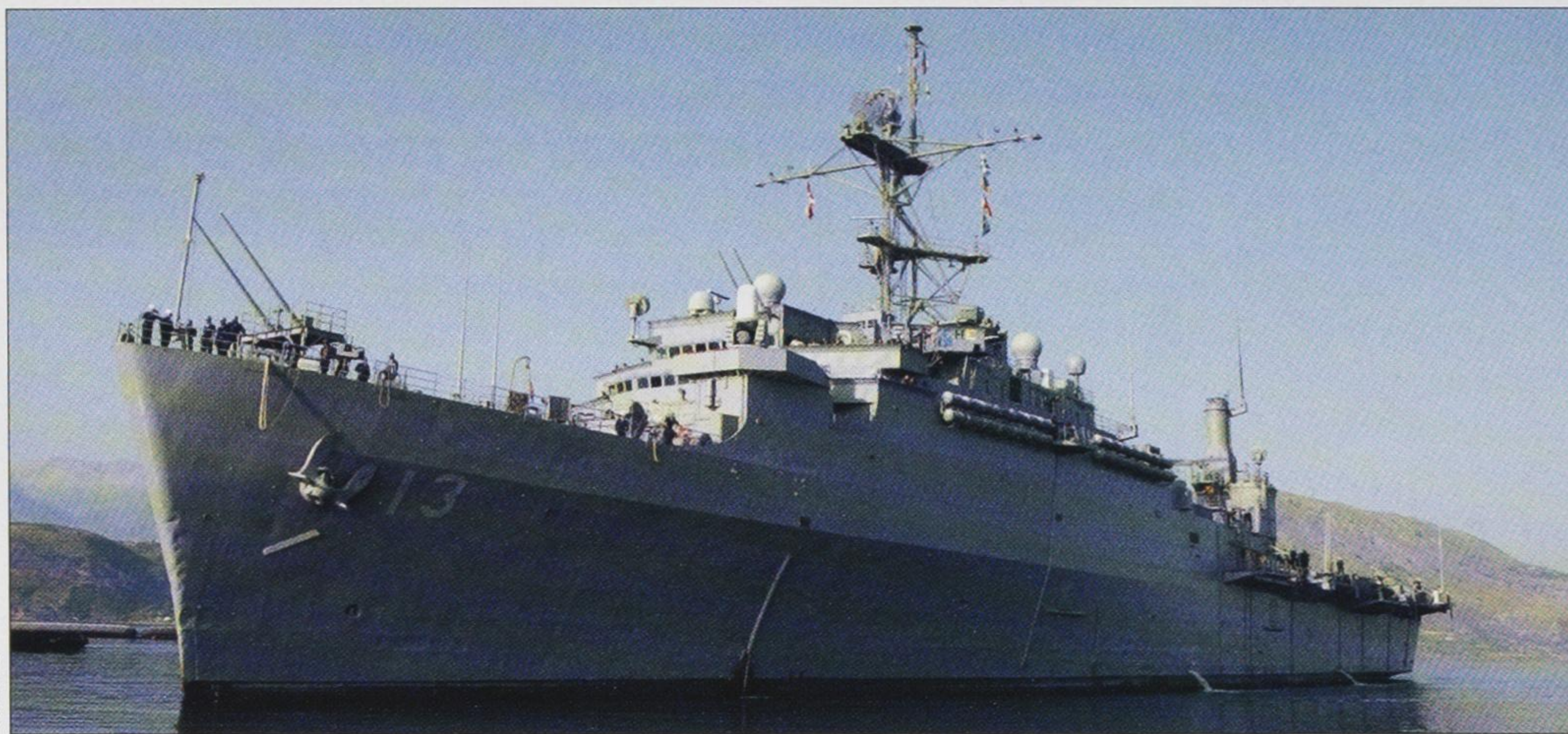
cell-phone markets make the switch to third-generation services.

"It is going to be a real struggle for other suppliers to catch up with [Skyworks and RFMD] in 2005, but opportunities moving ahead could still shake up GaAs device market share positioning," said Anwar.

According to the analyst, Skyworks managed to close the gap on RFMD in 2004 thanks to success in the Asia-Pacific zone, where it bundled sales of power amplifiers with other handset components.

Anwar added that Skyworks has done well in the wireless LAN sector.

GigaBeam uses InP for 10 Gb/s wireless



US NAVY

GigaBeam will design a millimeter-wave communication system for US Navy vessels.

High-speed wireless communications provider GigaBeam Corporation has acquired certain exclusive rights to use Vitesse's InP technology in its high-performance RF modules.

"The Vitesse technology and know-how being obtained under this new agreement will be incorporated into our next-generation 10 Gb/s products," said GigaBeam's CEO, Lou Slaughter.

The Herndon, VA, company is developing 10 Gb/s wireless products that conform to the 10Gig E and OC192 protocols. These products, which GigaBeam plans to launch in 2006, will replace its WiFiber 2 and WiFiber G Series modules that are based on either GaAs or silicon and operate at 1 Gb/s.

GigaBeam's WiFiber products employ the 71–76 GHz and 81–86 GHz radio bands,

which are part of the frequency spectrum that the US Federal Communications Commission has authorized for wireless point-to-point commercial use.

According to the company, the speed and reliability associated with its wireless technology is comparable to that delivered with terrestrial fiber, but it is much cheaper and quicker to deploy.

GigaBeam has also teamed up with US-based Epsilon Lambda Electronics to design and support a millimeter-wave communication system for the US Navy. This system will initially provide communication within ships.

"This initiative further underscores the importance of millimeter-wave technology in advancing military and government communications," said Slaughter.

Patents strengthen Anadigics' IC design

RF chip maker Anadigics has been granted five US patents that relate to the design and development of radio-frequency ICs.

The US-based company says that these patents strengthen its technological advantages across its wireless and broadband product families.

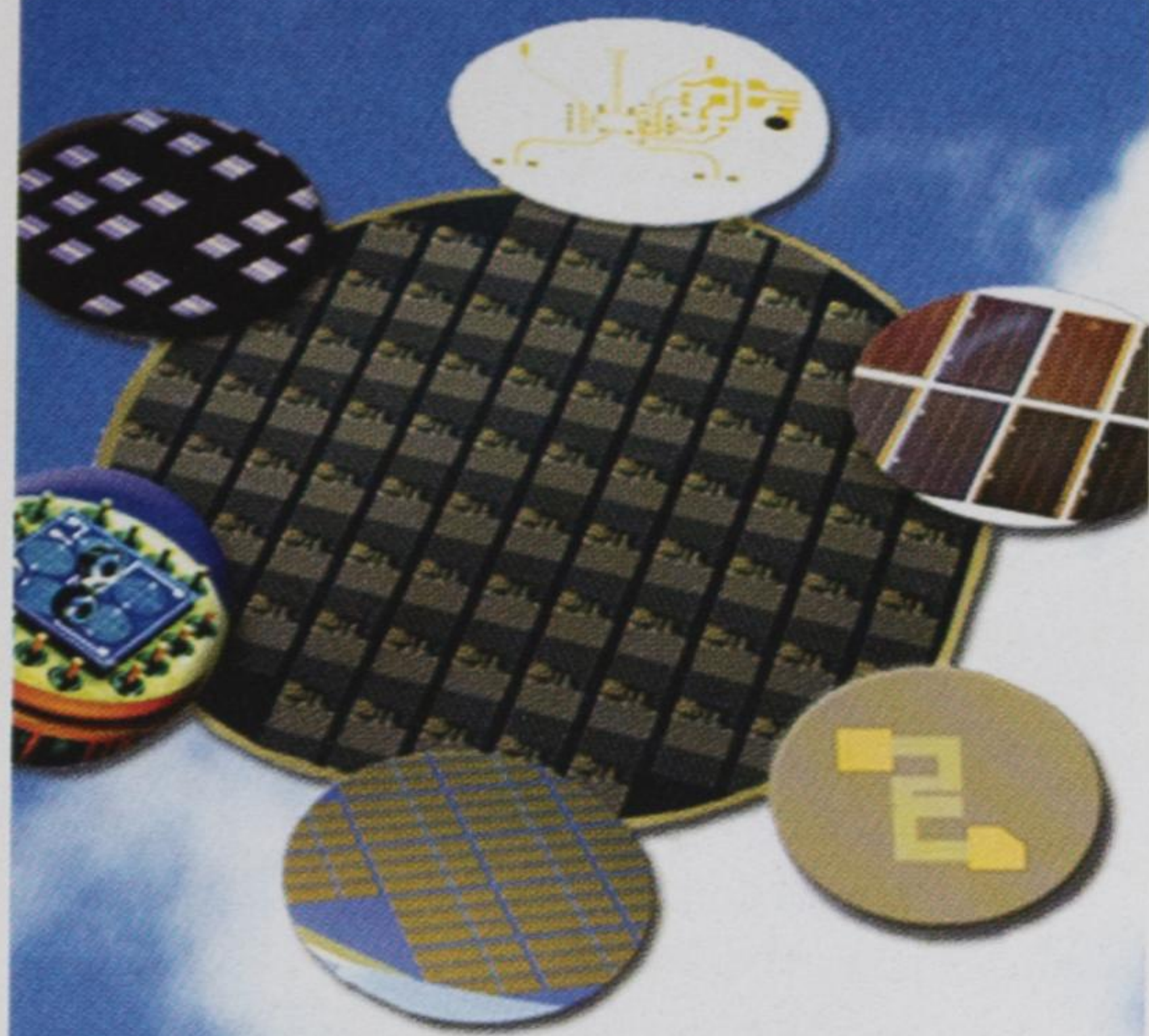
Patent 6,806,767 gives details of a load-switching circuit for linear power amplifier (PA) applications that improves efficiency at different output power modes. The greater efficiencies are produced by adjusting the output load according to the power requirements, which results in dynamic mode switching, says Anadigics.

A method for producing a compact wireless PA that delivers a higher level of performance through a novel circuit layout is described in patent 6,856,004. The amplifier consists of transistors on a substrate with a via hole, designed in a way that reduces the device's size and improves its performance.

Patent 6,853,526 describes a method for protecting voltage transients in cable-TV line amplifier ICs without distorting signals, modulating the power lines or damaging sensitive electronic components.

The other two patents, 6,842,075 and 6,882,227, describe modifications to the bias circuitry that either enable ICs to operate at lower voltages, thereby consuming less power, or improve the linearity of wireless local-area-network PAs.

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Hittite Microwave shares launched on the NASDAQ

Fabless RFIC designer Hittite Microwave has completed on its initial public offering (IPO) of common stock at \$17 per share.

The company's shares, which use the symbol "HITT", started trading on the NASDAQ on 22 July. The Chelmsford, MA, company offered 2.7 million shares for sale, while stockholders were offered 1.8 million shares. An additional 675,000 shares were to be offered if the IPO was oversubscribed.

Hittite designs and develops ICs, modules and subsystems that use a range of GaAs and silicon-based semiconductor processes.

Its chips are manufactured at several foundries, including Global Communications Semiconductors, TriQuint Semiconductor and M/A-COM in the US, United Monolithic Semiconductors in Europe, and Taiwan-based

WIN Semiconductor.

Hittite will not use the proceeds from the IPO to build a wafer fab. "We will continue to focus on investing in our core design and engineering competencies, while outsourcing the capital-intensive requirements of semiconductor fabrication," said the company.

According to its prospectus, Hittite's revenue has increased sequentially over the past 13 years, during which time it has remained consistently profitable.

In the second fiscal quarter of this year, Hittite posted revenue of \$18.9 million at a gross margin of 66%, and recorded a net profit of \$4.2 million – equivalent to \$0.16 per share.

The company expects third-quarter revenue to be between \$19.5 million and \$20.5 million, and profit to be at least \$4.2 million.

Filtronic ramps GaAs output to meet order

Filtronic, the wireless subsystem supplier that has its own GaAs fabrication facility in Newton Aycliffe, UK, says that it has ramped up to round-the-clock, seven-day-week wafer production for the first time.

The company has recently taken on staff and upgraded its facilities to accommodate the demand for GaAs PHEMT switches from US company RF Micro Devices (RFMD).

"The semiconductor foundry at Newton Aycliffe has now established itself as a leading source for 6 inch GaAs wafers using the PHEMT process," said Filtronic's Group CEO, John Roulston.

Filtronic began supplying wafers to RFMD in volume in April. The PHEMT switches are used in the company's front-end modules for mobile handsets.

Suppliers of power amplifiers and front-end modules have identified the antenna switch

as a key area for expanding the GaAs content in cell phones. And with the mobile market expanding faster this year than was originally expected, the prospects for Filtronic look good.

In the company's financial year that ended on May 31, its Integrated Products group, which includes the PHEMT switch business, saw revenue increase by 26%.

Although the division is still making a hefty operating loss, it should get close to breakeven with a full year of wafer supplies to RFMD. Roulston also hopes to attract other volume customers. "The volume switch market, which has taken longer than forecast to mature, is showing strength," he said.

Overall, Filtronic posted a pre-tax profit of £5.5 million (\$9.7 million) on sales of £262.9 million in the fiscal year 2005, compared with a loss of £0.9 million on sales of £245.1 million last year.

Kopin's HBT business remains steady

HBT supplier Kopin posted a net profit of \$1.8 million in the quarter ended June 25, despite a slight dip in the sales of HBT wafers.

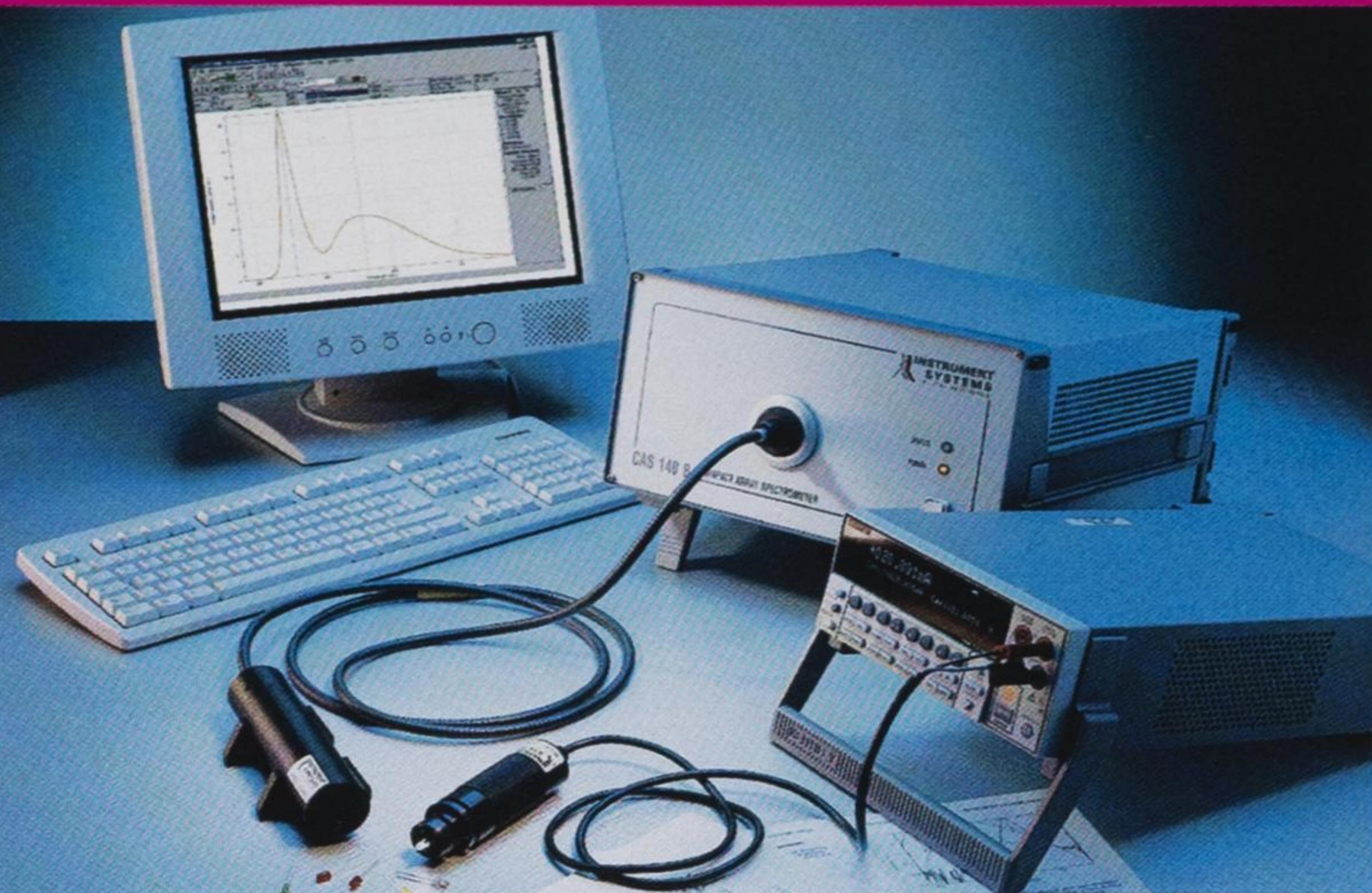
Revenue from the company's III-V business was \$9 million, down from \$10.4 million one year ago and \$9.4 million sequentially.

Thanks to the spin-out of its LED manufacturing operation to China and Taiwan,

which was announced this February, Kopin, of Taunton, MA, has reduced its costs massively compared with the same period last year.

This, coupled with strong sales of its microdisplay products, has seen the company turn the loss it posted in the same quarter last year into a profit – despite a slight drop in overall sales to \$20.5 million.

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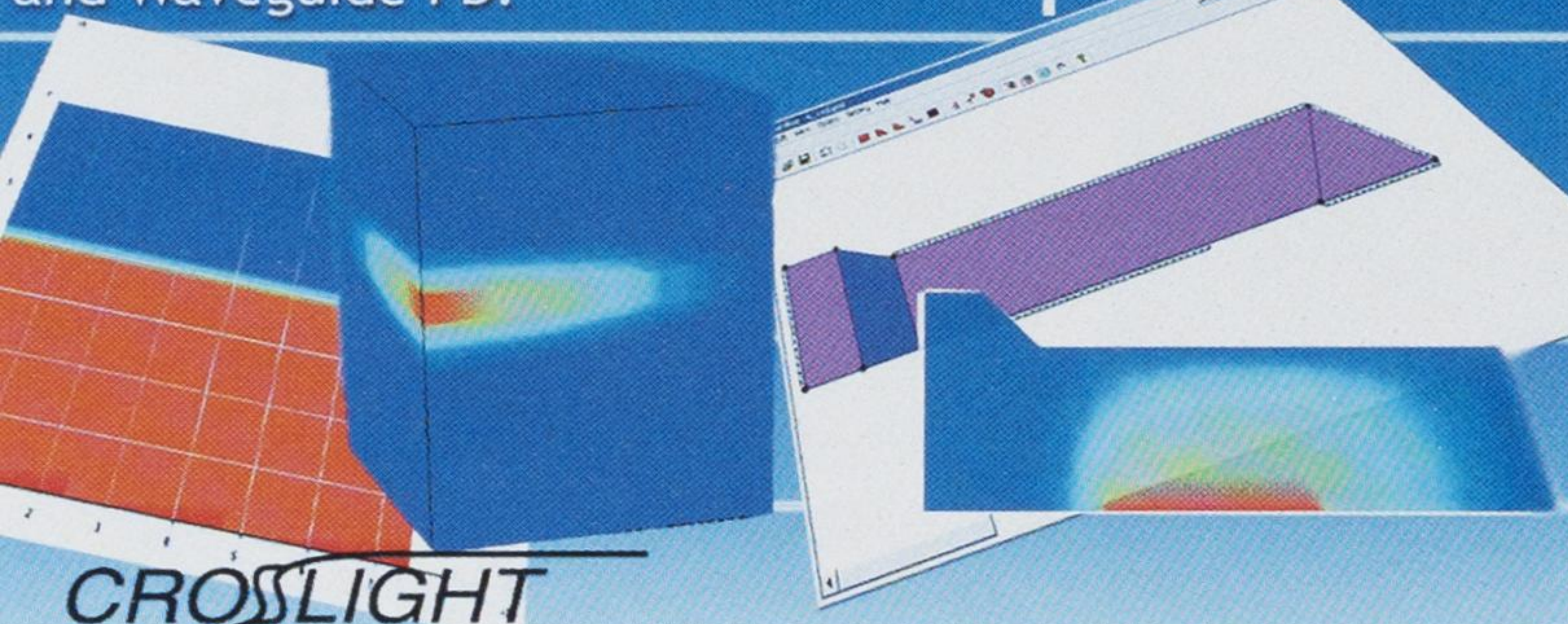
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Epistar and UEC form Taiwanese giant

Two of Taiwan's leading LED manufacturers, Epistar and United Epitaxy Company (UEC), are set to merge at the end of this year.

The new company, to be called Epistar, will be considerably larger than its rivals in the Taiwan LED industry in terms of operation and production scale. Epistar is already a leader in the high-luminance blue LED segment with its patented indium-tin oxide technology, and UEC has been Taiwan's largest

supplier of red-orange-yellow AlGaInP LEDs.

Epistar's president, B J Lee, told *Compound Semiconductor* that the new company will be able to deliver more than one billion AlGaInP chips per month. This, he said, would make it the largest AlGaInP chip manufacturer in the world. On the InGaN side, capacity will be 200 million chips per month, making it Taiwan's largest supplier.

Lee added that the combined resources

would still not be sufficient to meet its expansion plans for AlGaInP chip manufacturing. As a result, he does not expect any cuts in what will become a 1500-strong workforce.

The merger will take effect on December 30, 2005, when every 2.24 shares in UEC will be swapped for one Epistar share. After that, Epistar expects its annual revenue to reach NT\$12 billion (\$377 million), from a combined NT\$5.74 billion last year.

Record-busting Cree inks \$20 m USAF deal

Cree has capped another successful year with record sales of \$98.9 million in its fourth fiscal quarter. The figure, which represents 9% year-on-year growth, brought total sales for fiscal 2005 to \$389 million. This is a huge increase over the 2004 figure of \$307 million.

With improving profit margins, the LED and RF device maker also saw its net income shoot up 57% to \$91.1 million in the year ending June 26.

"On top of finishing the year with our best quarter ever, recent sales data suggests that Cree's revenue grew faster than our top competitors in both Japan and Taiwan during the year," said Chuck Swoboda, Cree's CEO.

The upward trend is set to continue, with 85% of Cree's sales target for the current quarter already booked and the company expecting to deliver revenue of between \$101 million and \$104 million.

Despite these positive predictions investors appeared to be disappointed with the outlook, and Cree's share price had sunk by almost 10% when trading re-opened after its earnings report. Since then, the company's stock has recovered some of that lost ground and has traded at around \$25.

Meanwhile, Cynthia Merrell, the company's chief financial officer, is to quit Cree after nearly nine years at the company. Merrell will remain until a successor takes office.

The Durham, NC, chip manufacturer has also won more funding from the US military to develop SiC-based MMICs for RF applications. A "technology investment agreement" with the US Air Force valued at \$19.7 million will help Cree to develop SiC MMICs for military radar and commercial applications. The project should be completed by March 2010.

iSuppli predicts slowdown in HB-LEDs

Market analyst company iSuppli is expecting growth in the LED lamp and chip market to slow significantly this year.

It says that the overall market will grow 11% this year to reach around \$5.2 billion. Growth of the HB-LED segment in particular, which iSuppli believes will be impacted by increasing competition and falling average prices, will slow to around 10% after three consecutive years of much stronger growth.

The analyst's report suggests that the uptake of HB-LEDs in new areas, such as large-screen LCD backlighting and automotive applications, will be slower than some people expect.

But better things are expected in the ultra-high-brightness sector, which is defined by iSuppli as LEDs that have a luminous flux of more than 20 lumens. Valued at only \$94 million in 2004, this market is expected to expand rapidly and be worth \$2.32 billion in 2010.

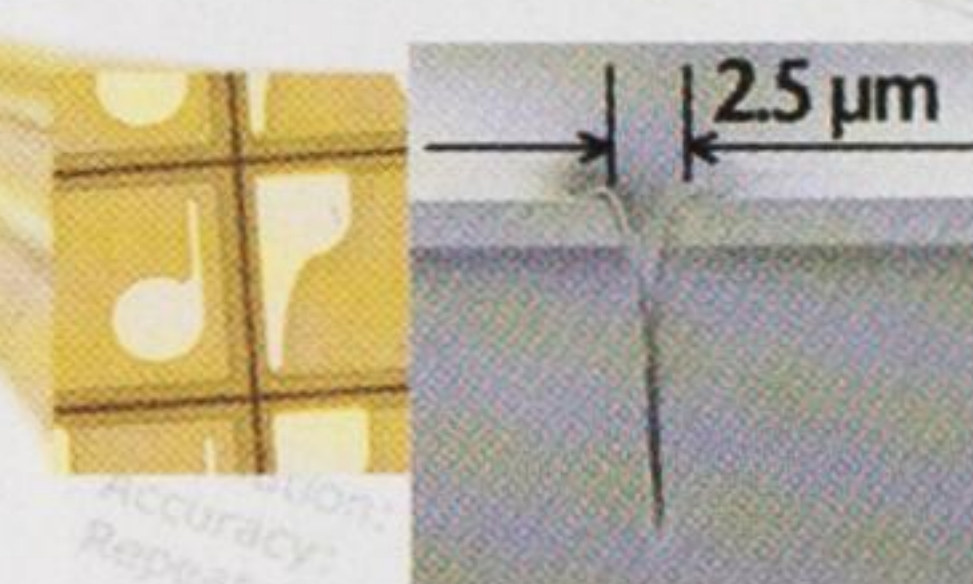
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Chip giant Vishay to buy CyOptics' Israel facility

Vishay Intertechnology, a Fortune 1000 company and one of the world's largest semiconductor manufacturers, is set to develop InP optoelectronic devices with the acquisition of a wafer fabrication facility built by CyOptics.

