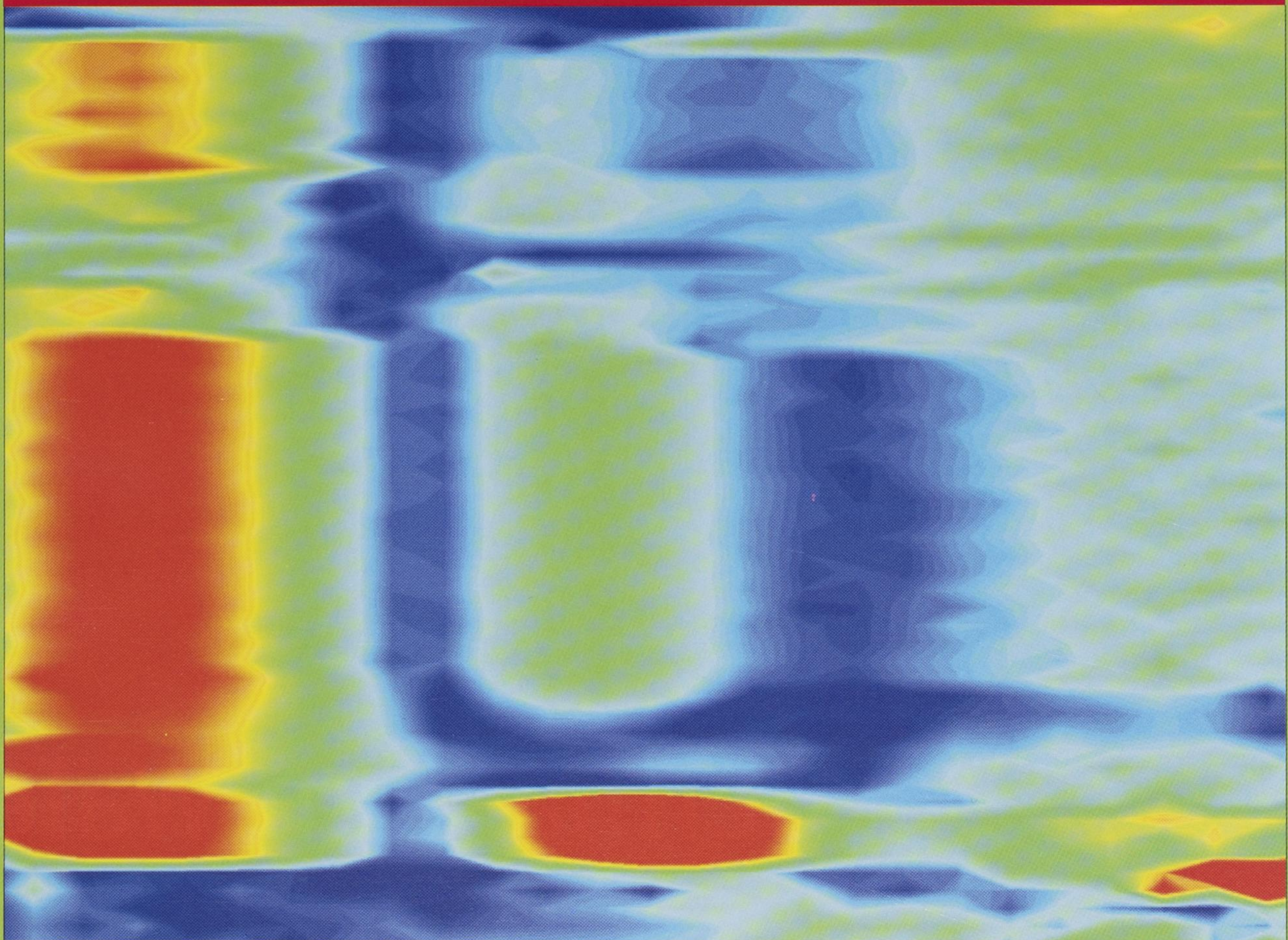


COMPOUND SEMICONDUCTOR

June 2002 Volume 8 Number 5

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Infineon GaAs unit**

**Nichia patents
under scrutiny**

**Raytheon teams
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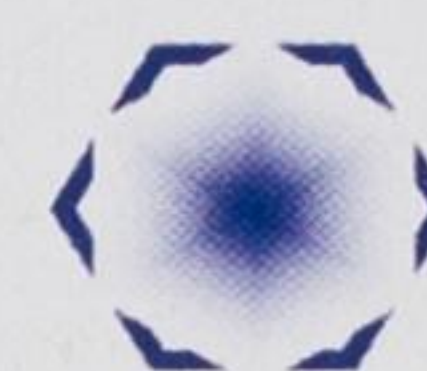
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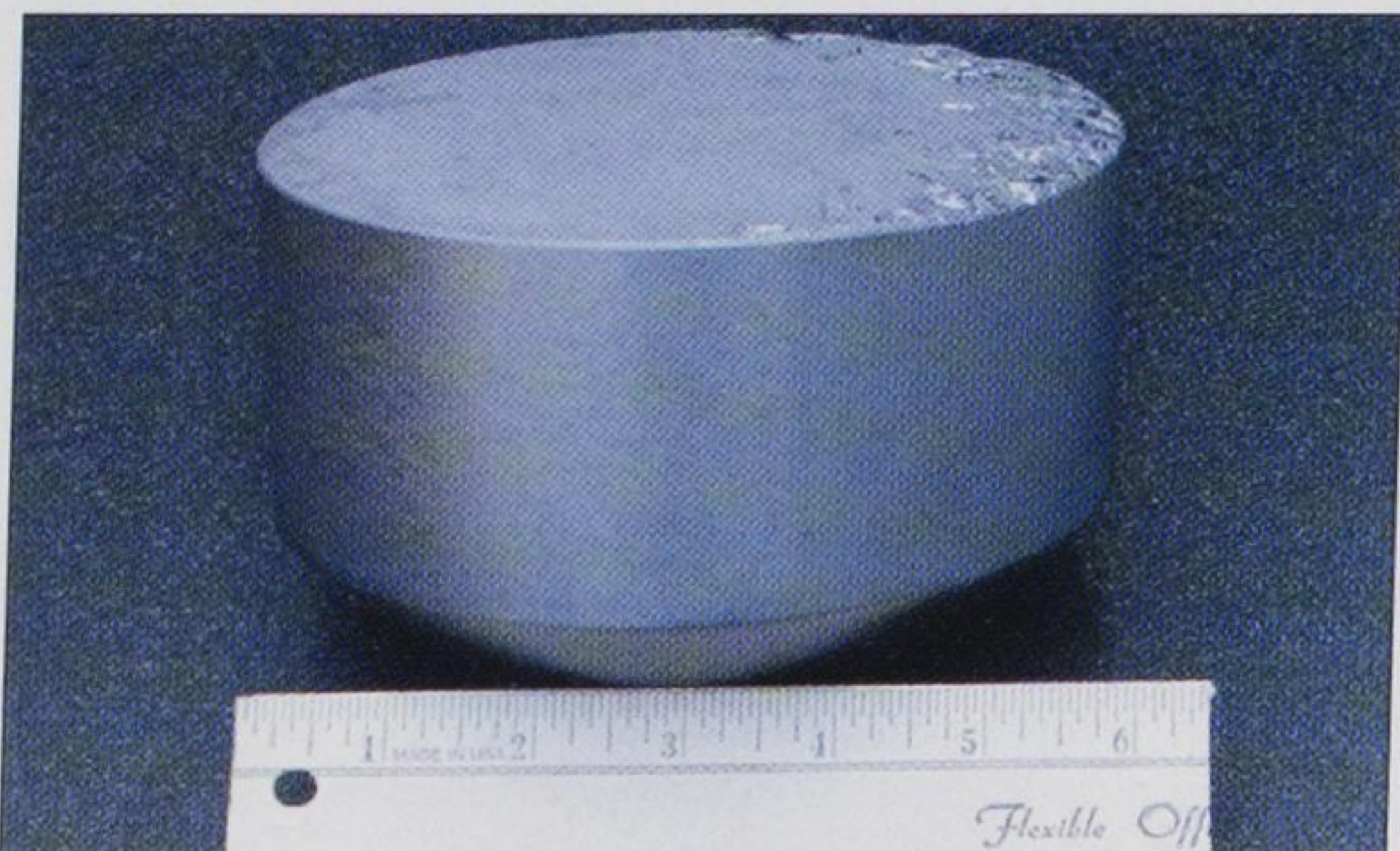
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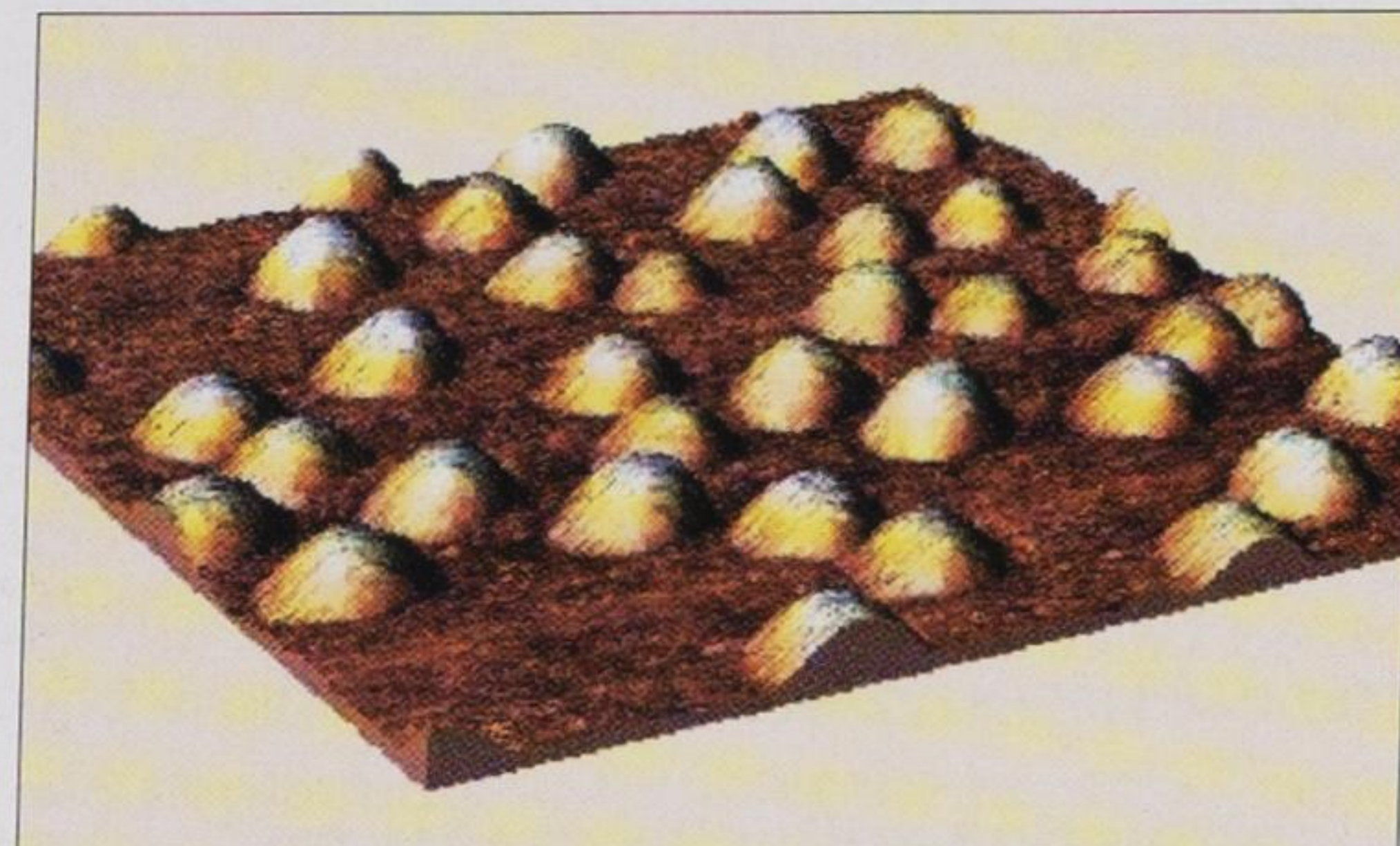
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TriQuint acquires Infineon's GaAs unit

By Richard Dixon

Consolidation in the wireless component industry continues with the news that TriQuint Semiconductor is to buy Infineon Technologies' GaAs IC business. The move is part of a collaboration between the companies to concentrate resources on developing RF front-end solutions for current and next-generation 3G wireless handsets.

The news follows the announcement at the end of last year that Alpha and Conexant are to merge their wireless businesses (see *Compound Semiconductor* December 2001, p3). That deal is on course to be completed by the end of June.

Also, at the end of May, Raytheon RF Components will announce a strategic partnership with WIN Semiconductors. In an exclusive article beginning on p35 of this issue, the companies describe how Raytheon's GaAs MMIC products have been ported to WIN's 6 inch line in Taiwan. Both companies can now manufacture drop-in replacement MMICs for handset power amplifier modules.

TriQuint estimates it will pay €50–80 million (approximately \$45–72 million) in cash for Infineon's GaAs business, depending on certain performance milestones. The deal is scheduled to close on July 1 subject to customary regulatory approvals. In the fiscal year ending September 30, 2001, Infineon's GaAs activities earned a total revenue of around €35 million.

New design center but no fab

TriQuint will not acquire Infineon's GaAs manufacturing operations as part of the deal. Instead, Infineon's GaAs processes will be transferred to TriQuint's Oregon fab. This is expected to take about a year, after which time Infineon will convert its GaAs fab for other uses. As part of an interim supply agreement between the companies, Infineon will continue to manufacture GaAs devices such as PAs and switches until TriQuint fully assimilates the company's technology.

However, TriQuint will strengthen its European presence with the opening of a design center in Munich, Germany. Around

70 former Infineon development engineers based in Munich will be offered positions with TriQuint, along with 10 or so at Infineon's design center in Nashua, NH.

According to TriQuint's president and CEO Steven Sharp, in future both companies will co-market advanced wireless handset products using Infineon's reference designs. Customers will buy baseband parts from Infineon and GaAs RFIC components from TriQuint based on these designs.

Also, at the end of May, Raytheon RF Components will announce a strategic partnership with WIN Semiconductors.

"The key benefits [of this partnership] to TriQuint include access to Infineon's broad technology, products and customers," said Sharp. "Infineon has a strong presence in CDMA and GSM power amplifiers and module designs, and we will gain access to its wireless systems house designs for next-generation phones. In addition, we'll gain a strong European presence and €35–45 million in annual revenue." The deal will also increase the utilization of TriQuint's GaAs facilities, which is currently 20–30%.

"This transfer of our GaAs products and capabilities in combination with our co-operation roadmap positions us as the leading player in radio solution technology, a key component of future mobile wireless devices," said Ulrich Hamann, CEO of Infineon's Wireless Solutions Business Group. "We are pleased to have TriQuint as a partner."

Infineon's GaAs portfolio

Infineon's GaAs processes include MESFET and InGaP HBT and PHEMT with gate lengths down to 0.13 μm . The company has also developed an enhancement-mode (E-mode) PHEMT. These processes are used to manufacture MMIC power amplifiers and

switches for cellular phones operating at frequencies up to 2.5 GHz, in addition to products for WLAN and WLL, Bluetooth, 12 GHz tuners, LMDS at 24–38 GHz and automotive radar at 77 GHz.

Infineon has qualified a number of these processes on 6 inch wafers, complementing TriQuint's 6 inch lines in Oregon and Texas (see *Compound Semiconductor* April 2002, p59). "In some cases, we're electing to re-design the products to better fit our processes, and in other cases, such as Infineon's PHEMT, we're planning to transfer the process," said Sharp. TriQuint has yet to specify any plans for Infineon's E-mode PHEMT design.

New markets for TriQuint

Sharp says one of TriQuint's aims is to improve its visibility in GSM wireless phone designs. The company is strong in CDMA and TDMA wins, but last year reported that only 9% of its wireless handset and base-station revenue went to GSM applications.

TriQuint recently made steps to rectify this situation, making a foundry deal with Philips Semiconductors to supply InGaP HBTs. This arrangement has already produced PA and front-end modules for GSM handsets.

"Infineon is our second initiative in GSM," said Sharp. "Infineon is one of the largest players in GSM phones, and a relationship working with them on reference designs is critical to success in the GSM market. In addition, Infineon is an important supplier of digital signal processing chipsets, and has a very significant market share for that business. Having a relationship with that group to supply the [whole] RF solution is very positive."

TriQuint says the initial product focus will include receivers and switches, with more emphasis on power amplifiers in the long term. The company will also gain access to new customers in Europe for its millimeter-wave business, which represents about 20% of Infineon's GaAs revenue.

"This is a long-term strategy to have a design center in Europe targeting cell phones, but also millimeter-wave systems and military systems," said Sharp.

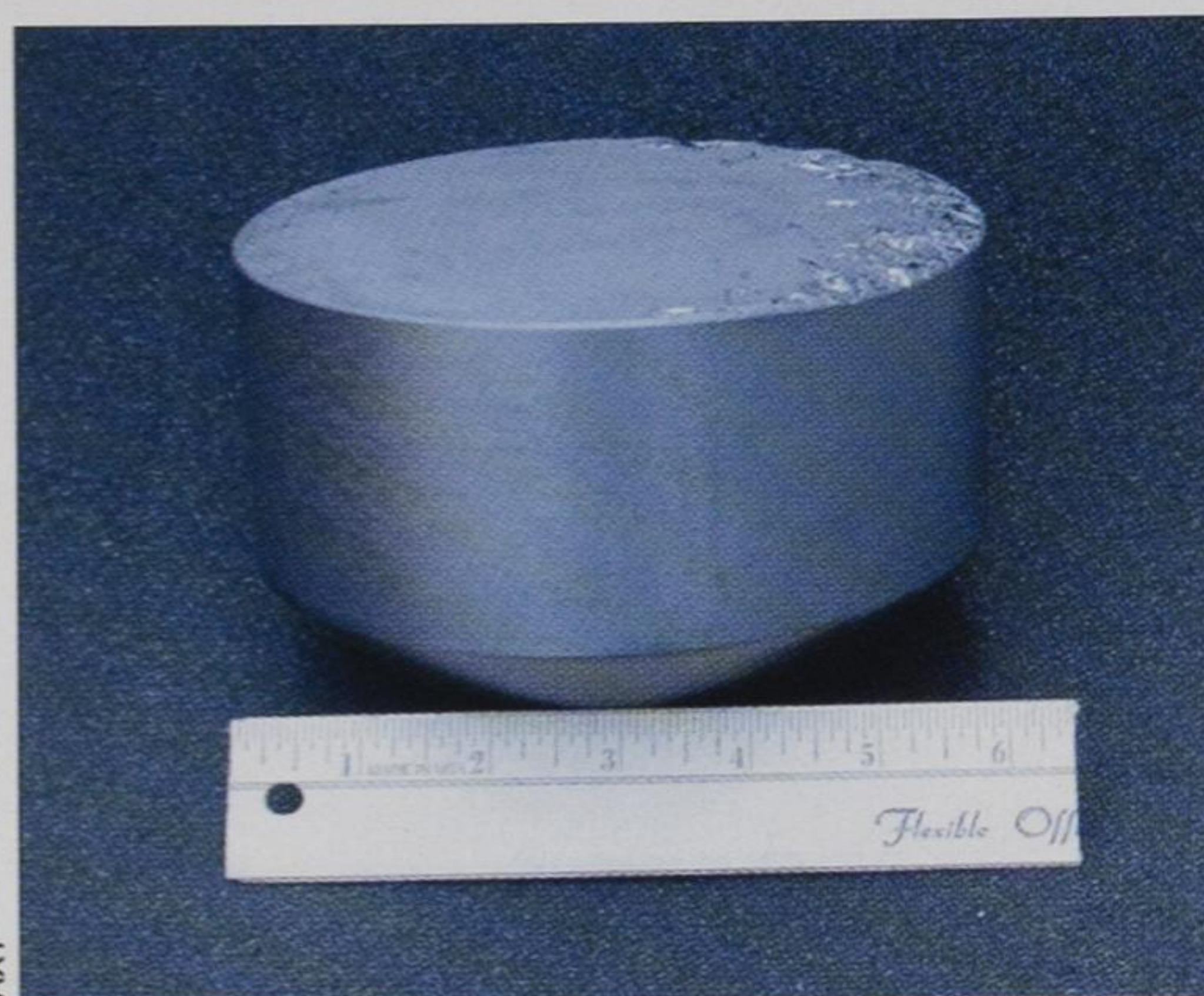
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AXT samples 6 inch InP substrates

AXT will begin shipping sample quantities of 6 inch diameter InP substrates in the June quarter. The announcement marks a further gathering of momentum in the development of 6 inch InP wafers. Showa Denko recently became the first company to announce it had successfully developed substrates of this size using LEC technology (see *Compound Semiconductor* May 2002, p4).

Large-diameter substrates are critical to increasing the yield and reducing costs during production of high-performance RF and optoelectronic circuits. In addition, new applications for InP are expected to be driven by demand for lasers, detectors and modulators operating at 40 Gbit/s, and the new generation of ICs required for 3G cellular phones featuring high-speed datacoms.

AXT's new substrates were developed using its proprietary vertical gradient freeze (VGF) crystal growth technology. This en-



The first 6 inch diameter VGF InP ingot that AXT has grown is 3 inches long and has a resistivity of $>1 \times 10^7 \Omega\text{cm}$.

abled the company to produce large-diameter InP substrates with high uniformity and a low number of defects. According to Gordon Liu, AXT's senior VP of marketing and sales, the

substrates exhibit dislocation densities of approximately $3 \times 10^3/\text{cm}^2$. Flatness is 5–6 μm across the whole diameter of the wafer.

"We have received interest from several of our optical communications customers, who would like to take advantage of the larger yield afforded by the bigger substrate area," explained Liu. "Currently we are sampling semi-insulating substrates, although there should be no problem supplying semiconducting InP substrates."

"A second important advantage of 6 inch wafers relates to processing," added Liu. "Our customers say the move to 6 inch substrates allows the use of more advanced processing equipment, which leads to better devices."

Liu says AXT will not start volume production until a sufficient market exists, although it could be done quickly if necessary. "The market is currently slow, and companies are not having a problem with capacity."

Umicore buys Sterling for around \$13 million

Umicore USA, a subsidiary of the Belgian materials company Umicore (formerly Union Minière), has agreed to buy the outstanding shares of Sterling Semiconductor, a subsidiary of Uniroyal Technology.

Umicore will pay approximately \$13 million in cash for Sterling, which is the world's second-largest producer of SiC substrates. The acquisition includes three production sites in Virginia, Connecticut and Florida and approximately 50 people.

Certain performance-related payouts are also part of the deal. For the financial year ended September 30, 2001, Sterling had sales of approximately \$3.7 million and an operating loss of \$7.0 million. Sterling has attracted funding from various US government agencies, and Umicore expects its new business to make a positive earnings contribution beginning in 2004.

Sterling Semiconductor, headquartered in Sterling, Virginia, was acquired by Uniroyal in April 2000. A large amount of investment was made to increase Sterling's SiC wafer production capacity as well as to accelerate epiwafer and device development, which includes SiC Schottky diodes (*Compound Semiconductor* October 2001, p20).

Recently, Uniroyal, which manufactures high-brightness LEDs, has been suffering

from a severe financial crisis and laid off 90 staff in early January. "There are only positives in this transaction," said Uniroyal's chairman and CEO, Howard Curd. "It puts Sterling in the ownership of a financially

Umicore expects its new business to make a positive earnings contribution in 2004.

strong parent, which will maximize the long-term potential of the business. It also enables Uniroyal to improve liquidity while allowing us to focus on our Optoelectronics business and maximize its long-term potential."

Germanium heritage

Umicore is a leading manufacturer of germanium substrates used to fabricate GaAs-based solar cells, and also makes germanium crystals for infrared optics. The company hopes to extend the use of germanium to other applications, and also broaden its expertise in substrate technology. It is already involved in research into InP and SiC substrates.

"At Umicore we recently began examining new opportunities that would allow us to leverage core competencies in germanium

crystal growth and wafer surface preparation technology," said Marc Vansande, Umicore's president of Advanced Materials. "We recently began sampling InP substrates, developed in a technology-transfer relationship with IMEC [the Belgian microelectronics research center]. SiC was also on our shopping list, and we decided to get into this area by buying Sterling."

The company is also assessing the potential of activities such as epitaxy, where Sterling has established expertise. "We have already developed MOCVD growth at IMEC using germanium wafers to make LEDs," said Vansande. "This is partly to understand our customers' applications but also to promote germanium for solar cells and sensor applications. Umicore's strategy is to continue with our core business of substrates and polished epi-ready materials. But in cases where we don't affect relationships with our customers, we will develop epitaxial growth processes."

**News from Asia
supplied by
OPTotech magazine –
see p19.**

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Judge points finger at false data in Nichia case

In the latest twist in the ongoing patent dispute involving Nichia, Cree and Shuji Nakamura, it appears that false data may have been submitted as part of the applications for various US patents now owned by Nichia. The patents in question (US patents 5,306,662; 5,578,839; 5,747,832 and 5,767,581) form the basis of a lawsuit filed by Nichia against North Carolina State University and Cree. Clearly if false claims were made the patents could be rendered invalid, which might prove highly detrimental to Nichia.

The issue came to light following a deposition made by Nakamura, who filed the patents while employed by Nichia. The judge hearing the case, James Fox, wrote to a US Attorney, Peter Kellen, stating that Nakamura "indicated that he intentionally submitted false data in conjunction with the applications for the aforesaid patents". Fox added, "It would appear that Nakamura either has committed perjury in this court, or alternatively

has committed perjury in filing applications for the patents listed."

William McLean, Nakamura's lawyer, does not believe that his client will be sued for perjury. In a letter to Kellen, McLean does not contend that the claims of submitting false data are incorrect. Instead, he claims that it is Nichia, rather than Nakamura, that holds responsibility for falsifying data.

"We will be able to show to you that the patent department at Nichia did all of the patent writing," McLean wrote. "We will also be able to show that fabrications and made-up data in the US patents were created by employees of Nichia and not Dr Nakamura."

McLean added that all of Nichia's patents were prepared in English by the company's internal patent office, and Nakamura was only given the signature page. "He did not see the content of the patent applications," McLean wrote. "Nakamura trusted his employer so signed the patent."

Oriol unveils vertical blue LEDs

LED manufacturer Oriol has developed a high-brightness LED with a vertical conducting structure. Like the company's recently introduced Gigabright InGaN-based blue LED (see *Compound Semiconductor* April 2002, p13), the Vertical Gigabright chip is grown by MOCVD on a sapphire substrate. However, the sapphire is then removed using a proprietary lift-off technique and a metallic base is bonded to the device layers. This allows LEDs to be fabricated with a vertical configuration, in which a single wire-bond is used for the top contact.

In the lateral designs typically used for InGaN-on-sapphire LEDs, two top contacts and additional processing are required. As well as facilitating electrical contact to the bottom of the device, the metallic layer in Oriol's new LED reflects light in the forward direction and eliminates the poor thermal conductivity of the sapphire substrate.

Oriol states that its new LED design has low thermal resistance and high electrical conductivity. The vertical design allows thinner packaging, and is strong enough to remain compatible with traditional die-mount tech-

niques, says the company. Other vertical GaN device designs (such as those manufactured by Cree and Osram) are grown on SiC substrates, which are conducting but are more expensive than sapphire, and also absorb light emitted in the substrate direction.

When packaged in a 5 mm lamp with a 15° viewing angle, Oriol's blue device delivers 6 cd at a forward voltage of 3.4 V and 20 mA current. LEDs are available in the 450–470 nm wavelength range, and the typical radiant flux exceeds 12 mW. Samples of the devices will be available in about 3 months. The company expects to begin production early in the fourth quarter of this year.

Chips in three sizes

"We are planning to introduce three sizes of chip," said marketing manager Tom Jory. "The 350 × 350 μm² device will address typical 5 mm lamp applications such as traffic signals and outdoor video signs, while a smaller die size will be used for power-sensitive cellular-phone applications. The third option will be a large-area 1 × 1 mm² die for high-flux packages used in lighting applications."

LumiLeds' white LEDs offer 120 lm

LumiLeds Lighting has released the 5-Watt, a high-power version of its Luxeon LED. A single white packaged Luxeon emitter now provides a luminous flux of 120 lm and uses only a third of the energy of an equivalent 15 W incandescent bulb. Potential applications include reading lights and flashlights, task and accent lighting, airport taxi-way lamps and architectural lighting.

The InGaN-on-sapphire chip in LumiLeds' new device has been quadrupled in size from 1 × 1 mm² to 2 × 2 mm². The larger die is driven at a forward voltage of 6.8 V and current of 700 mA, compared with around 3 V and 20 mA for conventional LEDs.

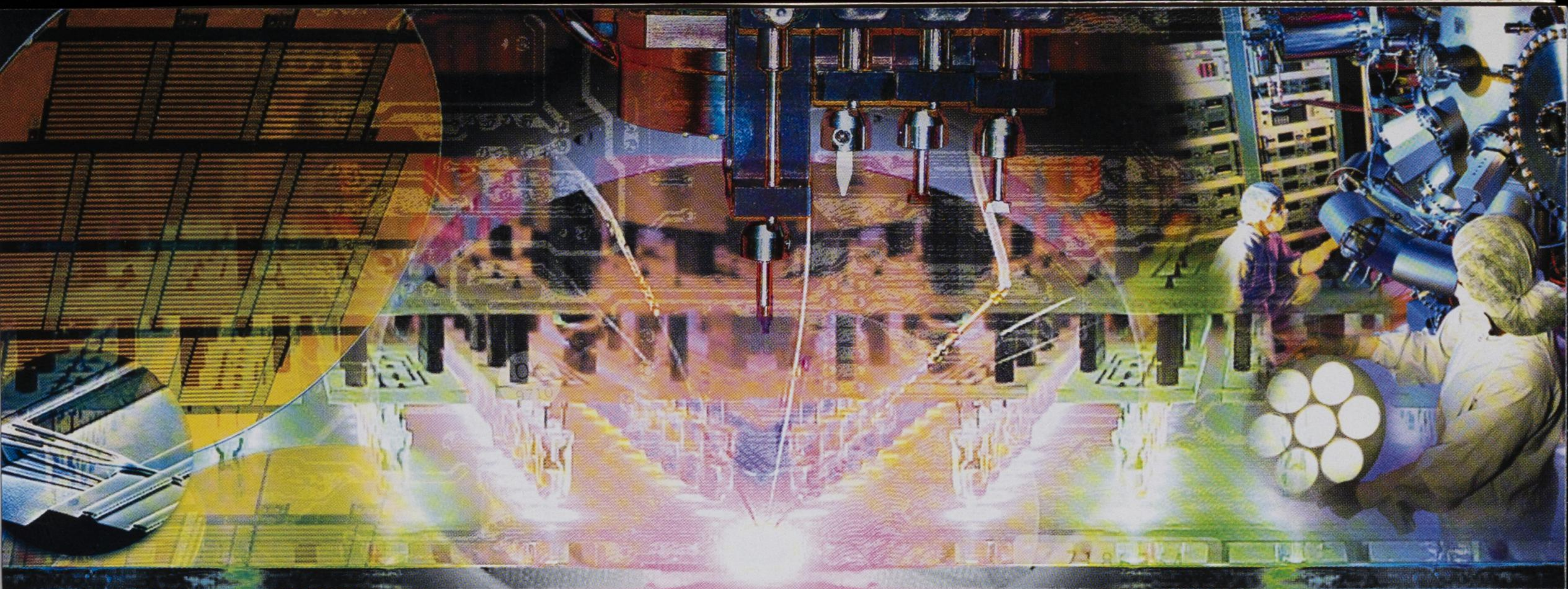


The aluminum heat-sink board is key to the Luxeon LED's high-power operation.

The white LED has the same footprint and uses the same Star package as the previous 30 lm white device. The color temperature is 5500 K and the viewing angle is 120°. Other colors are available, including a 455 nm royal-blue LED with a luminous flux of 30 lm as well as 520 nm green and 490 nm cyan devices each providing 130 lm.

The 5-Watt is available as a single emitter mounted on an aluminum PCB heat sink. LumiLeds' Paul Martin explained, "The new heat sink we are using provides a thermal resistance of around 15°C/W, measured from the temperature of the device junction to ambient temperature."

The firm says that conventional LEDs lose 30% of their brightness after just 3000 hours owing to the yellowing effects of organic epoxy resins used in the lens systems. But Luxeon LEDs use a clear silica-based opto-coupling gel that resists significant depreciation for at least 50,000 hours (*Compound Semiconductor* July 2001, p 11).



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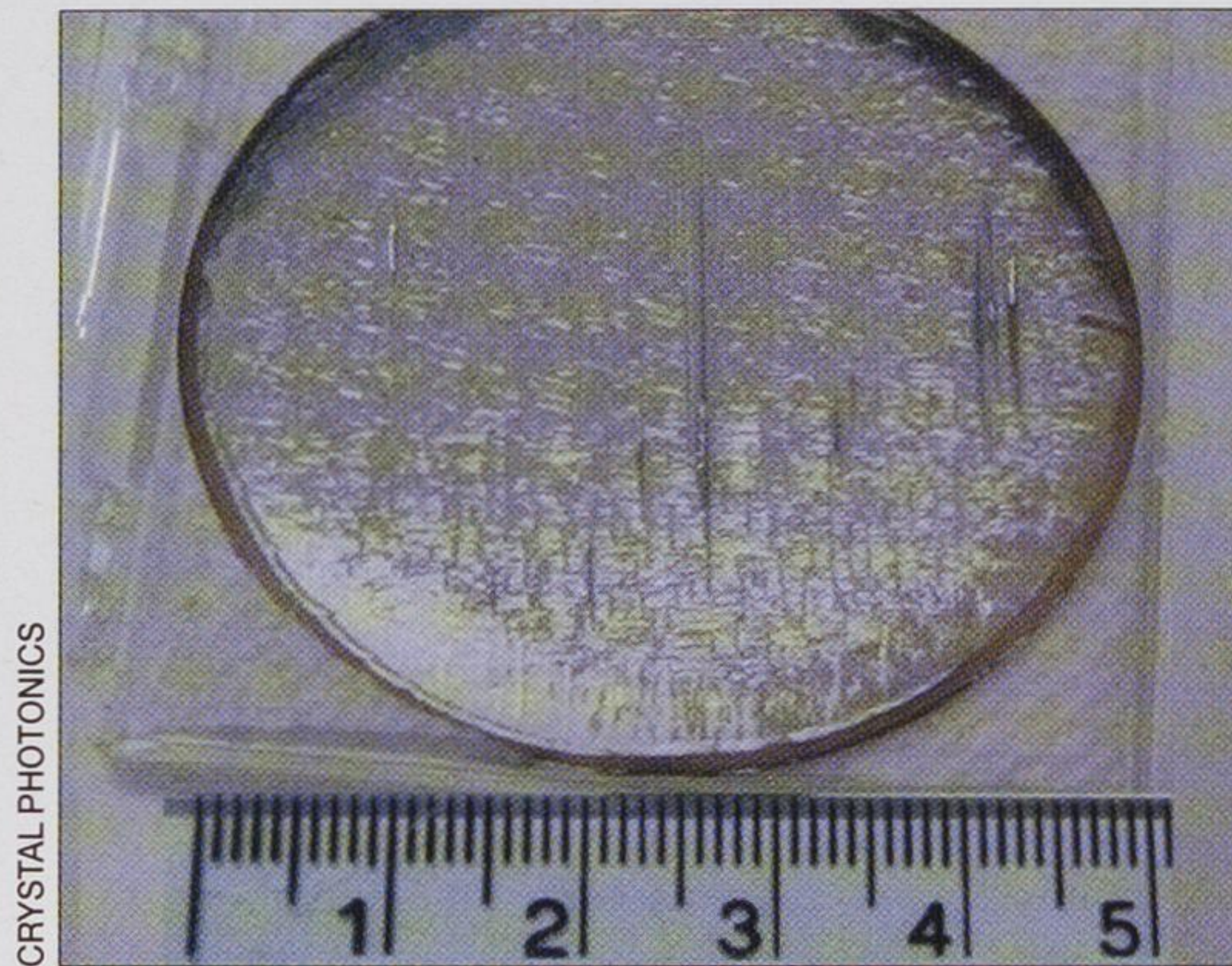
Crystal Photonics ships 2 inch GaN

Crystal Photonics, a developer of GaN substrates based in Sanford, Florida, is to export 2 inch GaN substrates to Japan. Grown on LiGaO₂ or LiAlO₂ substrates within a hybrid MOCVD/HVPE reactor, the GaN substrates will form the building-blocks of violet laser diodes for next-generation DVD systems.

"Our short-term goal is to reach 300 wafers per month, but our production facility can make up to 6000 wafers per month," Crystal Photonics' chief executive Bruce Chai told *Compound Semiconductor*. "And since Japan will be the leader in DVD player development [based on violet laser diodes], it is a good market to target."

Tackling growth problems

Given the problems of growing bulk GaN crystals, GaN substrates are often fabricated by depositing layers of material onto a sacrificial substrate, such as sapphire or SiC. "I was the first researcher to suggest growing GaN



A 2 inch free-standing GaN wafer before polishing. Crystal Photonics grows its GaN substrates using hetero-epitaxy on either LiGaO₂ or LiAlO₂ material.

on LiGaO₂ and LiAlO₂ substrates because of the good lattice-match between these materials and GaN," explained Chai. "But even though the lattice-match is good, the chemi-

cal compatibility is not and people lost interest after a lot of initial trials failed."

However, Chai says that he has overcome these problems by developing a MOCVD/HVPE reactor that provides a better deposition environment for GaN on LiGaO₂ and LiAlO₂. "We have achieved a growth rate of between 50 and 100 μm per hour and expect a defect density of less than $10^6/\text{cm}^2$," he said. "Because the bonding strength between GaN films and LiGaO₂ and LiAlO₂ substrates is weak, it is natural to grow a thick epitaxial film and later remove it to leave a true, single-crystal free-standing wafer."

Crystal Photonics currently uses the Japanese technology company Marubeni to sell its wafers in Japan and is hoping to find new customers in the US and other countries. "The initial UV laser-diode cost is high, which justifies the cost of our substrate," added Chai. "And the immediate demand for these devices isn't high, which suits our expansion plans."

Mitsubishi Chemical prepares to enter GaN laser-diode market

Recent developments at Mitsubishi Chemical reveal that the Japanese company, which already makes GaAs substrates and 980 nm pump lasers, plans to take a stake in the markets for blue and violet LEDs and lasers.

First, the company is collaborating with Tokyo Denpa, a Japanese manufacturer of single-crystal materials, to develop bulk GaN crystals. Tokyo Denpa managed to make 1 cm² ZnO crystal last year (see *Compound Semiconductor* September 2001, p26). Mitsubishi Chemical spokesperson Osamu Shimizu told *Compound Semiconductor* that his company plans to use Tokyo Denpa's technology to grow single-crystal GaN.

With the GaN substrates, Mitsubishi Chemical plans to make blue LEDs and laser diodes for solid-state lighting applications,

along with violet laser diodes for next-generation DVD systems. However, the company will not disclose details of substrate size or its epitaxy growth technique for device manufacturing. "We are considering starting a business with Tokyo Denpa," added Shimizu. "[Although] this is just one option."

Shimizu also confirmed recent reports that Mitsubishi Chemical has donated money to Tohoku University in Japan to develop single-crystal GaN. According to Japan news service *Nihon Keizai Shimbun* the company will give ¥150 million (\$1.16 million) to the university over the next 3 years.

"[Investing in the manufacture of GaN-based optoelectronic components] is essential to produce low-cost, reliable lasers with long lifetimes," said Shimizu.

Seiwa's shares soar thanks to blue LEDs

Shares of Seiwa Electric soared last month from ¥41 to ¥591 as the Japanese electronics company started selling volume levels of GaN-on-sapphire LEDs. Seiwa claims that

the blue LEDs do not infringe patents owned by rival manufacturer Nichia.

While Seiwa will not reveal fabrication details, a spokesperson says that the LEDs contain a semi-transparent, large-area ITO electrode to overcome current-crowding in the high-resistivity GaN top contact layer. This is a common problem in conventional

Cermet wins GaN defense contracts

Cermet, a manufacturer of GaN and ZnO materials based in Atlanta, GA, has won two Missile Defense Agency (MDA) contracts to develop bulk and thin-film GaN to be used in military applications.

Under the terms of the first contract, Cermet will tackle the problems of fabricating GaN in bulk and work to develop low-cost, low-defect-density GaN boules. The substrates will be used in high-power, high-frequency nitride transistors for advanced radar, on-board monitoring and communication systems.

Cermet will also develop GaN thin films for sensors that can be tuned across all UV wavelengths. The MDA plans to incorporate the tunable sensors in its missile-defense systems, and to use them in the detection of airborne biological agents.

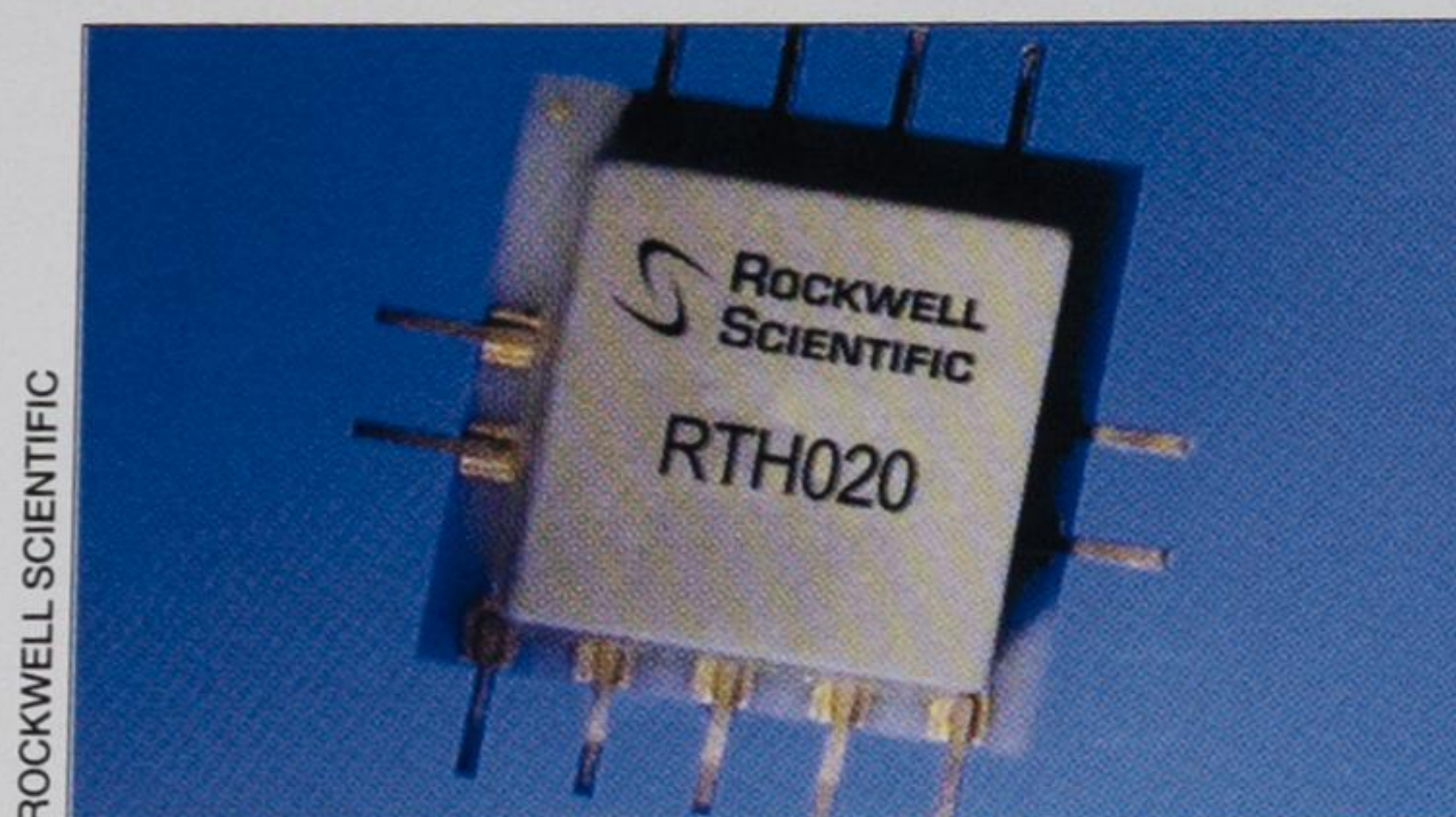
GaN-based LEDs that leads to non-uniform light transmission and reduces device lifetime.

"Our electrode layout allows electricity to flow with as little resistance as possible and the semi-transparent indium tin oxide does not prevent the transmission of light," said the spokesperson. "We are already shipping and our LEDs evade Nichia's patents."

Rockwell selects StratEdge packages

Rockwell Scientific Company (RSC) has chosen StratEdge to provide packages and assembly services for GaAs circuits used in data acquisition. StratEdge will provide a version of its DC-23 GHz ceramic packages for an IC developed by RSC that performs dualtracking and signal-hold functions. The IC turns a moderate bandwidth commercial analog-to-digital converter (ADC) into a 10 GHz ADC. It allows sampling of 1 GHz signals with 10 bit precision, and with minimal noise and aperture jitter.

The ceramic microwave package features four RF leads and multiple DC leads, in addition to cavities that are customized to accommodate the RSC chip and other components.



Rockwell's ADC chip will be assembled in StratEdge's DC-23 GHz packages.

StratEdge is manufacturing the package and is performing polymer die-attach, automated gold-wedge wire-bonding, lid sealing and marking services, and final lead trim for RSC.

"Rockwell Scientific's dual track and hold chip dramatically increases ADC bandwidth and is a major step for ultra-wideband data acquisition," commented Myung-Jun Choe, a team leader in Rockwell Scientific's High Speed Mixed Signal ICs department. "The StratEdge package handles the high speed and frequencies of our chip while providing a leaded package that can be easily assembled to our customers' boards."

EpiWorks hits record HBT performance

EpiWorks and the University of Illinois are claiming record values for f_t and f_{max} of 180 and 340 GHz for a single heterojunction InP

HBT. The device wafers were grown on 4 inch InP substrates by EpiWorks using MOCVD, and the university carried out the subsequent HBT fabrication. The results were achieved using a $0.35 \times 12 \mu m^2$ emitter, while larger $1.2 \times 12 \mu m^2$ emitters exhibited values for f_t and f_{max} of 178 and 244 GHz.

"Our work shows that InP HBTs behave according to theory even down to dimensions as small as $0.35 \mu m$," said Milton Feng, who led the project at the university. "This demonstrates that InP can continue to out-perform Si and SiGe circuits for high-speed, low-power applications."

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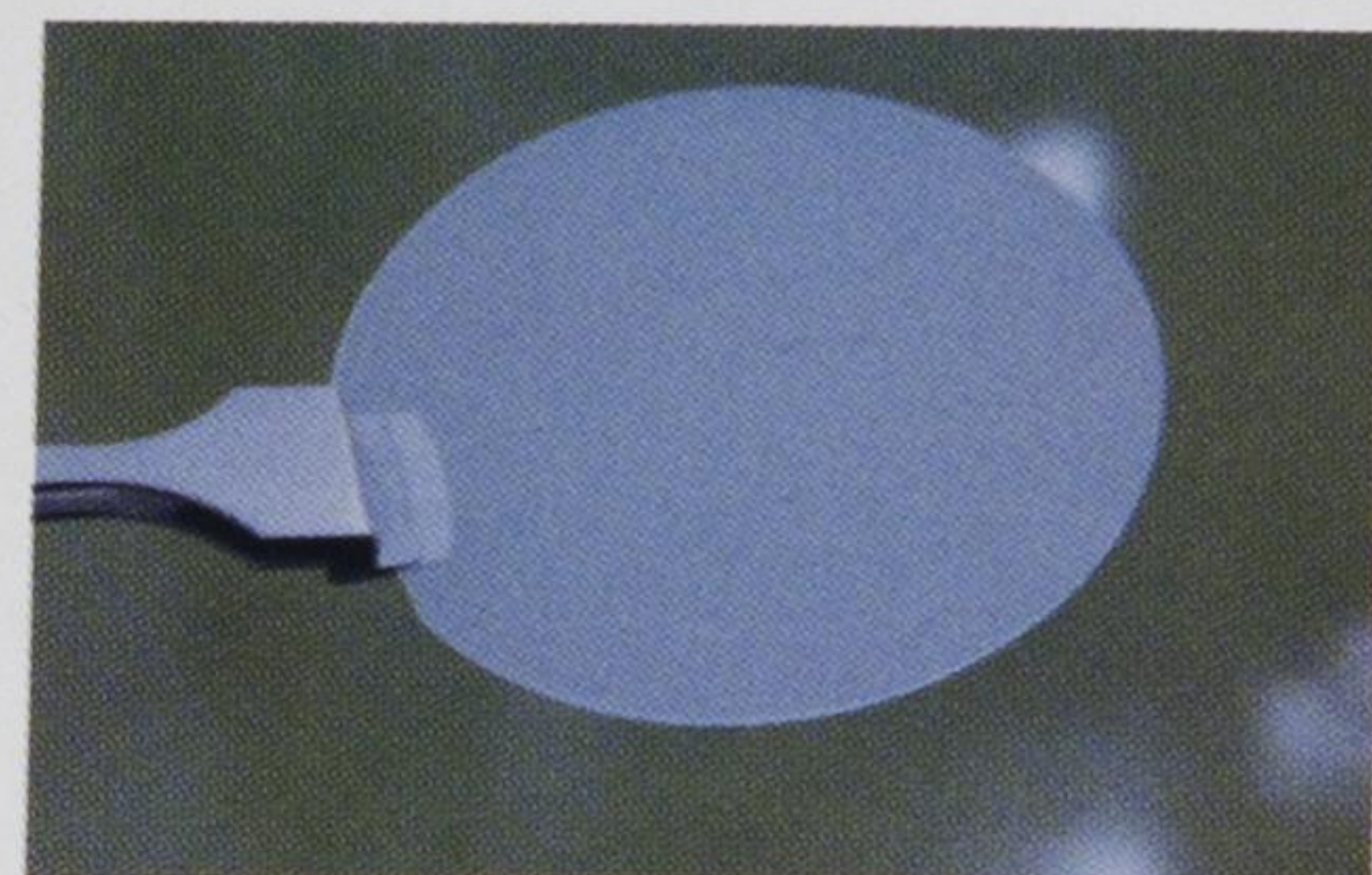


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TriQuint reorganizes its business units

TriQuint Semiconductor has reorganized its business to better manage new technologies, including modules, across the broad markets it addresses worldwide. The new structure will consist of four business units that will enable the company to focus more on front-end module design, development, marketing and sales, and also on the European and Asian markets.

"We want to create an organization to develop modules for different technologies and that meet the needs of different geographic markets," said CEO Steve Sharp.

The new business groups include Wireless Modules and Worldwide Sales that will have worldwide responsibility for the design and marketing of modules for the wireless handset market. The Sawtek unit, located in Florida and Costa Rica, will continue to design, manufacture and market SAW products.

A third unit, TriQuint Texas, will contain TriQuint's corporate R&D activities, in addition to 6 inch fabrication lines for manufacturing high-frequency GaAs ICs for military, satellite, optical networking and broadband

equipment markets. This operation currently leases space from the Texas Instruments campus in Dallas, but is relocating to a site in Richardson (*Compound Semiconductor* April 2002, p59).

Finally, TriQuint Oregon will handle the design, manufacture and marketing of ICs for wireless communications, infrastructure and CATV markets. This unit has 4 and 6 inch GaAs lines with MESFET, PHEMT and HBT processes and is also the center of TriQuint's foundry services.

In brief...

HBTs are highly reliable

Korean foundry firm Knowledge*on has reported a mean-time-to-failure of more than 1.5×10^8 hours or ~17,000 years for InGaP HBTs from its 6 inch production line. The results were obtained using a junction temperature of 125 °C, collector-emitter bias of 3.5 V and collector current density of 25 kA/cm². The company has a capacity of 3000 wafers per month and supplied its first InGaP HBTs last July.

Anadigics wins RF order

Anadigics has received a high-volume production order for its GaAs MMIC AWS5504 and AWS5518 RF switches from a major manufacturer of wireless handsets. The switches are designed for the antenna selection and transmit/receive switching applications in multimode, multi-band cellular handsets.

Toshiba's new C-band FET

Toshiba America Electronic Components (TEAC) has introduced the industry's first 60 W internally matched C-band GaAs HFET for satellite communications. The device operates in the 5.9–6.75 GHz range and is made using Toshiba's HFET process. This technique gives the device a higher Schottky barrier height than implanted GaAs MESFETs. The resulting higher gate breakdown voltage and lower gate leakage current are important attributes in high-power devices.



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First commercial QCL sensor arrives

By Rebecca Pool

Physical Sciences Inc (PSI) has launched the world's first gas sensors based on mid-infrared quantum-cascade lasers (QCLs). The sensors detect trace levels of NO and CO at sensitivities below 10 ppb, at atmospheric pressure and temperature.