CyOptics built the facility, in Yokneam, Israel, before it acquired TriQuint's fab at Breinigsville, PA. InP- and GaAs-based optoelectronic devices have been developed and mass-produced at the facility in Israel.

Vishay Israel says that it has signed a letter of intent to buy the site, subject to the completion of due diligence, as well as approval from the Israeli authorities.

The acquisition of the fab appears to be a good deal for the company, judging by its comment that the purchase price "would not be material to Vishay".

Felix Zandman, the chief technical and

business development officer at Vishay, said: "With its state-of-the-art wafer fab, the CyOptics Israel design team will provide the technological strength to place our existing optoelectronics division at the forefront of the GaAs and InP technologies."

"The fab can be adapted rapidly to the needs of Vishay and is part of the ongoing effort to advance the company for future markets," he added. Vishay says that it will develop new products at the site.

Since CyOptics acquired the TriQuint optoelectronics division, it has been consolidating the production of InP-based lasers and detectors at the Breinigsville site.

CyOptics' president, Ed Coringrato, said: "We built a world-class fab in Israel. We are delighted that it will remain a strong asset for the Israel economy."

Emcore boosted by \$8 m solar panel order

Emcore is to make solar panels for a major satellite manufacturer under a contract valued at \$8 million. The contract win means that Emcore will resume production at its solar panel facility in City of Industry, CA, which had been earmarked for closure this year. (See *Compound Semiconductor* May p16.)

Emcore still plans to close the plant, albeit at a later date than expected, probably in 2007.

The satellite manufacturer needs a batch of solar panels for a new communications payload, which one analyst believes could be part of a military program. The satellite will be

launched into a geosynchronous orbit with the solar panels, which are expected to ship in late 2006. Emcore says that several more solar panels may be needed in 2007.

The cost to Emcore of closing its City of Industry plant will be reduced as a result of the new business, and will be spread over a longer period.

The photovoltaic sector constitutes 27.6% of Emcore's business. This latest order will add momentum to the company's growing top-line revenue and should be reflected in an improved gross margin.

Princeton Lightwave targets eye-safe laser

Princeton Lightwave (PLI) has been awarded second-year funding from the US Department of Energy (DoE) to develop a 1 kW InP-pumped Er:YAG solid-state laser.

The eye-safe laser will be developed in conjunction with the Army Research Laboratory through funding awarded by the DoE's High Energy Laser Joint Technology Office.

PLI's efforts will contribute to the DoE's program to develop stacks of InP pump laser arrays operating at very high powers.

The InP pump lasers are designed to operate at wavelengths near the emission wavelength of the Er:YAG gain medium, because

this approach greatly reduces the undesirable heating of the gain medium.

"In addition to alleviating active media overheating, the use of InP-based pump sources avoids a critical problem inherent to GaAs diode lasers associated with the degradation of the diode lasers' mirror facets," said PLI chief scientist Dimitri Garbuzov. "The photon flux for InP pump lasers can be several times larger than that of traditional, GaAs-based pumps at comparable device lifetimes."

PLI has already demonstrated diode-pumped Er:YAG lasers with 100 W output emitting at 1.65 μm .

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Jenoptik's laser diode bar breaks 400 W barrier

By Oliver Graydon

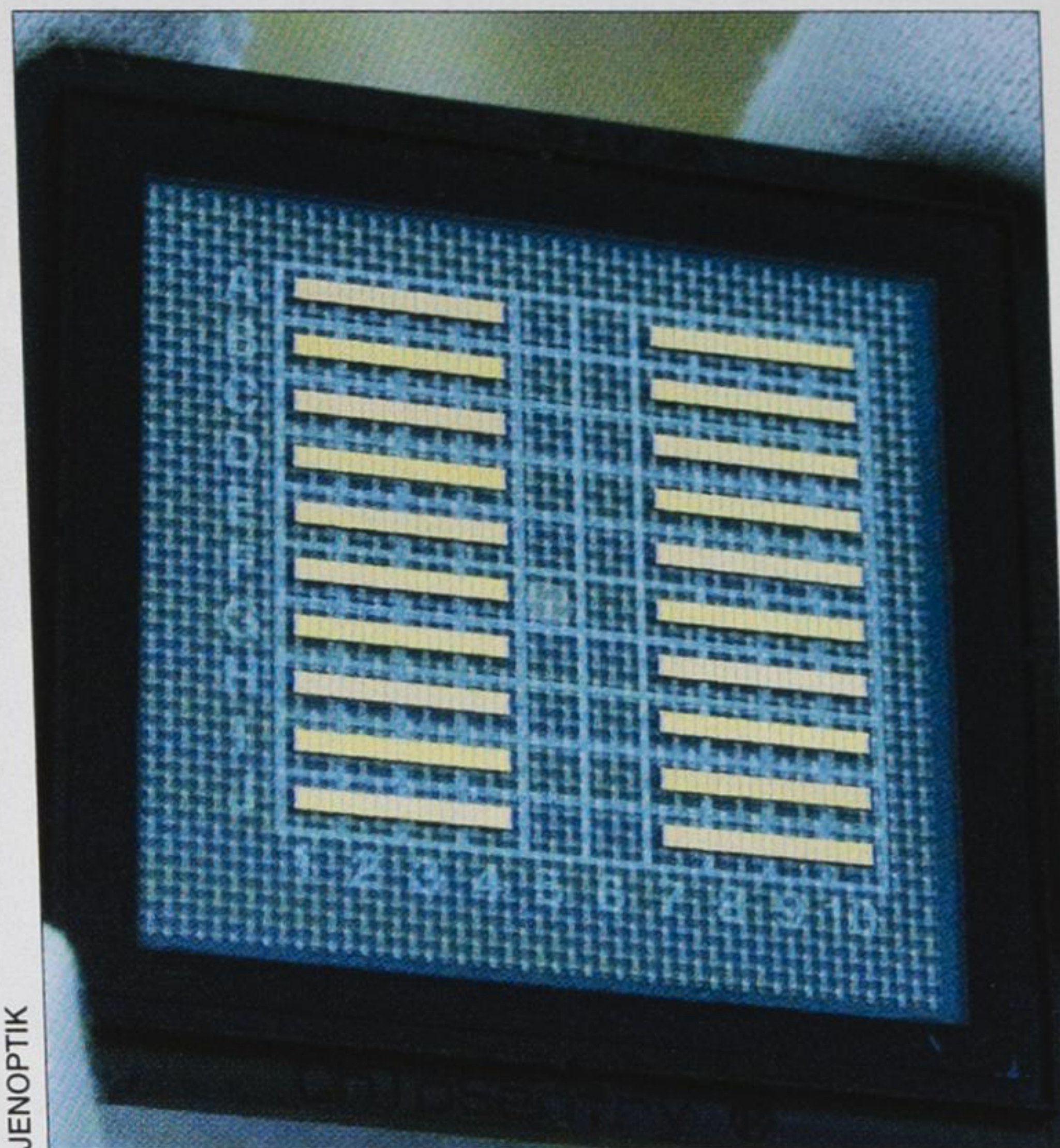
Jenoptik Laserdiode, the German manufacturer of semiconductor lasers, has fabricated a 1 cm laser diode bar that emits a record-breaking 454 W of continuous-wave infrared (940 nm) light. The result eclipses the previous records of 364 W and 320 W that were reported last year by nLight and Bookham.

Jenoptik's result was achieved with a bar measuring 1 cm x 2 mm that was made at its new semiconductor fabrication plant, Jenoptik Diode Lab, in Berlin.

"It was just a plain semiconductor bar that we use in production, nothing special," explained Detlev Wolff from Jenoptik Laserdiode. "Compared to the regular diode product, we simply changed the packaging to carry the larger current."

The water-cooled device emitted the record-breaking power when driven at a whopping 580 A. Despite this impracticality, the result shows that Jenoptik's semiconductor material is capable of being driven at high output powers without suffering catastrophic optical damage (COD) to its facets.

"The question for us is what is the weak point of a diode laser. This result shows that it is not the facet," said Wolff. "What we see is that the device is thermally limited rather than suffering from COD. This means that it is not the semiconductor bar that is limiting the next level in performance but it's the packaging and heat-sinking."



Jenoptik's laser diode bar emits an output power that is about four times greater than that of today's commercial devices.

This latest result means that there is now an even larger gap between the performance of laboratory demonstrations and commercial devices. The highest power bars on the market now deliver around 100–120 W continuous wave, and Wolff says this figure is unlikely to rise while manufacturers concentrate on improving the lifetime of devices rather than the output power.

Oliver Graydon is editor of Optics.org and Opto & Laser Europe magazine.

Alfalight bags equity and innovation funds

High-efficiency laser manufacturer Alfalight has won \$5.9 million under two separate programs funded by the US military, as well as an extra \$7 million in venture funding.

The Defense Advanced Research Projects Agency (DARPA) has provided Alfalight with \$1.4 million for the second part of its super-high-efficiency diodes (SHEDS) program.

The Wisconsin-based company recently demonstrated a laser bar emitting 55 W at 71% efficiency. This result has since been verified by the National Institute of Standards and Technology.

Now DARPA is setting an even stiffer target. The aim for Alfalight is to make a stacked array of lasers that produces 480 W with a

power conversion efficiency of 80%.

Although part of that improvement can be made by further reducing optical and electrical loss mechanisms, Alfalight says that it will also look to change the fundamental structure of the lasers, using quantum dots and improved epitaxy methods.

The company has won a further \$4.5 million through another military contract, this time with the Army Research Laboratory.

The goal of this 12-month program is to demonstrate a multimode laser diode with an output of 1 kW. Alfalight's latest funding round was supported by all of its major previous investors. The cash will be used to expand product lines.

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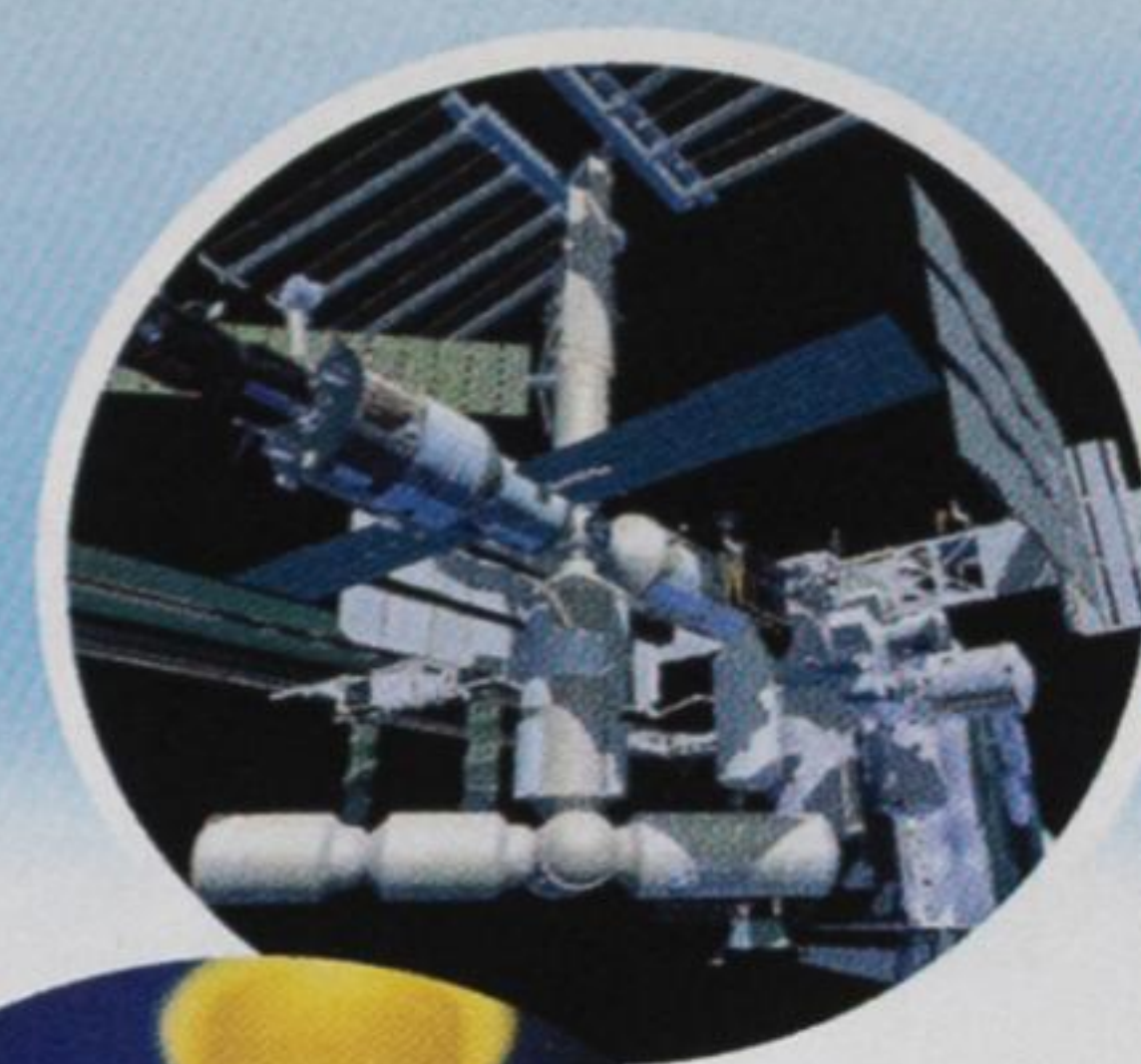
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Bookham outlines plan to raise cash as sales grow

InP chip maker Bookham is planning to raise up to \$35 million through public offerings of its stock over the next two years.

The company announced its intention to file a registration statement with the Securities and Exchange Commission to that effect when it revealed its fiscal 2005 financial results.

The latest Bookham sales figures revealed a 22% sequential increase in revenue to \$61 million, and CEO Giorgio Anania said that he saw strong signs of market growth.

Despite the largely positive outlook, Bookham is losing money fast, with cash and cash equivalents falling by \$92 million over the last year. The company posted a net loss of \$18 million – a figure that excluded an additional \$21 million in charges relating to severance payments and its acquisition of New Focus.

Bookham has recently reduced costs by moving much of its test and assembly operation from Paignton in the UK to Shenzhen, China. It has also substantially cut spending on research and development: to \$9.8 million in the latest quarter, from \$14.4 million in the equivalent period last year.

As a result of cost-cutting and the increased sales, Bookham is now operating at a gross margin of 19%. This is a big improvement on the situation one year ago, when the company achieved a gross loss of 11%.

But, as company CFO Steve Abely pointed

out in a conference call to discuss the figures, Bookham now needs to raise more money.

Apart from the intended public stock offerings, Bookham reckons on raising up to \$25 million through asset sales. This will include the sell-off of land and buildings over the next three months, as well as other assets that Abely declined to identify.

Several days after the conference call, the company announced that it has improved its cash flow through a tax break that frees up nearly \$12 million.

Bookham received £4.2 million (\$7.5 million) on August 10 under the terms of the deal, and will have access to a further £1 million on October 14; £1 million on July 14, 2006; and £0.43 million on July 16, 2007.

The deal involves Deutsche Bank; London Industrial Leasing, which is a subsidiary of the German financier; and a company called Creekside that deals in aircraft subleases.

Bookham has agreed to purchase all of the issued share capital of Creekside, which will now operate as its subsidiary. As a result, Bookham stands to receive payments that are due for the aircraft Creekside leases.

Creekside is based in the UK, although Bookham won't specify the exact location. This means that Bookham can transfer tax losses to its advantage, making an extra £6.63 million available in cash.

T-Networks and ASIP merge to form Apogee Photonics

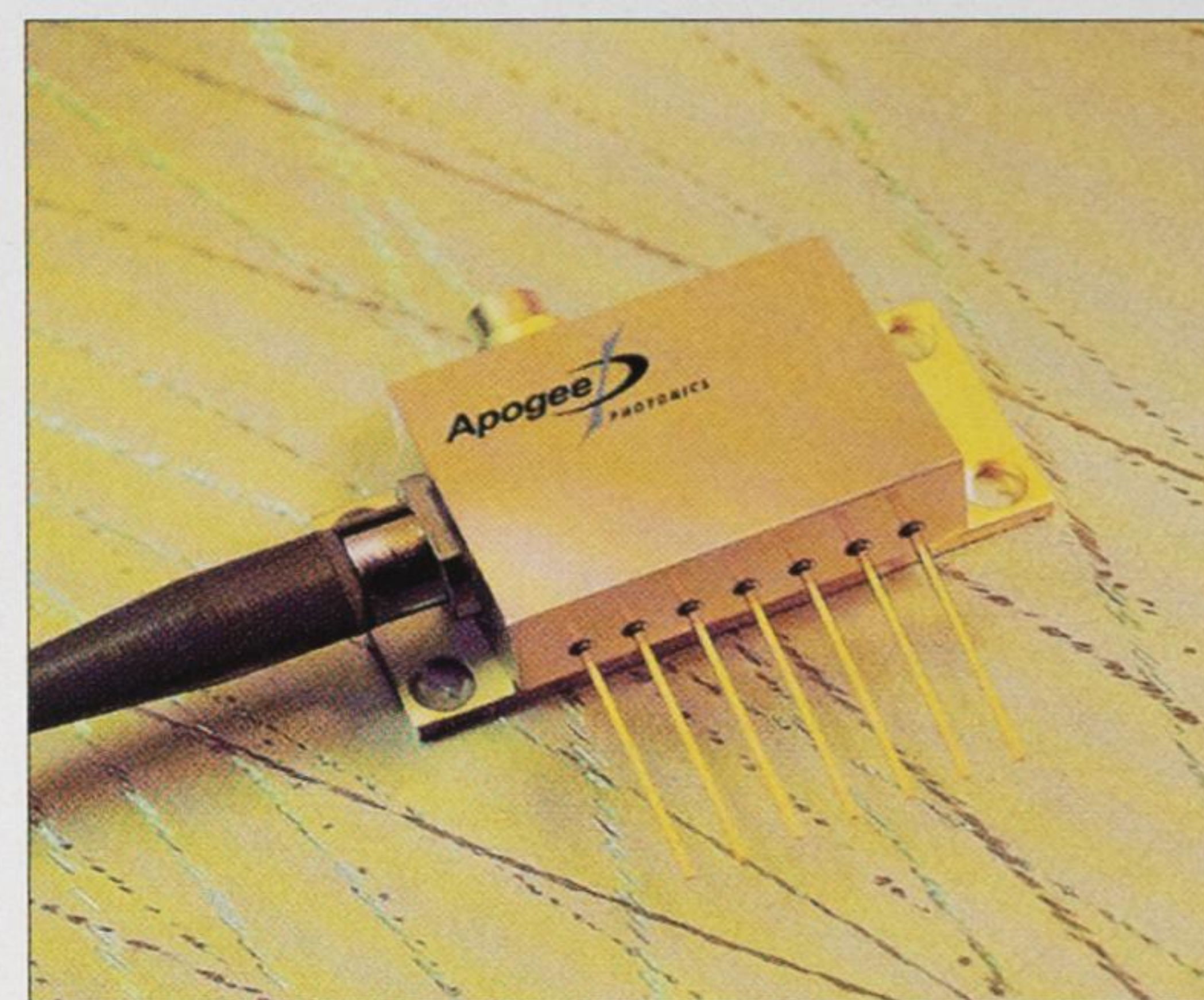
Optical component manufacturers ASIP and T-Networks of the US have merged to form a new company, Apogee Photonics.

Apogee has also secured \$9.7 million in new funding. This includes contributions from existing ASIP and T-Network investors BlueRun Ventures, Atlas Ventures, Finaventures, Intel Capital, Redpoint Ventures and TL Ventures.

The newly formed company will be able to address all segments of the 10 Gb/s fiber-optic market, from very short-reach datacom links to high-performance, dense wavelength division multiplexing transport networks.

Mike Decelle, the former CEO of ASIP, has been appointed CEO of Apogee.

Decelle says that the merger will improve operating efficiencies, because the products developed can be manufactured at a single fab. Chips will be manufactured at T-Networks' fab in Allentown, PA, and Apogee will maintain a presence at ASIP's headquarters in New



Apogee Photonics' modulated laser source operates at 1.55 μm . The newly formed company's products will cover all segments of the 10 Gb/s fiber-optic market.

Fiber component makers secure funding

Two fiber-optic component vendors have topped up their latest venture financing rounds as the optical networking sector continues to show signs of a recovery.

Picolight, of Louisville, CO, which specializes in 1310 nm VCSELs, has added \$14.5 million through a combination of equity investment and debt finance.

Investor Growth Capital (IGC), a new investor in the company, provided \$7 million, and Albert Kim from IGC will now join the board of Picolight.

ORIX Venture Finance has provided a debt facility worth an additional \$7.5 million.

Picolight says that it will use the money to scale up its manufacturing process. It also plans to extend its VCSEL product capability from 4 Gb/s to 10 Gb/s.

According to the company, revenue and orders have doubled during the past year as the fiber-optic sector has finally begun to regain momentum.

Also looking to scale up production is Alphion, a component vendor that specializes in InP integration.

Alphion, of Princeton, NJ, has secured an extra \$1.5 million, bringing its third-round equity investment to \$12.1 million and total funding so far to \$44.1 million.

The company's flagship QLight products, launched in February 2004, are based on monolithic integration on InP chips and advanced packaging technologies. The new funding is expected to help the company to expand its product range, which now includes amplifiers, switches and transponders.

Jersey. The merger will benefit customers, says Decelle, because they will be able to work with a supplier of a broader range of products.

The formation of Apogee has led to staff cuts at the merging companies.

Commenting on the merger, Tom Housken, the director of photonics research at Strategies Unlimited, said: "Both ASIP and T-Networks have innovative technologies and strengths that will allow Apogee to expand its product and customer base and provide solutions that integrate the source, modulator and amplifier."

new 4

WIDE BANDGAP NEWS

SiC modules set to cut size of ship transformers

Silicon carbide (SiC) chips will be the key component in a new generation of high-power electronic modules that promise to reduce the weight and volume of transformers used onboard US Navy ships.

The modules will be developed by Northrop Grumman Electronic Systems (NGES) under an \$8.9 million contract awarded by the Office of Naval Research. The award also forms part of the Defense Advanced Research Projects Agency's phase-two effort on wide-bandgap high-power switches.

NGES will construct high-frequency, power electronic modules using SiC chips developed and fabricated at its own facilities in Baltimore.

Devices under development include SiC MOSFETs, insulated gate bipolar transistors and PiN diodes. Powerex, a program partner of NGES, will assemble these devices to make

10 kV, 100 A half-bridge modules.

Other team members include GeneSiC and a series of US universities, and Northrop's Newport News sector will develop the solid-state power substation.

Modules made with the wide-bandgap material will form a major part of the transformers that distribute power on naval vessels.

The US Navy plans to use the technology on its new CVN-78 aircraft carrier. Construction is due to begin in 2007, and the carrier is slated to be placed in commission in 2014.

Steve McCoy, the director of advanced technology programs at NGES, said that US Navy ships featuring the technology would benefit from increased space and weight that could be used for extra sensors and weapons.

The use of SiC-based modules is expected to save 170 tons in weight and 290 m³ in space onboard the ships.

TDI unveils InN-on-sapphire templates

Technologies and Devices International (TDI), a US-based manufacturer of template substrates, has produced InN epitaxial layers and structures using its hydride vapor phase epitaxial (HVPE) technology.

The 2 inch-diameter InN-on-sapphire templates and InN/GaN heterostructures were shown at the 6th International Conference on Nitride Semiconductors in Bremen, Germany.

"This result is an important step towards HVPE technology for InN-containing materials and devices, including high brightness blue, ultraviolet and white LEDs," said Alexander Syrkin, TDI's crystal growth specialist.

TDI has previously produced GaN-based devices with its HVPE technology (see *Compound Semiconductor* December 2004 p15).

The latest process, developed in collaboration with the Army Research Laboratory and Texas Technical University, enables the company to deposit either InN epitaxial layers or

3D nanostructures in a controllable manner.

TDI has also launched templates that consist of a 10–18 µm-thick single crystal AlN film deposited on a conductive SiC substrate.

The low-defect AlN-on-SiC substrates are claimed to offer a good lattice and thermal match to GaN-based devices, and to combine the thermal conductivity of SiC with the high intrinsic electrical resistivity of AlN.

According to the Silver Spring, MD, company, the templates are suitable for ultra-high-power AlGaN/GaN HEMTs because the AlN layer is sufficiently thick to provide reliable insulation and low current leakage.

"Proprietary stress-control technology developed at TDI allows us to put in production these new substrate materials, which will allow the nitride community to speed up development and commercialization of advanced nitride semiconductor devices," said Vladimir Dmitriev, TDI's president and CEO.

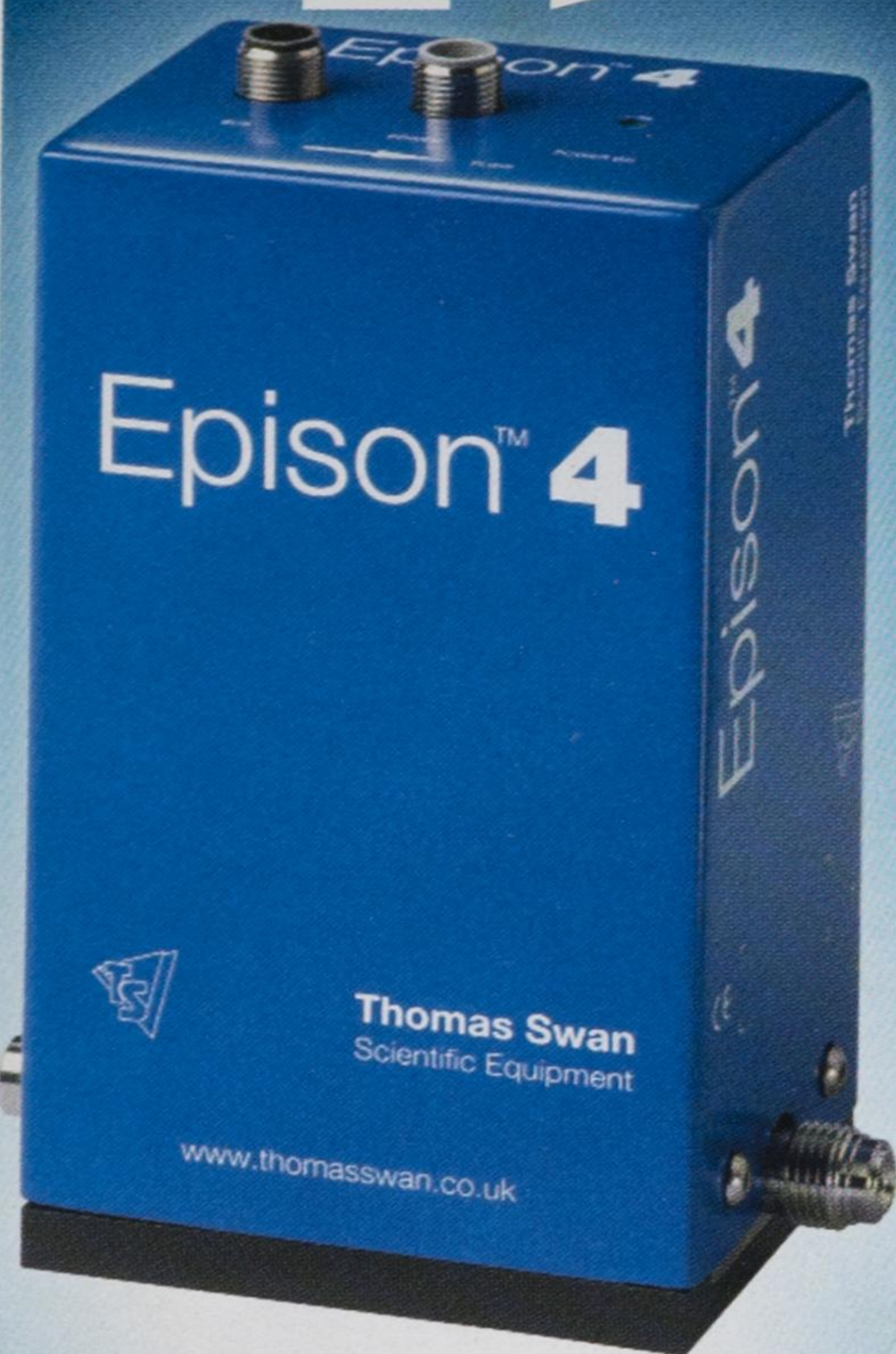
Raytheon wins \$10 m GaN radar contract

Raytheon has been granted a \$10 million contract to develop and demonstrate a GaN-based prototype module for use in radar systems.

The integrated multichannel module will receive and transmit signals using 28 V GaN

power amplifiers and efficient power supplies.

The development of the module, which should be completed by August 2008, will be shared between the company's Tewksbury and Andover sites in Massachusetts.



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A member of the AIXTRON group of companies

RETROSPECTIVE: 1995–2005

10
YEARSCelebrating a decade of
compound semiconductor coverage

Compound Semiconductor magazine is 10 years old. And, just like most of the rest of the industry, it has been through a few ups and downs during that time. Here, we take a look back at some of the highlights – and lowlights – that have shaped the industry over the past decade.

1995

Blue is the color



March • Nichia transfers its blue LED production line to a new factory • Nokia and RFMD agree a secret deal to use GaAs HBTs in the Finnish company's cell

phones • Spectra Diode Labs (SDL) raises \$35 million in its IPO.

April • Anadigics raises \$24 million in its IPO, and plans to switch from 3-inch to 4-inch GaAs production.

July • The premier issue of *Compound Semiconductor* focuses on blue LED and laser emitters • Near completion of a supercomputer that would have featured more than 100 different GaAs circuits, Cray files for bankruptcy – leaving behind a 4-inch GaAs fab line • Nichia increases capacity to ramp blue LED production to 10 million devices per month.

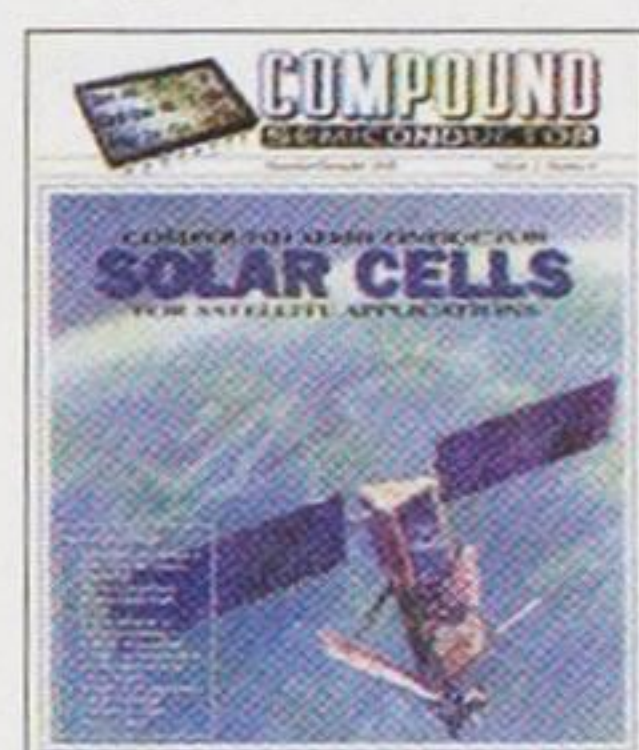
September • Nichia makes a green LED said to be 60 times brighter than conventional devices • Cree plans chip manufacturing expansion to meet expected demand for its new blue LEDs, and signs a three-year distribution deal with Sumitomo Corporation • Four MBE-grown GaAs/AlGaAs samples are fabricated on board the Wake Shield Facility, launched by

the Space Shuttle Endeavor • Matsushita Electric develops GaInP/AlInGaP-based red laser for DVD applications and plans to begin volume production in early 1996

• Fujitsu tops a survey of the major GaAs IC manufacturers with sales of nearly \$100 million.

November • Panasonic and Toyoda Gosei team up to make 1 million GaN-on-sapphire blue LEDs per month • M/A-COM buys Cray's 4-inch GaAs line and plans to make 2 million GaAs ICs per month.

December • Nichia team led by Shuji Nakamura produces a GaN-based semiconductor laser operating at 417 nm.

1996
Spaced

January • Shipments of GaAs substrates surge 42% in Japan on the back of demand for mobile communications applications • TriQuint enters the market for RF power amplifiers • AXT begins building a 50,000 ft² facility to produce GaAs substrates in a \$20 million, five-year investment • Aixtron ships its 200th deposition system • Agilent develops a GaAs-HBT process.

March • TRW and RFMD reveal plans to

produce GaAs HBTs in volume • Hewlett-Packard is rated the top-ranking compound semiconductor producer in 1995, with revenue of \$675 million. Japanese firms NEC, Sharp, Toshiba, Matsushita, Rohm and Fujitsu take the next six positions, and the overall III-V market is estimated to be worth \$3.7 billion • Sony says it will spend \$100 million on a new III-V device processing line for CD and DVD lasers.

May • Anadigics plans to lease a 70,000 ft² facility for GaAs IC production.

June • Nichia constructs a factory to double blue LED production.

July • Anadigics says that it will invest \$35 million to construct a 10,000 ft² cleanroom for GaAs IC production on 4-inch wafers • Westinghouse makes high-power SiC transistors for digital television transmitters, in what is thought to be the first commercial application of such technology • United Monolithic Semiconductors is revealed as the joint venture between Thomson-CSF and Daimler-Benz, and becomes the sixth GaAs fab located in Europe • Picogiga completes IPO on France's Nouveau Marche.

September • RFMD says that it will build the world's largest GaAs fab to manufacture HBTs • Hewlett-Packard moves away from the traditional shape of LEDs with a

RETROSPECTIVE: 1995-2005

flip-chip approach • Vitesse says that its Colorado Springs 6-inch GaAs facility will be up and running in late 1998.

November • In anticipation of DVD uptake, Sharp reveals plans to double laser production to 10 million units per month • A research group at Toshiba becomes the third to make a GaN-based laser diode, using a facet-cleaving process • Nichia readies the world's first GaN-based white LED lamps for volume production • Motorola's plan to launch Iridium, a 66-satellite communications network, boosts III-V device makers. Each satellite is set to incorporate 24 m² of compound semiconductor material for solar cells, while GaAs ICs will be used in the wireless links using the Ka-band. But Iridium proves expensive both to build and for subscribers. Motorola later axes the service, although it is saved from bankruptcy by venture capitalists and \$72 million from the Pentagon. • Coherent acquires MBE wafer specialist Tutcore of Finland for aluminum-free laser production.

1997 The HBT cometh



January • Shuji Nakamura's announcement of the first continuous-wave 405 nm nitride laser to operate at room temperature caps a remarkable year in

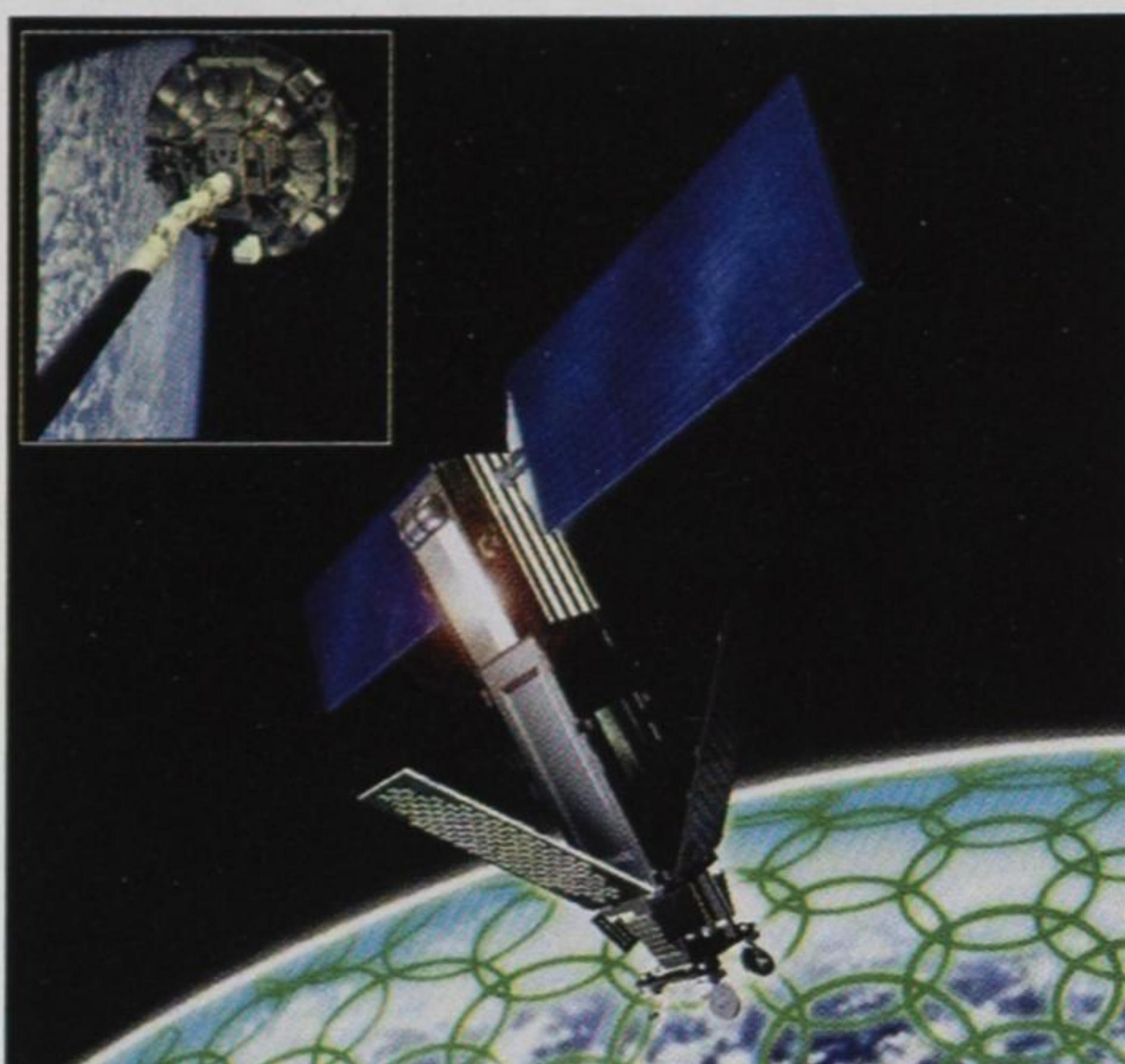
GaN optoelectronics • Agilent develops first VCSELs for gigabit-Ethernet transceivers.

February • Anadigics nets around \$55 million in a public offering of its stocks.

March • Emcore completes \$22.5 million IPO • Rockwell's far-reaching MOCVD patent, which had been licensed to more than 40 III-V companies worldwide, is ruled invalid by a US Federal Court after SDL argues successfully that several of its key claims are just – well – obvious • Uniphase acquires IBM's 980 nm pump-laser fab in Zurich, Switzerland, for \$45 million in cash – plus a further \$27 million in licenses.

April • Anadigics ships millionth GaAs IC for Qualcomm CDMA PCS handsets • Kopin triples GaAs epiwafer capacity with two Aixtron AIX 2400 systems.

June • Rockwell ramps HBT production to 700,000 units per month on the back of demand from cell-phone handset makers



IRIDIUM/NASA

Space was a strong theme in 1996, with MBE experiments aboard NASA's Wake Shield Facility (inset) and great hopes for Motorola's Iridium project.

Qualcomm, Samsung and Lucky Goldstar (now LG) • RFMD's IPO receives a warm welcome on Wall Street.

July • Cree makes the first SiC-based laser – a pulsed device emitting at 403 nm.

September • Hewlett-Packard enters the blue LED market with InGaN-on-sapphire 475 nm devices, and forecasts a major ramp in capacity • Cree says that it will make fake diamonds based on SiC under a supply deal to C3, a company led by Eric and Jeff Hunter, brothers of Cree CEO Neal Hunter.

October • Sharp increases diode laser production to 6 million units per month • After initial demonstration at the company's laboratories in July, details of Nichia's blue laser with a 10,000 h lifetime are revealed to the wider world at the International Conference on Nitride Semiconductors in Japan. Nichia plans to sample blue lasers by the end of 1998.

November • Aixtron goes public on the Frankfurt stock exchange, with its IPO oversubscribed by more than 30 times.

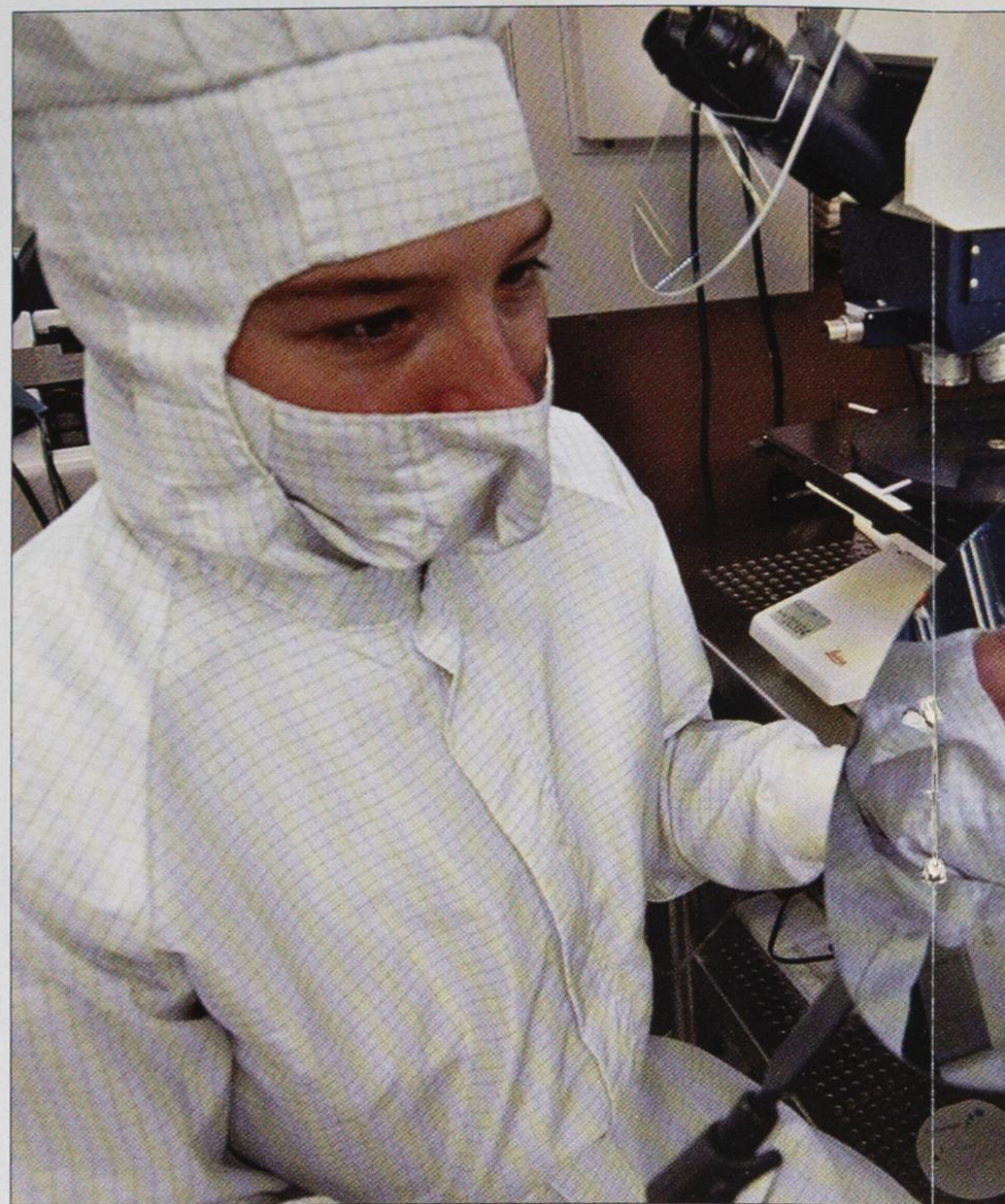
December • TriQuint moves all operations to Oregon, including a 16,000 ft² wafer fab.

1998 Year of the nitrides



January • TriQuint buys Raytheon TI Systems' GaAs MMIC business, which becomes TriQuint's Texas operation • HBT production begins at

RFMD's GaAs fab in Greensboro, NC, and the company reveals details of a major deal to supply Nokia's new series of GSM



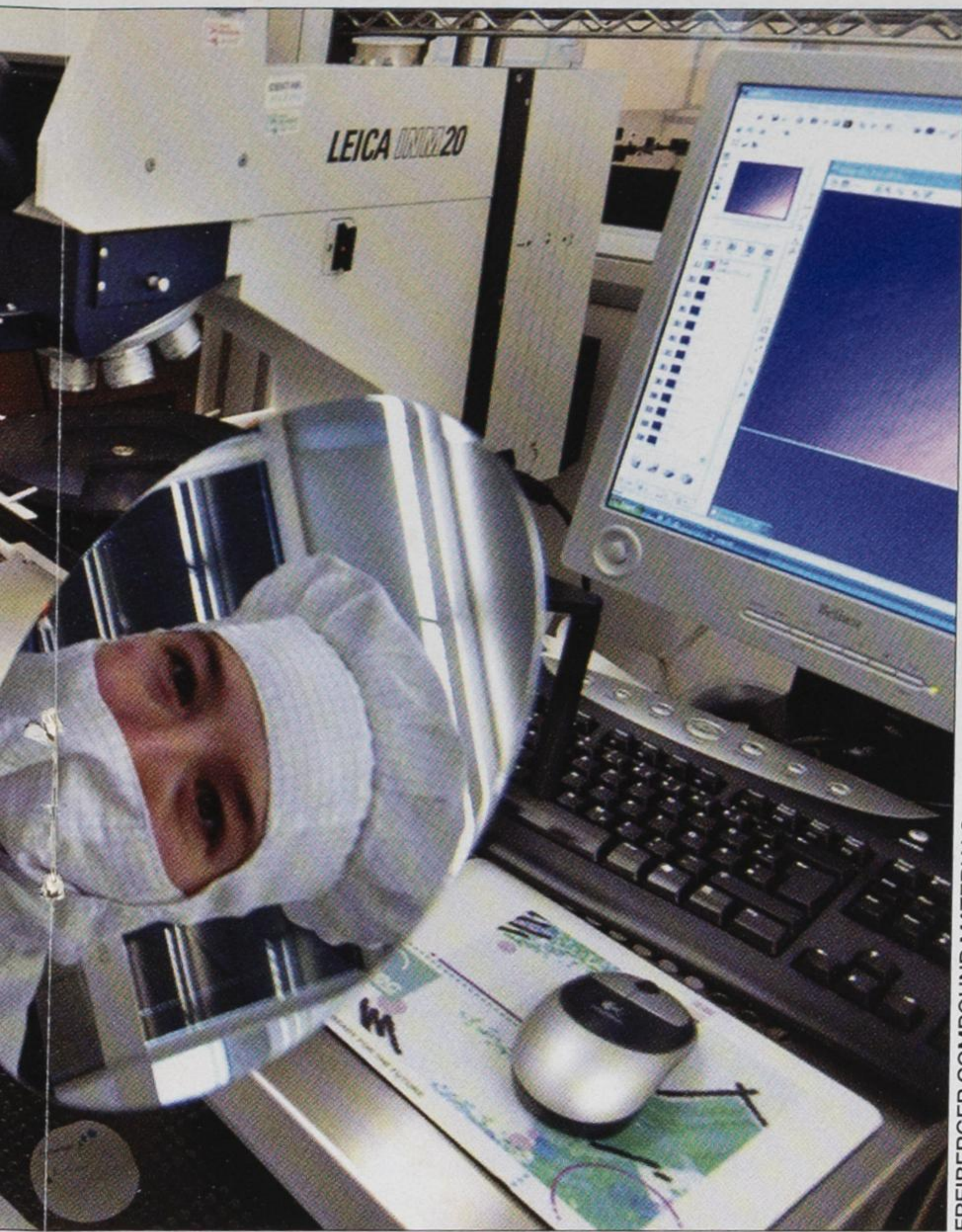
Also celebrating 10 years in the compound semiconductor business that time, the German company's workforce has grown from 100 to 1,000 share, serving both optoelectronic and microelectronic applications. A new technology center for semiconductor materials at the

phones with power amplifiers • Watkins-Johnson (now WJ Communications) plans to acquire Samsung Microwave Semiconductor, including a 3-inch and 4-inch GaAs processing line.

February • 9000 people attend the Optical Fiber Communications conference (OFC) in San Jose, CA, as healthy growth is predicted for the fiber-optic sector.