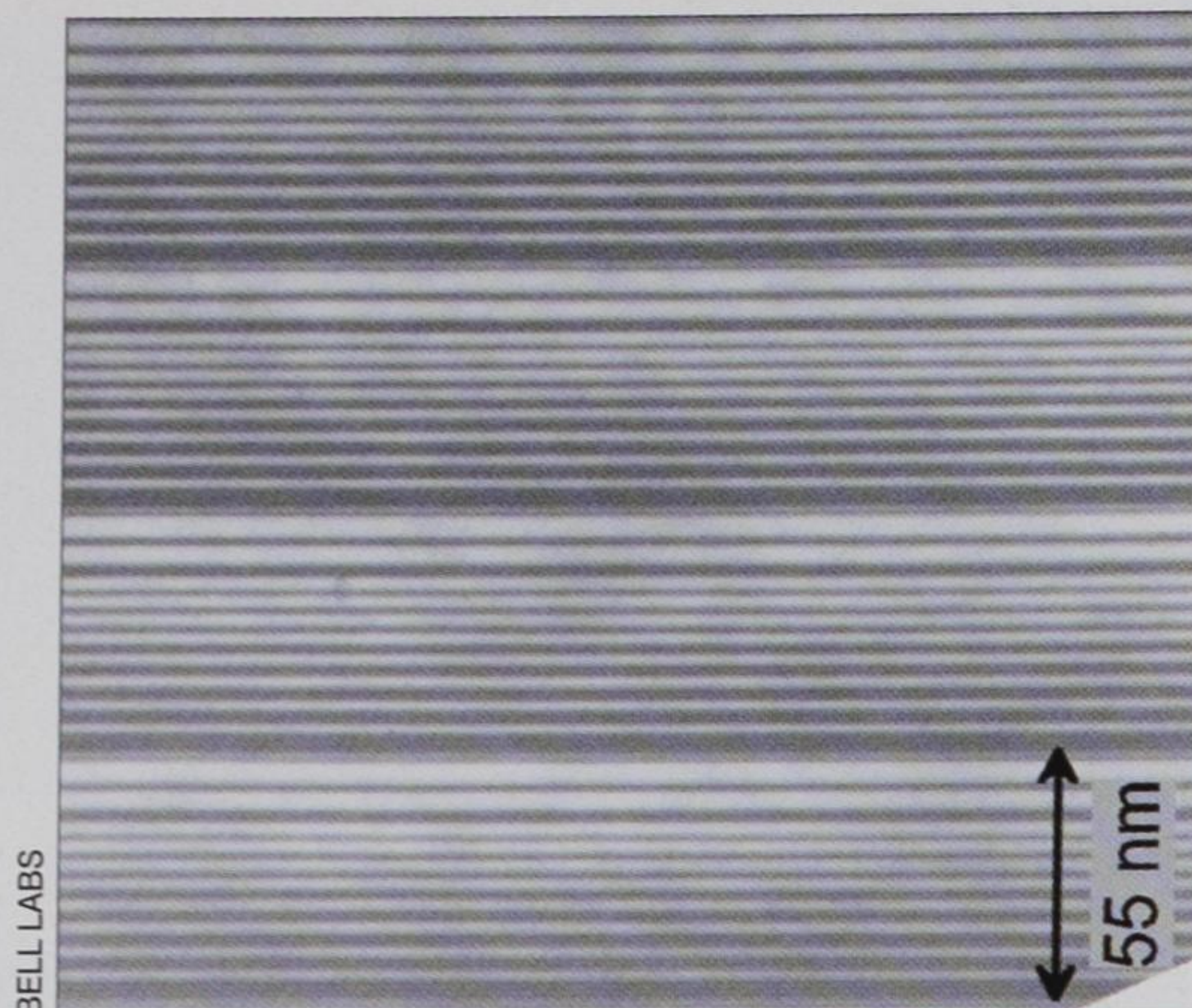
"Near-infrared or other diode laser technologies have detection limits of only 1 ppm," explained Mark Allen, vice-president of PSI's Photonics Division. "But by incorporating these mid-infrared QCLs into our systems, we have improved the detection limit by a factor of 100."

The technology for QCLs was first developed by Bell Labs, the research arm of Lucent Technologies, in 1994. Applied Optoelectronics of Sugarland, TX, and Alpes Lasers of Switzerland are licensed suppliers of Lucent's technology and manufacture the QCLs for PSI's sensor systems.

Fabricated by depositing InGaAs and AlInAs layers on an InP substrate, each QCL is designed as a room-temperature, single-mode, distributed-feedback laser. The sensor system that detects NO uses a QCL that emits at 5.2 μm , while the CO system contains a 4.6 μm QCL.

QCL technology

QCLs emit light via a different mechanism to standard semiconductor lasers. Within a direct bandgap semiconductor such as GaAs, a photon is emitted when an electron from the conduction band falls into the valence band and recombines with a positive hole. The photon's wavelength is determined by the bandgap between the two bands. However, QCLs do not emit light via electron transitions between bands, but rely on transitions between the electronic states or sub-bands that sit within each of the many active regions in the QCL structure.



A TEM image of four stages of active regions and injectors of a QCL that emits at 4.6 μm . The light-gray layers are InGaAs and the darker layers are AlInAs. The active regions consist of a thin InGaAs layer followed by two thicker InGaAs layers, with layers of AlInAs in between.

QCLs consist of many alternate active and intermediate injector regions (see image). In the current examples the active regions contain InGaAs quantum wells and AlInAs barriers, and also support various electronic sub-bands. Photon emission occurs via inter-sub-band transitions in each active region. Electrons are supplied to the active regions from the InGaAs/AlInAs injector regions, which are doped with silicon.

As electrons flow through the structure in a top-to-bottom direction, photons are emitted by the inter-sub-band transitions within each active region. As an electron emits a photon it loses energy. But because each active region is engineered to have a lower energy level than the one before it under an applied external electric field, the electron continues to traverse the structure and emit photons. This is known as the "cascade effect".

By altering the thickness of the layers

within the active regions, the QCL can be engineered to emit at the required wavelength and optical gain. According to Bell Labs scientist Claire Gmachl, this has allowed researchers in her team to build QCLs based on established material systems.

"We can choose a very mature material system then, just by changing layer thicknesses, make that material emit light in a wavelength range that is best for sensing trace gases," said Gmachl. "We use MBE to deposit between 500 and 1000 [alternate] layers of InGaAs and AlInAs on InP. The thickness has to be tightly controlled and MBE is suited to this."

For gas sensing it is crucial to make the lasers emit in the mid-infrared wavelength range as this is the region where most trace gases reveal tell-tale chemical-absorption characteristics. To achieve mid-infrared emission, the total thickness of one period of active and injector layers in Lucent's 4.6 μm QCL has been engineered to 55 nm. The thinnest layers in the structure are only 0.9 nm thick.

To detect the narrowband absorption feature of a gas, a singlemode QCL is also crucial. This is achieved by fabricating the QCLs as DFB lasers. Lucent's DFB QCLs have the active/injector layers sandwiched between InP cladding layers, with a DFB grating either buried between the active region and upper cladding, or etched on top of the ridge.

Future sensor systems

Following the CO- and NO-detecting sensor systems, PSI's Allen says that the company plans to release additional sensors for SO₂, SO₃ and formaldehyde detection later this year, and is also working on QCL sensors for trace species in human breath. "Our first units are marketed largely for industrial researchers who will buy them for their own research efforts. We expect to reach volume production levels within 2-4 years," he said.

Sensors-Demeter unveils a 640 × 480 InGaAs IR camera

Sensors-Demeter Components Group based in Princeton, NJ, has developed a room-temperature infrared camera that uses a 640 × 480 pixel InGaAs focal-plane array. The company's previous InGaAs cameras had

320 × 240 detector arrays.

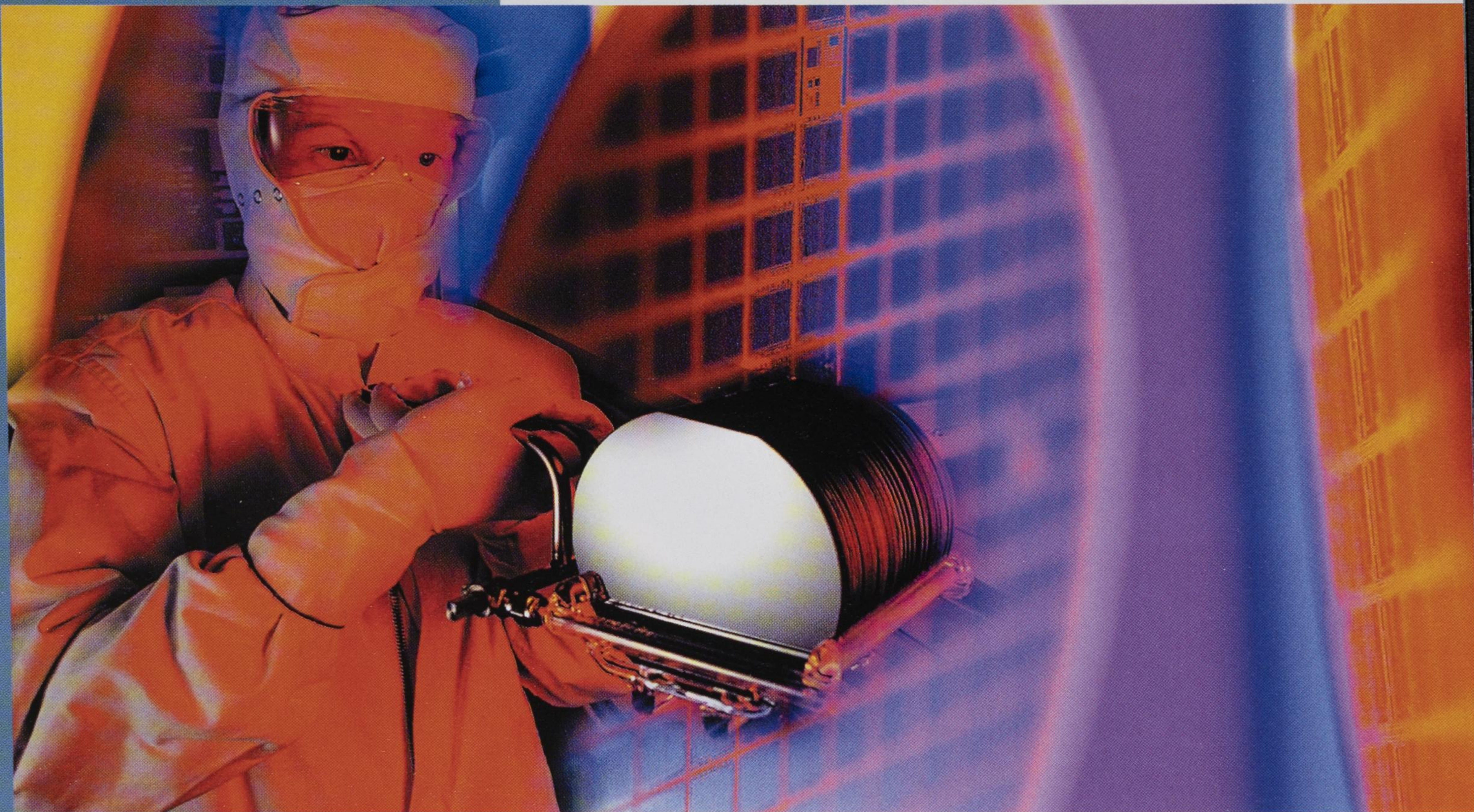
The high-resolution imaging system operates at room temperature in the 0.9-1.7 μm wavelength range. Target applications include laser profiling, emission microscopy and imaging spectroscopy. The new focal-plane array features a pitch of 27 μm compared with 40 μm in the previous array, and uses almost twice as much chip area.

"The new 640 × 480 InGaAs chip is the largest that the industry has ever produced

commercially," said Martin Ettenberg, imaging product manager at Sensors-Demeter Components Group.

To enable adequate yield of its large die, Sensors-Demeter buys large InP-based epiwafers, which are processed in house.

"We currently use InGaAs epiwafers 3 and 4 inches in diameter," said Ettenberg. "To improve yields we will soon be receiving a batch of 6 inch InP substrates. We can take advantage of the increased diameter."



So who is the real MBE market leader?

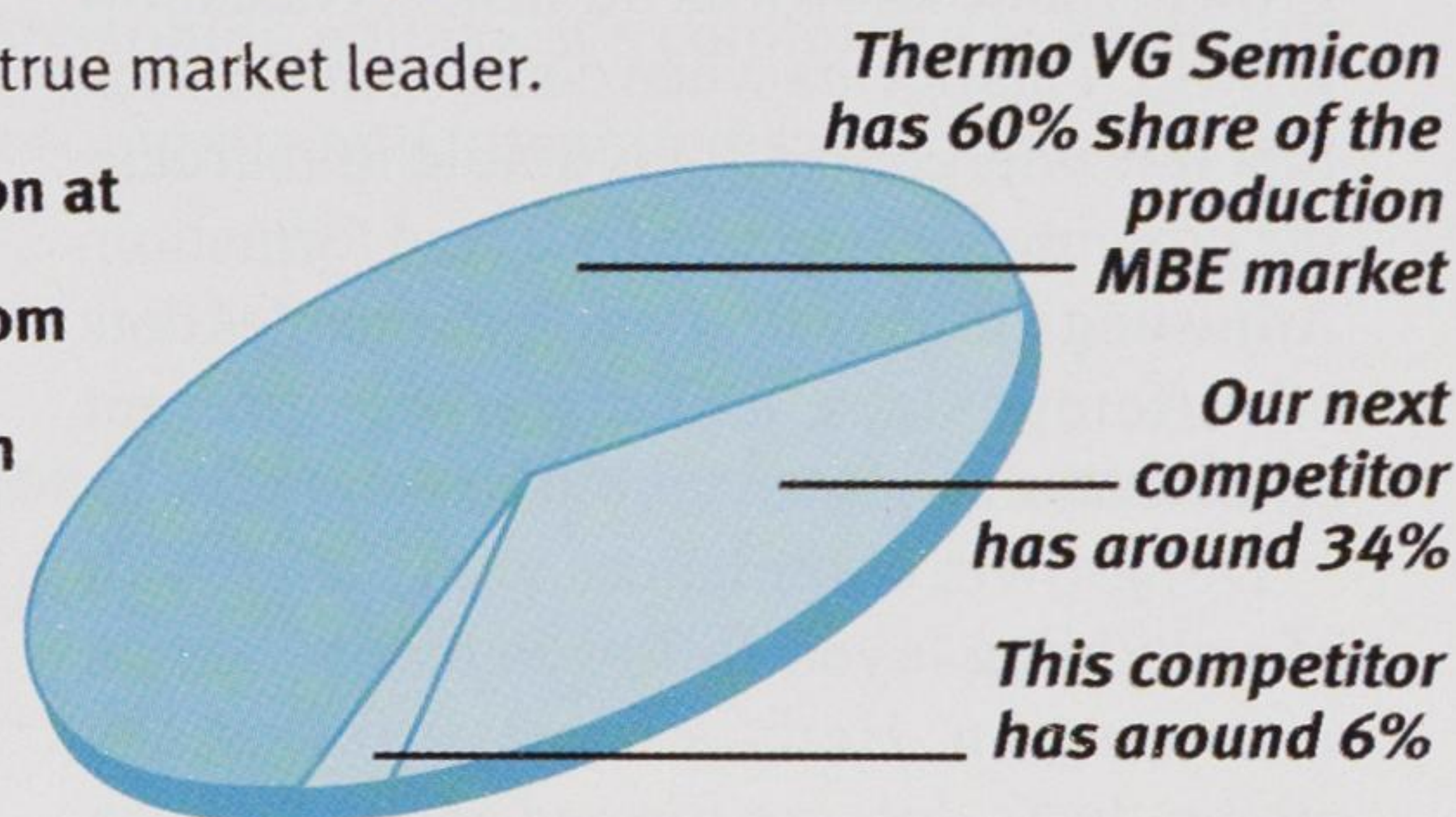
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Zia's quantum-dot lasers ready to challenge quantum-well dominance

By Jon Newey

The ability to grow high-quality quantum wells opened up a whole new range of optoelectronic devices to researchers. Probably the biggest commercial success to date for the QW has been the laser diode. However, another family of devices that uses the principles of quantum confinement in a rather different way is about to challenge the QW laser. There are a number of organizations currently investigating the optoelectronic properties of nanometer-sized three-dimensional semiconductor structures known as quantum dots (QDs). One such organization is Zia Laser, a company based in Albuquerque, NM, who announced at OFC in March that it had made some important moves towards commercializing its QD laser technology.

Founded in May 2000, the venture-capital-backed company has successfully produced an uncooled 1310 nm DFB laser on a GaAs substrate with an output power of at least 5 mW. The output power has five times the stability of uncooled QW lasers at typical operating temperatures. GaAs substrates are also significantly cheaper than the InP substrates typically used for lasers operating at this wavelength. Zia Laser has also developed a device based on its 1310 nm structure that can operate at wavelengths from 1277–1333 nm, making it suitable for CWDM applications. A third product is a 1550 nm gain chip that is tunable across the S, C and L bands with a maximum power output of 40 mW. Zia manufactures the chips and customers integrate these with external cavities to make tunable laser modules.

How quantum dots are formed

Quantum dots are formed during MBE in a growth mode known as Stranski–Krastanow growth. This occurs when conditions are such that it is energetically favorable to increase the growing surface area by island formation. Adjusting the growth conditions enables dots of different sizes, and therefore different optoelectronic properties, to be formed.

Dot growth commences with the growth of a cladding layer, followed by the laser's active region. Here, a layer of InGaAs is grown, InAs dots are formed and then these are overgrown with InGaAs. Dot formation and overgrowth are repeated several times

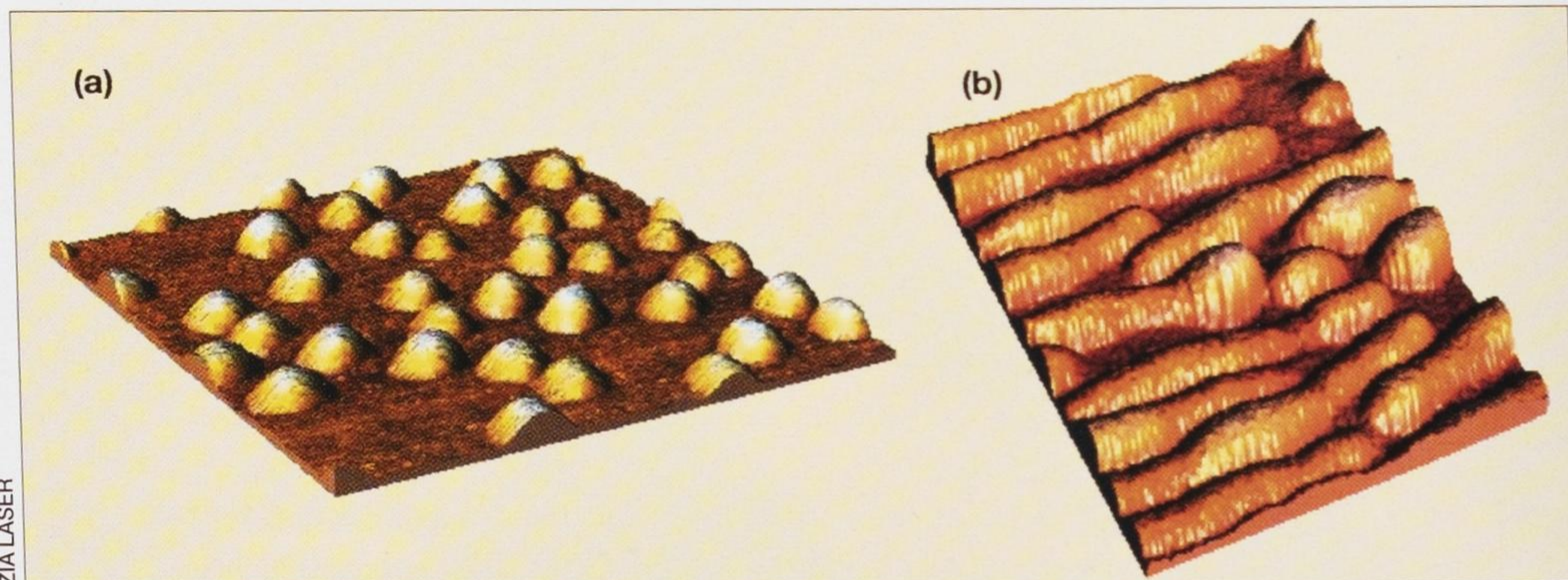


Fig. 1. AFM images taken over a $0.25 \times 0.3 \mu\text{m}^2$ area of InAs quantum dots on InGaAs (a) and InP (b). The dots on InGaAs are 7 nm high, whereas the dashes formed on InP measure about $300 \times 25 \times 5$ nm. A typical laser diode contains three to five million dots.

to construct the active region.

Test structures are shown in figure 1. Dot density is about $5 \times 10^{10} \text{ cm}^{-2}$ for InAs dots on an InGaAs layer. For the 1550 nm devices, InAs dot density on an InP substrate is about $1 \times 10^{10} \text{ cm}^{-2}$. For InAs dots on InGaAs, dot size is about 20 nm across the base and 7 nm in height (figure 1a). InAs dots on InP have a different shape, typically measuring $300 \times 25 \times 5$ nm, and are referred to as quantum dashes (figure 1b).

Dots versus wells

There are three main areas where QD lasers can outperform QW lasers. They are highly temperature insensitive, have a broad gain spectrum and ultra-low linewidth. The insensitivity of the emitted wavelength to temperature is a result of the low threshold current density ($20\text{--}30 \text{ A/cm}^2$) of QD devices. The threshold current density is about half that of a QW laser with a comparable diode design. This is because the device's active area is small, and so there is a smaller volume to populate with electron-hole pairs, unlike QW lasers where the active region extends across the entire device. Zia Laser quotes a wavelength stability of $0.3 \text{ nm/}^\circ\text{C}$ and $0.25 \text{ nm/}^\circ\text{C}$ for its 1550 nm InP-based and 1310 nm GaAs-based devices, respectively. The best data reported for QW lasers show $0.5 \text{ nm/}^\circ\text{C}$ for 1550 nm lasers and $0.4 \text{ nm/}^\circ\text{C}$ for 1310 nm lasers.

The dot formation mechanism leads to a distribution of dot sizes, and hence a distribution of energy levels. The wavelength spectrum over which gain is achieved extends across

these energy levels. The low threshold current density required for population inversion, coupled with rapid gain saturation of the lower energy levels, means that the higher energy levels can be inverted at low current densities. Zia Laser has demonstrated a gain spectrum spanning 170 nm for its 1550 nm devices and 200 nm for its 1310 nm devices at bias current densities of 6 kA/cm^2 and 3 kA/cm^2 , respectively. Similar tuning ranges can be achieved using QW lasers, but only with a tenfold increase in current density.

The ultra-low linewidth makes the laser less sensitive to the effects of back reflections, and also results in lower chirp when modulating the laser directly.

Network economics

Zia Laser sees QD technology as being ideally suited to the current needs of network systems and module suppliers, who are demanding both lower costs and improved performance. "Based on my experience with the commercialization of VCSELs, the QD device has a more profound systems-level impact," said Thomas Brennan, president and CEO of Zia Laser. Laser performance figures aside, the QD lasers do not need a TEC cooler, thermistor or external modulator, which simplifies module construction and lowers costs.

The coming year will be a busy time for Zia Laser. The company plans to start sampling the 1550 nm tunable gain chip family, and the 1310 nm DFB laser in April, with the 1310 nm CWDM laser scheduled to begin sampling in August.



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OpNext partners with Vitesse and WIN for 43 Gbit/s ICs

Optical network components maker OpNext has revealed four new 43 Gbit/s analog ICs. The products follow a collaboration with IC maker Vitesse Semiconductor of Camarillo, CA and Taiwanese GaAs foundry service provider WIN Semiconductors.

Designed by OpNext's Advanced Products Development Center, the ICs include a modulator driver, an integrated transimpedance amplifier/limiting amplifier (TIA/LA), a stand-alone limiting amplifier and an automatic gain control amplifier (AGC).

Vitesse built the three receiver ICs using its InP HBT process, while WIN fabricated the driver with its GaAs PHEMT process. Each product will be incorporated into transceivers for 40 Gbit/s optical networks.

"The ICs exhibit high gain, wide bandwidth, short rise/fall times, low jitter and well-opened eye diagrams," said KC Wang, VP of Advanced Products at OpNext. "This makes them ideal for 40 Gbit/s transceivers."

The modulator driver has differential outputs, which each have more than 2.5 V with a 0.4 V input. Additional jitter is less than 2 ps peak-to-peak, and rise/fall times are less than 10 ps. The integrated TIA/LA has an overall transimpedance of 57 dBΩ and a bandwidth of 35 GHz. The stand-alone limiting amp has a 26 dB gain and 37 GHz bandwidth, while the AGC demonstrates a controllable gain from -0.7 to 24 dB over a bandwidth of 34 GHz.

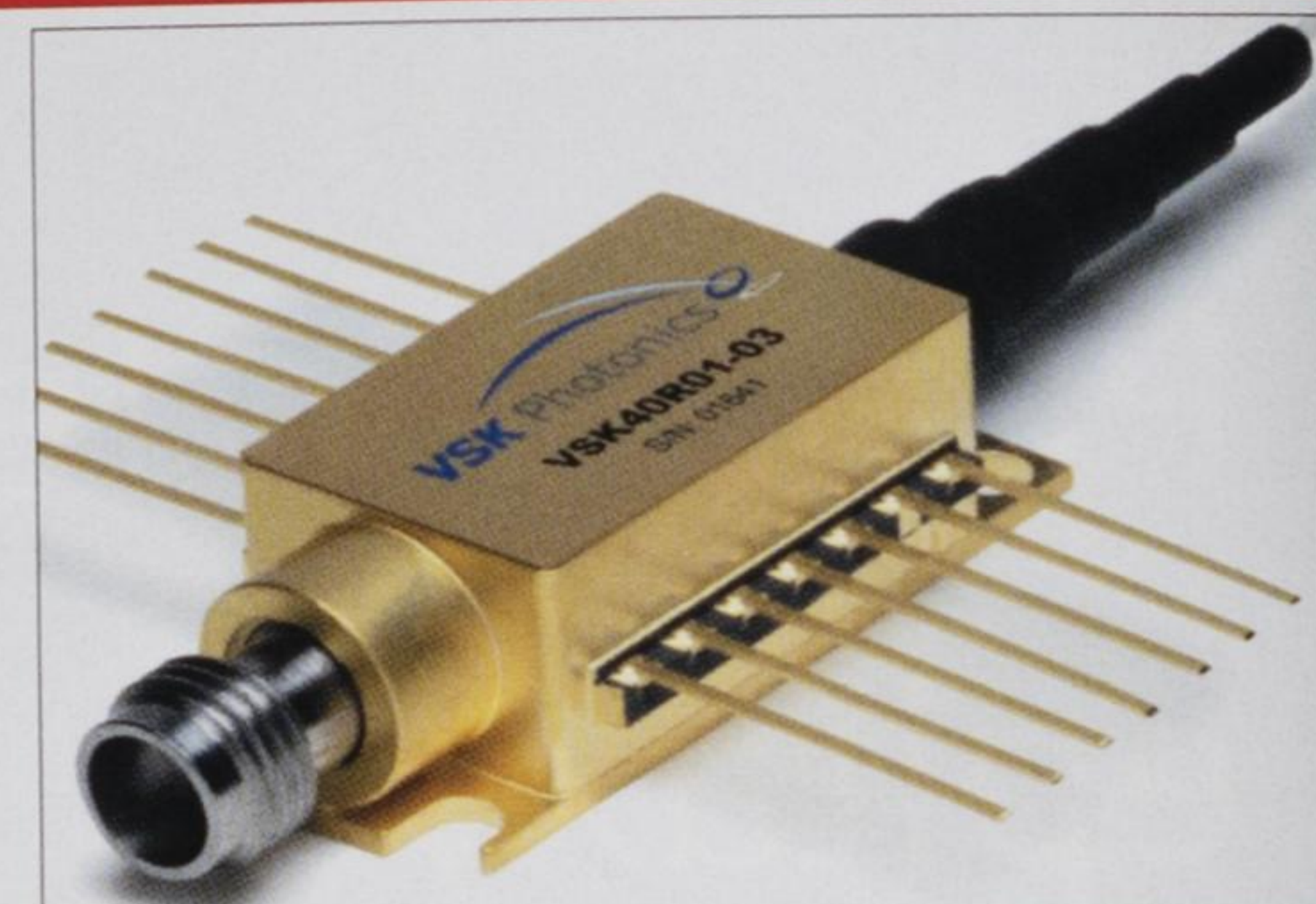
All ICs operate at 43 Gbit/s, with open output eyes at room temperature and 100 °C.