March • Months ahead of schedule, Vitesse ships the first chips from the world's first 6-inch GaAs fab in Colorado Springs • Hewlett-Packard is still ranked top of the compound semiconductor pile, as Strategies Unlimited says that the total 1997 market for III-V devices was worth \$3.9 billion • Shuji Nakamura reveals substrate removal to be a major factor in successful manufacture of blue GaN lasers.

April • Excellence in Communications (EiC) opens Fremont, CA, foundry to produce HBT-based ICs • Despite a successful 1997, in which it led the power amplifier market, Anadigics feels the pinch of competition and the Asian financial crisis. Sales drop by 50%, its share price collapses, 15% of the company's workforce is shed and the opening of a new fab is delayed by a year • Softening demand for



FREIBERGER COMPOUND MATERIALS

ductor business is substrate supplier Freiberger. During 1999, revenue grew from 85 to 230 as it has gathered a 30% overall market share in electronic applications. In early 2005, the company helped found a research center at the local University of Freiberg.

GaAs ICs hits the share prices of leading manufacturers hard.

May • 13 years after its founding, Anadigics ships its 100 millionth GaAs IC • Specializing in substrates grown using the relatively new vertical gradient freeze (VGF) method, AXT goes public on the NASDAQ • Uniphase plans a buy-out of Philips Optoelectronics, and opens its a laser diode fab in Zurich, turning the San Jose company into a major player in the telecom laser business.

June • TriQuint establishes a GaAs foundry business at Hillsboro, OR.

July • Uniroyal Technology Corp (UTC) says it is ready to begin ordering equipment for making blue LEDs at its new fab in Tampa.

August • Sony is the third company (after Nichia and then Cree) to produce a blue GaN laser with continuous-wave operation.

October • At the first European Microwave Week, Siemens reveals plans for a 6-inch GaAs fab, the first for analog chips.

November • After an investment of \$3 billion, Motorola's Iridium global phone service becomes available, with the first call on the network placed by a great-grandson

Epitaxy highlights

We asked Gerald Stringfellow, distinguished professor of engineering at the University of Utah, to nominate his favorite epitaxy-related research papers from the last decade. Here's what he said about his choices:

- *Lateral epitaxy of low defect density GaN layers via OMVPE* – R Davis et al. 1997 *Appl. Phys. Lett.* **71** 2638.

"This process is the key to

making GaN lasers, the critical component for next-generation disc players."

- *Extremely large N content (up to 10%) in GaNAs grown by gas-source MBE* – Kondow et al. 1996 *Journal of Crystal Growth* **164** 175.

"Making dilute nitride materials has been the most fascinating problem of the last decade. Kondow and his group have made the greatest contribution to the developing these

materials, which have already been used for high-performance lasers."

- *Synthesis of branched 'nanotrees' by controlled seeding of multiple branching events* – L Samuelson et al. 2004 *Nature Materials* **3** 380.

"What impresses me about Lars Samuelson's work is the sheer beauty of being able to grow these wires. It's very, very pretty work."

of Alexander Graham Bell.

December • Hewlett-Packard launches its first HBT-based products, which feature InGaP emitters. The prescalers and Darlington feedback amplifiers are grown using MOCVD • With its silicon device operation suffering, Siemens plans to spin off its semiconductor activity, which includes one of the world's biggest GaAs fabs, into a private company. The newly spun-off semiconductor operation is later christened Infineon Technologies • Anadigics says that it will focus on GaAs PHEMT development in 1999.

1999 Gold rush!



January • Rockwell International spins out its semiconductor business as Conexant Systems • 980 nm laser chips from Uniphase are deemed reliable enough

to pump amplifiers in submarine optical networks, and the company receives a huge order from Lucent Technologies. Uniphase then merges with JDS Fitel to become JDS Uniphase (JDSU) • Anadigics unveils plans for a 6-inch GaAs fab in Warren, NJ, to streamline operations and lower overheads • Osram Opto Semiconductors is established by Siemens.

March • SDL and Mitsubishi join JDSU as suppliers of 980 nm submarine lasers • Nokia moves ahead of Motorola as the world's top mobile phone supplier • GaAs foundry Global Communication Semiconductors sets up in Torrance, CA

• North Carolina State University researchers demonstrate a technique known as pendeo-epitaxy for growing nearly defect-free GaN • Raytheon plans a 6-inch GaAs fab set to open late 2000.

May • Nichia says its ongoing patent dispute with Toyoda Gosei over blue LEDs is "developing into an all-out war" • A number of chip, materials and equipment producers post record revenue figures.

June • Epiwafer suppliers Epitaxial Products International and Quantum Epitaxial Designs (QED) merge to form International Quantum Epitaxy (IQE) • RFMD officially opens the world's biggest MBE facility.

July • PHEMT and MESFET production begins at Anadigics' 6-inch GaAs fab.

August • RFMD ships 100 millionth PA • With just 15,000 subscribers rather than the hoped-for 500,000, satellite phone service provider Iridium files for bankruptcy.

September • Hewlett-Packard names its semiconductor manufacturing spin-off Agilent Technologies, which spawns Silicon Valley's biggest IPO • Lucent plans a \$30 million expansion to meet demand for fiber-optic components • Chip capacity build-out continues with Filtronic's massive new 6-inch GaAs fab in the UK and RFMD's second HBT facility • Laser manufacturers seduce Wall Street, with JDS Uniphase and SDL quadrupling in value in just one year.

October • Aixtron acquires MOCVD company Thomas Swan Scientific Equipment, and follows with the buy-out of

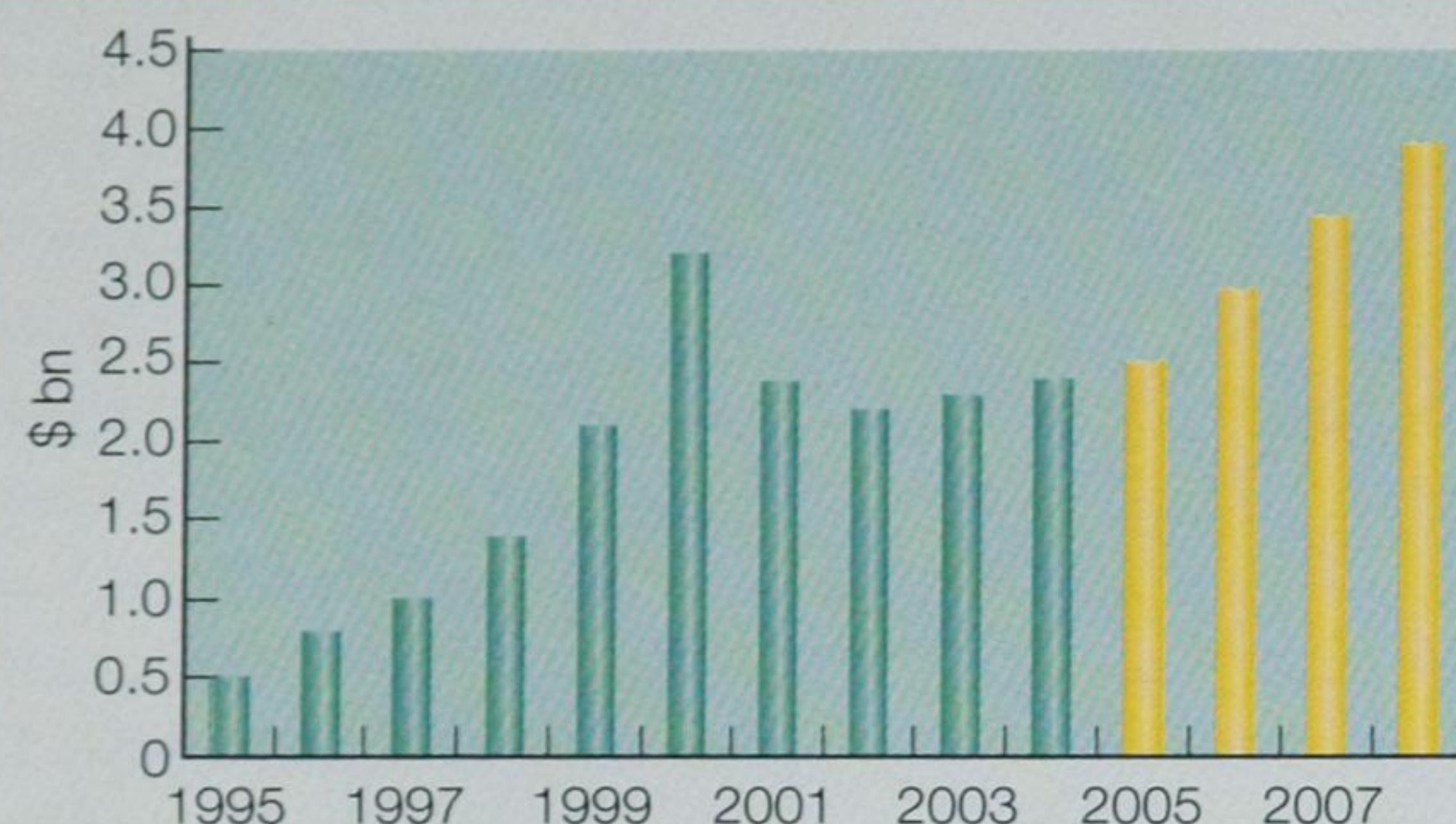
RETROSPECTIVE: 1995–2005

The GaAs rollercoaster: 1995–2005

Somewhat resembling a stage profile from the Tour de France, the figures for the GaAs RF device and material market from the last 10 years show just what a rollercoaster ride this sector has endured.

Faced with boom and bust – perceived undercapacity followed by gross overcapacity – predicting this business must have been an analyst's worst nightmare. But when all is said and done, in the last 10 years the global GaAs device market has grown from \$500 million to \$2.5 billion at a healthy compound annual growth rate of 17%. However, today's market is still worth far less than the \$3.2 billion peak recorded in 2000.

Back in 1995, with the cell-phone handset market in its early stages and the telecom bubble still a few years away, the GaAs market was dominated by low-volume applications, such as military radars and supercomputers. Then the HBT emerged as a key building block of the cell-phone as the GaAs device market tripled in size



GaAs markets 1995–2009: substrate shipments (right) have mirrored fluctuations in the device market.

between 1997 and 2000.

As well as the burgeoning cell-phone market, the 2000 peak was a result of rapid growth in the fiber-optic communications industry, with digital GaAs components used in laser drivers, transimpedance amplifiers, multiplexers and demultiplexers. Since then, SiGe and silicon technology has gained an increasing market share in both 2.5 Gb/s and 10 Gb/s fiber-optic applications, leaving the cellular business as the primary GaAs market.

An explosion in cell-phone sales globally since 2002 has sustained the market since then. This application now

accounts for 52% of the sector's value, although revenue has been tempered by a steady decline in the average selling price (ASP) of devices. The trend is set to continue, along with rising sales of 3G phones that have a higher GaAs content to deliver multi-band operation.

In the same time frame, sales of raw GaAs semi-insulating substrates have mirrored the fluctuations seen in the GaAs device market – in terms of the total area of material shipped. During 2000 expectations of continuing demand for the following year, combined with fears of a 6-inch wafer shortage, fueled a record 14 million square

inches of GaAs substrate shipments. However, by 2001 several customers had inventory levels equivalent to a 10 month supply and year-on-year shipments fell by 40%.

Substrate sales have tracked the device market, but declining substrate ASPs have had a major impact since 2000. Global sales hit \$430 million, then plummeted to just \$136 million in 2003. More recently, the rising price of raw gallium and a steady increase in wafer demand suggest that the market could return to around the \$200 million level by 2009, although this is still less than half of the 2000 peak.

Swedish CVD outfit Epigress.

November ● Agilent and Philips Lighting launch Lumileds ● Shuji Nakamura leaves Nichia, taking up a post at UCSB three months later.

December ● Alcatel pours \$100 million into its Nozay manufacturing facility in France, and Nortel constructs a 3-inch InP fab in Ottawa, Canada ● Nichia ramps LED capacity to 50 million units per month ● Spectrolab makes a triple-junction solar cell with world-record efficiency of 32.3%.

2000 Fab-ulous



February ● TriQuint acquires a state-of-the-art facility in Richardson, TX.

May ● TriQuint completes Hillsboro, OR, GaAs fab

expansion.

July ● SDL and JDSU set up a merger worth \$41 billion ● UK prime minister Tony Blair opens Filtronic's \$35 million GaAs fab.

September ● Hitachi spins out Opnext to produce chips for fiber optics.

November ● Agilent plans 6-inch GaAs fab to make E-mode PHEMTs ● Zhores Alferov and Herbert Kroemer share one half of the Nobel Prize for Physics for their developments in semiconductor heterostructures (IC inventor Jack Kilby scoops the other half) ● Taiwanese GaAs foundries proliferate as chip demand skyrockets ● Sony showcases prototype DVD player based on a blue laser.

December ● Nortel Networks reassures investors over its predicted revenue, despite worries about the wider telecoms market ● Lucent's chip-manufacturing spin-off Agere Systems files for an IPO.

2001 Wall Street blues



January ● GaAs IC companies suffer a "Wall Street crash" amid overcapacity fears ● Toyoda Gosei mass-produces 380 nm GaN LEDs ● WIN

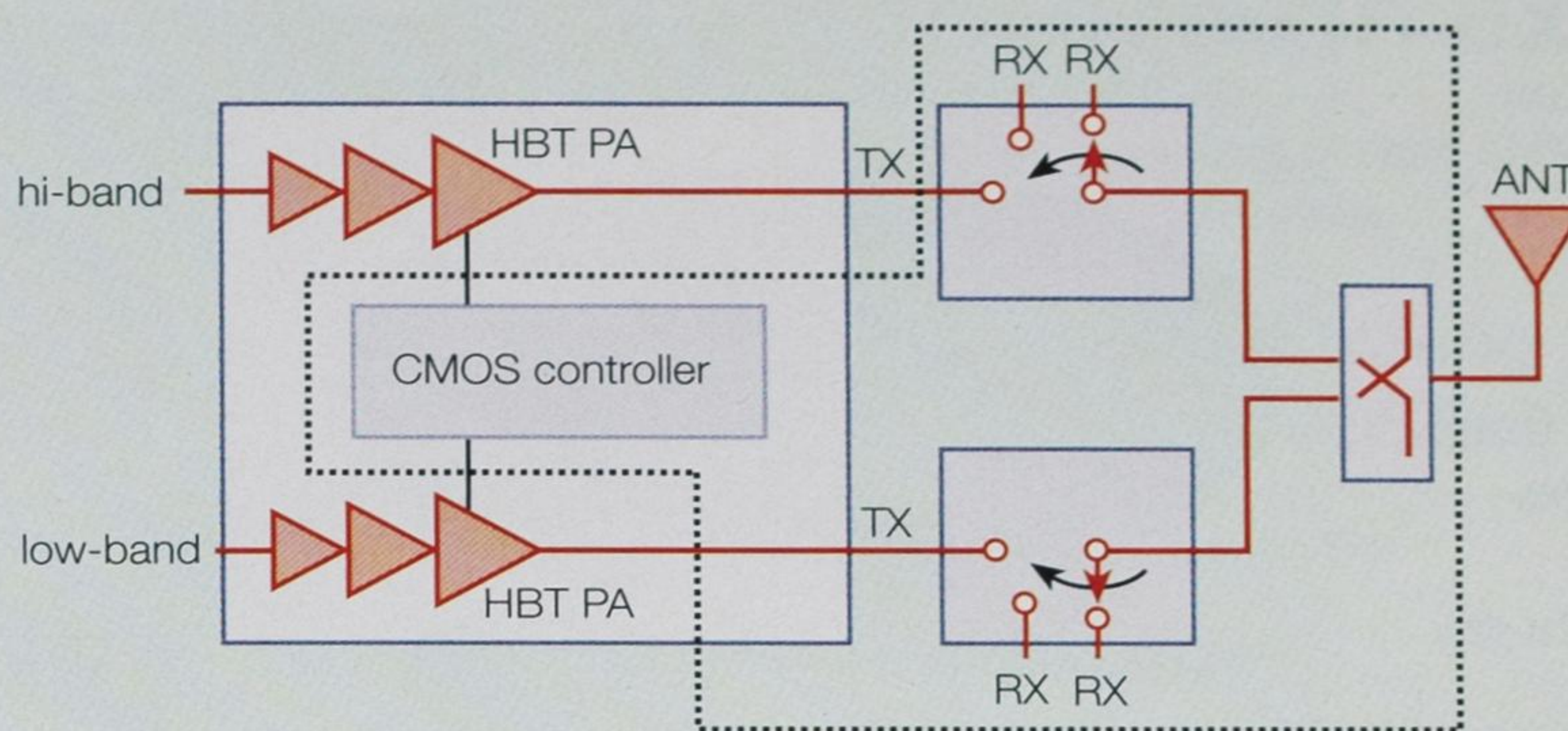
Semiconductor makes Taiwan's first 6-inch GaAs MMIC wafer.

February ● JDSU sells its 980 nm laser facility in Zurich for \$2.5 billion in Nortel stock. Shortly afterwards, Nortel shocks the market, saying that its 2001 revenue will be only half of that predicted. Nortel's share price tanks, along with JDSU's proceeds from the Zurich plant sale ● Almost immediately after merging with SDL, JDSU warns that there is a "lower level of near-term visibility" in the fiber-optic sector. However, the company assures worried investors thus: "We do not believe this is a long-term trend."

Handset evolution: how GaAs and CMOS might co-exist in future front-ends

Without a doubt, the cell-phone handset has been the killer application of the last decade – for both HB-LEDs and GaAs RFICs. As handsets and chip technology evolve, the future could see CMOS and GaAs combined in a novel type of RF front-end, believes Rodd Novak, VP of marketing and business development at Peregrine Semiconductor.

Peregrine has pioneered so-called UltraCMOS chips, which use an insulating sapphire substrate. While leading GaAs firms are looking to the antenna switch as a route to growth for products such as PHEMTs, Novak reckons that the added complexity of future handsets demands a better solution.



UltraCMOS die could integrate the functions inside the dotted line.

With perhaps six radios required for various bands, the antenna switch becomes critical to improving the phone's electrical efficiency. At the moment, power is drained when the output of the PA stage ramps up in simple situations – such as

the user holding the phone to his or her ear. This is largely because the antenna is not firing out the RF signal effectively.

To get around the problem, either multiple antennae can be used, or a single antenna can be power-matched more

effectively. Both solutions require intelligent switches, which is where UltraCMOS could come in. "This is about bringing smarts to the power amplifier," said Novak. Much of the front end could be integrated on the same die (defined by the area enclosed by dotted lines in the diagram), which Novak believes will "bring Moore's law to the RF world".

A lot depends on how the leading GaAs PA companies approach the issue, but as far as Novak is concerned, UltraCMOS can solve a key problem that they face, allowing them to concentrate on PAs. If that collaboration takes place, it could have a marked effect on future handset architectures.

● Nitronex Corporation makes a GaN HEMT on a 4-inch silicon substrate.

April ● Analyst firm CIBC says that it now expects the first downturn in the history of the GaAs industry ● Leading GaAs manufacturers, including RFMD and Vitesse, issue profit warnings ● The 2000 compound semiconductor component market is valued at \$18 billion – more than double the 1998 figure.

May ● CyOptics builds an InP fab in Yokneam, Israel.

June ● TRW creates 4-inch InP foundry Velocium.

July ● Analysts describe Nortel's financial report as "below the worst-case scenario" ● Nokia issues profit a warning, Anadigics lays off 10% of its workforce and RFMD shares slide alarmingly ● In a rare spot of good news, Nichia begins making 30 mW blue lasers in volume ● Lumileds launches high-power Luxeon LED emitters.

August ● Corning closes its Lasertron facility before it is even opened officially ● Shuji Nakamura's book slams Nichia's corporate culture and he files a lawsuit against his former employer.

September ● Osram buys Infineon's 49% share in Osram OS for \$509 million, and lays the foundation of the company's new 40,000 m² fab in Regensburg ● JDSU reports the largest corporate loss in history,

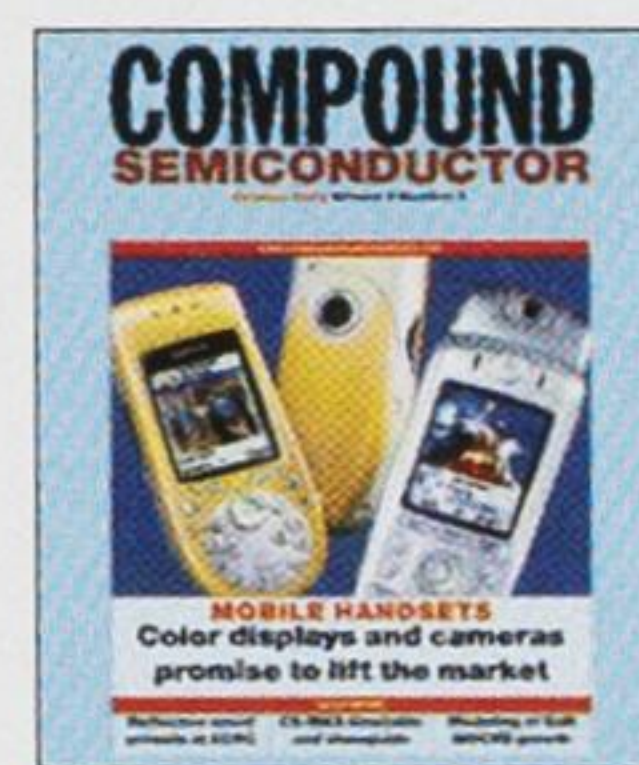
including a \$44.8 billion write-down on its balance sheet.

October ● As the shock of 9/11 attacks on the US reverberates, Motorola and IQE show off 12-inch GaAs-on-silicon technology ● Veeco acquires MBE equipment vendor Applied Epi.

November ● Litton Airtron shuts down its GaAs substrate operation, disposes of 3 tons of stockpiled gallium and sells its SiC substrate business to II-VI.

December ● Nortel auctions huge amounts of wafer fab equipment.

2002 Hangover period



components business, including the Caswell, UK, GaAs fab ● Uniroyal TC's financial crisis is revealed in its annual report – the company soon files for bankruptcy.

March ● TriQuint completes switch to 6-inch GaAs manufacturing.

April ● Sony launches Blu-ray disc data storage technology ● Falling price of blue LEDs prompts a profit warning from Cree.

May ● RHK's chief analyst John Ryan tells

Jan/Feb ● Alpha and Conexant merge their wireless activities and name the new company Skyworks Solutions ● Bookham buys Marconi's optical

components business, including the Caswell, UK, GaAs fab ● Uniroyal TC's financial crisis is revealed in its annual report – the company soon files for bankruptcy.

March ● TriQuint completes switch to 6-inch GaAs manufacturing.

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May ● RHK's chief analyst John Ryan tells

OFC delegates: "In 1999 and 2000 everyone spent money like drunken sailors. Now we're in the hangover period."

June ● TriQuint buys Infineon's GaAs business.

July ● A USCB/IQE team reports a 450 GHz InP DHBT ● Alcatel Optonics cuts workforce by 25%.

September ● Nichia and Toyoda Gosei settle their long-standing differences ● Agere and ADC bail out of the increasingly gloomy-looking fiber business ● Filtronic closes its Santa Barbara GaAs fab.

October ● Toshiba and NEC launch a next-generation DVD format to rival Sony's Blu-ray ● Phone sales pick up thanks to introduction of color screens, driving both GaAs IC and LED growth ● *The Economist* blames the telecoms bubble on WorldCom chief executive Bernie Ebbers talking up Internet traffic growth figures. In July 2005, Ebbers is sentenced to 25 years in jail.

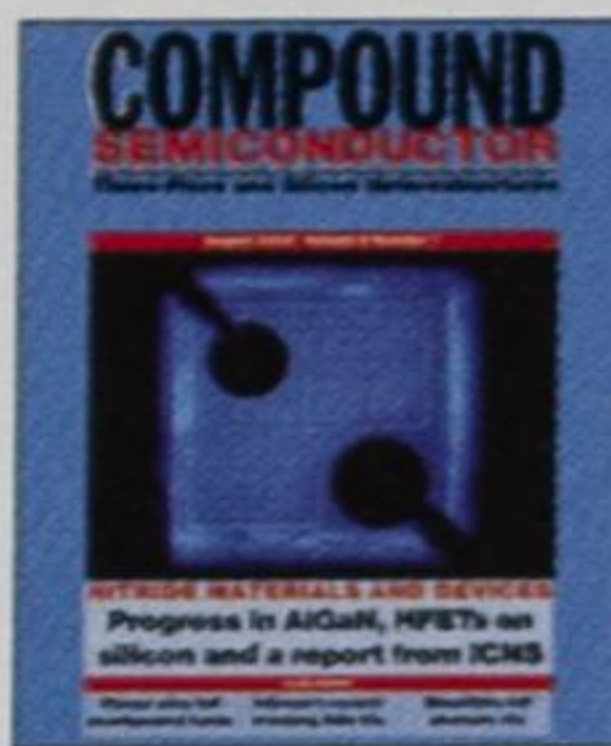
November ● Bookham snaps up Nortel's optical components business ● Nakamura loses the first round of his patent battle with former employer Nichia.

December ● TriQuint buys Agere's optoelectronics business for \$40 million cash ● Cree's LED sales bounce back on demand from camera phones ● RFMD converts to 6-inch GaAs fab ● Fujitsu makes a 562 GHz HBT.

RETROSPECTIVE: 1995–2005

2003

Mergers & closures



January/February

● Nichia and Sony ally on 405 nm lasers ● InN's bandgap turns out to be 0.7 eV, not 2.0 eV as previously thought.

March ● Dow Corning buys Sterling from Uniroyal ● The HB-LED market surges 50% on mobile phone demand.

April ● Sony unveils a commercial Blu-ray disc recorder ● ATMI sells its GaAs epiwafer business to Sumitomo Chemical.

May ● Cree bags a \$100 million LED purchase order from Sumitomo Corporation ● Bookham closes its 3-inch InP fab in Ottawa and ships it to Caswell.

June ● Avanex buys the Alcatel and Corning optoelectronics units.

July ● Former Cree CEO Eric Hunter and his wife sue the company for \$3 billion, later dropping the claim.

August ● Agilent closes its UK optoelectronics fab.

September ● Vitesse closes its 6-inch GaAs fab – the industry's first ● RFMD ships its 250 millionth PA module.

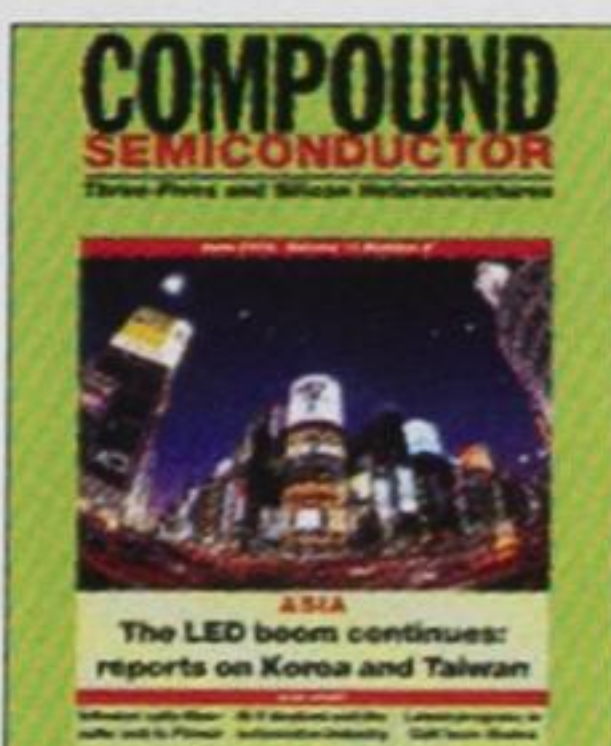
October ● Nichia sues Taiwan-based Epistar over blue LEDs ● Oxford Instruments buys Thermo VG's MBE business.

November ● Raytheon sells its commercial GaAs unit to silicon giant Fairchild Semiconductor ● A University of Illinois at Urbana-Champaign (UIUC) team makes an InP/InGaAs HBT with an f_t of 504 GHz ● MOCVD pioneer Emcore sells its TurboDisc business to Veeco.

December ● Ommic becomes the first European InP foundry.

2004

LED boom time



January ● Fujitsu Quantum Devices and Sumitomo Electric Industries' Electronic Devices merge to form Eudyna Devices

● Analysts say 500 million

phones sold in 2003 ● Audi's A8 is the first production vehicle to feature LED-based forward lights.

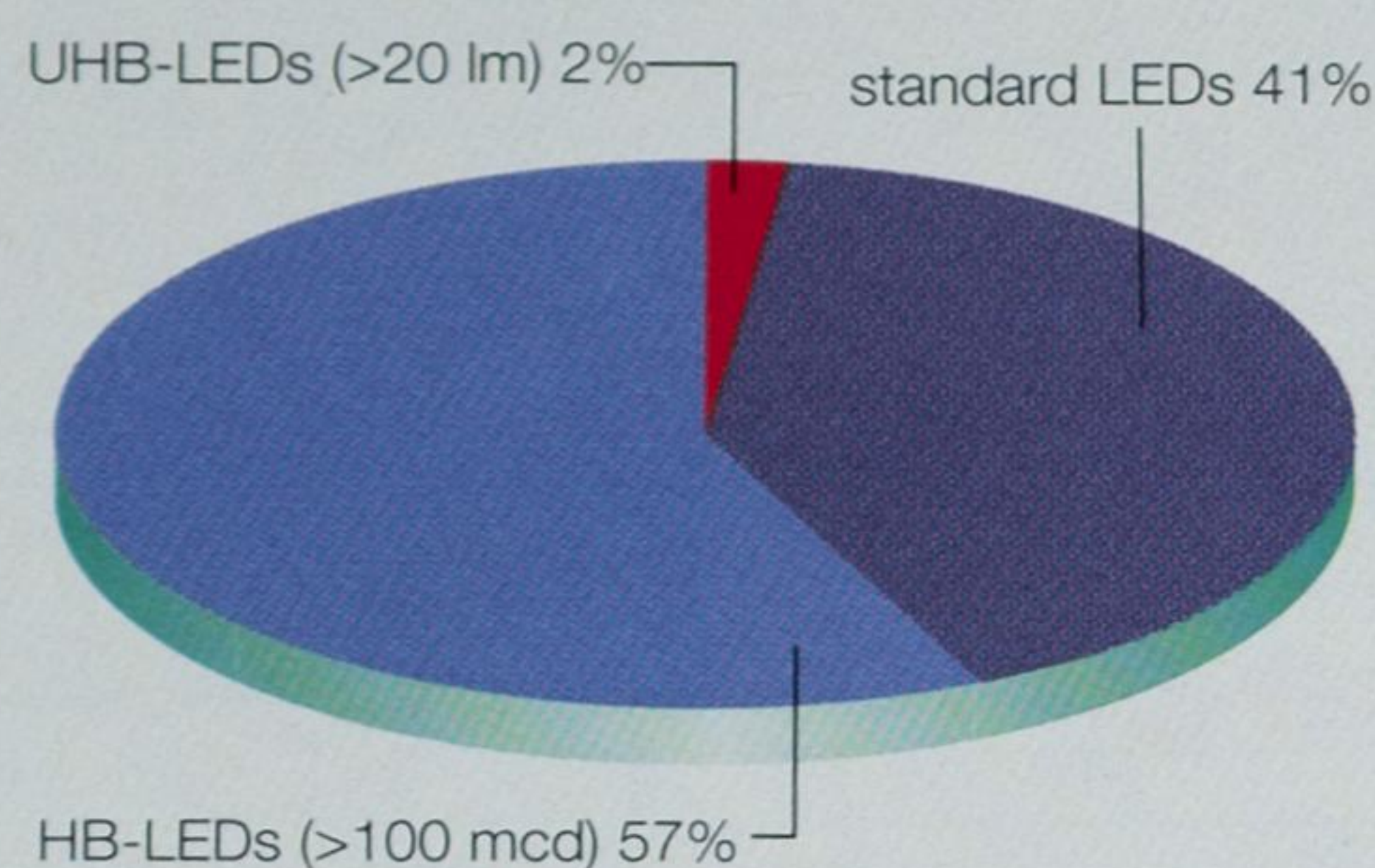
March ● Shuji Nakamura wins \$189 million compensation from Nichia in a Tokyo court.

May ● ATMI sells its GaN unit to Cree.

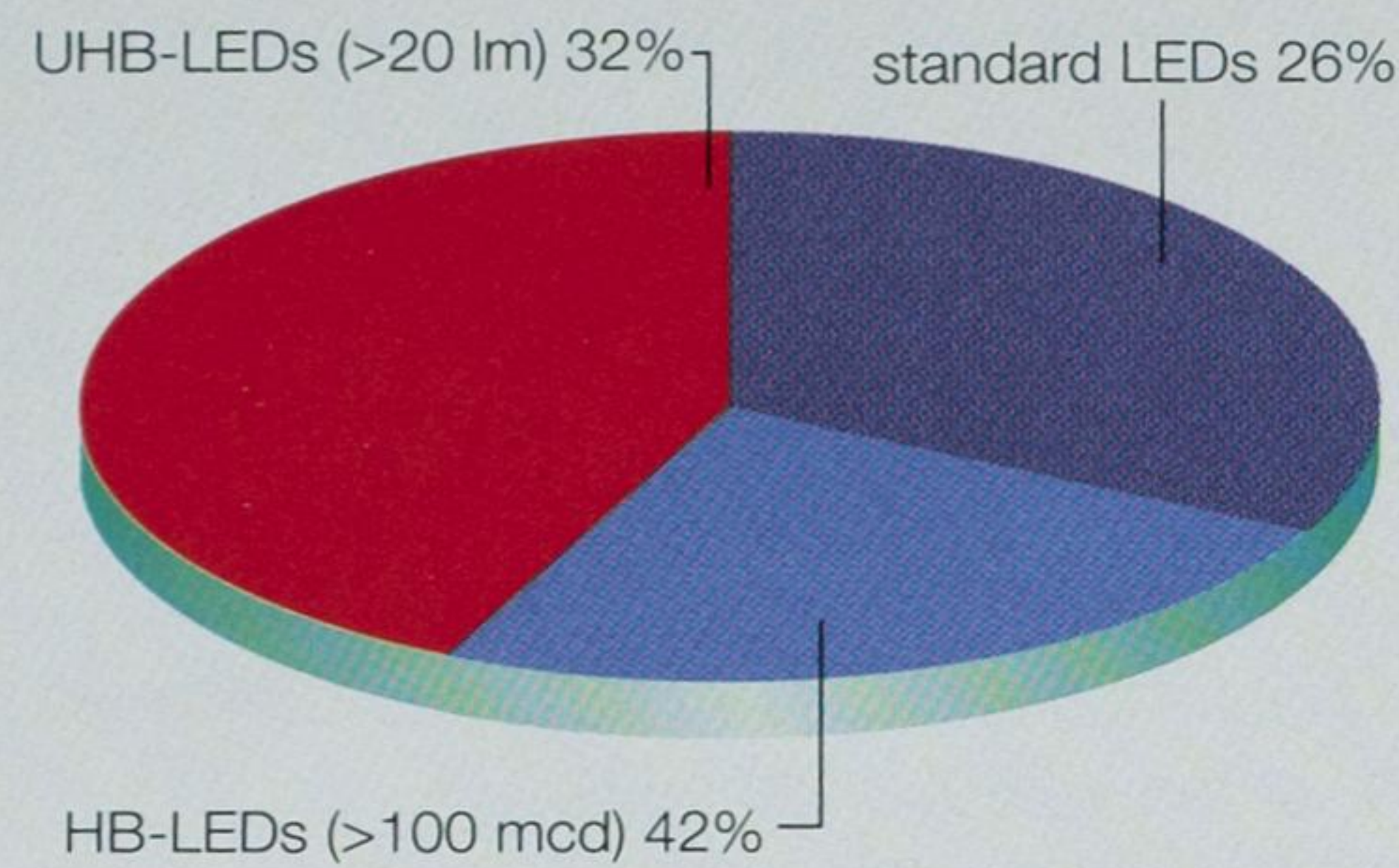
July ● Bookham exits the GaAs MMIC

A decade of stunning growth for LEDs: what now?

2004: \$4.7 bn



2010: \$7.4 bn



The UHB-LED (>20 lm) market is expected to grow 70% annually through 2010.

Unlike the boom–bust cycle that has impacted on GaAs IC uptake, the HB-LED market has grown consistently since 1995. The only exception was a flat period in 2001.

Now, as the saturating mobile handset market slows, the period of very rapid growth appears to be over. There are plenty of new applications waiting in the wings – but the big question is, when will these take off?

iSuppli analyst Jagdish Rebello warns that although solid-state lighting will penetrate applications such as car headlamps, large-screen backlighting and, eventually, general

illumination, the industry may have to be patient.

“Except for camera flash-lighting applications, most new markets for UHB-LEDs in the automotive and general illumination industries are not yet close to commercialization,” he cautioned.

As a result, Rebello is only expecting 10% growth in the HB-LED lamp and chip market this year, compared with a recent average of around 50%. That's a trend set to continue, with only single-digit growth annually over 2006–2010. “Several high-profile applications, such as the backlighting of large-screen LCD displays,

will likely not live up to the early hype,” he said.

And it will be at least 2010 before LED lights really penetrate the general illumination market and become a commodity item like today's light bulbs.

In terms of rapid growth, the action is now switching to what Rebello describes as ultra-high-brightness (UHB)-LEDs, defined by him as devices with a luminous flux of at least 20 lm. UHB-LEDs will command a market of \$2.3 billion by the end of the decade, he predicts, by which time general illumination applications should be worth around \$875 million.

business pioneered at its Caswell fab.

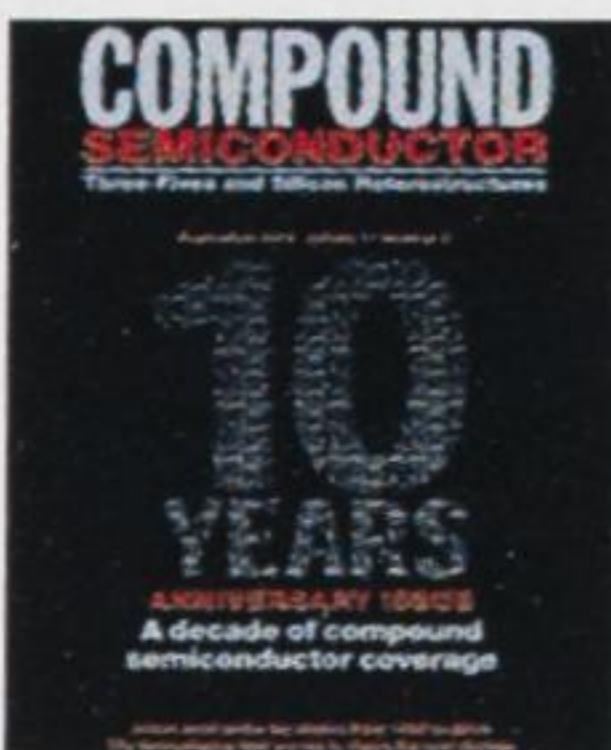
August ● Taiwanese foundry Procomp is at the center of a financial scandal ● Aixtron seals its biggest-ever sale in an MOCVD supply deal with Lumileds ● Motorola spins off Freescale as a separate venture.

September ● Nichia and Optotech collaborate on GaN LEDs.

December ● Taiwan GaAs foundries WIN Semiconductor and GCTC merge.

2005

Bouncing back



January ● Finisar and Infineon wrangle over the value of the German company's fiber-optic division ● The Nichia versus Nakamura case is

finally settled, with the UCSB professor receiving “just” \$8 million from a delighted Nichia.

April ● DARPA's wide-bandgap project sees \$100 million invested in GaN.

May ● TriQuint sells its InP optoelectronics business to CyOptics ● UIUC researchers break another record with a 600 GHz InP-based HBT.

July ● Japanese company Yokogawa plans to spend \$230 million building a GaAs fab to manufacture optoelectronic switches.

August ● Agilent sells its semiconductor division to a private equity group for \$2.66 billion in cash, with Philips Lighting buying out Agilent's stake in Lumileds for \$950 million ● Taiwan-based Epistar and United Epitaxy Company merge, forming an LED manufacturing powerhouse.

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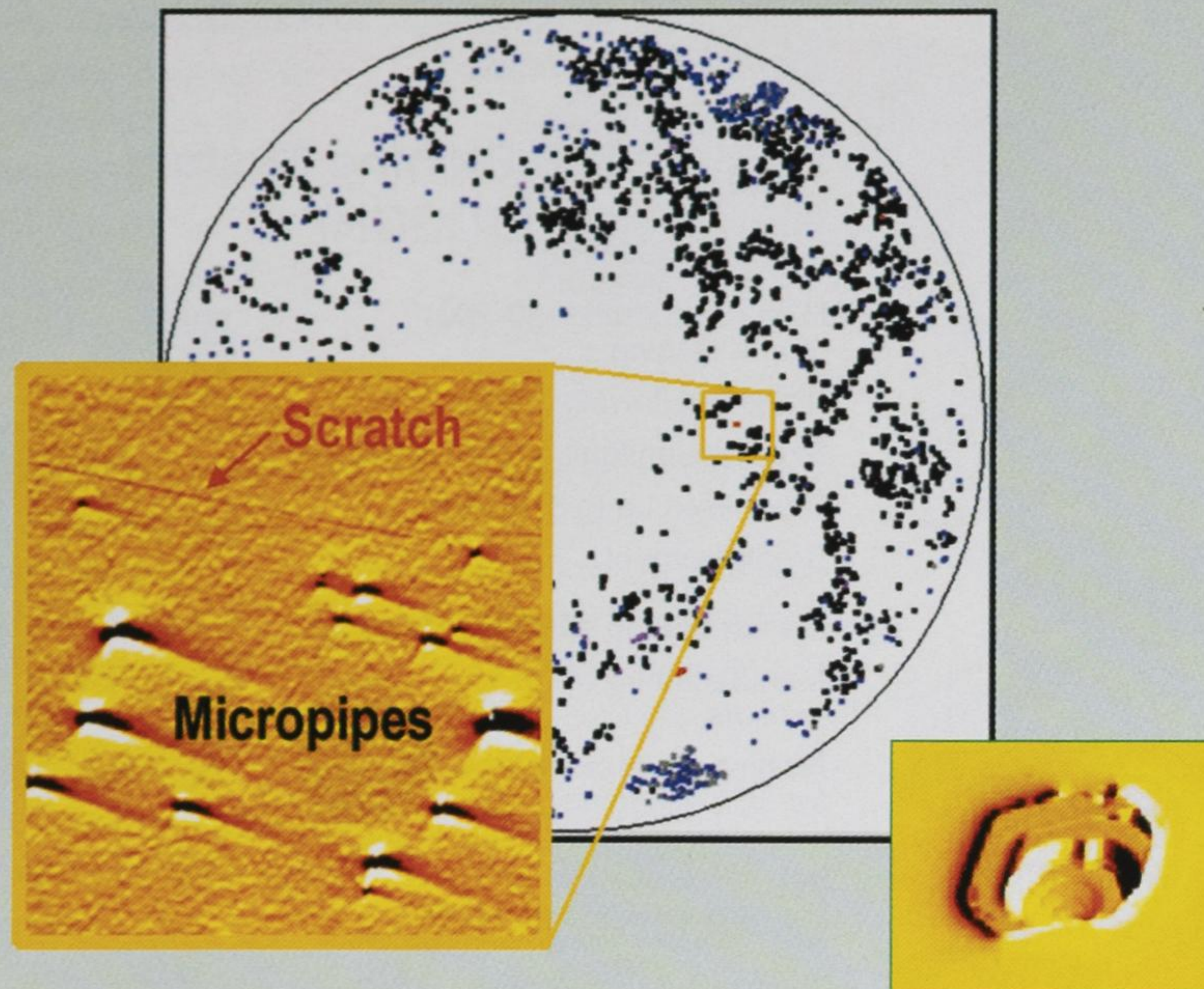
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HBT MANUFACTURING

Kopin bandgap engineering improves HBT performance

High-speed MMICs with lower turn-on voltages can be built by switching GaAs-HBTs for GAIN-HBTs with a dilute nitride base, say **Matt Micci** and **Roger Welser**. The advancement could allow mobile phone designers to build more reliable handsets operating at higher data-rates.

During the past decade GaAs heterojunction bipolar transistors (HBTs) have strengthened their position as the technology of choice for fabricating wireless handset power amplifiers (PAs). By 2004, more than 75% of the 650 million mobile phones sold employed GaAs-HBT technology for power amplification. This dominance resulted from several cost and performance factors that enabled GaAs-HBTs to outperform entrenched silicon and competing GaAs-FET technologies for PA designs.

GaAs-based bipolar transistors offered a powerful combination: high linearity and efficiency over a wide frequency range; high breakdown voltage; and single-supply voltage operation. Consequently, PAs built using GaAs-HBTs delivered the RF performance and robustness required for demanding mobile-phone applications. From a manufacturing perspective, several factors have allowed GaAs-HBT PA production costs to be highly competitive: the much smaller MMIC die sizes enabled by the vertical HBT device; extremely high fabrication yields resulting from the larger, easy-to-process device geometries; streamlined quick fabrication processes; and ease of integration. Finally, ongoing bandgap engineering of the material structure has kept GaAs-HBT technology at the industry's leading edge by continually offering cost and performance improvements for PA ICs and modules.

Nobel laureate Herb Kroemer's early vision of wide-bandgap heterojunction structures delivering superior transistor performance is embodied in today's GaAs-based HBTs. The success is partly due to the many advances in material synthesis. For example, improvements to the reliability and performance of HBTs have been delivered through alterations in the emitter layer, most notably the replacement of AlGaAs alloys with InGaP. Still, given the ever-increasing sophistication of emerging wireless products, and the resulting

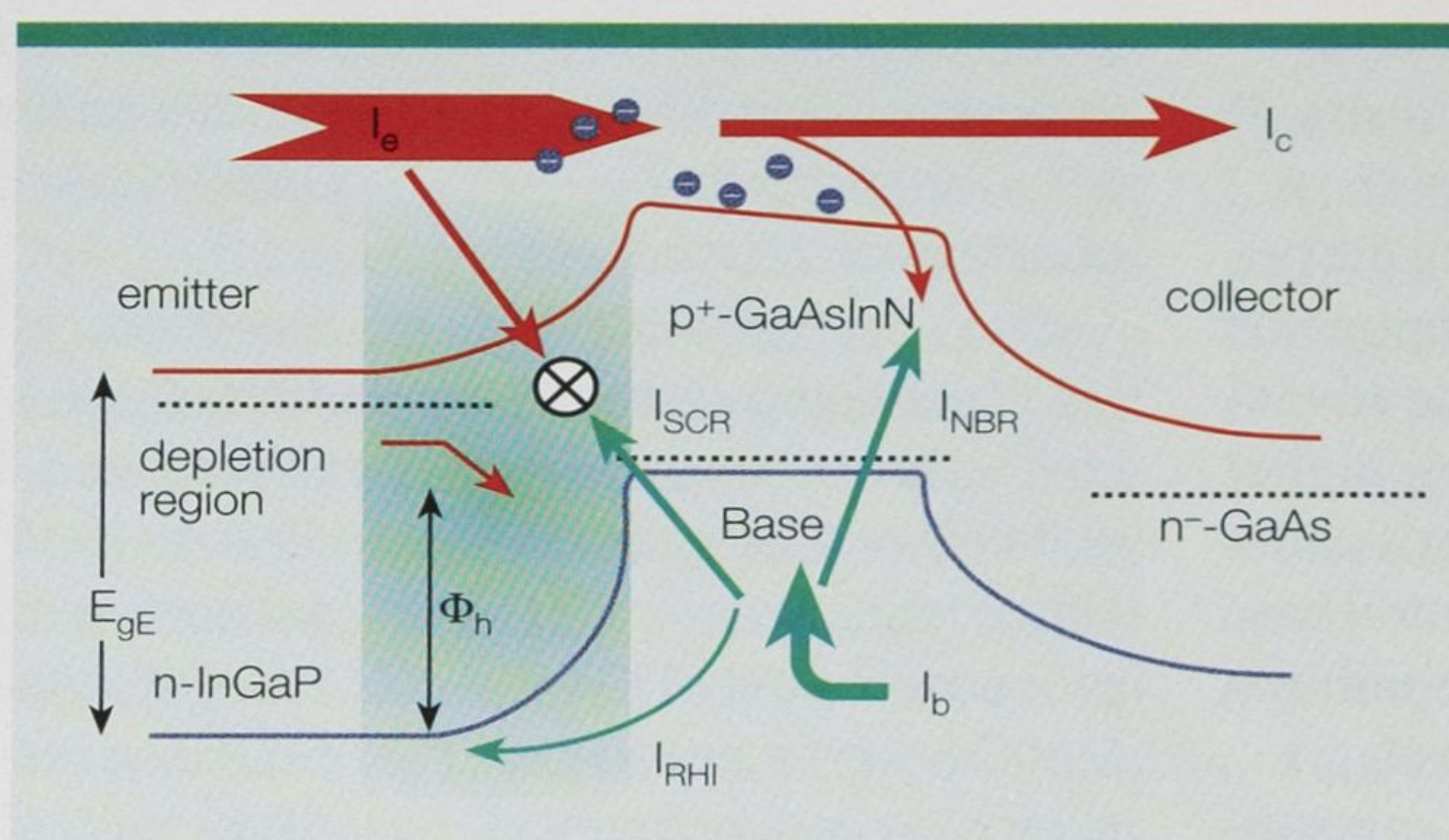


Fig. 1: GAIN-HBT devices consist of a compositionally graded GaAsInN base inserted into an otherwise standard InGaP/GaAs-HBT. The net result enhances collector current (I_c) while minimizing the key base current (I_b) components: neutral base recombination (I_{NBR}), space charge recombination (I_{SCR}), and reverse hole injection (I_{RHI}).