VSK launches first InP-based products

Optical component start-up VSK Photonics, based in Lake Forest, CA, has unveiled three new InP-based receivers. The VSK10R01, VSK12R01 and VSK40R01 are designed for 10 and 40 Gbit/s networks.

The VSK10R01 is a 10 Gbit/s optoelectronic IC receiver module for metro and long-haul systems, and is designed to replace avalanche photodiode receivers. The VSK12R01 is a 12.5 Gbit/s version of this model, and is also designed for long-haul applications using forward error correction. Each device operates at 5 V and contains an active photodetector circuit and integrated preamplifier.

The VSK40R01 contains a waveguide photodetector and, according to VSK, can be used instead of surface-illuminated *pin*-based receivers in 40 Gbit/s networks.



The VSK40R01 InP receiver is suited for 40 Gbit/s long-haul applications that require forward error correction.

VSK has already opened a 2800 sq. ft fab with a capacity for 10 million InP-based devices per year. The products come just one year after the company's initial financing round and a second funding round earlier this year (see *Compound Semiconductor* March 2002, p19).

T-Networks gets funding boost

T-Networks of Pennsylvania has received \$30.6 million in funding to develop InP-based 10 and 40 Gbit/s electroabsorption modulators. The company had already won \$29 million in first-round funding at the end of 2000, and says the latest cash injection will be used to support additional personnel and the sales infrastructure.

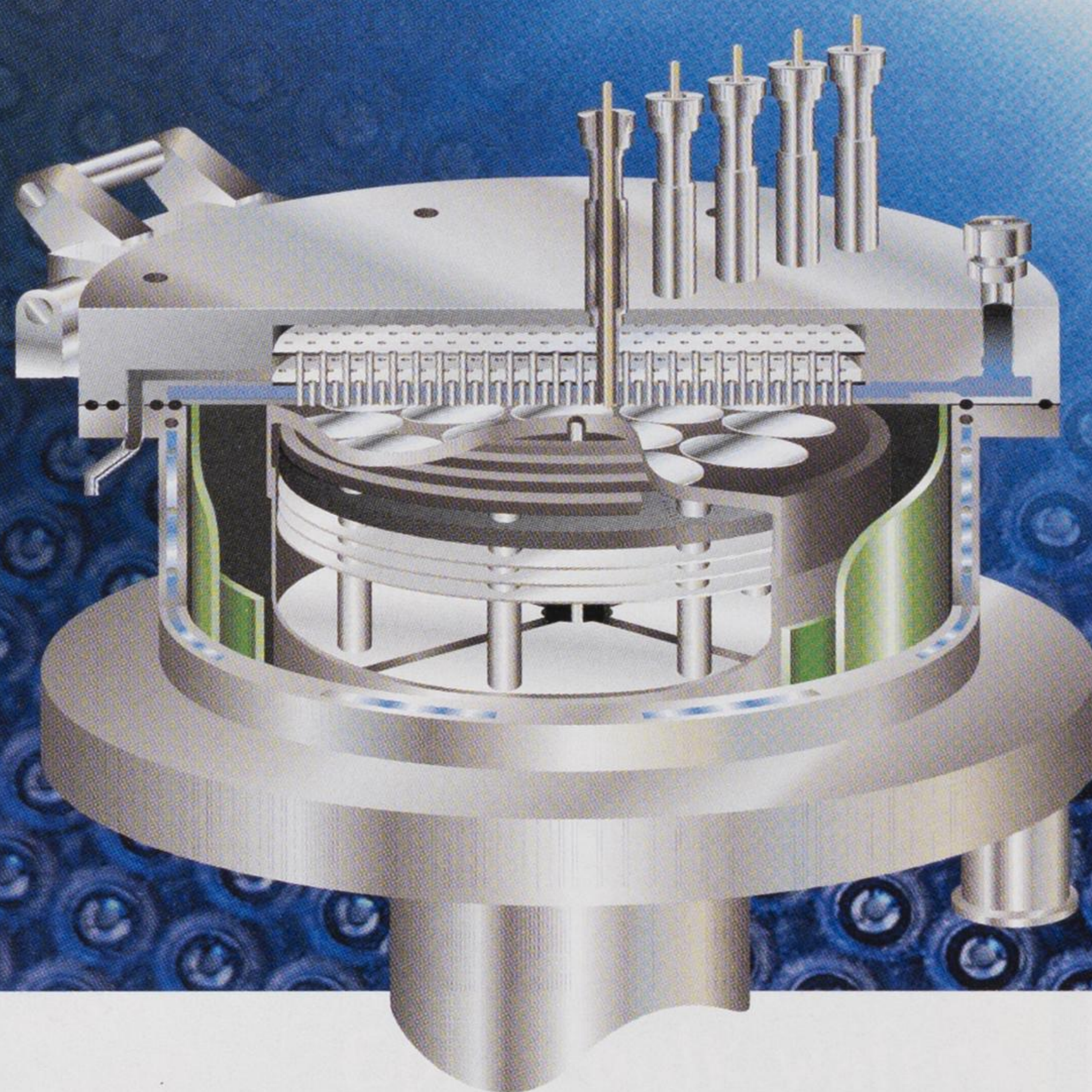
The current round of funding comes from

several original investors including Intel Capital and Vitesse, as well as a new investor, TL Ventures. T-Networks plans to start generating revenue and to reach volume production by the second half of this year. The company has already reported sales of its 10 and 40 Gbit/s modulators. These components will compete with incumbent lithium niobate devices.

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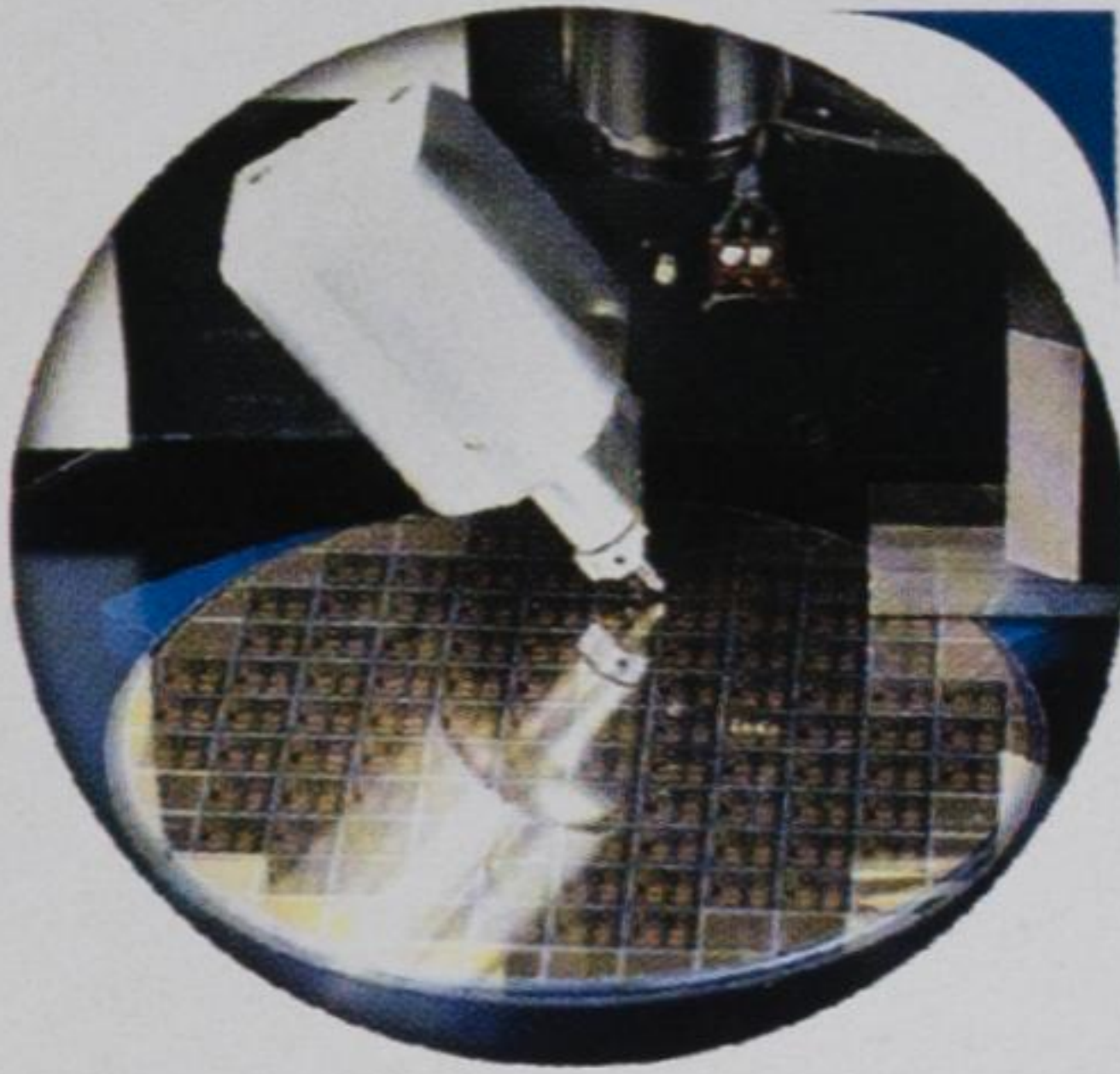
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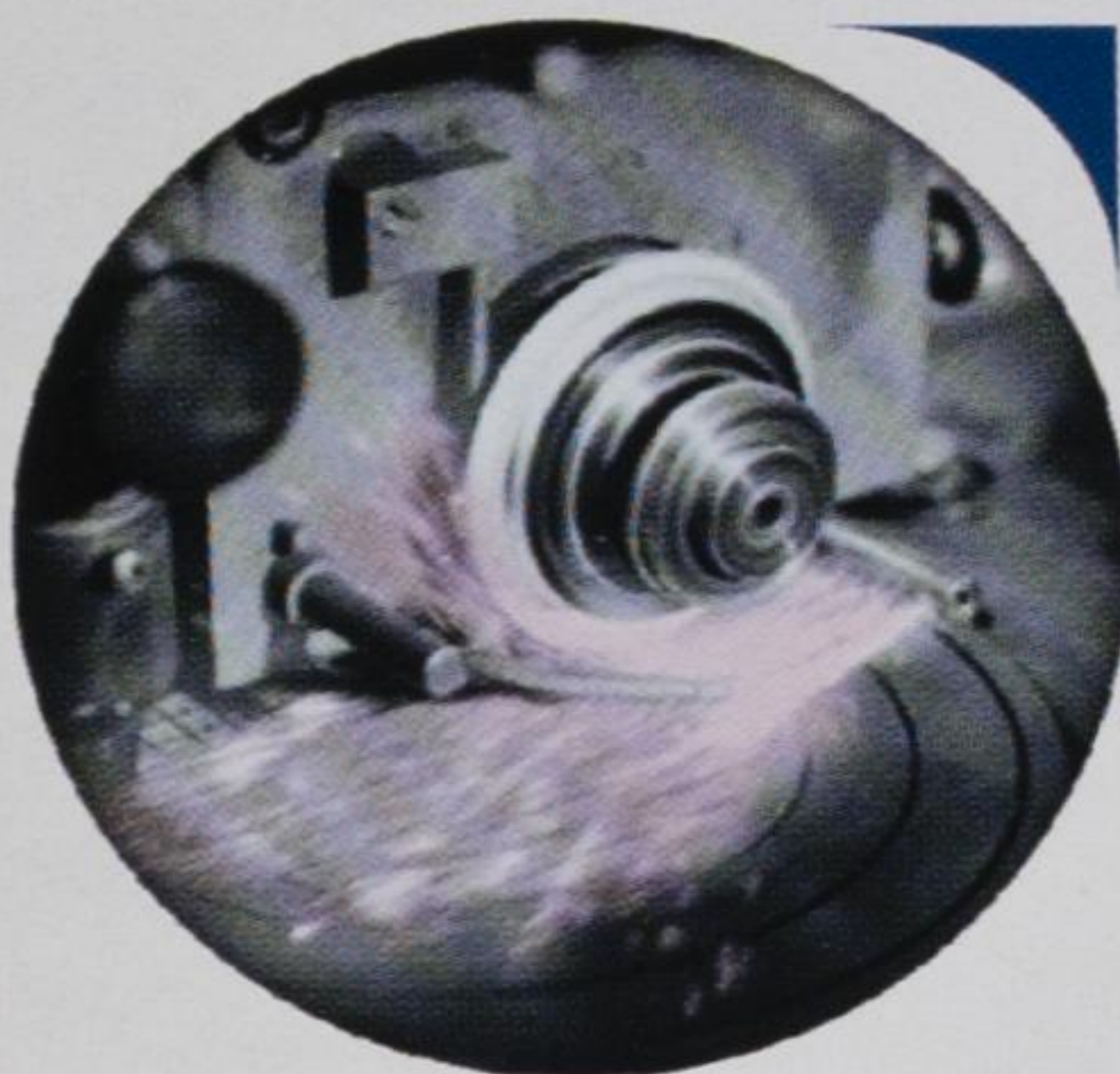
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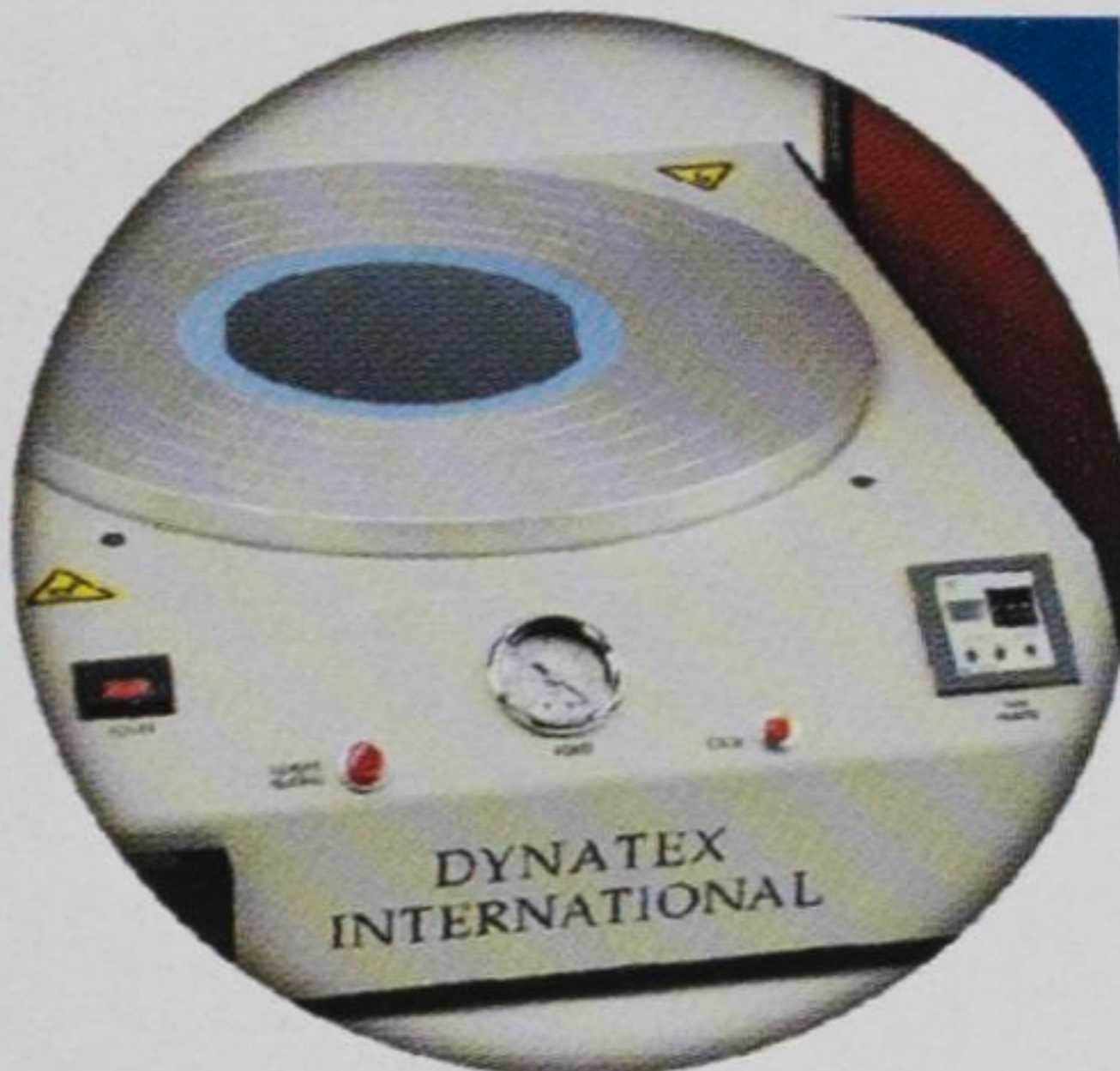
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Sparkolor unveils 40 nm tunable laser

Sparkolor of Santa Clara, CA has developed a laser that tunes across a 40 nm wavelength range. Tunable lasers are crucial to DWDM manufacturers that are keen to add transmission channels to their networks. These lasers also reduce sparing requirements, which means that service providers don't have to stock costly spare parts.

Using planar hybrid integration, Sparkolor combined a Fabry-Perot laser diode with a silicon substrate containing a tunable grating of deposited silica (see *Compound Semiconductor* January/February 2002, p16). The laser operates at a 25 GHz channel spacing and has the potential for remote tuning across any one of 400 DWDM channels.

"Planar hybrid integration allows us to integrate our tunable grating structures with commercially available broadband diodes on a single substrate," said Sparkolor's CTO Dave Deacon. "By doing this we can apply the economics of semiconductor manufacturing to optical components and subsystems." Sparkolor has also demonstrated tuning across 80 nm, covering all of the C- and L-bands.

Agere and Multiplex settle patent debate

Agere Systems and Multiplex have signed a patent cross-license agreement that settles all pending lawsuits between the companies.

In August of last year, Agere filed two lawsuits against Multiplex accusing its competitor of patent infringement and property theft (see *Compound Semiconductor* September 2001, p13). The patent infringements related to pump lasers and emitters for short- and long-haul applications. The settlement details are confidential.

Alcatel and Multilink seal transceiver deal

Alcatel Optonics of France and Multilink, a fabless mixed-signal IC manufacturer based in New Jersey, have joined forces to develop a 10 Gbit/s transceiver module for long-haul and submarine markets. Planning to sample in the fourth quarter and start production by mid-2003, the team will also develop 40 Gbit/s transceivers.

OPTOtech deal aids Taiwan news service



Compound Semiconductor is very pleased to announce a strategic alliance with OPTOtech magazine that will significantly enhance its coverage of the optoelectronics industry in Taiwan. OPTOtech is a Chinese-language trade magazine published in Taiwan by Infoworkstation Ltd. As part of the agreement, OPTOtech will provide a monthly update of news from Taiwan's optoelectronics industry. The first installment from OPTOtech is included in the current News from Asia section. In exchange, OPTOtech will publish certain articles that have previously been published in Compound Semiconductor.

Rohm releases blue LEDs

Reports in the Japanese press indicate that Rohm will introduce a blue LED in June. The products will target markets such as cellular handset displays, home-video game machines and display panels. Rohm is initially aiming for monthly sales of ¥10 million (\$77,000), and will look to increase this by a factor of 10

in the near future. The company has refrained from commercializing its blue LED products in the past due to concerns over the ongoing patent dispute between Nichia and Toyoda Gosei, among others. Rohm has also developed a blue laser and hopes to put this device on the market soon.

China is opened up to Taiwan's LED manufacturers

By Lee Shu-Hui, OPTOtech

The LED industry in Taiwan reported good sales in March, and was boosted by the news that the Taiwan Ministry of Economic Affairs has made a preliminary decision to allow chip makers and packaging companies to set up factories in mainland China. As a result, the stock prices of LED makers such as Tyntek, Everlight and Epistar rose significantly.

According to chip manufacturer Tyntek, a

number of LED packaging factories have already been established in China to take advantage of low labor costs. In addition, Tyntek and United Epitaxy Company have set up factories to perform the manual inspection of chips prior to packaging. Tyntek says that the lack of import and goods taxes in China can reduce costs by 12–15%.

However, due to the relatively high technical level of epitaxial growth, manufacturers have not been willing to move such activities to China. Epiwafer and LED maker Epistar says that although it has no firm plans to set up in China, it is evaluating such a move, and may establish a facility if its downstream packaging customers need a local epiwafer supply.

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PIDA reveals Taiwan sales figures

According to annual reports from manufacturers in Taiwan, which were compiled by the Photonics Industry Development Association (PIDA), the 2001 revenues of most LED companies were 3–15% lower than in 2000, due to the global market recession. However, the end of last year is thought to have been the low point in sales.

“Starting from late 2001, the demand for LED products has increased,” said Robert Su, a PIDA analyst. “Local LED packaging companies have reported better facility utilization rates, and it is estimated that the outcome

Production of LEDs and lasers in Taiwan

Production value (\$ million)	2000	2001	2002	2003	2004
packaged LEDs	431	396	403	419	440
packaged laser diodes	20	27	32	39	47

in 2002 will be even better.” As shown in the table, PIDA predicts that LED sales will increase by around 1.5% in 2002, and grow at a rate of 4–5% in the next two years.

For laser diode packaging companies in Taiwan, investment has shifted from laser pointers to high value-added components. “A

number of the companies that assemble transceiver modules have upgraded to the manufacture of epitaxy and chips,” said Robert Su. “Also, since more companies have established VCSEL production facilities, it is estimated that the production value of laser diode packaging will increase steadily.”

Procomp receives qualification for laser diode epiwafers

By Lee Hsun-Ying, OPTotech

Since optical heads for CD-RW and DVD players are currently in short supply, Japanese manufacturers have started to look to external suppliers for some of the key components. The world’s largest optical head manufacturer, Sharp, qualified laser diode epiwafers from Procomp last September. The customer now accounts for 10–20% of Procomp’s total output, which is around 8000 epiwafers per month, and has also promised that future orders will increase each month. Since the unit price for this product is quite high, Procomp expects it to account for 20% of the business revenue for the whole year. Demand has risen because of the growing number of PCs with more than one type of optical drive (e.g. DVD and CD-RW), and because of the growing

popularity of DVD players.

Procomp has indicated that its revenue for the first quarter of 2002 is set to fall by approximately 10–20%, compared with the fourth quarter of 2001, to around NT\$1.6–1.8 billion (\$46–52 million). The company estimates that revenue for the current quarter will not show a significant increase compared with the first quarter, although it does expect recovery and growth to appear in the third quarter.

Beginning in the current quarter, Procomp has plans to install a further two epitaxy machines per quarter, and hopes to have 25 machines by the end of this year. The company predicts that its epiwafer business will grow by 15% in 2002, and that epiwafers will account for more than 30% of the company’s total revenue.

GigaComm buys packaging line

By Hu Chao-Wei, OPTotech

GigaComm, a fiber-optic component manufacturer owned by LED maker Epistar, recently purchased a VCSEL TO-can packaging line from Everlight for less than NT\$10 million (\$289,000). The line has a maximum capacity of 100,000 units per month, and has already been relocated to GigaComm’s factory. Quantity production is expected to start at the end of May. Since Yeh Yin-Fu, the chairman of Epistar, is the major shareholder of both Everlight and GigaComm, the transaction was concluded at a price lower than market quotations.

Everlight’s VCSEL packaging line was originally an OEM factory supplying companies such as Emcore, Cielo and E20. Due to poor economic conditions and a low utility rate, Everlight had the intention of selling out and concentrating on LED packaging. Since GigaComm planned to integrate downstream from laser diode epiwafer and chip production to packaging, the deal was a natural fit for both companies.

Tan Chang-Lin, GM of GigaComm, points out that some OEM customers will be lost following the acquisition. However, one of Everlight’s main customers, E20, also owns 25% of the GigaComm shares. Since E20’s Singapore factory is almost fully utilized, there should still be some OEM orders.

GigaComm also plans to invest another NT\$30 million to set up an automated package production line for FP lasers in TO-cans. The line will produce both 1310 and 1550 nm FP lasers at a rate of 10,000 units per month for both products.

Translogic opens Taiwan factory

By Hu Chao-Wei, OPTotech

Advant, a US company based in Silicon Valley that is developing fiber-optic transponder products, has decided to set up a new company in Taiwan during the first half of this year. Advant’s OC-192 (10 Gbit/s) transponder product has already been qualified by Cisco. The company, which has also developed OC-48 (2.5 Gbit/s) transponders and electroabsorption modulator laser (EML) modules, plans to change its name to Translogic after the new company is established in Taiwan.

Translogic is planning to set up a quantity production factory in Hsinchu Science Park during the first half of the year, while the branch company in Silicon Valley will set up a trial production line. Both OC-48 and OC-192 transponders will enter volume production by May 2003, and will be followed by EML modules. Approximately NT\$1.4 billion (\$41 million) has been invested in the company, of which NT\$400 million has been spent mainly on research and development, with the remaining NT\$1 billion being used to build the production line.

Sharp accelerates laser schedule

In July, Sharp plans to commence production of laser diodes at its new plant in Mihara, Hiroshima Prefecture, two months ahead of schedule. The plant will make red lasers for DVD players and have a capacity of 5 million units per month. Sharp already makes 14 million laser diodes a month, mainly for CD-R drives,

at its factory in Nara Prefecture. The schedule change has come about due to a renewed demand for PCs, which now contain at least one optical data storage device. Sharp's sales of semiconductor lasers fell 34% in fiscal 2001 to ¥30.7 billion (\$239 million), but are projected to rise by 40% to ¥43 billion in fiscal 2002.

Ryosan invests in Infomax Optical

By Hu Chao-Wei, OPTOtech

Taiwanese fiber-optic component manufacturer Infomax Optical has received NT\$150 million (\$4.3 million) from Japanese company Ryosan, the exclusive agent for NEC components in Japan. Ryosan's main shareholders are NEC, Fujitsu, Mitsubishi and Sumitomo. A US company is also expected to invest in Infomax soon. Ryosan has invested in Infomax in expectation of a strong market demand for fiber-to-the-home (FTTH) technologies; NEC and Fujitsu are the main companies constructing FTTH networks in Japan.