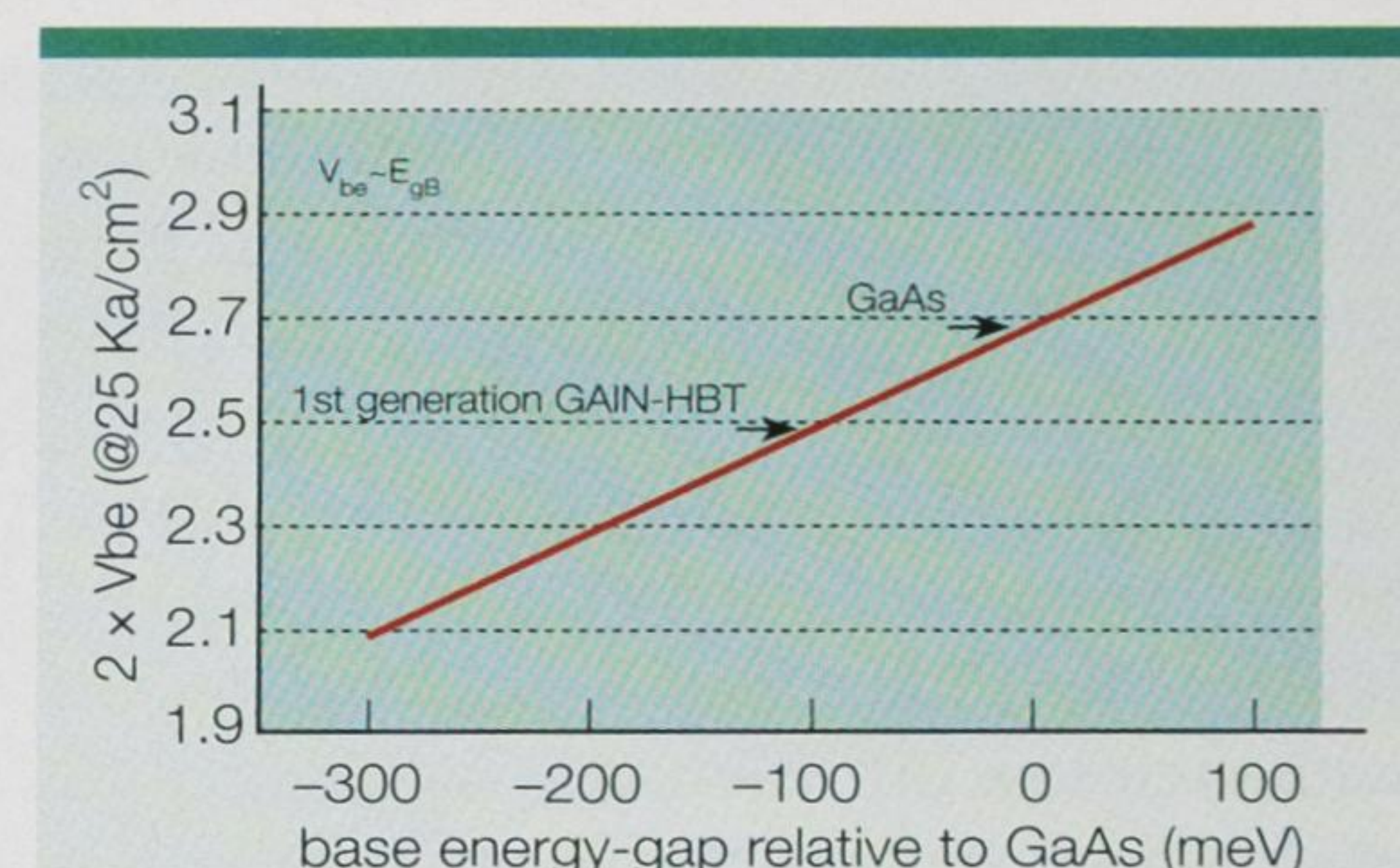
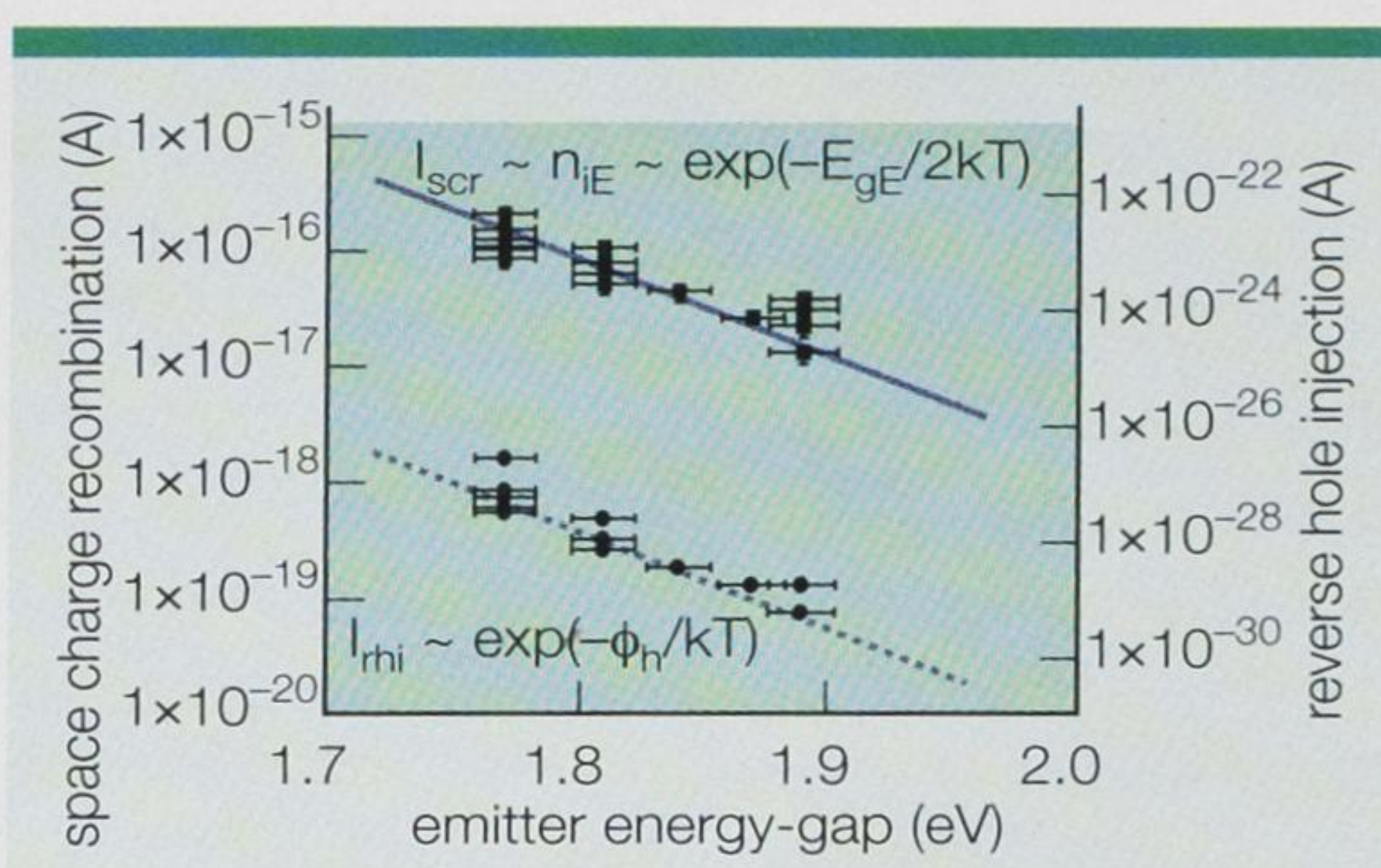


Fig. 2 (left): Increasing the emitter layer energy-gap (E_{gE}) reduces space charge recombination (I_{SCR}) and reverse hole injection (I_{RHI}), improving device reliability and enhancing stability over temperature and bias. Fig. 3 (right): Replacing two GaAs-based HBTs configured in series with two GAIN HBTs reduces operating voltage by 100 meV to 2.5 V, a critical threshold given today's battery technologies and mobile-phone architectures.

search for improved PA capabilities, new approaches to further enhancing the transistor's performance must be explored.

Bandgap engineering

At Kopin, efforts have been directed at engineering the bandgap of the base layer material – what we call GAIN-HBT technology. Incorporating dilute-nitride alloys into the base layer of the GaAs-HBT lowers the turn-on voltage, as well as enabling implementation of more sophisticated compositionally-graded device structures. Recently, we reported results from first-generation GaAsInN-HBT (GAIN-HBT) ICs in pilot production. As predicted,

using GAIN-HBT devices in the MMIC reduced turn-on, offset and knee voltages while improving speed performance and circuit stability with temperature and bias. These enhancements were achieved without any changes to our customers' device processing – a truly plug-and-play solution.

The baseline material structure of a GAIN-HBT transistor consists of an InGaP emitter, a graded GaAsInN base, and a GaAs collector (figure 1). This structure incorporates all of the previous improvements to our InGaP/GaAs-HBTs, but further leverages performance through the insertion of a new base layer material. Material properties play a key role in crit-

HBT MANUFACTURING

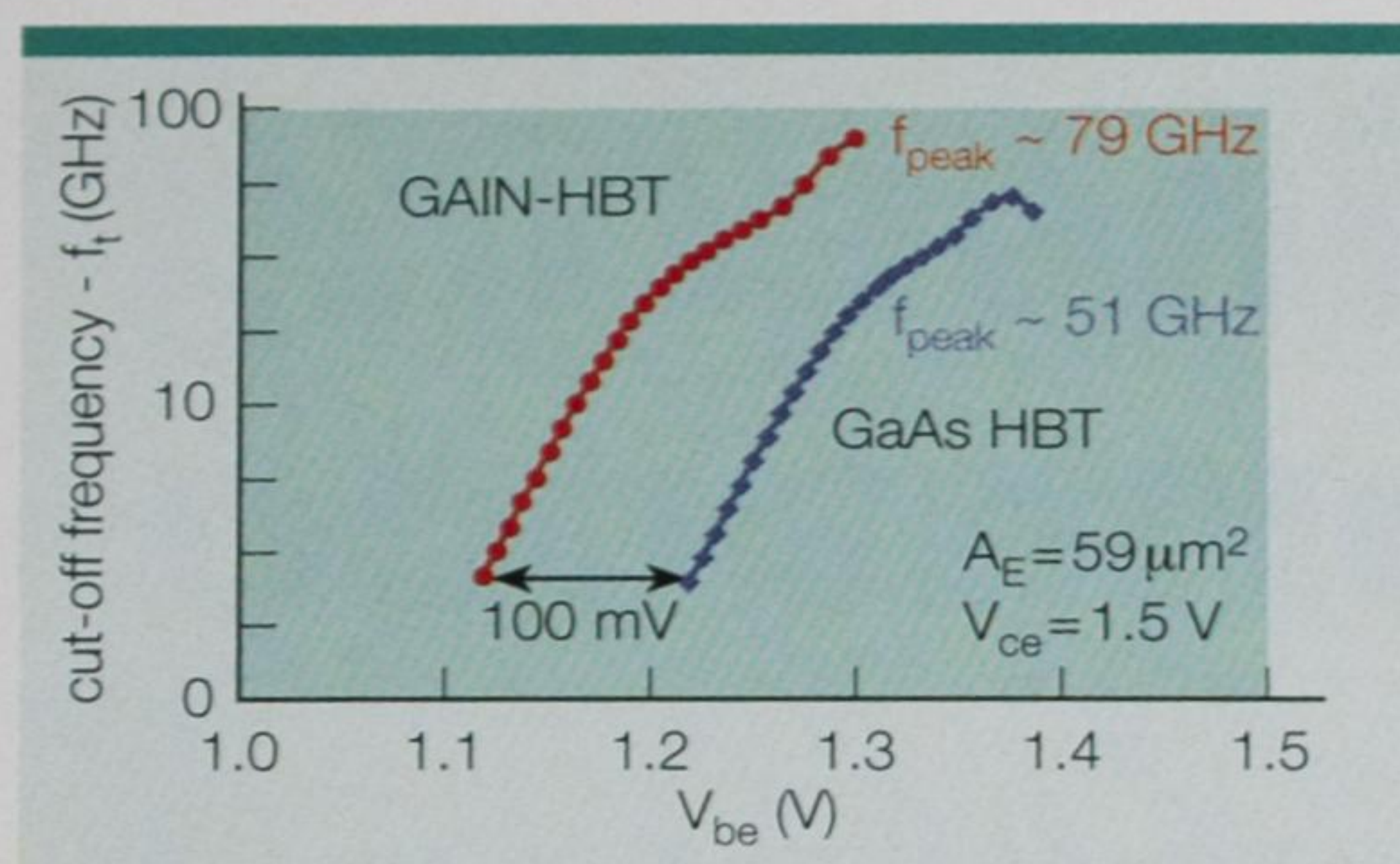


Fig. 4: GAIN-HBT technology can be engineered to enhance RF performance. Here, a 50% better maximum cut-off frequency is achieved in a GAIN-HBT device compared with a standard GaAs-HBT of similar collector structure.

ical HBT device parameters, including the primary base and collector current components depicted in figure 1. The performance advantages of GAIN-HBTs arise from their higher collector current and the suppression of undesirable base current components – neutral base combination (I_{NBR}), space charge recombination (I_{SCR}) and reverse hole injection (I_{RHI}).

The HBTs' wider emitter energy gap suppresses reverse hole injection, thereby enabling higher base doping levels – a key element of HBT performance. This combination means that HBTs can combine high DC gain with low base sheet resistance and short base transit times for increased RF power gain. Much of the early work on GaAs-HBTs was directed at achieving high, stable doping levels in the base, either by using carbon dopants (with their low diffusion coefficients), or by developing techniques that suppress beryllium dopant diffusion. GAIN-HBT devices use very high base doping levels ($4\text{--}5 \times 10^{19} \text{ cm}^{-3}$) produced by special growth techniques that compensate for the tendency of carbon doping to decrease with the addition of indium.

The collector structure of GaAs-HBTs also directly impacts on the transistor's breakdown voltage and microwave power gain. However, the addition of indium and nitrogen to the base layer has no effect on the device parameters typically governed by the collector design. With GAIN-HBT technology, collector thickness and doping can be readily tuned to meet specific RF power and robustness requirements, just as in standard GaAs-HBTs.

Reliability gains

In the early days of GaAs-HBT development, reliability was a concern for the newer, novel devices. However, in time, material engineering increased mean-time-to-failure (MTTF)

GAIN-HBTs combine plug-and-play with excellent reliability

New technology often faces formidable barriers to its adoption into high-volume products. In addition, circuit and process development costs, and reliability concerns, can derail even the most promising of technologies. However, the properties of GAIN-HBT devices can help reduce these barriers to entry and allow a smoother path through customers' arduous platform qualification procedures.

One advantage of GAIN-HBT technology is that it is built upon existing GaAs epitaxial and integrated-circuit fabrication processes. GAIN-HBT MMICs can be processed alongside conventional GaAs-HBT circuits, using identical etches, metallization and circuit designs. Consequently, GAIN-HBT devices can be inserted into established circuit products for enhanced performance.

GAIN-HBT devices are also intrinsically more reliable. This was recently demonstrated by the technical teams at

rates to over 1 million h. This was primarily achieved by optimizing the emitter's layer properties. First, the emitter's thickness and doping were adjusted to ensure the effectiveness of the ledge passivation of emitter material left around the device perimeter.

Once recombination at the surface of the base layer was suppressed with a properly designed emitter ledge, recombination enhanced defect reactions at the emitter-base junction were found to limit device reliability. Emitter properties again played a critical role in improving average MTTF. As larger emitter energy-gaps suppress both the space charge recombination and reverse hole injection components of the base current (figure 2), device reliability was improved through

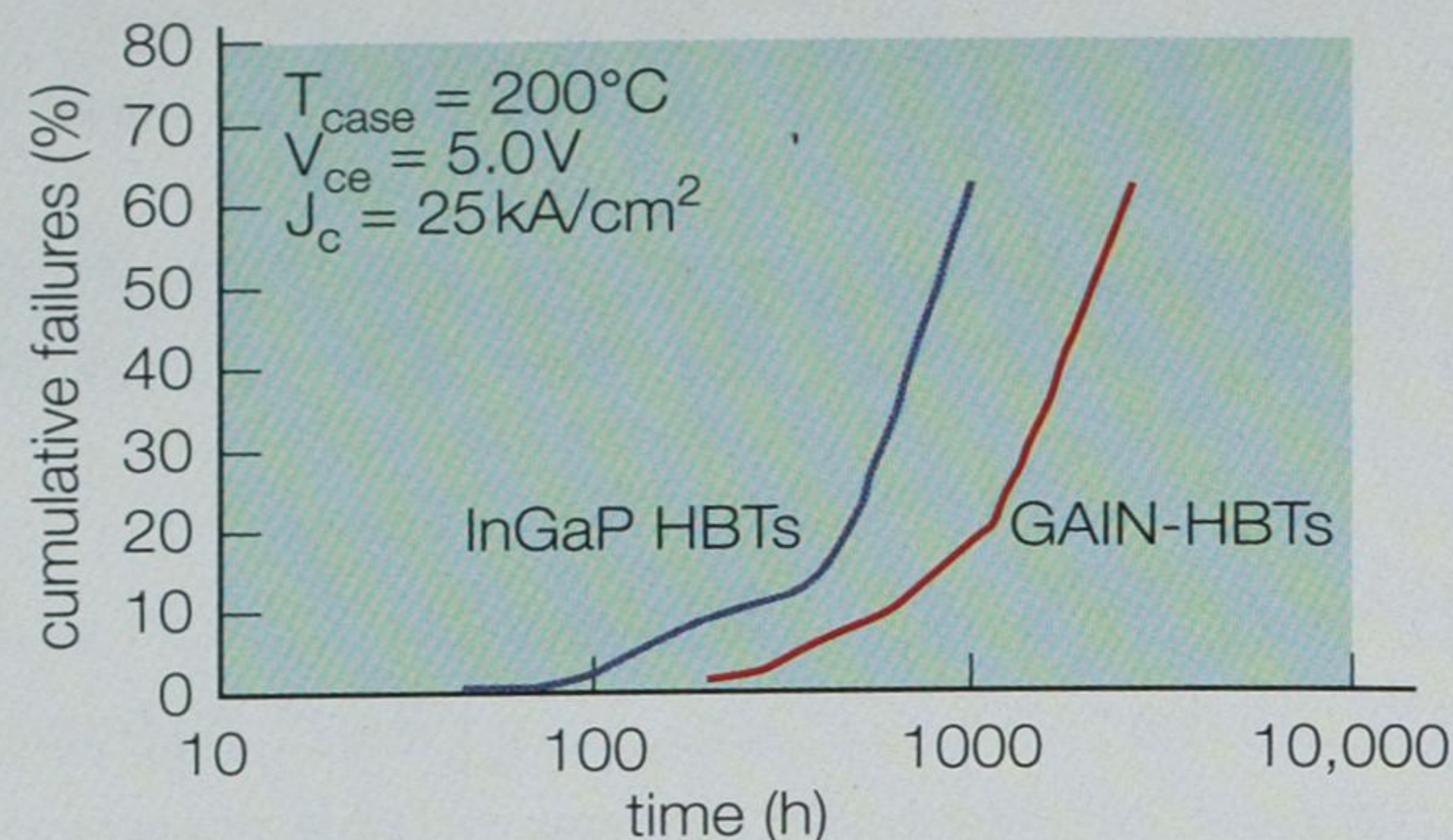


Fig. 5: GAIN-HBT structures offer excellent reliability. Accelerated ageing tests reveal that under typical operating conditions the lifetime of these devices exceeds that of GaInP/GaAs devices, at more than 1 million h.

Skyworks. In a presentation at the 2005 MANTECH Conference, GAIN-HBT devices exhibited MTTFs exceeding standard InGaP/GaAs-HBTs (figure 5). These results fulfilled expectations based upon the current understanding of GaAs-HBT reliability physics. The increased difference in energy-gap between the base and emitter layers in GAIN-HBT structures is expected to reduce recombination currents at the base-emitter junction, and lower the recombination-enhanced defect reactions that limit GaAs-HBT

reliability.

With proven gains in baseline device performance, high reliability and straightforward implementation, GAIN-HBT technology offers an effective, practical roadmap for the GaAs-HBT community. We anticipate a revolutionary impact on the design of wireless power amplifiers and high-speed digital integrated circuits currently employing GaAs-based HBTs, including lower-voltage operation, reduced power consumption, improved linearity characteristics and higher-speed operation.

increasing the emitter's energy-gap – typically by using an InGaP emitter.

Device performance also benefited from suppressing the base current with larger emitter energy-gaps, which improved properties such as the stability of the DC characteristics with both bias and temperature. Although InGaP and high aluminum-containing AlGaAs emitter layers both minimize base current, the lower conduction band discontinuity of InGaP can deliver ideal injection efficiency. For this reason, GAIN-HBT structures retain InGaP as the emitter material.

Next-generation, feature-rich cellular phones will continue to demand greater performance and robustness due to increased data-rates and duty cycle requirements. While

modifications to the emitter and collector have helped enhance GaAs-HBT performance, even greater improvements can be produced by bandgap engineering of the base layer. Kopin's GAIN-HBT technology offers a greater level of design freedom by utilizing dilute nitride GaAsInN alloys to enhance the various device characteristics that are governed by base-layer properties.

One key parameter is the transistor's turn-on voltage. GaAs' relatively large energy-gap leads to a fairly high turn-on voltage (~ 1.35 V @ 25 kA/cm²). When two transistors are stacked together – which is a common configuration for PA control circuitry – the minimum voltage required to operate the circuit is fundamentally constrained by the GaAs base layer. Previously, lower energy-gap materials lattice-matched to GaAs have not been available to address this issue. However, nitrogen-containing III-V alloys are known to have unique bandgap-bowing properties, enabling the growth of reduced energy-gap materials that can be lattice-matched or strain-minimized to GaAs. Just a modest 100 mV reduction in the base-layer energy gap can

extend the minimum operating voltage below 2.5 V for GaAs-HBT PAs (figure 3).

The higher collector current resulting from a lower-bandgap base material alters the ratio of collector and base current components (figure 1) in ways that improve transistor stability and efficiency. Researchers at Virginia Tech, VA, and elsewhere have shown that the DC characteristics of GAIN-HBT devices are stable from 50 to 200 °C. Because GAIN-HBT devices use a lower energy-gap material in the base, they are really double heterojunction structures. Such structures have additional device performance benefits, but extra care is needed to suppress barriers to electron flow at base-emitter and base-collector junctions, as is routinely done for high-speed, higher-cost InP-based devices. GAIN-HBT devices also possess the expected lower offset voltages required to bring the bipolar transistor out of saturation, which can be used to improve the RF power efficiency of amplifier circuits.

Perhaps GAIN-HBT technology's most exciting feature is its use of sophisticated base-layer structures. True bandgap engineering is achieved through the incorporation of com-

positional grading across the base layer. The resulting built-in quasi-electric field accelerates electrons through the base, lowering the overall transit time. Improved electron transport enhances several fundamental device properties. Peak current gain is increased in devices employing compositional grading due to a reduction in neutral base recombination. At the same time, microwave performance is improved through a cut in base transit time (figure 4). This ability to simultaneously enhance DC and RF properties equips device and circuit designers with new tools to optimize GaAs-based PA performance. ●

Further reading

L Rushing *et al.* 2005 *CS MANTECH Digest* p57.

B Dickerson *et al.* 2003 *GaAs MANTECH Digest* p295.

R E Welser *et al.* 2004 *J. Phys: Condens. Matter* **16** S3373.

Matt Micci is VP of sales and marketing for the GaAs HBT group at Kopin. Roger Welser is director of Transistor Technology.



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PHOTONIC CIRCUITS

Infinera moves in for the long haul as fiber recovers

At the height of the photonics boom, Dave Welch helped orchestrate the merger of SDL and JDS Uniphase. Now chief technology officer at start-up Infinera, he's led the development of a digital optical network system based on massively integrated InP chips. **Michael Hatcher** hears about Infinera's recipe for success as growth returns to the optical telecoms business.

Californian start-up Infinera has racked up \$205 million in venture financing on its way to developing a networking system that is powered by two highly integrated InP chips. Infinera's CTO Dave Welch – who was previously at SDL and then JDS Uniphase, following the pair's high-profile merger in 2000 that was initially valued at \$41 billion – describes how Infinera has developed its system using a top-down philosophy and adopting manufacturing techniques used in other areas of the electronics business.

Michael Hatcher: What does Infinera have to show for its \$205 million financing?

Dave Welch: The majority was there to build a telecommunications system. A smaller fraction was used for the development of photonic integrated circuits [PICs] based on InP. We've developed two parts, a transmitter and a receiver. The transmitter carries 10 wavelengths, each operating at 10 Gb/s, and combines the functionality of lasers, modulators, electro-absorption modulators and multiplexing elements, as well as structure for wavelength locking and power control.

The receiver side has the inverse of that: the demultiplexer, photodiodes and more control structure. Essentially, we have a standalone 100 Gb/s DWDM transmitter and receiver, based on two chips made here in Sunnyvale at our own facility.

MH: What chipmaking facilities do you have?

DW: It's probably one of the world's most advanced optoelectronics fabs. We're heavily focused on process control, and have taken a lot of the tools, philosophies and manufacturing processes from the [wider] electronics industry – both silicon and III-Vs – that weren't previously used in optoelectronics, for example our metrology tools. We're also



Infinera CTO Dave Welch says that the company is growing ahead of expectations, with systems deployed and carrying live traffic in North America, Europe and Asia.

monitoring all of our process parameters, so that we have hundreds of points with which to monitor our process capability.

From a materials and a process control point of view, I can't say we're the absolute best in InP, but we're one of the very few leaders.

MH: How did you go about developing the PIC technology?

DW: We were a bit different to most. First, we set out our vision of the component we wanted to make. We looked at the market and saw that the rest of the world was driving network systems towards all-optical solutions. There are some shortcomings to that approach, and we believed in a different technology.

[For our solution] you need very low-cost optical-electronic-optical components to create a digital optical network. We set out to build

"We [Infinera] probably have one of the world's most advanced optoelectronics fabs."

DAVE WELCH, INFINERA

a team to make a component that nobody had made successfully before. So we hired some of the best InP design teams in the industry. We also hired guys from the LED industry, because of the very materials-centric, high-volume manufacturing philosophies involved in that business [Fred Kish, Infinera's VP of development and manufacturing, was previously at Agilent Technologies, where he was instrumental in the development of AlInGaP LEDs]. Combining that basic knowledge [of InP] and experience in high-volume optoelectronics manufacturing has been a huge success, and has really enabled us to change the industry.

We began shipping products about a year ago and our PICs have been deployed in live networks since last fall. We've been ramping since then, and are now manufacturing a pretty reasonable number of wafers.

MH: How do you deal with the overheads of running an InP fab?

DW: I don't think the inherent costs of a fab are as great as people state. If you look at distributed feedback [DFB] or Fabry-Perot laser chips, they are cheap and yet come from places where the fabs aren't running 24/7. It is different to silicon fabs – you're using technologies that were built around smaller wafer sizes. We're pushing the technology to the next generation, and so we also run a lot of engineering wafers through our fab.

We've also developed 10 × 40 Gb/s technology, so we can make a small die with

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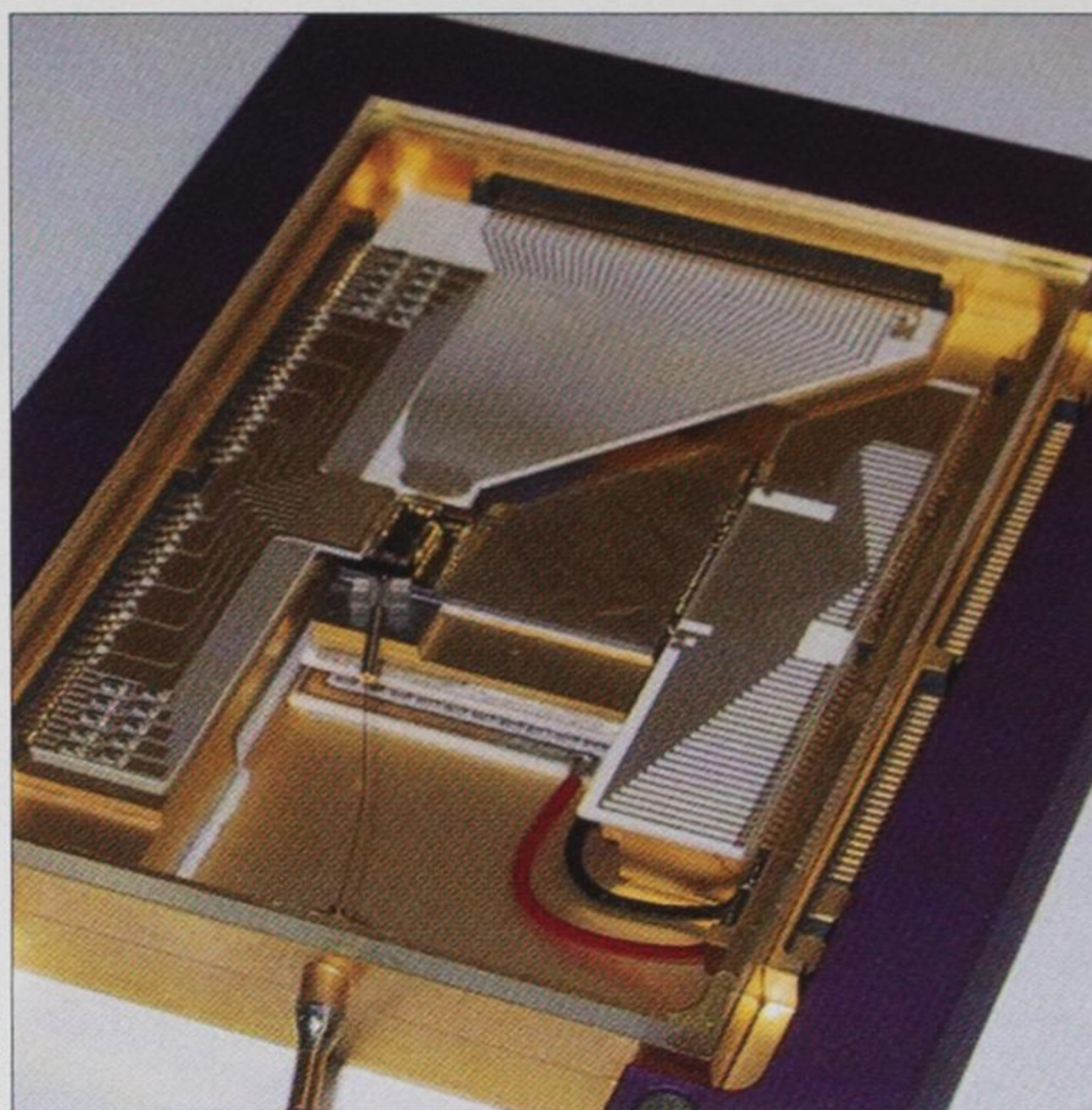
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nology, so we can make a small die with 400 Gb/s capacity. We have engineering projects looking at how to make these things work without cooling, and we've shown that that's possible as well.

MH: What's driving 400 Gb/s development?

DW: The cost of high-capacity systems is dominated by optics. The more of the optics that you can pull onto a monolithic chip, the greater the impact you can make on the overall cost structure. And if you can get the cost of the transmission components to approach that of the amplifiers then all of a sudden the network architecture changes. Then you've got a true network where you can add and drop information everywhere in the system, and manage the bits electronically instead of in the optical realm. That gives the carrier a huge advantage through better performance monitoring and bit management.

But the key is to eliminate the cost of converting photons to electrons. If you can make that transformation cost small enough, then you are far better off doing all of the bit management in electronic form.



Infina's 100 Gb/s transmitter module is based around highly integrated InP optoelectronic components. Combined with a similar receiver module, the technology is the key to Infina's digital optical network system, which network operators say allows them to deliver high-bandwidth optical services more flexibly than they can using conventional analog dense wavelength-division multiplexing.

MH: How can Infina make the vertically integrated business model work when the likes of Nortel and Lucent have failed?

DW: That's a good question. It's all about enabling the component breakthrough and then taking advantage at the system level. Today, I can't get the components [that I need] for our system from anywhere else and I believe it will be a number of years before such components are commoditized, or are readily available in the outside world. Certainly if they are, we'll focus our fab on areas that give us differentiation.

If you're in the optics business, you need to have control over the optics that give you differentiation. The great breakthroughs in optical communications have been made at the component level. Back in the early 1990s it was the erbium-doped fiber amplifier (EDFA) which changed the landscape in communications systems and enabled the cost benefits of wavelength-division multiplexing (WDM). Nortel rode on the back of two technologies—lithium niobate and III-V materials for 10 Gb/s electronics. Without those component breakthroughs they would have been unable to pen-



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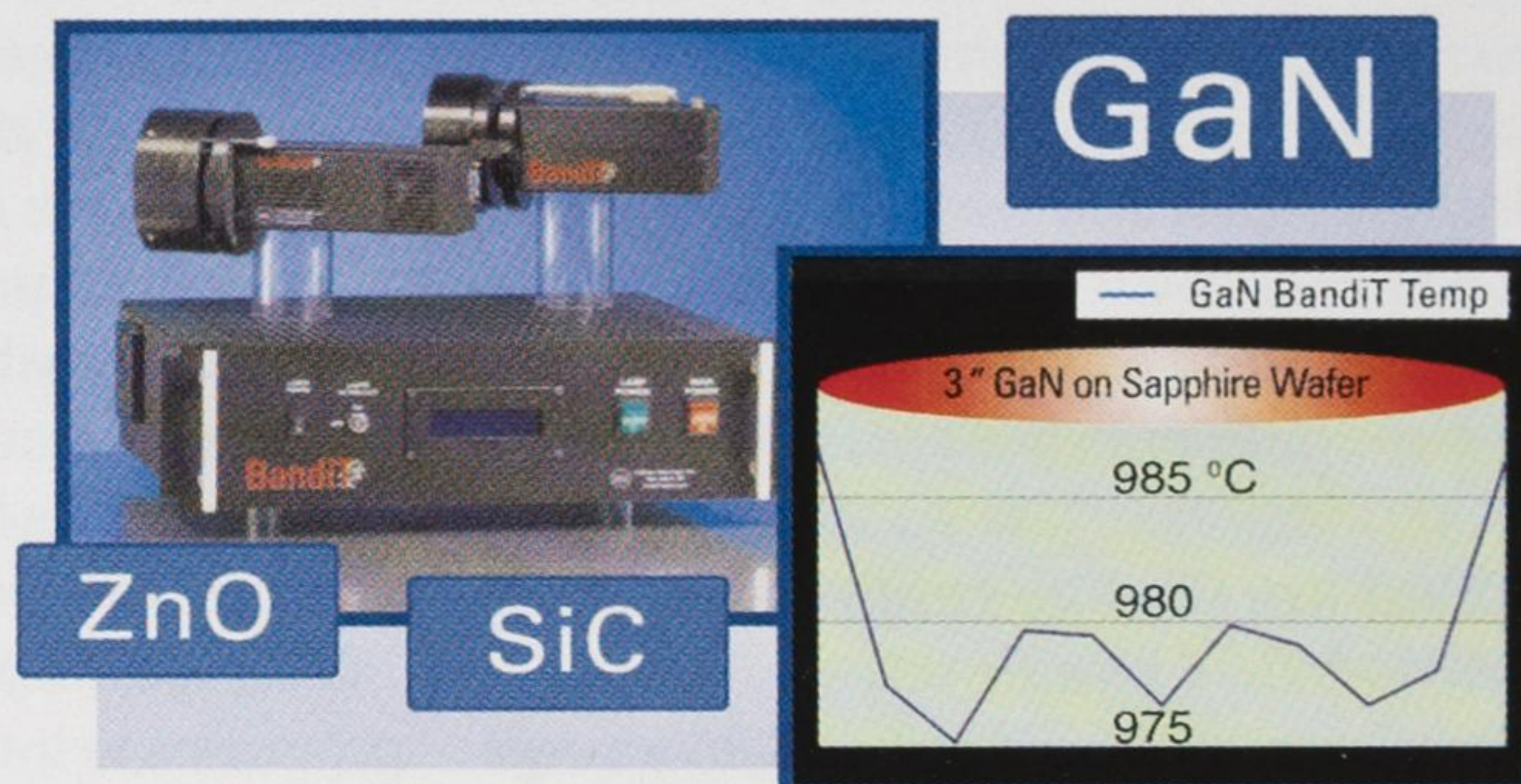
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COVER STORY

PHOTONIC CIRCUITS

strate the market, as they were not the dominant player in 2.5 Gb/s transmission systems.

On the other hand, we do buy optics from external sources – we use a lot of XFPs on the client side [of the system]. On the line side we feel that we can improve system performance by making something that isn't available in the wider market. But for those companies that are selling what I'd call commodity chips, it's a pretty tough market these days. The volumes just aren't there.

MH: How would you describe business at the moment?

DW: Somewhere between very good and exceptional. We're very pleased with the uptake of our product, and when we deploy a 2000 km route, it comes up in a very short amount of time compared to our competitors. That's indicative of the robustness of our product. Customers have been very pleased with that, and at this point the growth rate of our business is exceeding expectations.

MH: Does that growth reflect a general upturn, or are you taking market share?

DW: The majority is from market share – however, the overall market is also growing. All the customers that we've been engaged with have indicated that data traffic continues to grow at a healthy clip. They've now exhausted their systems inventories, and their acquisitions of other networks and excess bandwidth have been absorbed. So I think we're starting to see a recovery too. For us, it's a multi-billion-dollar market and we have a chance to take a good chunk of it. We have traffic on our PICs in Asia, North America and Europe, and I feel pretty confident about our prospects.

MH: What are the key challenges facing Infinera now?

DW: Our first phase was very engineering-oriented and company-centric, and we've rapidly transitioned to being customer-centric. I think a good measure of that can be seen with our Level 3 deployment, which is going really well. Now, the challenge is to drive market share and profit growth while making sure that we're innovating for the next generation.

MH: How do you see the future of the InP photonics sector?

DW: There are some products that will be standardized – I think you'll end up with two or three winners and then half-a-dozen hangers-on. With more modules based on multi-source agreements, only the companies that

PIC deployments in 2005

- January: Germany-based network operator Freenet deploys Infinera's digital optical system to carry Internet traffic to 6 million customers, saying it took just three days to turn up the initial 700 km route.
- May: Level 3 Communications announces that it will install Infinera equipment across a "substantial" portion of its 23,000 km fiber-optic network in the US and Europe. Installation is expected to be completed by the end of the year.
- June: OnFiber Communications, US, deploys PIC-based equipment in a number of US metropolitan networks.
- July: After a nine-month trial of Infinera equipment, Citynet installs, tests and turns up a 1100 km ring network in three days. "Other systems would have required four to five times as long," said Citynet.

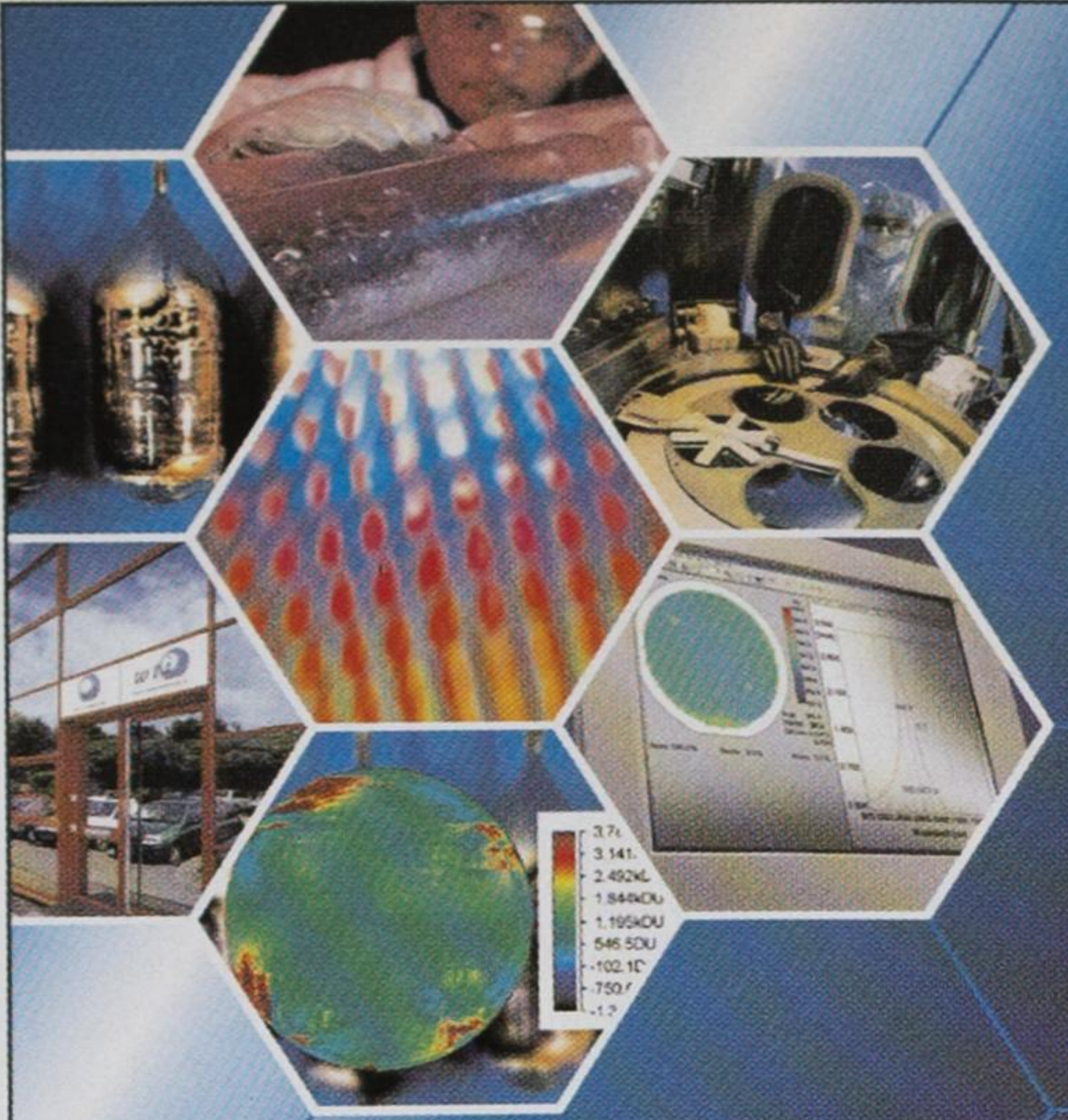
can differentiate in that area will survive.

It's unclear to me why you need foundries for that type of product. You have to be able to drive enough volume to justify the business that you're in, and by going to a foundry model you just split your profit margin. And there are some foundries out there, so the industry doesn't need to establish them – they already exist. The problem is that there just isn't enough volume in the telecoms market, or the right product set, to do that.

Outside of the component we make ourselves there is a unique set of functionalities [that we require], and if we could find processes capable of doing that then a foundry model makes more sense. However, if all the world wants is lots of DFB laser chips I'm not sure that the foundry buys you a lot.

The foundry's value is to apply common processes to lots of different applications, but if there are only a small number of applications then I'm not sure about the need for it. If you need a lot of different functions then maybe that model starts making more sense. But, unlike silicon, optoelectronics only has a small set of functions to serve – essentially to transmit or receive light. Until you start trying to manage the bits photonically I'm not sure how diverse that set of applications really is. ●

Infinera's Fred Kish will present a talk at CS-MAX 2005 on the company's PIC development and the manufacturing methods it has adopted. See compoundsemiconductor.net/csmax for the full conference agenda.



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Bookham targets integration sweet spot for metro network

A tunable laser and a broadband modulator provide the best option for next-generation metro networks, according to Bookham. This combination can ease the transition from fixed-wavelength components to broadband monolithic transmitters. **Richard Stevenson** reports.

Optoelectronic integration represents the future for InP, says Andy Carter, Bookham's vice-president of research and development. He believes, however, that some technologists have become carried away with producing very large, highly integrated chips, and that they are overlooking issues of cost and yield.

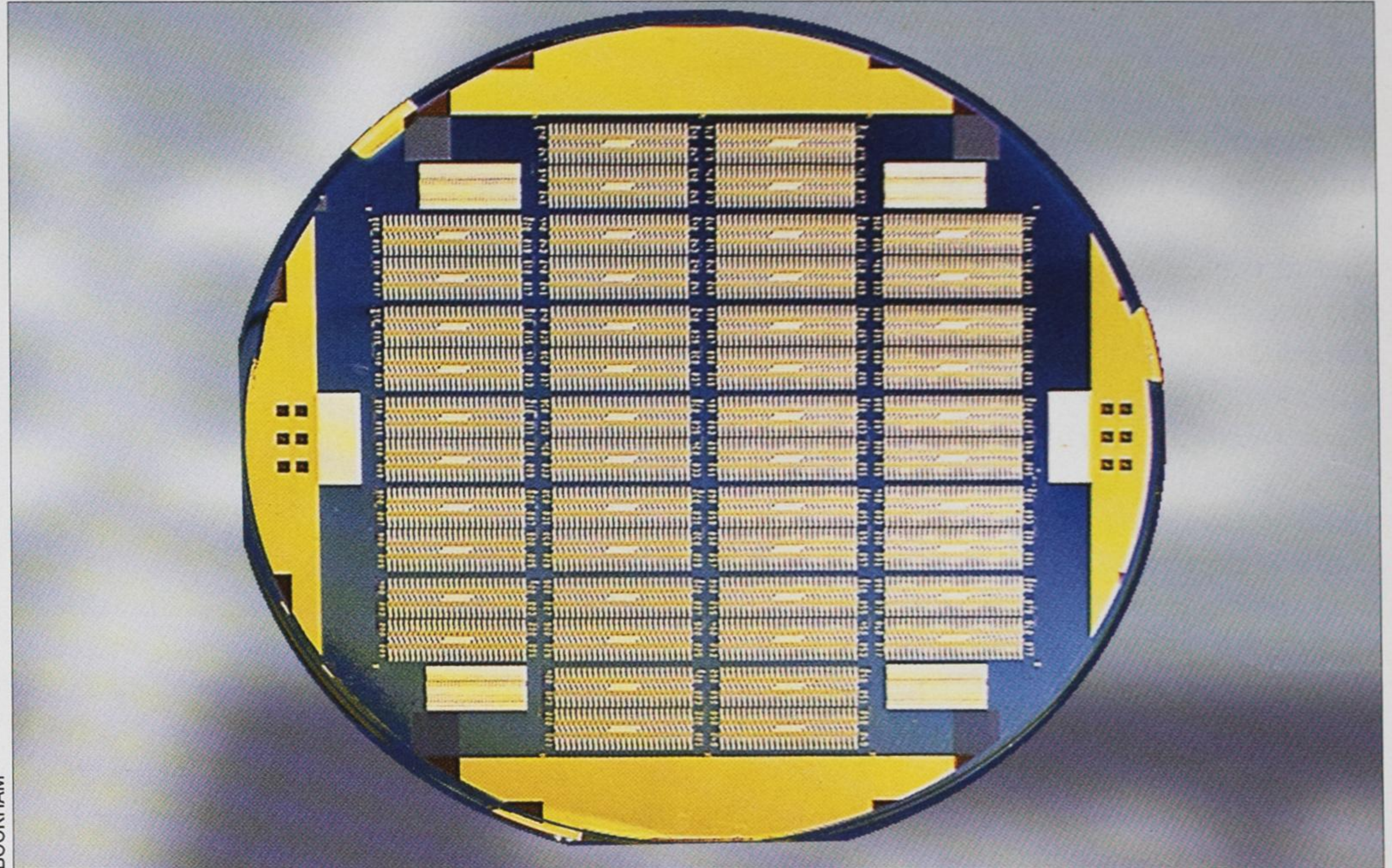
"[Bookham has] the right balance between high yields and the performance that the market demands," said Carter. According to him, Bookham's unique combination of a tunable laser and an integrated broadband modulator provides the ideal small-form-factor solution for 10 Gb/s metro networks.

Bookham's method is to select the best materials technology for each device, as opposed to manufacturing overly complex devices that "force functions" onto a particular material system. The company believes that its linear integration approach, which uses a sequence of components for a signal channel rather than parallel integration of multiple channels, is driven by market demand.

Bookham has packaged a digital supermode distributed Bragg reflector (DS-DBR) laser with a spot-size converter Mach-Zehnder (SSC-MZ) modulator to produce a broadband transmitter that targets the 10 Gb/s metro overlay network. This module, which builds upon the company's fixed-wavelength design, uses an industry-standard butterfly box, with the laser and modulator mounted on a common thermo-electric cooler to improve stability.

Carter points out that Bookham's customers are not demanding higher levels of integration in which the tunable laser and broadband modulator are combined on the same chip. However, the company's laser and modulator could be scaled monolithically to meet future network requirements.