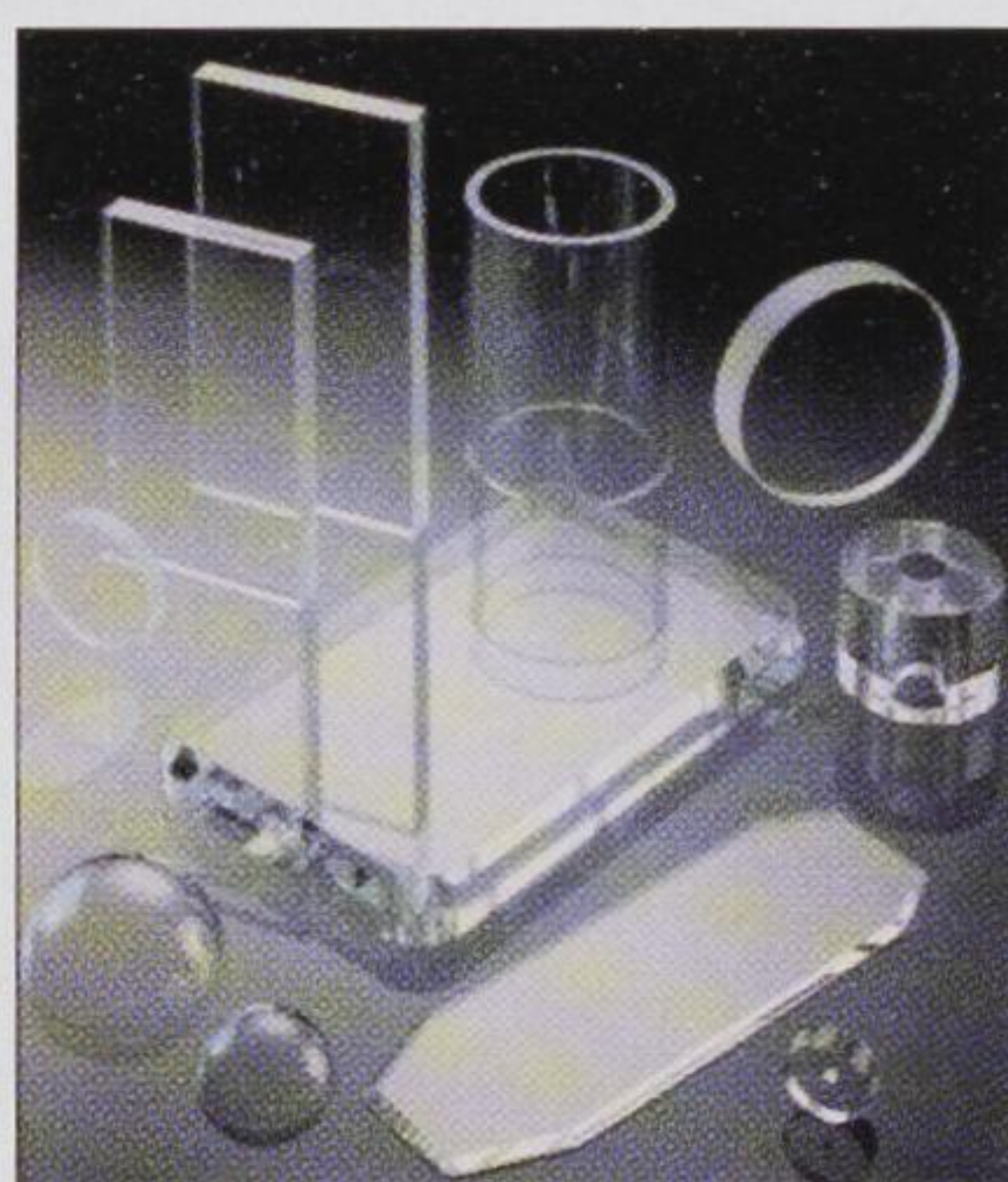
Infomax will use the capital to build a fully-automated TO-can package production line, and expand its production capacity for laser diodes and optical sub-assemblies. The automated TO-can line should be in full production by the third quarter, and will quadruple the monthly capacity to 120,000 units. Laser-diode production will increase from 150,000 at present to 500,000 during the second quarter. The productivity of optical sub-assemblies will remain at 50,000 units per month, and strategic alliances with domestic manufacturers will be sought.

Fiber-optic market creates business for CMOS foundries

By Hu Chao-Wei, OPTOtech

The fiber-optic market has created business opportunities for CMOS foundries in Taiwan, such as TSMC and UMC. At this year's Optical Fiber Communication conference (OFC), Intel restated that all its CMOS transceiver ICs will be made in Taiwan, and two IC design companies – Broadlight and Transpectrum – indicated they would place orders in Taiwan.

Last year, UMC adopted a 0.13 μm CMOS process for 10 Gbit/s ICs developed in collaboration with AMCC. Wafers for 40 Gbit/s ICs will use a 0.1 μm CMOS process and will be introduced next year. Transpectrum plans to introduce its first 40 Gbit/s ICs fabricated using 0.13 μm CMOS technology during the third quarter of this year. Broadlight is developing fiber-to-the-home ICs using 0.18 μm CMOS, and is targeting an extremely low price point, making the use of Taiwan's CMOS foundries a virtual certainty.



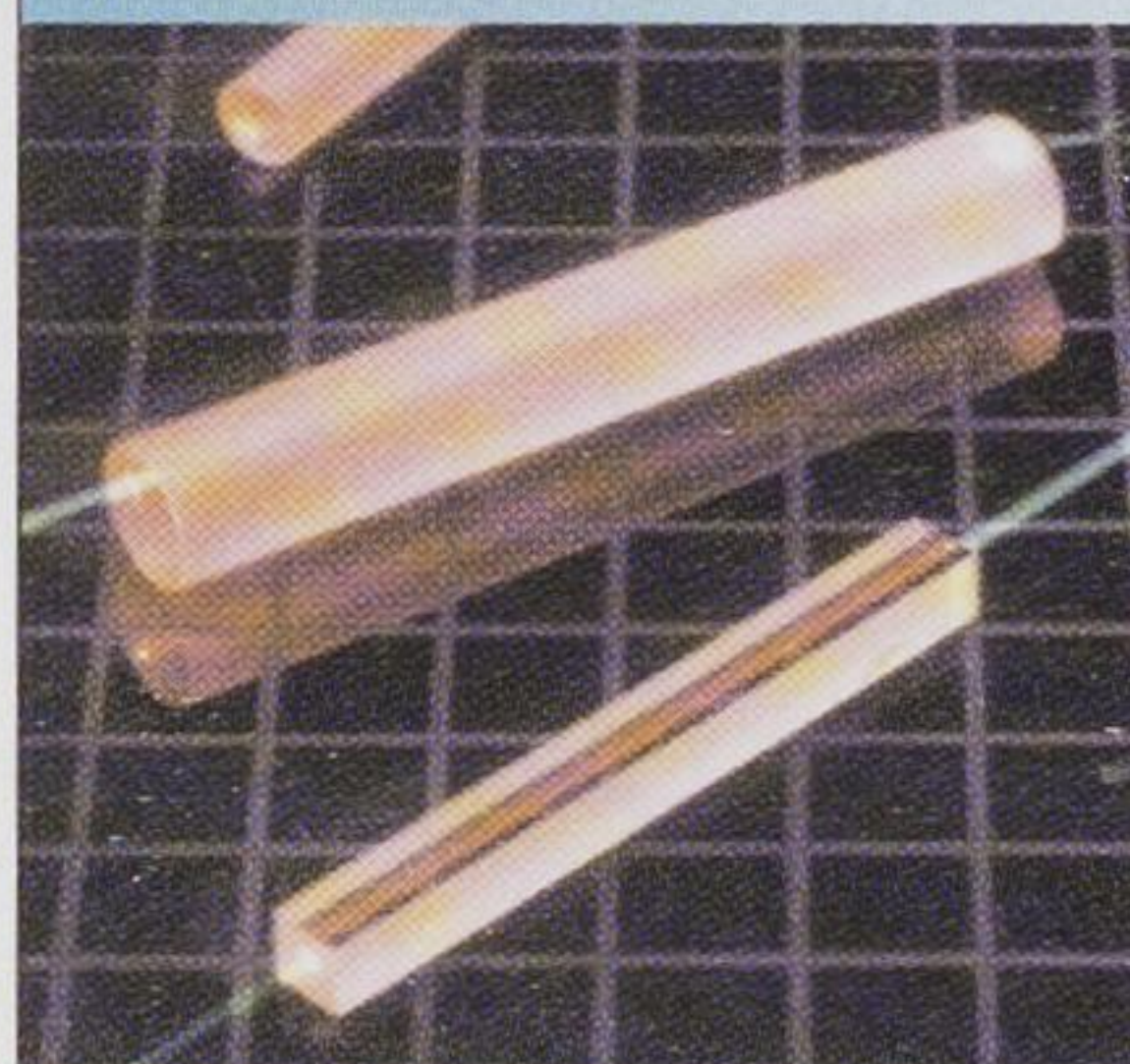
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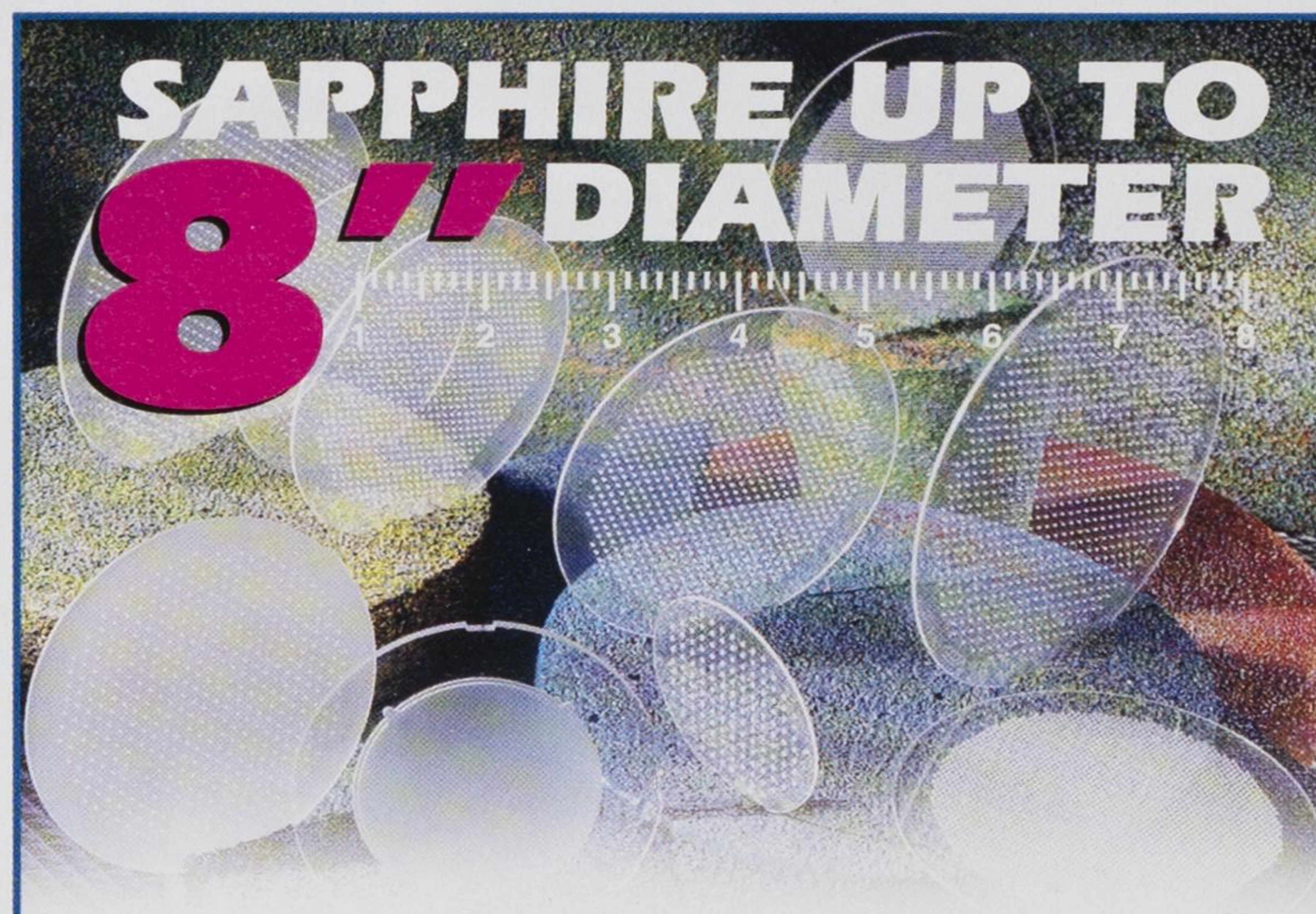
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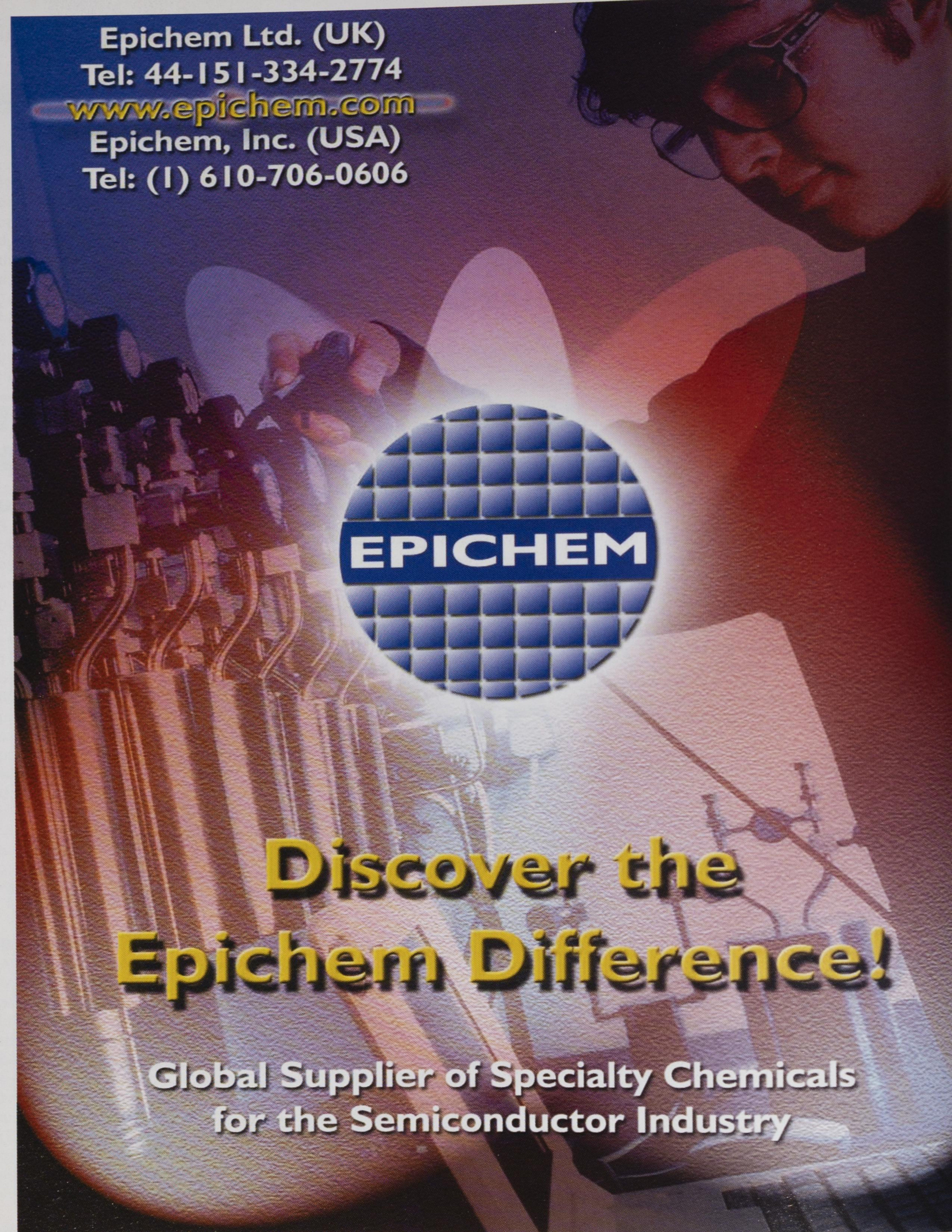
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Lasers and detectors set to lead a slow recovery

The lack of capital expenditure by carriers continues to hurt optical network equipment and component manufacturers. According to a report by Strategies Unlimited, spending by carriers will fall by 21% in 2002 resulting in revenues for optical subsystem and component vendors falling by 65% and 60% respectively. The report predicts that components such as lasers and detectors that combine high unit sales with high unit prices will begin to see some recovery in 2002. Strategies Unlimited adds that the sector as a whole will see gentle recovery in 2003.

Another report, from RHK, forecasts that capital expenditure by carriers in North America will decline from \$77 billion in 2001 to \$46–51 billion in 2002. Capex is expected to be flat in 2003 with growth beginning in 2004, even though Internet traffic is predicted to double in 2002. Only 35% of long-haul

capacity is used at present and, with service providers finding ways such as WDM to extract extra capacity out of installed networks, there is no immediate need for expenditure on new infrastructure.

However, the picture in Europe appears less gloomy – RHK predicts a smaller decline in capex for the region compared with North America. European carriers spent less than their North American counterparts during the 1999–2000 capex bubble and most of the decrease in European spending is expected to come as a result of reductions in spending in the core and metro networks.

Market Update – April 2002 Optical Networking Components is available from Strategies Unlimited, while *North American Telecom Is In For a Slow Recovery* is available from RHK. For more information see www.strategies-u.com and www.rhk.com.

Nokia reacts to Q1 results by reducing 2002 sales forecast

Nokia has reduced its sales forecast for 2002 on the back of disappointing first-quarter results. The company now expects overall sales to grow by 4–9% compared with 2001. Nokia's mobile-phones business is expected to show growth of 5–10% for the full year, with 0–5% growth in the infrastructure business. The company had previously forecast full-year sales growth of 15% for both units.

Nokia has also reduced its estimate of the number of handsets that will be sold during 2002. "Mobile-phone market volumes in the first quarter of 2002 were broadly in line with company expectations," said Jorma Ollila, Nokia's chairman and CEO. "However, Nokia now believes that general weakness in all key regions will affect mobile-phone demand for the remainder of the year. We are therefore lowering our total market volume estimates for 2002 to 400–420 million units." Nokia had previously forecast handset sales of 420–440 million for 2002. Gartner Dataquest estimates that 399.6 million phones were sold in 2001, although Nokia's estimate for the same period is 380 million units.

Handset ICs to hit \$31 billion in 2006

A report from Allied Business Intelligence (ABI) says that increased demand for cellular handsets with a higher IC content than today's models will drive impressive growth in the market for cellular ICs. The report updates ABI's forecast in August 2001 that the total cellular IC market would grow from \$13.9 billion in 2001 to \$26.4 billion in 2006. ABI now puts the 2001 figure at \$9.7 billion, growing to \$31.5 billion in 2006.

The delay of 3G services is slowing moves to develop chip-sets specifically for 3G handsets. These will need to handle data as well as conventional voice traffic placing increased demands on the ICs. As a result, the value of semiconductors in 3G phones will be 49% greater than in 2.5G devices.

The report also looks at the strengths of the different material technologies used for various functions within the handsets. While SiGe is expected to further penetrate the PA, LNA and mixer functions where GaAs devices are widely used, GaAs-based HBTs are expected to remain the most common PAs in the next 3–5 years.

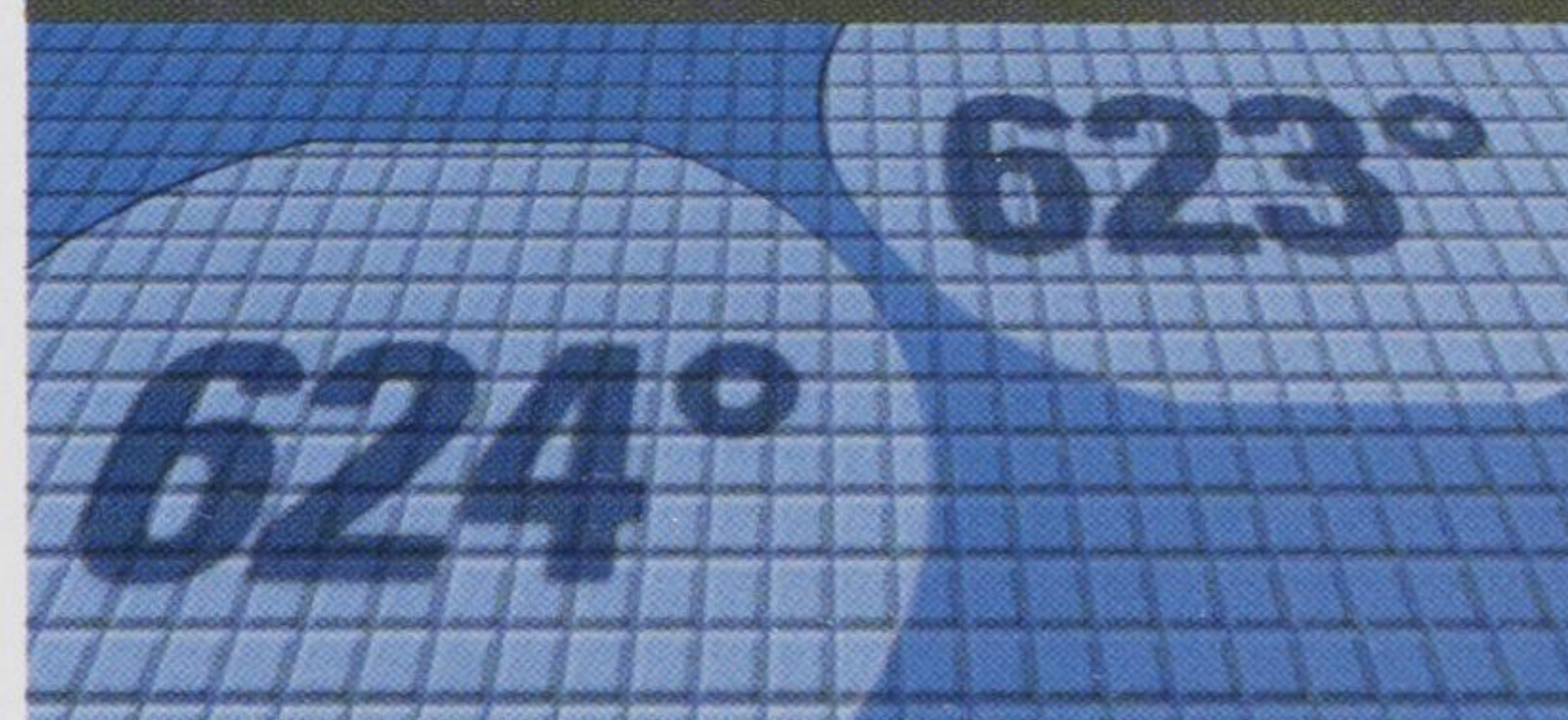
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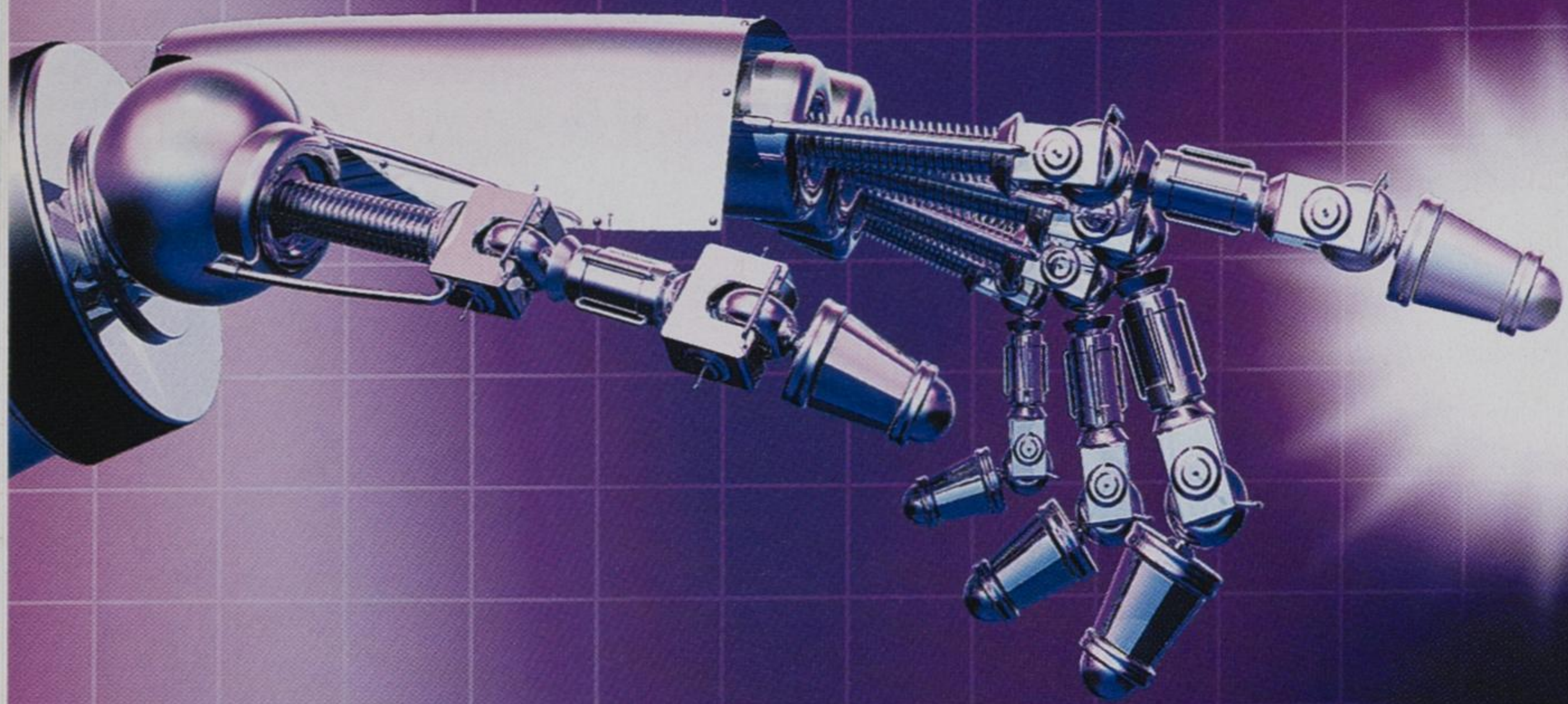
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SAES names Aeronex in lawsuit over gas purifier

SAES Getters, the Italian parent company of SAES Pure Gas, has cited gas purifier maker Aeronex in a patent infringement lawsuit. Aeronex is located in San Diego, CA.

The action hinges on US patent number 6,241,955, that was awarded to Aeronex for its GateKeeper and Infinity GPS hydride gas purification systems. These systems use gettering to remove oxygen and other contaminants from ammonia.

However, SAES alleges that Aeronex's purifier infringes its US patent 5,716,588, which broadly claims the use of iron and manganese in a gettering process. Aeronex denies the allegations and says that its gas purifier technology is not covered by SAES's patent.

"We are a technology development company that has been granted some 15 patents, and we are not interested in using the technology of other companies," commented Aeronex president Jeff Spiegelman. "We will prove that our technology is different and that there is no infringement."

Purifier problems

Ammonia is used during the MOCVD epitaxial growth of nitride-based devices such as LEDs, lasers and high-frequency micro-electronic circuits. To prevent impurities contaminating ammonia and degrading the device properties, getter purifiers contain a metal that reacts with these impurities and binds them at the metal surface. The impurities then diffuse into the bulk metal leaving the surface free for more adsorption (see *Compound Semiconductor* December 2001, p51).

SAES's design is based on an inert silicate or zeolite support substrate that contains elemental manganese and iron to remove oxy-

gen from ammonia. Aeronex's purifier also uses manganese and iron as its gettering medium, but in the form of metal oxides with different oxidation states. The oxides of manganese and iron are mixed to provide the active medium and support structure. Aeronex's patent, which refers to SAES's earlier work, says that the purifier removes carbon dioxide and moisture, as well as oxygen.

Escalating conflict

SAES filed the patent infringement claim in the Federal District Court of the Southern District of California, but may now extend it to claim false advertising and unfair competition by Aeronex when selling its iron/manganese oxide getter-based purifiers. As well as unspecified financial compensation, SAES is seeking an injunction against the sale of the purifiers, a retraction of the false and misleading claims, and another injunction against continued false advertising.

"Aeronex seems to be operating under the erroneous assumption that their purported 'improvement' patent gives them free license to infringe SAES's pioneering patents in this field, and allows them to make false and misleading claims concerning their products," said Giulio Canale, managing director of SAES Getters. "Since our attempts to resolve these issues directly with Aeronex have failed, we must now unfortunately seek resolution through appropriate legal channels."

Spiegelman disagrees: "During the application we let the patent office know what other technology existed, and were granted our patent. These kinds of lawsuits hinder innovation and tend to severely restrict the options available to end-users."

Equipment sales

● **Tekcore**, a Taiwanese manufacturer of GaN-based LED epiwafers, has ordered an **Aixtron AIX 2600G3HT** 24 x 2 inch MOCVD reactor. The company plans to expand production capacity for blue and green LEDs.

● Korea's **Electronics and Telecommunications Research Institute** has bought a Hall Effect measurement system from **Accent Optical Technologies**. The HL5500PC measures resistivity, carrier

concentration and mobility. The institute will use the system to develop InP-based material for 1.3 and 1.55 μm VCSELs and optoelectronic devices, as well as AlGaIn and InGaIn HEMTs and other high-frequency circuits.

Gallium Arsenide

Indium Antimonide

Indium Arsenide

Indium Phosphide

Gallium Antimonide

Gallium Phosphide

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Silicon

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wafer technology

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Europe's suppliers beat US and Japan

A survey from semiconductor market analyst VLSI Research reveals that in 2001 European equipment suppliers seized market share at the expense of their US and Japanese rivals. European sales were \$4.44 billion, down 27% year on year. However, US sales fell 40%, while Japanese sales saw a 30% decline.

In terms of Europe's highest-selling semiconductor equipment makers, the survey ranked compound semiconductor manufac-

turers Unaxis, Aixtron and Suss MicroTec in third, fourth and fifth place respectively. Unaxis's sales reached \$273 million, with Aixtron selling \$214.9 million and Suss MicroTec bringing in \$185.9 million. Silicon suppliers led the field, however, with ASML coming in first at \$1544 million, followed by ASM International with \$463 million.

Other compound semiconductor vendors that made the top 15 include Oxford Instru-

ments, Trikon Technologies, Surface Technology Systems and BOC Edwards.

More success for suppliers

A customer-satisfaction survey, also from VLSI, rates Aixtron and Oxford Instruments among the 10 best equipment suppliers in Europe. VLSI collected 1345 responses from European manufacturers including AMD, Infineon, Intel, Motorola and Philips.

Suss buys BLE to expand its range of coating systems

Suss MicroTec has bought the assets of German equipment maker BLE Laboratory Equipment. BLE's products include spin-coating technology for applying photoresist to wafers, wafer-mounting technology for processing thin compound semiconductor

materials, and other wafer and substrate processing equipment.

"BLE's equipment is found in research institutes, universities, start-ups and leading IC manufacturers," said Suss MicroTec's president and CEO, Franz Richter. "This provides us with an early introduction to the process needs of our customers."

BLE was founded in Singen in 1993 and employs 100 people. Its customers are low-volume semiconductor manufacturers as well as R&D centers.

Bede Scientific wins 2002 Queen's Award

Bede Scientific Instruments has won the 2002 Queen's Award for Enterprise in International Trade. The top UK business award honors outstanding achievement in international trade.

"We are delighted to receive our fourth Queen's Award," said managing director Neil Loxley. "The award was based on success in international trade during a period of intensive growth for the company, which culminated in floating Bede on the London Stock Exchange in November 2000."

Picopolish to close plant in Switzerland

Epiwafer vendor Picogiga's GaAs and Si wafer reclaim subsidiary, Picopolish, is to close its facility in Bevaix, Switzerland. The plant was opened in December 1999 after Picopolish's French facility was severely damaged by a fire.

The company's activities have been hit by the fall in demand for GaAs and Si wafers. Despite signs of a strong recovery in its reclaim business, costs at Picopolish's Swiss operation have continued to rise. The company will relocate the plant's activities to a cheaper location in France later this year.

Tegal develops high-etch-rate process

Tegal has developed a process for its plasma-etch tools that can give GaAs etch rates of more than 10 $\mu\text{m}/\text{min}$. The process is designed for high-throughput etching of via holes 100 μm deep and with more than 20:1 selectivity to photoresist.

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Antimonide base for low-power HBTs

Because of their excellent linearity and high PAE, InGaP emitter HBTs are now being used for the PAs in mobile-phone handsets. One of the major trends for future high-performance mobile handsets is to realize low-power operation so as to extend the time between battery recharges. Current GaAs HBTs have a relatively large emitter-base turn-on voltage, which is not favorable to low-power operation.

A collaborative effort between researchers from The University of Hong Kong and The Chinese University of Hong Kong has recently resulted in a low turn-on voltage InGaP/GaAsSb/GaAs DHBT (*Elec. Dev. Lett.* 2002 **23**(4) 170). The reported device features a fully strained pseudomorphic GaAs_{0.92}Sb_{0.08} base layer and an InGaP emitter layer. The InGaP/GaAsSb/GaAs DHBT structure was grown by MOCVD on a semi-insulating GaAs substrate. The devices were fabricated using optical lithography and selective wet chemical etching for mesa definition. The turn-on voltage of the DHBT was typically 0.93 V, which was 150 mV lower than that of a commercially available InGaP/GaAs HBT used for comparison, indicating that GaAsSb is a suitable base material for reducing the turn-on voltage of GaAs-based HBTs.

III-V heterostructures formed in nanowhiskers

Recently, interest in one-dimensional semiconductor materials known as nanowhiskers has grown. Devices such as diodes have been fabricated using a number of differently doped whiskers. Attention is now turning to nanowhiskers containing heterostructures that allow discrete devices to be contained within individual whiskers.

The growth of III-V nanowhiskers is usually catalyzed by a gold seed particle that also controls the diameter, with length being controlled by growth time. The small whisker diameter allows lateral lattice relaxation, thus allowing heterojunctions between materials with large lattice mismatches to be grown successfully.

A team from Lund University in Sweden has used CBE to grow whiskers of alternating InAs and InP regions with atomically abrupt interfaces (*Appl. Phys. Lett.* 2002 **80**(6) 1058). They then investigated the I-V characteristics of 40 nm wide InAs whiskers with a single 80 nm long InP region. At 80 nm, electron tunneling through the InP barrier does not dominate over the thermal excitation of carriers over the barrier. Reference InAs whiskers gave perfect ohmic behavior, while InAs whiskers with the InP barrier gave temperature-dependent non-linear I-V curves. At higher temperatures, overall current increased at lower bias voltages as more electrons were thermally excited over the barrier.

A second group from Harvard University used vapor-phase growth on gold seeds to form 20 nm diameter nanowhiskers containing GaAs/GaP heterojunctions (*Nature* 2002 **415** 561). Photoluminescence measurements showed emission from spots along the wire corresponding to the position of the GaAs, with no emission from GaP, which is an indirect gap semiconductor. The team suggest that such whiskers could be used as nano-barcode labels for imaging. Additional information could be encoded by using different semiconductors to give different emission wavelengths.



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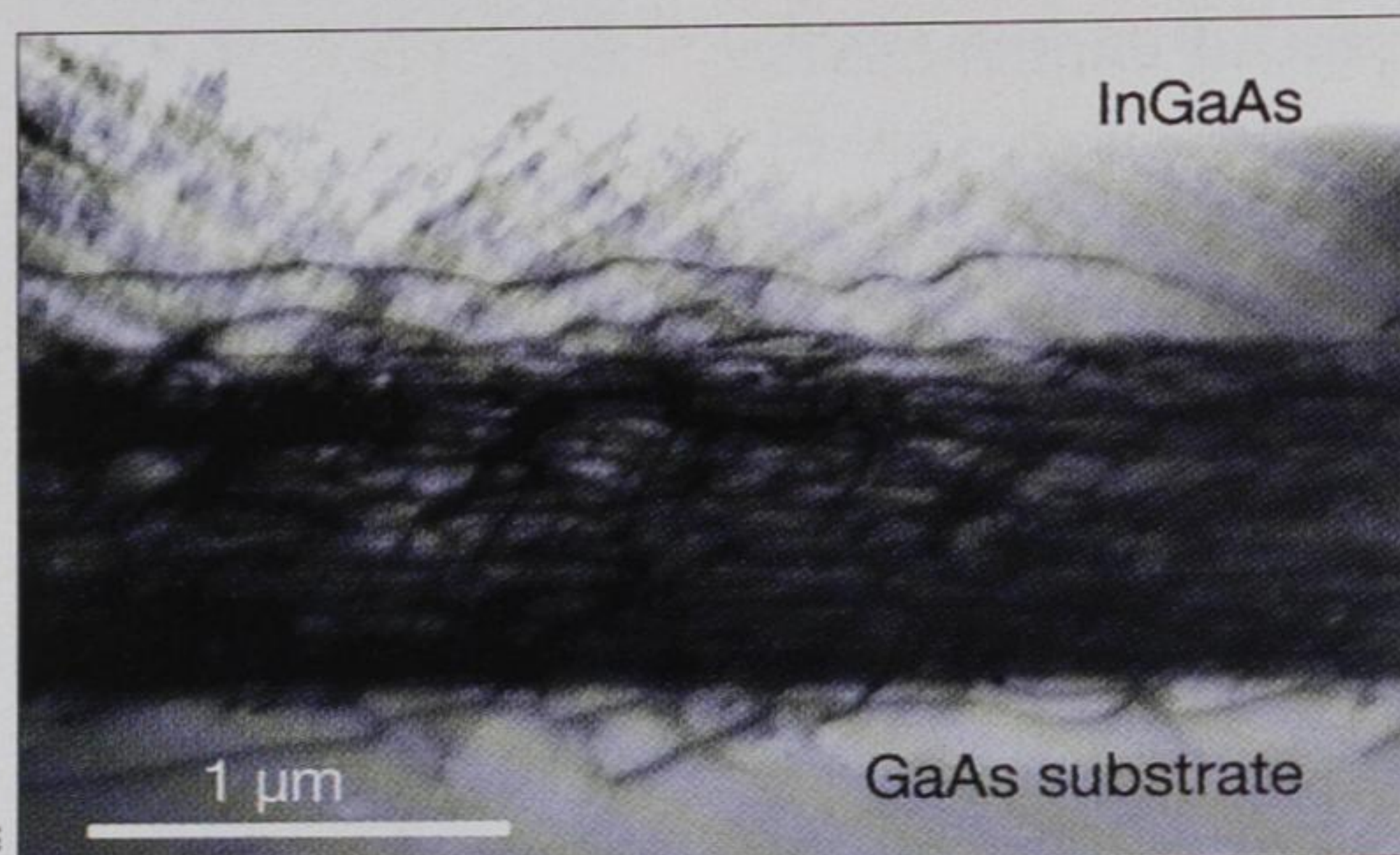
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MOVPE yields good-quality, high In-content InGaAs-on-GaAs substrates

In MBE, low-temperature growth is known to be effective in achieving smooth surfaces for InGaAs layers on GaAs substrates. However, there has been little work done on the low-temperature growth of InGaAs with an In composition above 35% on GaAs substrates by MOVPE, because of the low growth rates at low temperatures. Yasushi Takano and colleagues at Shizuoka University and Ehime University in Japan have recently achieved the growth of high-quality InGaAs layers with high In composition on GaAs substrates by MOVPE (*Appl. Phys. Lett.* 2002 **80**(12) 2054).

InGaAs layers with an In composition of 0.57 were grown by low-pressure MOVPE on GaAs (100) substrates using graded buffer layers. Growth temperatures were between 450 and 630 °C, though no mirror-like surfaces were obtained at growth



Cross-section TEM of an InGaAs layer grown at 450 °C. Dislocation density is very high in the buffer layer, leaving the subsequent InGaAs layer relatively dislocation-free.

temperatures above 500 °C. A good surface morphology with a cross-hatch pattern was achieved for InGaAs layers at a temperature of 450 °C, and the threading dislocation density for growth at 450 °C was determined by TEM to be $1 \times 10^7 \text{ cm}^{-2}$. The graded buffer layer and the constant composition layer were both 1 μm thick, and the growth rate of the InGaAs at 450 °C was around 1 μm/h, which is comparable to that seen in MBE growth.

Even at high temperatures a smooth surface was obtained using a low buffer grading rate and a high V/III ratio for the buffer layers. However, under these conditions source materials were consumed at a high rate. The

group expects that by further optimization of the growth parameters, low-temperature MOVPE of InGaAs layers with a threading dislocation density of less than $1 \times 10^7 \text{ cm}^{-2}$ will be possible.

Record current densities for InGaAsN QW lasers

InGaAsN QWs have attracted interest as the active region of 1300 nm VCSELs and edge-emitting lasers because of the difficulty in lattice matching an InP-based active region to GaAs substrates, and GaAs-based cladding and DBRs. The highest performance InGaAsN QW lasers are typically grown by MBE. However, MOCVD is preferred for fabricating VCSELs due to the high growth rate for the thick DBR layers and the ease of composition control for the heterointerfaces of the DBR. Difficulties in growing InGaAsN QWs by MOCVD, with arsine as the As-precursor and dimethylhydrazine (DMHy) as the N-precursor, arise because of the need for a low AsH_3/DMHy ratio for sufficient N incorporation and the low purity of DMHy.

Researchers at the University of Wisconsin-Madison have successfully fabricated high-performance 1295 nm InGaAsN QW lasers by MOCVD, with threshold- and transparency-current densities as low as

289 and 110 A/cm^2 , respectively (*IEEE Photon. Tech. Lett.* 2002 **14**(4) 444). These results represent the lowest threshold- and transparency-current densities reported for 1300 nm MOCVD-grown InGaAsN QW lasers, and are comparable to those achieved using MBE growth.

The design of the active region is based on a strain-compensated InGaAsN QW with a very high In content (around 40%) and a minimum N content of 0.05% to achieve 1300 nm emission. Strain compensation of the InGaAsN QW, achieved by utilizing GaAsP tensile barriers, yielded up to three times the optical luminescence intensity of lasers with uncompensated QWs. Tensile-strained buffer layers of InGaP and GaAsP were also utilized to improve the optical quality of the highly-strained InGaAsN QWs grown on high Al-content AlGaAs cladding layers. The 1300 nm InGaAsN QW lasers have shown low temperature sensitivity, with characteristic temperature coefficients of threshold current (T_0) and external efficiency (T_1) as high as 130 K and 400 K for 1500 μm cavity length devices. These results demonstrate MOCVD-grown InGaAsN to be feasible for the realization of high-performance 1300 nm GaAs-based lasers.

Sb boosts InGaAsN laser emission beyond 1.4 μm

While InGaAsN lasers can operate up to 1300 nm, raising the operating wavelength to the important 1550 nm mark has proved difficult. W Ha and co-workers from Stanford University, CA, have achieved the operation of InGaAsN QW lasers at 1400 nm by incorporating N into the barrier layers to compensate for lattice mismatch with the well layers. However, device performance was seriously compromised using this approach. To achieve emission beyond 1400 nm, the In composition of the QWs must rise above 40%, which is difficult because of the lattice mismatch between GaAs and InAs.

The Stanford group has achieved QW layers with an In content of up to 46% and photoluminescence at 1600 nm by incorporating Sb into the well and barrier layers (*Elec. Lett.* 2002 **38**(6) 277). Sb acts as

a surfactant during epitaxy, promoting two-dimensional growth and therefore enabling good-quality, high In-content layers to be grown.

Three MQW laser structures were grown by MBE with different Sb fluxes and annealed *ex situ* to improve material quality. The N content was 1.7% and 2% in the well and barrier layers, respectively, and the In content of the QWs was 45%. A ridge-waveguide laser was fabricated from material containing three $\text{InGa}_{0.017}\text{As}_{0.933}\text{Sb}_{0.05}$ QWs and $\text{Ga}_{0.02}\text{As}_{0.93}\text{Sb}_{0.05}$ barrier layers. Laser emission at 1465 nm was achieved with 70 mW output power. Threshold current density was 930 A/cm^2 per QW, the lowest reported for an InGaAsN QW laser operating above 1400 nm and grown on a GaAs substrate. Laser emission at 1550 nm is expected as the In, N and Sb compositions are optimized.

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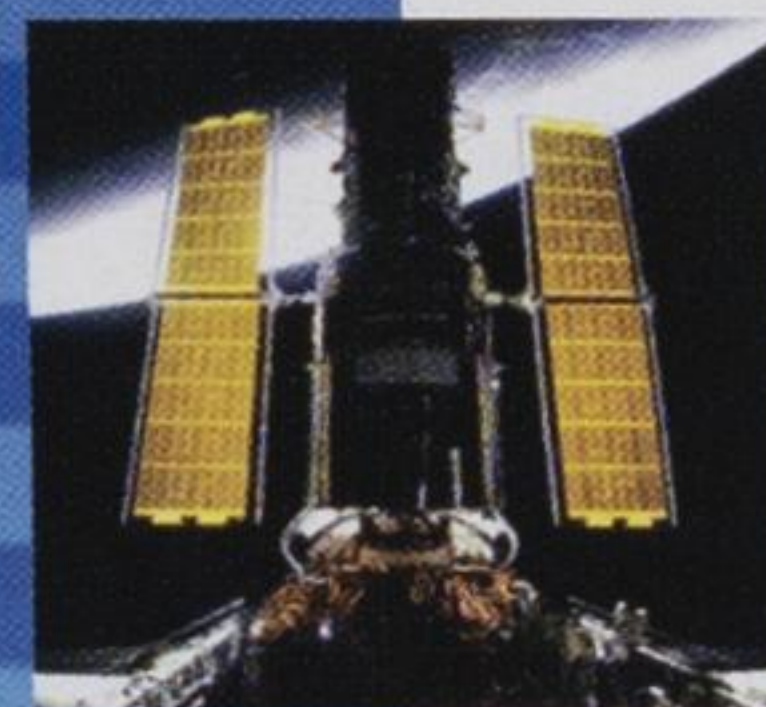
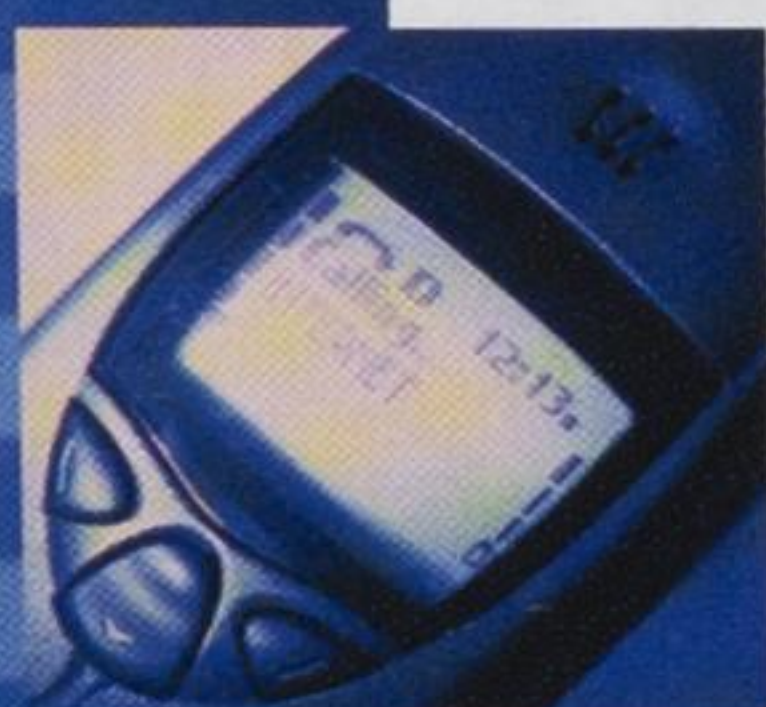
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Communicant's SiGe:C fab secures \$325 million

Communicant Semiconductor Technologies has secured \$325 million of private equity, which will be used to fund the construction of a new foundry for the fabrication of SiGe:C and LDMOS-based ICs. Communicant's investors, namely Intel, The Dubai Airport Free Zone Authority, and the Investment Bank of the State of Brandenburg, will provide part of the equity for the \$1.3 billion facility, which is to be built in Frankfurt (Oder), Germany. The remaining funds are to be provided in the form of government incentives and loan guarantees.

The Communicant fab will be operational in the first quarter of 2003, and production will commence in the third quarter. At full capacity, the facility will have an output of 30,000 8 inch wafers per month.

"We have now secured the funds necessary for a speedy completion of our facility," said Klaus Wiemer, Communicant's CEO. "In a most difficult capital market, this achievement is a measure of the attractiveness of the con-

cept of a differentiated foundry, and the outstanding technologies we offer."

Communicant Semiconductor Technologies is a "pure-play" IC foundry serving the RF and mixed-signal markets, and offers a range of advanced, modular SiGe:C and LDMOS-based CMOS and BiCMOS technologies. The company was founded in February 2001 with strategic investments from Intel and IHP, a publicly funded German R&D center. Intel transferred its 0.18 μm CMOS technology to Communicant, while IHP provided its SiGe:C technology.

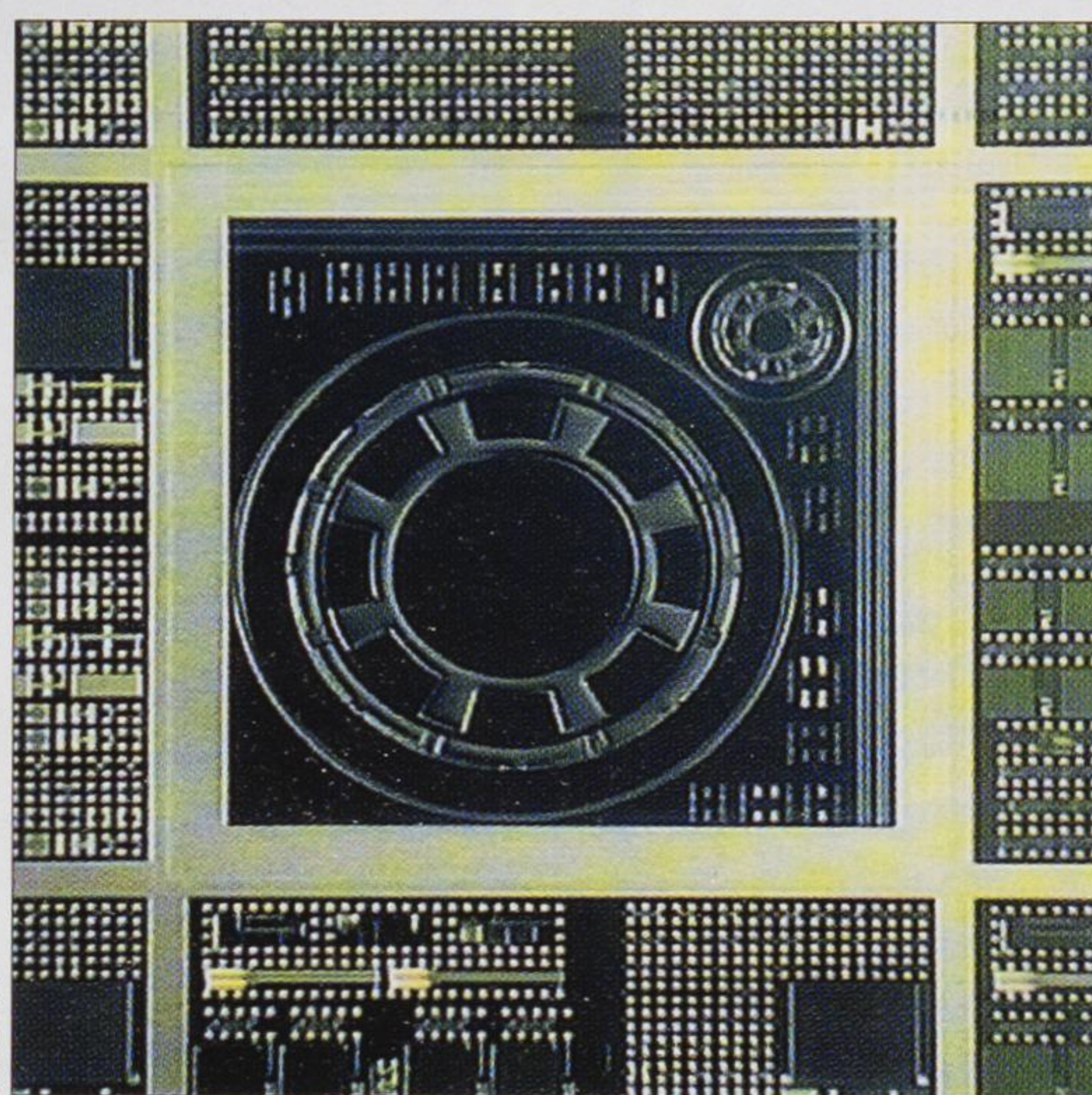
The incorporation of carbon into the base of SiGe HBTs enhances performance by preventing the out-diffusion of boron dopant atoms during post-growth processing. At last year's IEDM meeting in Washington, DC, IHP demonstrated SiGe:C devices with f_t and f_{max} values of 100 and 130 GHz, respectively, and a breakdown voltage of 2.5 V (see *Compound Semiconductor* January/February 2002, p31).

QinetiQ to head microsystems technology consortium

UK research company QinetiQ has been selected to lead a new microsystems technology (MST) manufacturing consortium called Integram, as part of the European Community's Europractice program. Worth approximately €1.3 million (\$1.2 million) over three years, the Europractice contract will help small companies and universities gain access to MST, and will also reduce the risks for larger companies by prototyping micro-electro-mechanical systems (MEMS) devices in small quantities.

The Integram (Integrated Microsystems) consortium links QinetiQ, which has the largest MST development and prototyping team in the UK, with Coventor, a world-leading software design house, as well as an as yet unidentified CMOS foundry partner.

Through Integram, companies will be able to have access to QinetiQ's novel process and product technologies, which incorporate sensors, actuators and microelectronics. To provide links between micromechanical de-



An integrated MEMS gyro, fabricated by QinetiQ using microsystems technology.

vices and drive, control and signal-processing circuitry, Integram will focus on processes that can be integrated with microelectronics on the same substrate.

IQE buys MOCVD machine for oxides

IQE Silicon Compounds (IQE-SC), a subsidiary of epiwafer vendor IQE, is to install its second Aixtron Tricent MOCVD system. This will enable the development of strontium titanate (STO) template films on silicon wafers up to 300 mm in diameter. STO-based technology is being investigated for high-k dielectrics in the silicon industry and also for three-fives-on-silicon (TFOS).

While IQE has used Aixtron's MOCVD tools within the compound semiconductor industry for many years, the ability to extend the epitaxial process into traditional silicon fabs has until recently been limited. To increase the functionality and performance of electronic devices, designers are moving away from increasingly expensive reductions in device linewidths, and are turning towards materials re-engineering. IQE-SC is developing emerging Si-based technologies such as STO for TFOS, as well as SiGe and strained silicon.

Business news in brief...

Conexant names foundry

Conexant Systems has announced that its foundry spin-off will be named Jazz Semiconductor. The company, of which 55% is owned by The Carlyle Group and the remainder by Conexant, will offer foundry services for RF and mixed-signal applications using SiGe, CMOS and BiCMOS technologies.

Motorola licenses SiGe:C

Motorola has licensed its 0.35 μm RF BiCMOS SiGe:C technology to Atmel, a semiconductor manufacturer based in San Jose, CA. By the fourth quarter of 2002, Atmel will provide a second source for the process after it has been transferred to the company's high-volume 8 inch fab in Rousset, France.