Although Carter believes that monolithic transmitters have issues associated with cost and yield, fixed-wavelength monolithic designs are available on the market. For example, Apogee Photonics, which was formed by



Bookham produces tunable laser chips at Caswell, UK. The lasers are designed at Caswell and in Kanata, Canada, prototyped in Paignton, UK, and assembled in Shenzhen, China.

the merger of T-Networks and ASIP (see p15), manufactures a 10 Gb/s electro-absorption modulator and a single-frequency laser on a single chip; and Infinera Corporation has deployed highly integrated photonic circuits in its own digital network system (see p29).

Slashing inventories

Bookham's DS-DBR lasers, which were first launched at OFC 2004, are said to offer several advantages over fixed-wavelength sources and to make ideal drop-in replacements in metro networks.

Today's metro networks typically operate at 2.5 Gb/s across the C-band (1530–1565 nm) using fixed-wavelength lasers. However, Carter says that the move from circuit-based services to packet services has increased the deployment of 10 Gb/s Ethernet networks. Bookham's tunable laser, alongside its broadband modulator, can be adjusted to emit at any wavelength within the

band and to support the increased data rates. Tunable lasers benefit manufacturers because they can reduce the number of components that are produced, and customers can carry a vastly reduced inventory, says Carter.

One advantage offered by DS-DBR lasers that is highly valued by Bookham's customers is what Carter describes as "wavelength protection". Since tunable laser emission can be set remotely, if one of these lasers is fitted into a network it can be used to replace any fixed-wavelength laser that fails. And looking further ahead, customers may be able to improve data transmission by adjusting the wavelengths of their tunable lasers, noted Carter. The laser also features "dark tuning", which prevents network interference by switching out transmission when the laser is retuned.

Bookham's 1.7 mm-long DS-DBR design features four main sections: a rear phase grating, which produces a comb of reflection lines; a phase control section; a multiquantum

well gain section; a multicontact grating at the front of the device, which is used for coarse wavelength selection (figure 1). A semiconductor optical amplifier is situated beyond the front grating to provide 3–4 dB of gain.

The DS-DBR laser is capable of broadband gain. Its emission wavelength is coarsely tuned by adjusting the front and rear gratings, before the phase current (I_{phase}) is used to fine-tune the wavelength. The front grating has a broad reflection profile, but the rear grating contains seven sharp reflection peaks between 1520 nm and 1560 nm spaced 6.8 nm apart. These sharp peaks control the lasing wavelength and prevent modal competition by selecting just one of the available longitudinal modes.

The tunable lasers are manufactured in a similar way to the fixed-wavelength sources that Bookham has produced for many years. The process starts with two separate MOCVD growth steps on 3 inch InP wafers. This is followed by grating fabrication, further growth, and additional steps that involve dielectric and metal depositions and photolithography. The wafer is then thinned, cleaved, coated and finally packaged. The resulting lasers have a 42.5 nm tuning range that covers 214 different telecommunication channels, and an output power of 13.5 ± 0.1 dBm.

Broadband modulators

Bookham has developed broadband MZ modulators that can be integrated with the company's lasers to form fullband tunable transmitters for metro networks. Until recently, Carter believed that the linearity of these modulators might be insufficient for broadband operation, and he was surprised that only small adjustments enabled this device to cover the entire C-band.

MZ modulators are sophisticated optical switches that contain an interferometer. Laser light entering the device is split into one of two paths, and the phase difference between the two recombining signals dictates the device's output. If no phase difference exists, recombination is constructive (the "on" state), but if the two signals are exactly out of phase, destructive interference occurs corresponding to no light output from the device (the "off" state).

The relative phase is adjusted by biasing the two waveguides. Changes in the applied electric field alter the refractive index of the waveguide, adjusting its refractive index and its relative phase shift. In fact, Bookham has designed these modulators to split the incoming light into two signals of differing magni-

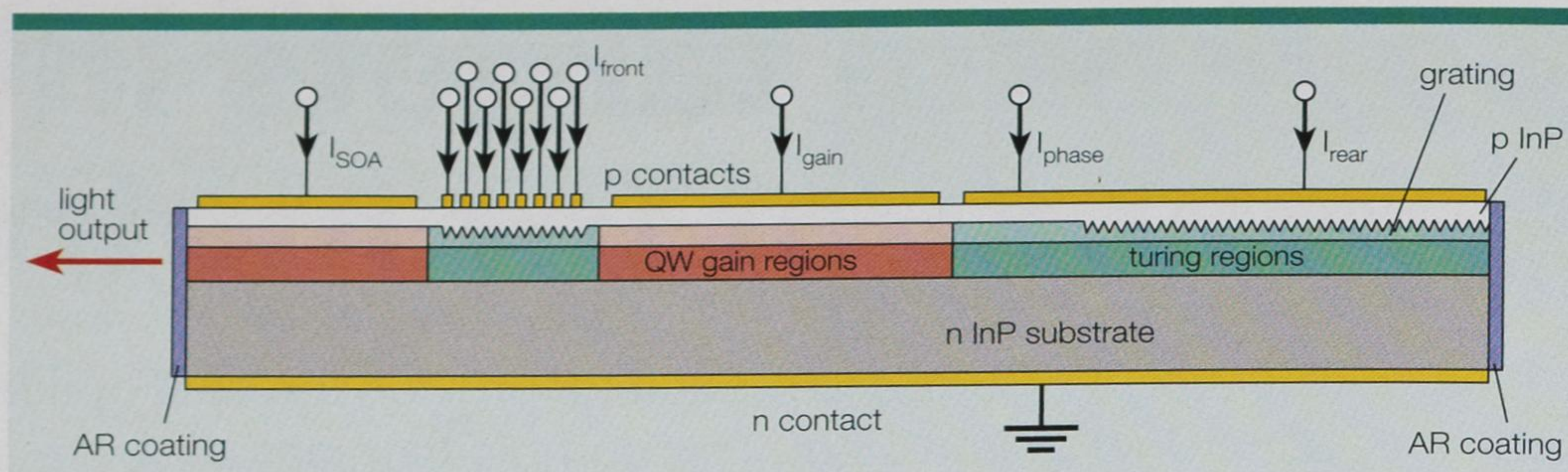
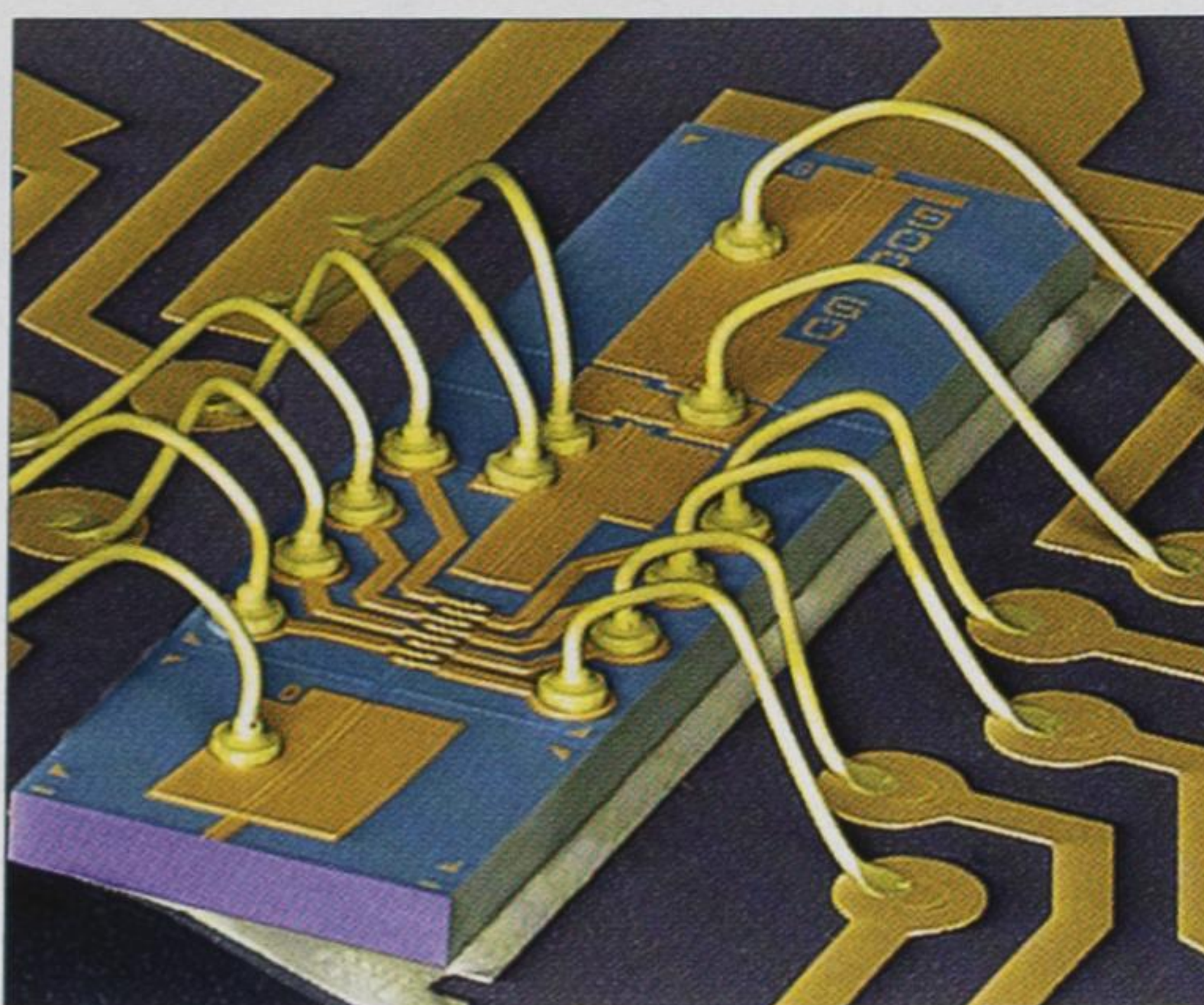


Fig. 1. Bookham's tunable lasers have a broadband gain, and the emission wavelength is coarsely selected by adjusting currents for the front and rear gratings (I_{front} and I_{rear}), and then fine-tuned with I_{phase} . The output power is adjusted with I_{gain} and I_{SOA} .



Varying the current applied to the contacts of the tunable laser can sweep its emission across the entire C-band, which is used in metro networks. Bookham hopes that this feature will fuel the sales of replacement parts for fixed-wavelength emitters.

tude. By using differential biasing, the device can impart a negative chirp to the emitting light. This increases the distance that the light can propagate before dispersion compensation is needed.

Bookham is now producing its third generation of MZ modulators, although these latest devices are the company's first to be really suited to broadband operation. "The InP modulator has its genesis within Nortel, who were pioneers of this component from the mid-1990s onwards," said Carter.

Bookham has built on Nortel's earlier development of low-voltage modulators by improving features such as chirp and extinction ratio (the difference in light intensity between the on and off states). Carter cites the introduction of SSCs as one example of a technology that has been used to meet the changing demands of customers. Earlier modulators had a very small spot size, which made them difficult to package with a low loss. However, the SSC delivers efficient, low-cost coupling into the MZ waveguide.

Process control

The company's latest SSC-MZ modulator, which is used in products such as the LMC10 series of transmitters, has an overall chip length of 3 mm. Incorporated into the device is an input SSC, an MZ modulator, a multi-stage electro-absorption variable optical attenuator (VOA), a tap/detector that can be used with an external circuit to adjust the bias on the modulator and optimize performance, and an output SSC.

A key advantage of the SSC-MZ modulator is that the performance of the VOA and detector, as well as the RF bandwidth, which reveals the maximum switching speed of the device, can be predicted and controlled without screening every manufactured component. Instead of full-scale testing, the RF performance of a small proportion of the modulators is determined by chip-on-carrier measurements. Insertion losses, switching voltages, DC extinction ratios, and absorption as a function of voltage are also measured for various wavelengths.

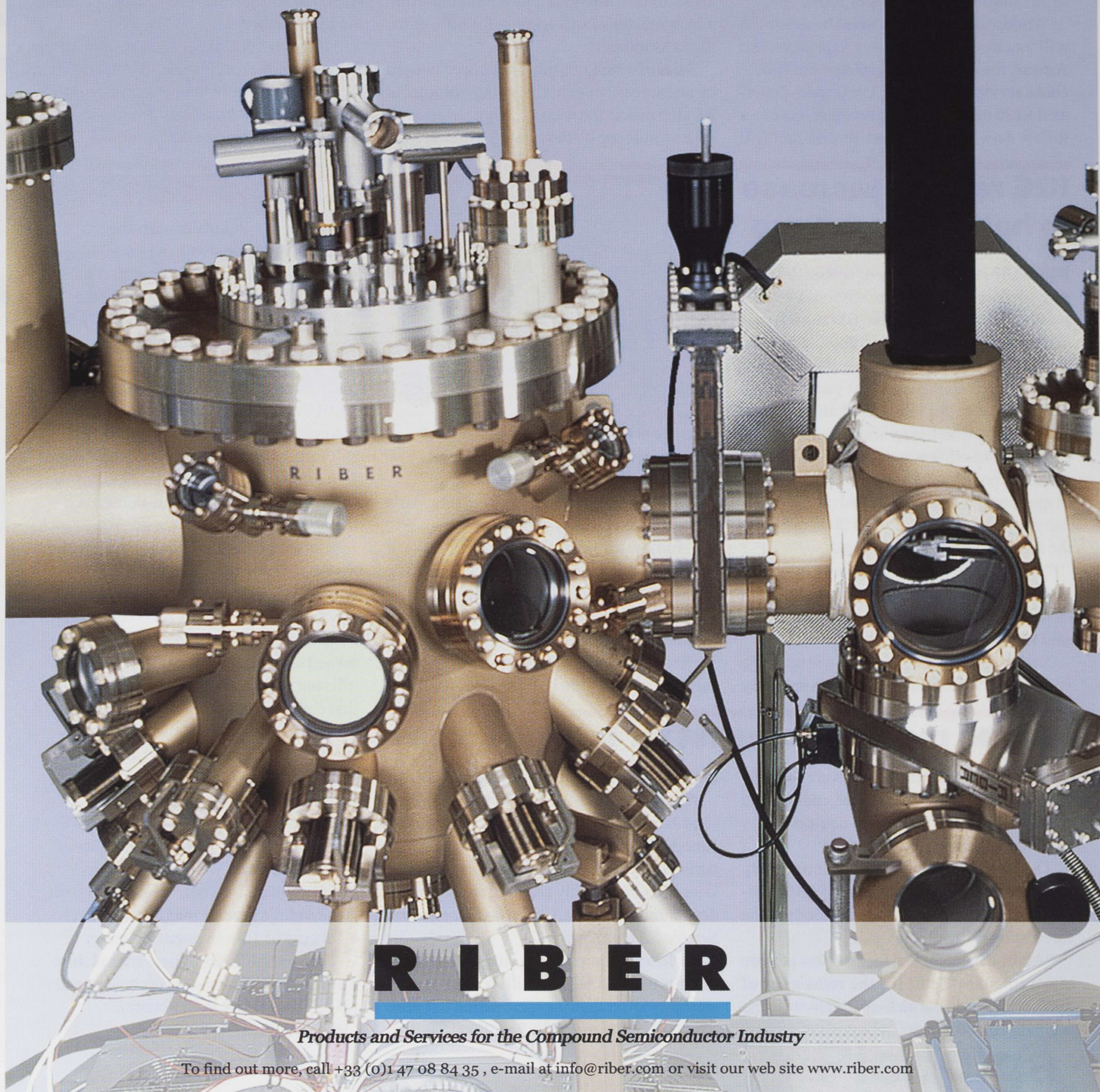
Carter says that after recording data from more than 20,000 devices fabricated on more than 100 wafers, Bookham has demonstrated the high yield of the process. This is because the chip's location on the wafer produces only small variations in performance, provided that the wafer has been grown and processed to specification. The performance of Bookham's MZ modulators is at least the equal of their larger legacy LiNbO₃ rivals, which are already deployed in metro networks, says Carter.

In trials, Bookham's integrated laser/modulator package has transmitted 10.7 Gb/s across the whole C-band, through dispersion of 1600 ps/nm over standard industry fiber with penalties below 1 dB. The company will start sampling the transmitter to customers later this year. The response could shape the type of products seen in tomorrow's network, and the level of integration seen in optoelectronic components.

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Freiberger makes gains as GaAs ramps

By Richard Stevenson

Market research firm Strategy Analytics predicts that the global semi-insulating (SI) GaAs substrate market will increase by 43% in terms of area over the next five years.

Sales of SI GaAs substrates, which are used by the microelectronics industry to make devices such as power amplifiers, are expected to rise from 14 million square inches in 2004 to 20 million square inches in 2009.

Worldwide revenue for SI GaAs substrates will increase by 9–10% each year, says Asif Anwar, the director of Strategy Analytics' GaAs service. In 2003 SI GaAs sales generated \$136 million, and, if revenue increases follow Anwar's prediction, this market will

be worth more than \$200 million by 2009.

Freiberger Compound Materials, which has the second largest share of this sector, is continuing to make gains on the market leader, Sumitomo Electric. The shipments from these two manufacturers, along with those from third-placed Hitachi Cable, accounted for more than 90% of all wafers shipped in 2004.

Although 2003 was expected to mark the cross-over from 4 inch to 6 inch material, 4 inch substrates still account for 50% of the SI GaAs market.

Sales of 4 inch substrates have been buoyed by an increase in manufacturing volumes at RF chip maker Skyworks. Eudyna of Japan is also producing its devices on a 4 inch line,

even though the company has both 4 inch and 6 inch facilities.

Anwar says that a rise in the use of HBT technology for cell-phone power amplifiers is increasing the demand for substrates produced by vertical gradient freeze (VGF) technology. AXT uses this technology exclusively, Sumitomo and Freiberger use both the VGF and the liquid encapsulation Czochralski (LEC) technique, while Hitachi Cable uses the LEC method only.

Although AXT had just a 6% share of the SI GaAs market in 2004, Anwar believes that the company should not be "written off". He says that AXT is pricing its products aggressively and has good cash reserves.

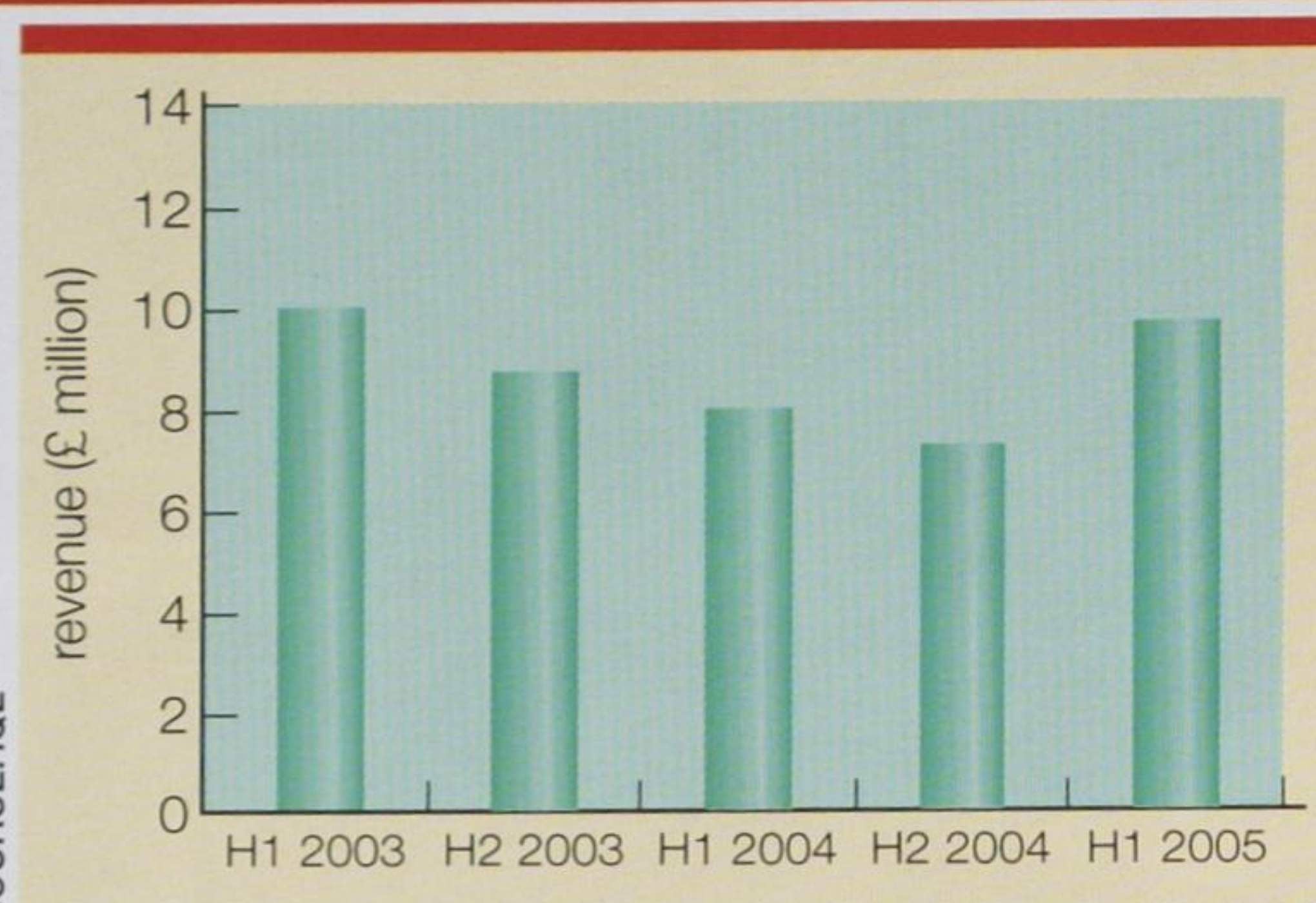
IQE reports increase in half-year revenue

IQE, a UK-based producer of epitaxial wafers and substrates, has posted revenue of £9.7 million (\$17.3 million) for the fiscal half-year ending June 30. Sales were up £2.3 million sequentially, and were £1.6 million higher than the equivalent period last year.

The net loss for the latest half-year was £2.9 million, which is an improvement on the losses of £4.6 million and £5.5 million posted in the two previous half-year periods. Increases in operating efficiency helped cut the company's gross loss from 25% in 2004 to 5% for the first half of this year.

"We exceeded our goal of monthly cash break-even in June and posted our first monthly operating profit since June 2001," said IQE's CEO, Drew Nelson.

"Although the coming months will see some variability, we expect to achieve a monthly



In its latest half-year, IQE posted its first sequential increase in sales since 2001.

cash break-even or above on an ongoing basis during the later part of 2005."

Profits would help to strengthen IQE's cash position, which has fallen over the last year from £15.5 million to £5.9 million.

In order to improve efficiencies, IQE has reduced the number of staff at UK-based Wafer Technology, a substrate manufacturer that forms part of the IQE Group.

Aixtron reduces forecast for full-year sales

Germany-based Aixtron has lowered its revenue guidance for the fiscal year, and has said that low spending on capital equipment by LED manufacturers is to blame.

The MOCVD equipment vendor originally expected to post full-year sales of €160 million to €170 million, but has now dropped the forecast by €10 million.

"Aixtron believes that the business climate may remain difficult for the remainder of 2005, with a possible pick-up in activity in the second half of the year," reported the Aachen

outfit in its second-quarter results.

Aixtron posted a revenue of €44.4 million (\$54.8 million) in the quarter that ended June 30. This figure was 33% up on the same period last year, but the latest results included sales from the recently acquired atomic-layer-deposition specialist, Genus (see *Compound Semiconductor* April p42).

Orders for equipment during the last three months totalled €28.4 million. This is considerably lower than the same period last year, when the figure was €36.9 million.

In brief

● **Veeco Instruments** has reported sales of epitaxy equipment worth \$14.6 million in the quarter that ended on June 30. The Woodbury, NY, company said that the HB-LED market remained weak. While Veeco's other market sectors gathered strength, bookings for MBE and MOCVD machines stood at \$12.4 million.

● MBE equipment manufacturer **Riber** has posted revenue of €5.4 million (\$6.7 million) for the first half of 2005, up 50% year-on-year. The sales included one MBE 49 production machine and one Compact 21 research machine. The French firm's sales order backlog on June 30 was €13.6 million. This included orders for one MBE 7000 production machine and for 13 reactors designed for research.

● **Bandwidth Semiconductor**, a wholly owned subsidiary of Spire Corporation, is offering MOCVD-grown epitaxial wafers that emit between 630 nm and 655 nm.

The wafers can be designed as red surface-emitting LEDs or VCSELs, to meet customers' needs. "VCSELs and LEDs fabricated from Bandwidth Semiconductor's MOCVD wafers have demonstrated high yield for a number of different devices. We give customers exactly what they want," said Ed Gagnon, Bandwidth's general manager.

● **Tekcore** of Taiwan, a manufacturer of GaN-based LED chips, has ordered three Thomas Swan close-couple showerhead MOCVD reactors from **Aixtron**.



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