W-Link buys SiGe modules

SiGe Semiconductor, based in Ottawa, Ontario, has supplied SiGe-based power amplifier modules for incorporation into the Bluetooth products manufactured by Taiwanese company W-Link.

Soitec and SiGen both claim SOI patent victory

A jury in the US District Court of Massachusetts has delivered its verdict in a long-running patent lawsuit between SOI wafer manufacturers Soitec and Silicon Genesis (SiGen). Soitec filed the lawsuit three years ago, claiming that SiGen's commercial manufacturing processes infringed on US patent 5,374,564. Soitec was later joined in the suit by French research organization CEA, holder of the patent.

The patent forms the basis of Soitec's Smart-Cut process that uses implantation and wafer bonding to form SOI substrates. A Si wafer is oxidized, implanted with hydrogen ions and then bonded to a second Si wafer. The wafers are then separated along the cleavage plane formed by the implanted ions, leaving an SOI substrate and a reusable Si wafer.

SiGen was found to have infringed one of the patent's claims, and was ordered to pay \$3 million in damages to Soitec. However, the jury also found claims 1, 2, 3, 5, and 9 of the

patent invalid because they did not meet the enablement requirement of US patent laws. A patent must contain enough detail to allow persons skilled in the art to make and use the full scope of the invention. The claims were judged to be invalid because they included the use of rare-gas ions in addition to hydrogen ions.

The two companies had mixed views on the rulings. "We are gratified by the jury's finding of infringement and the award of damages against SiGen," said Soitec's president André Auberton-Hervé. "However, we believe the jury erred in finding the other patent claims invalid." Conversely, SiGen claimed that the damage award relates to early R&D experimentation, and does not apply to its current commercial processes since these operate in a different temperature regime. "The damages should not affect our ability to ship SOI products and equipment," said Francois Henley, president and CEO of SiGen.

In brief...

Philips measures thin SOI

Philips Analytical has characterized ultra-thin SOI wafers using laser ellipsometry and reflectometry, which can be used to measure the thickness of top Si and buried oxide layers in the 300–1000 Å range. The use of ultra-thin SOI is driven by the need to move from partially to fully depleted CMOS devices.

ASML targets MEMS

ASML has introduced a new family of 5X i-line reduction steppers for high-volume MEMS manufacturing and other devices including compound semiconductors.

Tronics orders thick SOI

Tronics Microsystems of Grenoble, France is to use thick-film SOI wafers from Soitec for the surface micromachining of MEMS structures, including a micro-gyrometer for motion-capture applications.

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Laser Diode Array (Material: InP)

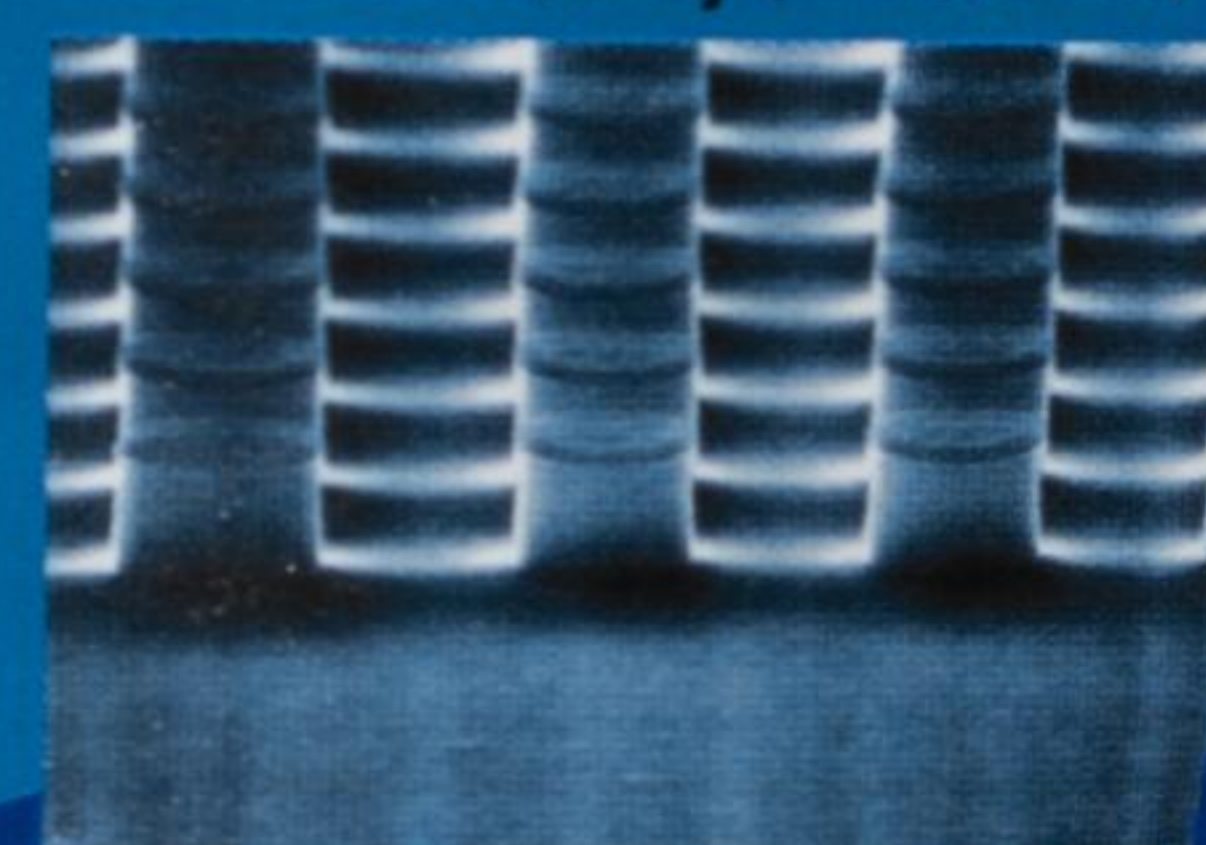
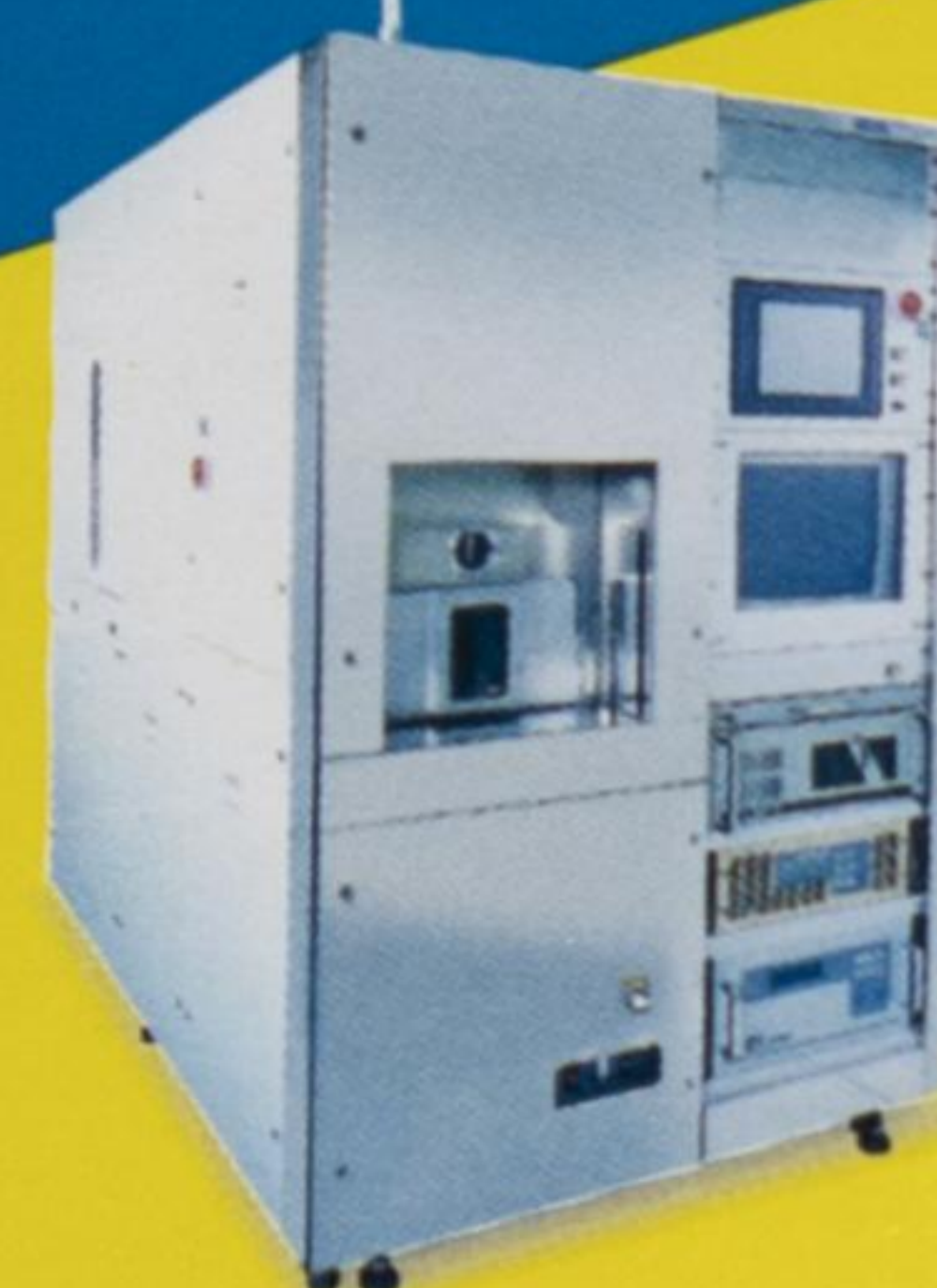
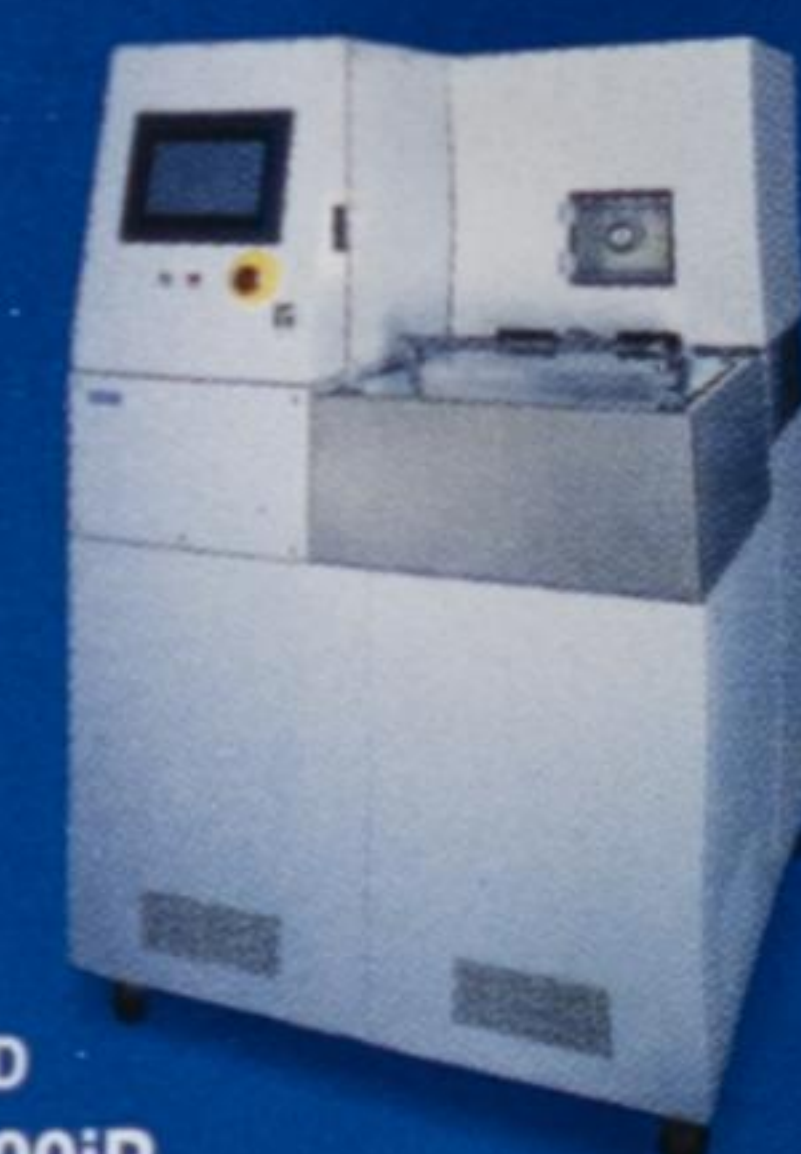


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LDMOS turns up the power

LDMOS transistors with a power density of more than 2 W/mm at 1 GHz and 70 V will compete very effectively with more expensive GaN-on-SiC devices for base-station power amplifiers.



It will be exceedingly difficult for more expensive GaN-on-SiC or SiC devices to compete with this level of performance.

GaN HEMTs are ideally suited for high-power, high-voltage RF applications such as base-station amplifiers for mobile-phone systems. The large output powers required in base-station amplifiers necessitate supply voltages of 26–28 V, and in the near future these voltages will migrate up to 48 V. There is no disputing the fact that GaN HEMTs exhibit outstanding RF power characteristics, with reported power densities of 9.8 W/mm at 8 GHz operation with 45% power-added efficiency (Wu *et al.*). However, these values are for devices grown on expensive SiC substrates.

It is necessary to consider the trade-off between performance and cost. If a GaN-on-SiC device can deliver 10 W/mm, and a Si device generating only 1 W/mm can deliver the same total power with a 10 times larger gate periphery, then the GaN-on-SiC solution will only become attractive if it can be manufactured more cheaply than the larger Si device. A secondary concern is the actual die size, which would become more important in portable devices.

Dual-layer RESURF structure

High breakdown voltages are a direct artifact of the large bandgaps (3.0–6.0 eV) inherent in the AlGaN material system. Silicon, with a bandgap of only 1.1 eV, must work a bit harder in order to achieve the level of breakdown required for devices operating up into the 50 V region. One way to do this is to use a lateral structure, such as the laterally diffused MOS (LDMOS) device shown in the figure, which was devised by researchers at Uppsala University and Chalmers University in Sweden (Olsson *et al.*).

The high operating voltages required for power-amplifier applications are achieved through optimized design of the drift region between the gate and the drain

of the LDMOS transistor. To achieve high breakdown characteristics, the typical LDMOS design relies on a drift region formed by an n-type diffusion well placed in a p-type substrate. Additional control of the behavior of the drift region is obtained by the placement of a buried p-layer (labeled p-top) and a surface n-layer (labeled n-top) at the surface of the drift region, which can be used to generate a reduced surface field (RESURF) structure. The actual channel region of the LDMOS transistor is formed by the lateral diffusion of the p-type base beneath the n⁺ source contact. So while the n⁺ poly-silicon gate in this process is 1.5 μm in length, the active MOS channel length created by the p-type diffused region under the poly-Si gate is only 0.3 μm.

Closer examination shows that a depletion region extends into the drift region from both the substrate (formed by the n⁻ drift/p-substrate junction), and from the surface (formed by the p-top/n⁻ drift junction). Depleting from both sides allows an increase in the n-well doping level (which improves the turn-on characteristics and the on-resistance of the device), without decreasing breakdown voltage or causing punch-through in the narrow p-base region.

LDMOS power results

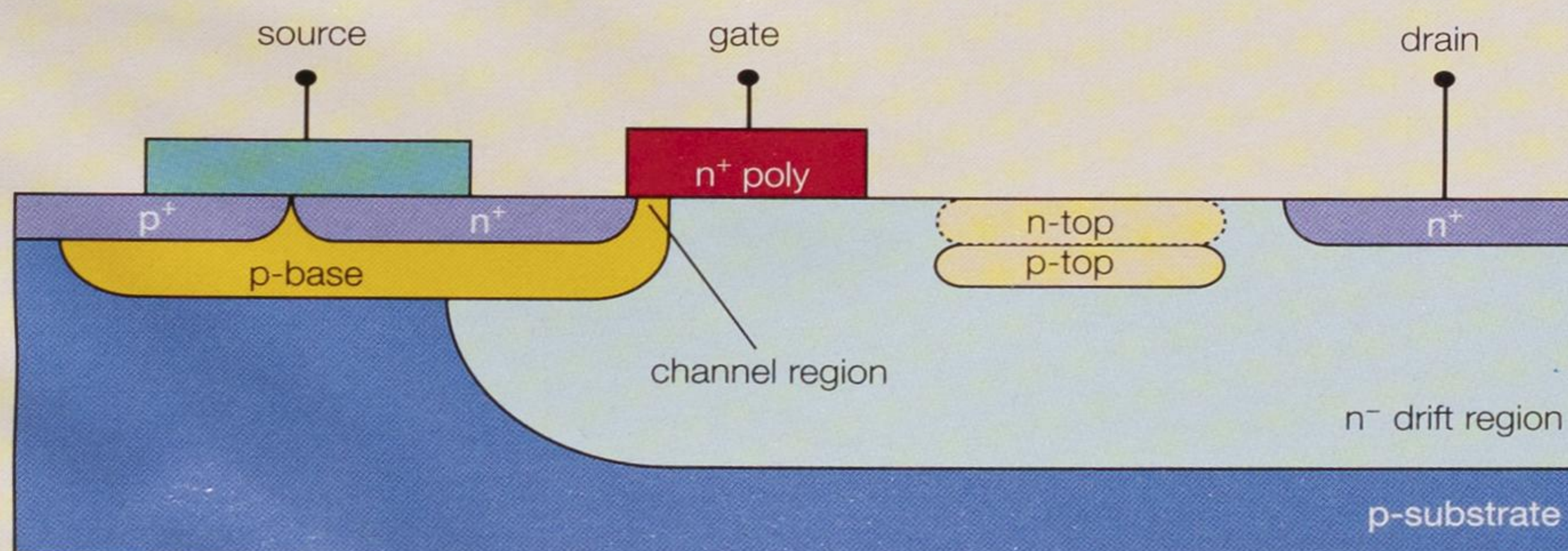
The LDMOS structures were fabricated using a very basic 1.0 μm CMOS process that required only two layers of metal. The implementation of the RESURF region resulted in optimized output characteristics, with an output resistance of 10 kΩ/mm at a gate-source voltage (V_{GS}) of 3 V. The breakdown voltage of the devices was around 100 V, making them well suited for applications requiring supply voltages up to 48 V. The output power density was greater than 2 W/mm at 1.0 GHz operation and a drain-source voltage (V_{DS}) of 70 V, with a gain of 23 dB at a V_{DS} of 50 V. At 3.2 GHz operation, the power density was more than 1.0 W/mm at a V_{DS} of 50 V, and 0.6 W/mm at a V_{DS} of 28 V.

These data represent the best reported performance to date for Si power MOSFETs. It will be exceedingly difficult for more expensive GaN-on-SiC devices (or SiC MESFETs) to compete with such performance, when one considers that the LDMOS devices are fabricated in a very basic CMOS process requiring absolutely no specialized processing techniques. ●

Further reading

Y-F Wu *et al.* 2001 *IEEE Trans. Elec. Dev.* **48**(3) 586.
J Olsson *et al.* 2002 *IEEE Elec. Dev. Lett.* **23**(4) 206.

LDMOS devices challenge GaN and SiC



Schematic of the LDMOS transistor with the dual-layer RESURF in the drift region.

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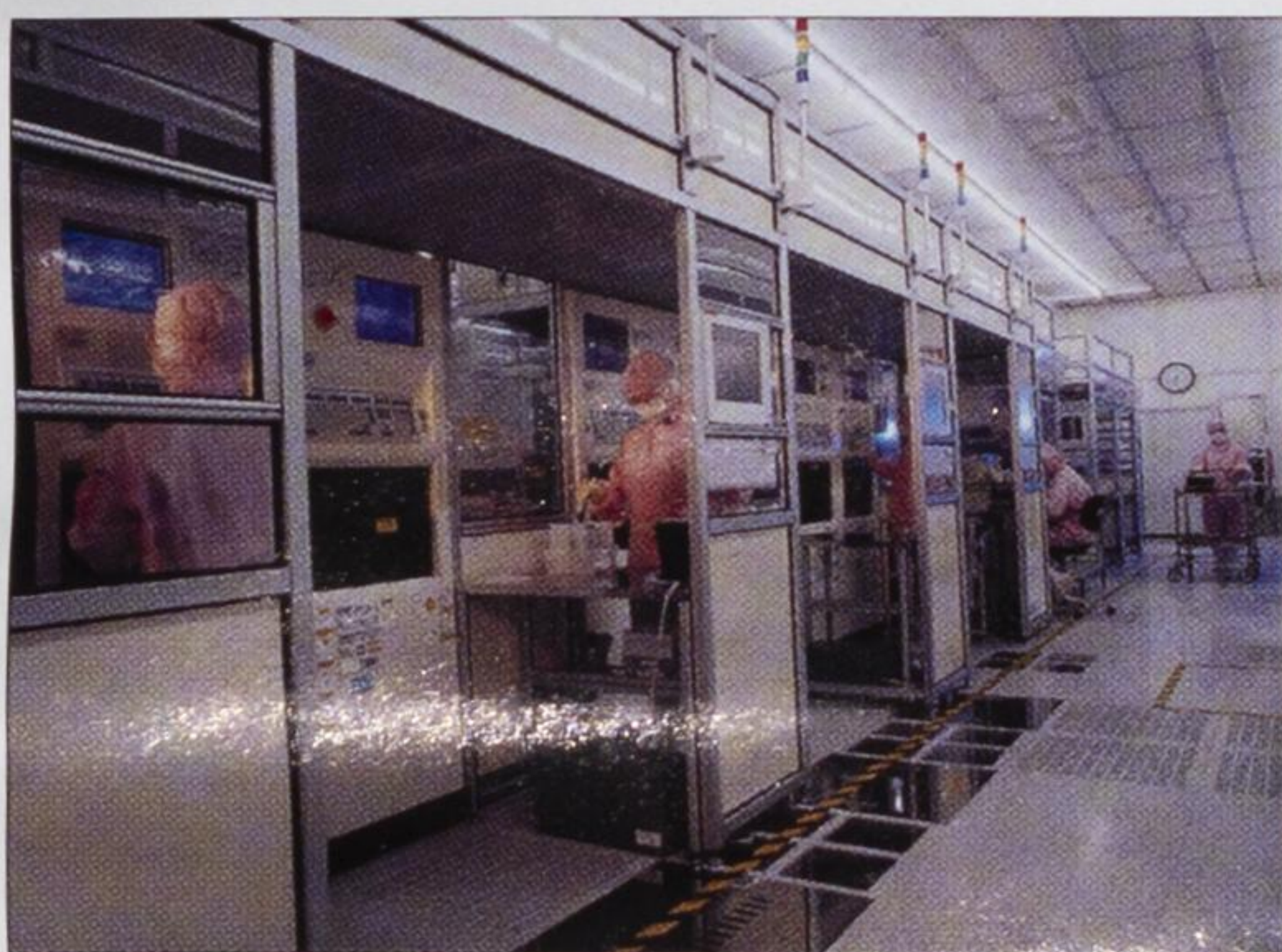
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Process porting provides a path to production scaling

As a result of a strategic partnership between Raytheon RF Components and WIN Semiconductors Corp, the two companies are now able to manufacture drop-in replacement GaAs HBT MMICs for handset power amplifier modules. According to **Dennis Williams and colleagues**, the chips are equivalent to established Raytheon products in terms of dimensions, topography and performance, rendering the once-sacred microwave MMIC just another line item on the assembly bill of materials.



Comparison of capabilities at RRFC and WIN Semiconductors

	Raytheon RF Components	WIN Semiconductors
inception	1988	1999
location	Andover, MA	Tao Yuan, Taiwan
cleanroom	20,000 sq. ft in two fabs (research/MBE and production)	20,000 sq. ft ballroom structure
capacity	>15,000 4 inch wafers per year	100,000 6 inch wafers per year by 2005
technology	InGaP HBTs, 0.15, 0.25 and 0.5 μ m PHEMTs; MHEMTs; wide-bandgap devices	1, 2 and 3 μ m InGaP HBTs; 0.15, 0.35 and 0.5 μ m PHEMTs; E-mode HEMTs; MHEMTs
certification	ISO9001	QS-9000/ISO9001

Fig. 1. Raytheon RF Components will move developing technologies from its moderate-volume fab to WIN's high-volume facility (left).

Component manufacturers seeking a competitive advantage have three options: build a new factory, modernize an existing one, or outsource. For fabs, economy of scale has driven GaAs wafer diameters up to 6 inch, the standard for years to come. A new fab is expensive; the \$100 million required for a GaAs fab is small change compared with the \$3 billion required for a silicon facility, but market conditions since the halcyon days of 2000 make the decision to build less appealing. Large new captive fabs may address the supply issue for the integrated device manufacturer, but they do so at the long-term risk of substantial investment.

For manufacturers still at the 4 inch wafer size, tough markets and excess industry capacity make the outsource option attractive. Given a producer's ability to provide device performance, delivery execution and certainty of supply can determine whose component gets into which platform. Raytheon RF Components (RRFC) of Andover, MA and WIN Semiconductors of Tao Yuan, Taiwan have taken a creative approach to address the cell-phone handset power amplifier market. The international team has moved an InGaP/GaAs HBT fab process and an RF product line sim-

Porting eliminates the need for customers to re-qualify a product containing chips from a new source. The MMICs are the same in terms of performance and reliability.

ultaneously from a 4 inch diameter, dual-use defense and commercial fab to a high-volume, 6 inch commercial factory.

Porting

Moving product lines is a routine procedure in the silicon industry where circuit and process models are mature. It is more complicated in the compound semiconductor industry, where product performance is considered to be inextricably tied to the process line. Moving a fab process usually involves the transfer of an exact copy, including the tool set, at great expense. Even then products must routinely be redesigned, or at least re-tuned, to accommodate process-related changes in perfor-

mance. Conversely, moving a product line to an existing process always involves redesign, extensive product redevelopment, and often multiple expensive iterations.

When the goal is to create chip-for-chip drop-in replacements, a better way is to "port" the process, i.e. move it cell by cell without changing the products made using it. By adopting the basic methods used in the silicon industry, and by paying attention to process details that affect performance, successful porting is faster, much less expensive and less disruptive to the flow of the product, and results in multiple qualified fab sites for a given product. An added benefit is that multiple geographically separated production facilities make the supply chain immune to disruption by natural disaster or power interruption. Porting eliminates the need for customers to re-qualify a product containing chips from a new source. The MMICs are demonstrably the same in terms of performance, behavior over temperature, and reliability at the unit cell and product levels.

Synergy

Process capabilities align well at RRFC and WIN Semiconductors. RRFC is a leading supplier of GaAs-based MMICs, modules

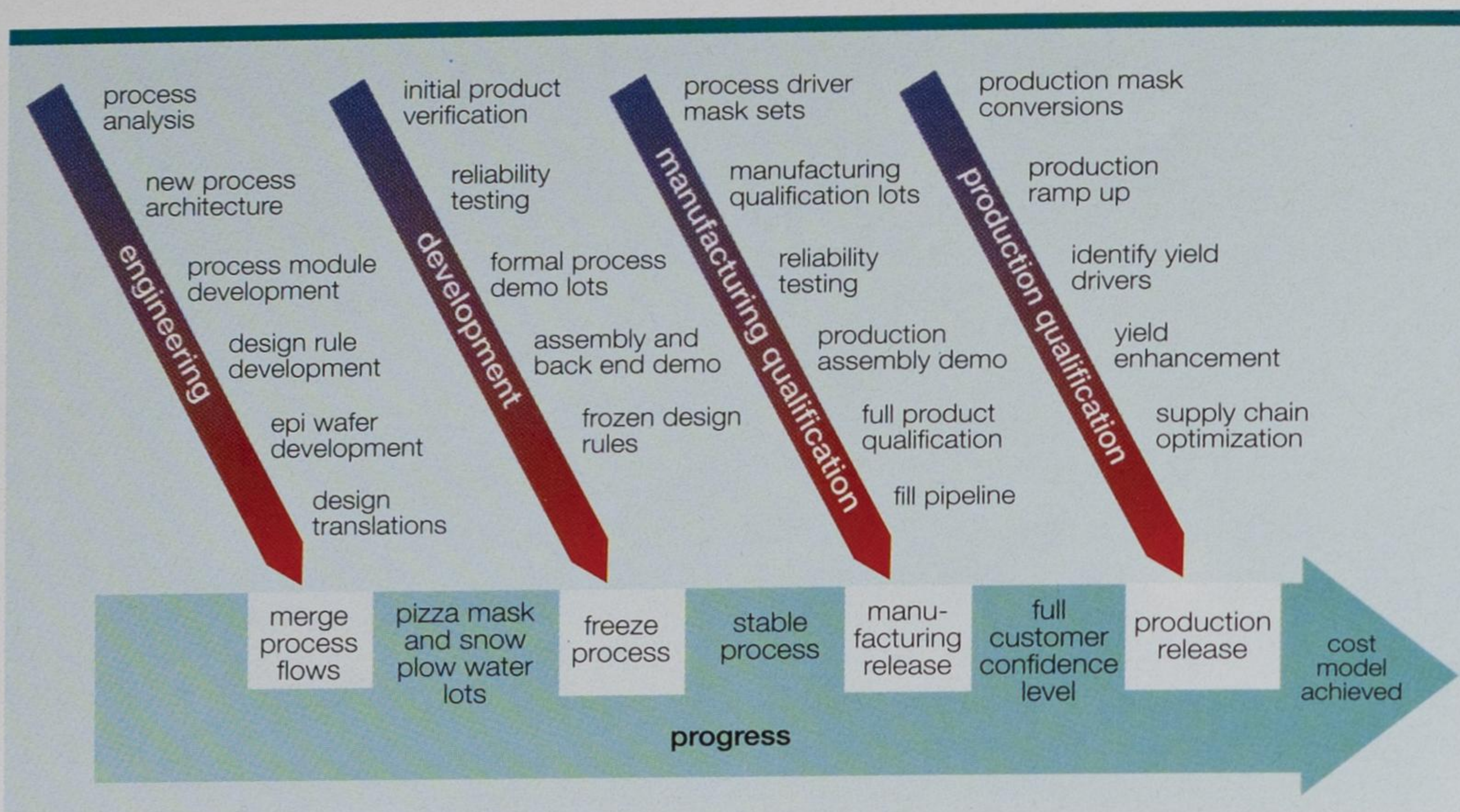


Fig. 2. A process porting activity plan that highlights early parallel development.

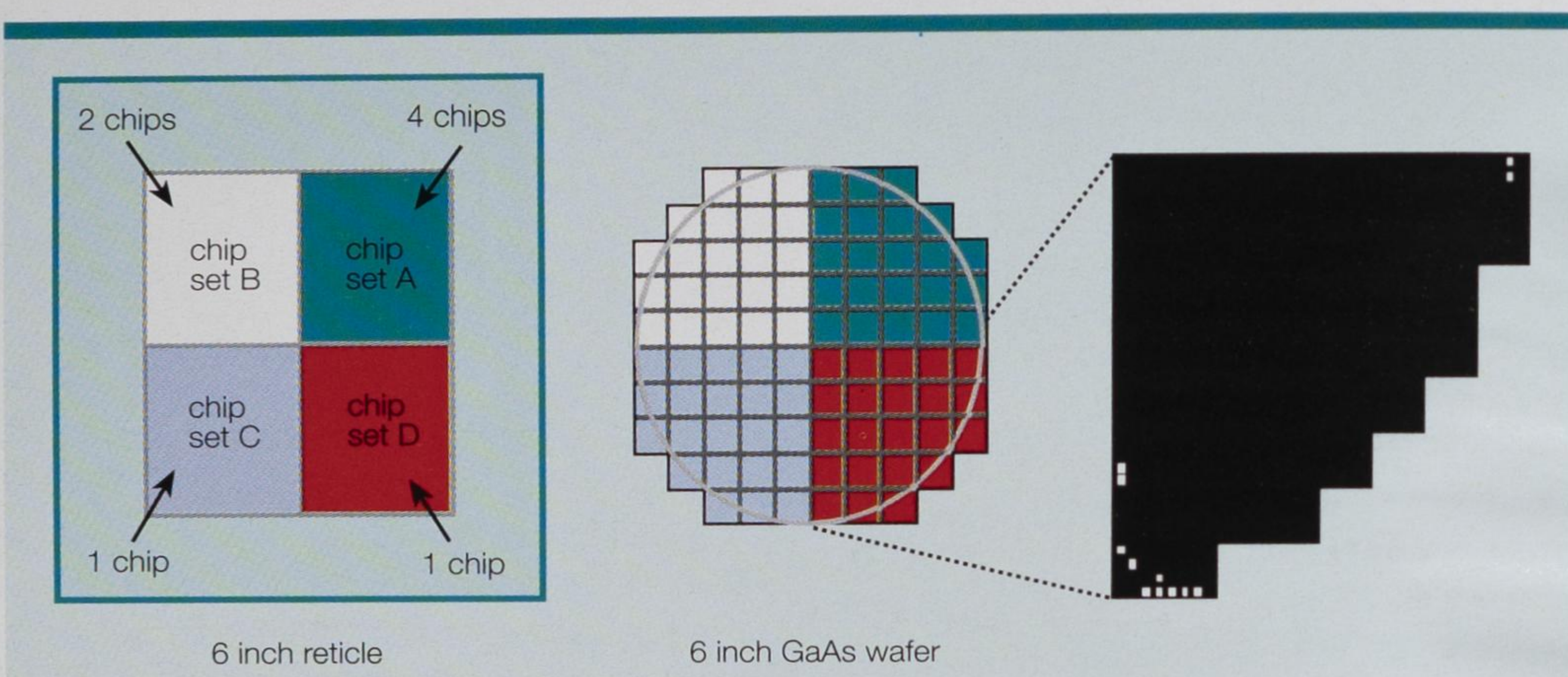


Fig. 3. Eight chip designs with six different x-y footprints are arranged on a photolithographic reticle (left). Each subset of chips is grouped into an $8900 \mu\text{m}^2$ field with additional modeling and test structures. After completion, wafers are scribed into quarter sections (center), and each quarter is then scribed into individual die. At right is a DC probe map for a quarter wafer, showing 98% yield for complex, product-specific electrical tests (white dots show failed die).

and wireless systems for land, mobile and space-based communication systems. A classic dual-use facility, RRFC leverages government-funded advanced R&D into technology and products that serve systems divisions within Raytheon Company, as well as a broad range of commercial customers. The company's 4 inch wafer process technologies cover 900 MHz to 100 GHz (see figure 1). Fab outsourcing to WIN provides access to a total additional capacity of 100,000 6 inch wafers per year, without adding risk or \$100 million in investment to RRFC's cost structure. This enables RRFC to focus on its core strengths of advanced process and epitaxial material development and RF design. As new technologies mature along the price curve, RRFC will move them from its fast prototyping and moderate-

volume local fab to WIN's high-volume outsource facility in Taiwan.

WIN Semiconductors has a new facility supporting many of the same technologies but at the much more economical 6 inch wafer diameter. WIN's tool set is closer to the state of the art, has a higher level of automation, and enjoys a level of service similar to that common in the silicon industry.

WIN derives multiple benefits from its association with RRFC. As a new company, WIN is seeking to develop its credibility as well as its technology to ensure success. Securing a customer of the size and reputation of Raytheon has enhanced WIN's credentials as a volume producer of GaAs MMICs, and will provide opportunities to participate in the development of new technologies as

Raytheon's business expands into new applications. As the relationship develops, WIN and Raytheon have committed to work together to develop new markets, products and technologies. Over the life of the association WIN can expect a clearer view of future markets than it might otherwise have had, and for a significant portion of its business, it now has a predictable level of demand and revenue stream.

Considerations and objectives

The Raytheon/WIN team faced an aggressive schedule; move a line of eight basic InGaP HBT cell-phone PA chip designs supporting numerous power amplifier module (PAM) products from the US to Taiwan in under eight months. Both companies have their own proprietary HBT processes up and running. As a supplier of PAMs, Raytheon has a substantial investment in design intellectual property, and little interest in returning to the design-fab learning curve by moving into a new fab process. Ideally, Raytheon's products would be placed into WIN's fab line, resulting in minimum disruption, no need for Raytheon's designers to learn new models or processes, and little or no requirement for customers to re-qualify products. Most importantly though, the performance of the MMICs – and the modules they go into – must be identical in every meaningful way.

For RRFC's products, multiple frequencies, modulation schemes and biasing approaches need to be supported, each placing specific demands on the fab process and resulting parametric behavior. The duplication of DC parameters between the two process lines is critical in order to support biasing, quiescent currents in devices, and current under drive, without the need to adjust off-chip components within the module. Duplication of the application-specific RF behavior, such as power-added efficiency (PAE), gain, or adjacent channel power ratio (ACPR), is clearly a challenge in light of the conflicting requirements (e.g. raw output power and PAE for GSM applications, high efficiency and linearity at backed-off power operation for CDMA).

To support the overall schedule, the team adopted a structured multi-phase approach, focusing on parallel activity in the areas of epiwafer design, process architecture, process development and stabilization, and product qualification. Figure 2 shows the program, with clearly defined phases of engineering, development, and manufacturing and production qualification.

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Development

The ported process is designed to serve applications through 6 GHz. A detailed comparison of the process flows in the two fabs identified the key differences. Raytheon's process aligned well with most of WIN's basic process modules for wafer cleaning, photoresist coating, metallization etc, which could be used without alteration at low risk. A modified process flow was defined that combined the best features of both and addressed all issues that could impact performance. The team focused on the differences in passive elements, particularly the basic transistor. Passive elements are sensitive to metal line and dielectric thickness and the capacitance associated with interconnect crossover. The HBT itself may be treated as an ideal current source, with the RF behavior determined by junction capacitance produced by the thickness, doping, composition and physical dimensions of the emitter-base and base-collector diodes. Paying attention to these physical parameters resulted in closely matched RF behavior. Essentially, the fab processes were merged.

The process modules were developed in parallel. WIN worked closely with its qualified epiwafer supplier to match the basic transistor characteristics of RRFC's process, and prove them out on a 6 inch line. A series of quick-turn growth and device evaluation runs dialed in key parameters such as current gain, emitter resistance and junction capacitances, reducing the variables to a narrow epitaxial design corner experiment. Three new process modules were executed at WIN to preserve Raytheon's chip layout dimensions. These were designed to address differences in the value of the TaN thin-film resistor material, the unit capacitance of the MIM capacitor dielectric layer, and polyimide crossover to replace low-yield air bridges. Target values were quickly dialed in, and wafer-to-wafer repeatability was verified through multiple wafer lots. Across-the-wafer uniformity for film thickness was evaluated and guaranteed. Burnout current limit and temperature coefficient values for the TaN resistor film were fully characterized. Pinhole and stress testing ensured thin SiN quality, and the sidewall slope of polyimide vias was optimized for metal-to-metal crossovers. A first cut at process-related mask biases was established.

A pizza with everything

Eight RRFC chip designs were translated into the new process by essentially changing layer numbers, and all eight designs were included

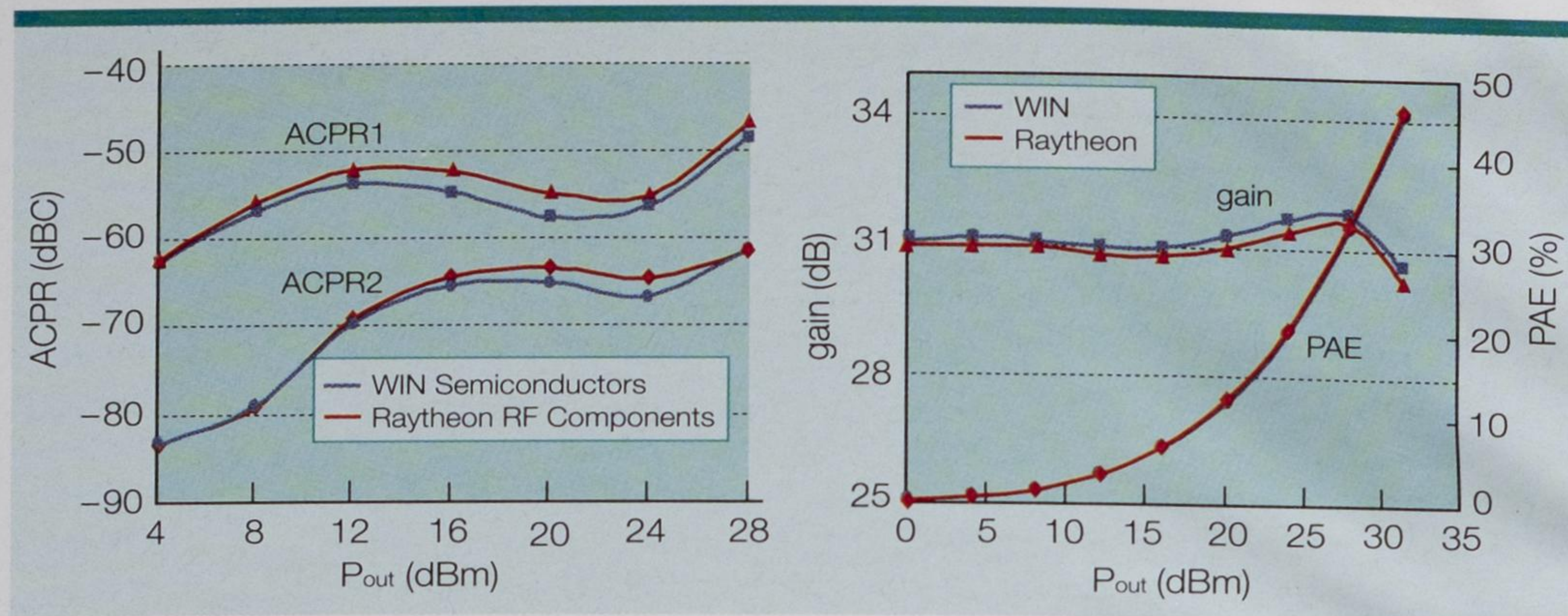


Fig. 4. Comparison of RF output characteristics measured at 836.5 MHz, for dual-mode cellular CDMA power amplifier modules fabricated by Raytheon and WIN.

Performance comparison between RRFC and WIN Semiconductors

		29 dBm P_{out}	28 dBm P_{out}		
		PAE (%)	ACPR1 (dBc)	gain (dB)	PAE (%)
RRFC control	average	32.9	-48.45	26.93	29.6
	standard deviation	1.0	2.72	0.65	0.9
WIN lot 1	average	33.1	-48.93	26.87	30.0
	standard deviation	0.4	1.37	0.29	0.4
WIN lot 2	average	33.0	-48.80	26.86	29.8
	standard deviation	0.5	1.68	0.37	0.5

Fig. 5. A comparison of the key parameters for the RMPA1951-102 PCS power amplifier module with advanced DC power management. Variation in all parameters is reduced on the WIN line, providing improved overall process capability indices for the modules.

The exercise of merging the fabrication processes resulted in a hybrid version containing all of the positive attributes of the parent processes.

in a single multichip "pizza" mask. A clever reticle design was used to place six different footprints onto a single wafer, allowing dicing to each chip's original x-y dimensions (see figure 3). RRFC was able to evaluate all of its designs in feature-by-feature, dimension-by-dimension duplicates alongside control populations of standard products from the Andover fab line, with no change to the module component list or assembly diagram.

The integrated process was proved out through a series of highly experimental "snow plow" wafer lots that simultaneously tested the merged process, the 6 inch epiwafer growth, and the design translations to the new technology (the equivalent idiom in Mandarin translates to "bowl cleaner", as there is little

use for snow plows in Taipei). Lots were turned in 12 days, start to ship, and four preliminary epiwafer designs were evaluated (these had been defined in early epiwafer vendor in-house quick turns). Process-control monitor (PCM) test results quickly identified one of the designs as a virtual match to RRFC's standard. Wafer probing using RRFC's testers, standard probe cards, methods and specifications achieved 95–99% DC yield on the very first wafer tested to complex die-level product specifications for up to 40 parameters. Seven of the eight chip designs achieved a high first-pass DC probe yield. The eighth design contained a layout error which was corrected for the second snow plow lot, producing 99% probe yield.

Small-signal evaluation of discrete transistors and passive elements confirmed the almost identical behavior of devices fabricated on the two different lines. More importantly, RF bench testing of PA designs covering cellular, PCS and GSM-DCS schemes showed that characteristics such as gain at rated power, saturated output power, ACPR and PAE fell within distributions produced by control populations from the RRFC line (see figure 4). Swept frequency analysis showed S-parameter equivalence, with S21 and S11 falling

curve upon curve. Indeed, subtle RF behavior ordinarily thought to depend on process variables has been accurately reproduced.

Manufacturing qualification

Design conversion was reduced to a simple set of rules executed by layout personnel. With the newly frozen process, formal integration lots were fabricated to improve statistics and provide large quantities of chips for RF package testing, product qualification, DC and RF reliability testing, and customer samples. Again, lots were turned in 12–15 days, start to ship, and PCM testing confirmed the basic manufacturability of the merged process. Modules were assembled offshore using standard bills of materials and assembly diagrams, and were then tested at RRFC using standard methods and specs on an HP84000 production test system and handler. Yields of the RMPA0951A-102, a cellular CDMA PAM, and the RMPA1951-102, a PCS PAM, were equivalent to or higher than control populations of RRFC-fabricated MMICs (see figure 5). Stability over temperature extremes of -35°C to $+85^{\circ}\text{C}$ was verified, and reliability testing confirmed an equivalent mean-time-to-failure. DC wafer probe yields continued to be in the 95–99% range, exceeding the minimum level required to eliminate wafer-level testing, and providing another opportunity for cost reduction.

Benefits

One major benefit of the relationship between WIN and RRFC is that the companies' talent and experience have been combined into one team with no requirement to consolidate, as might be the case with a merger or acquisition. RRFC continues to focus energy and resources where they will do the most good, in advanced processes and materials as well as RF design and systems. WIN continues to focus on its core strength, namely the volume manufacturing of new compound semiconductor technologies as they become subject to price pressure. Here economy of scale is key to achieving competitiveness.

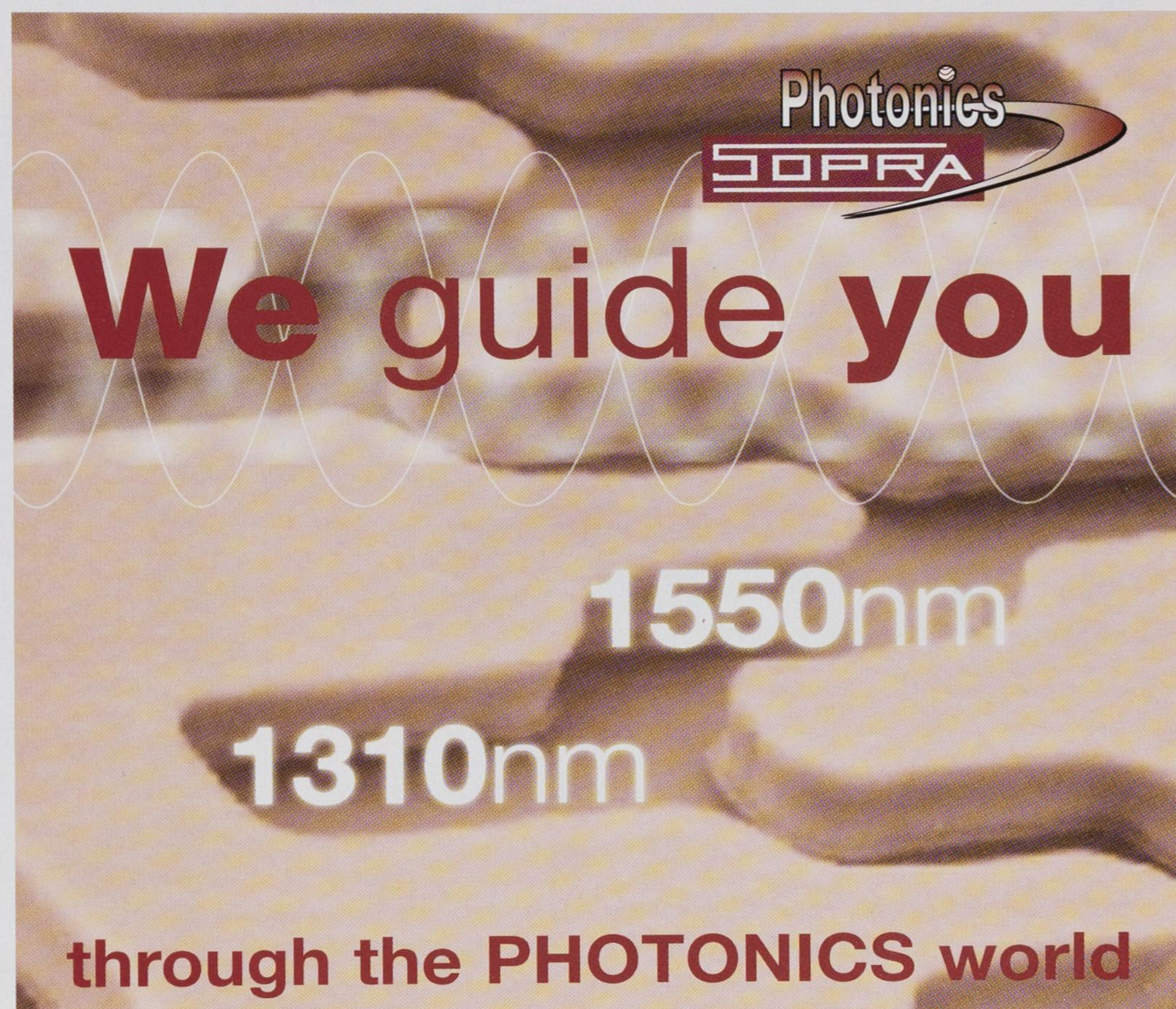
The exercise of merging the fabrication processes resulted in a hybrid version containing all of the positive attributes of the parent processes. Existing designs and products are maintained with no requirement for customers to re-qualify. For all of the PA designs converted to date, no design re-simulation, on- or off-chip tuning, or product re-development is needed. InGaP/GaAs HBT MMICs fabricated at WIN are actually just

dropped into place in existing module designs, resulting in equivalent performance across the board. RRFC designers can simply continue to use existing models and layout rules.

Dual geographically isolated fab lines for RRFC's cell-phone products are now in operation. A model for future technology collaboration has been established between RRFC and WIN, who share a range of fabrication capabilities up to the millimeter-wave regime. Low-

cost manufacturing of Raytheon's volume products drives wafers into WIN's outsource foundry, a classic win-win situation. ●

Dennis Williams (dwilliam@rrfc.raytheon.com) is outsource technology director, Raytheon RF Components. P C Chao is senior VP and CTO, Yu-Chi Wang is dept. manager, HBT Technology Development Group, and Chan-Shin Wu is president and CEO of WIN Semiconductors.



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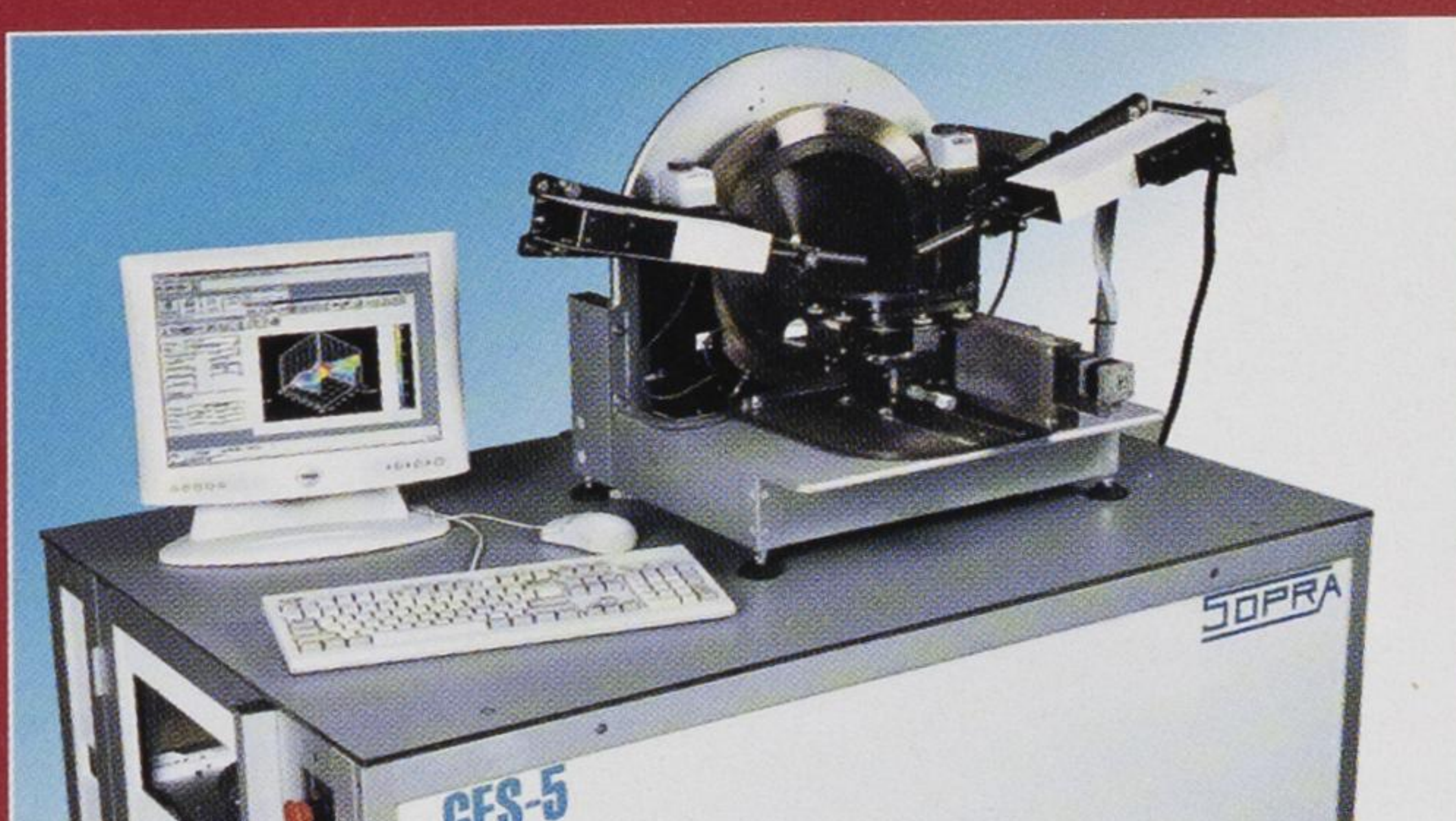
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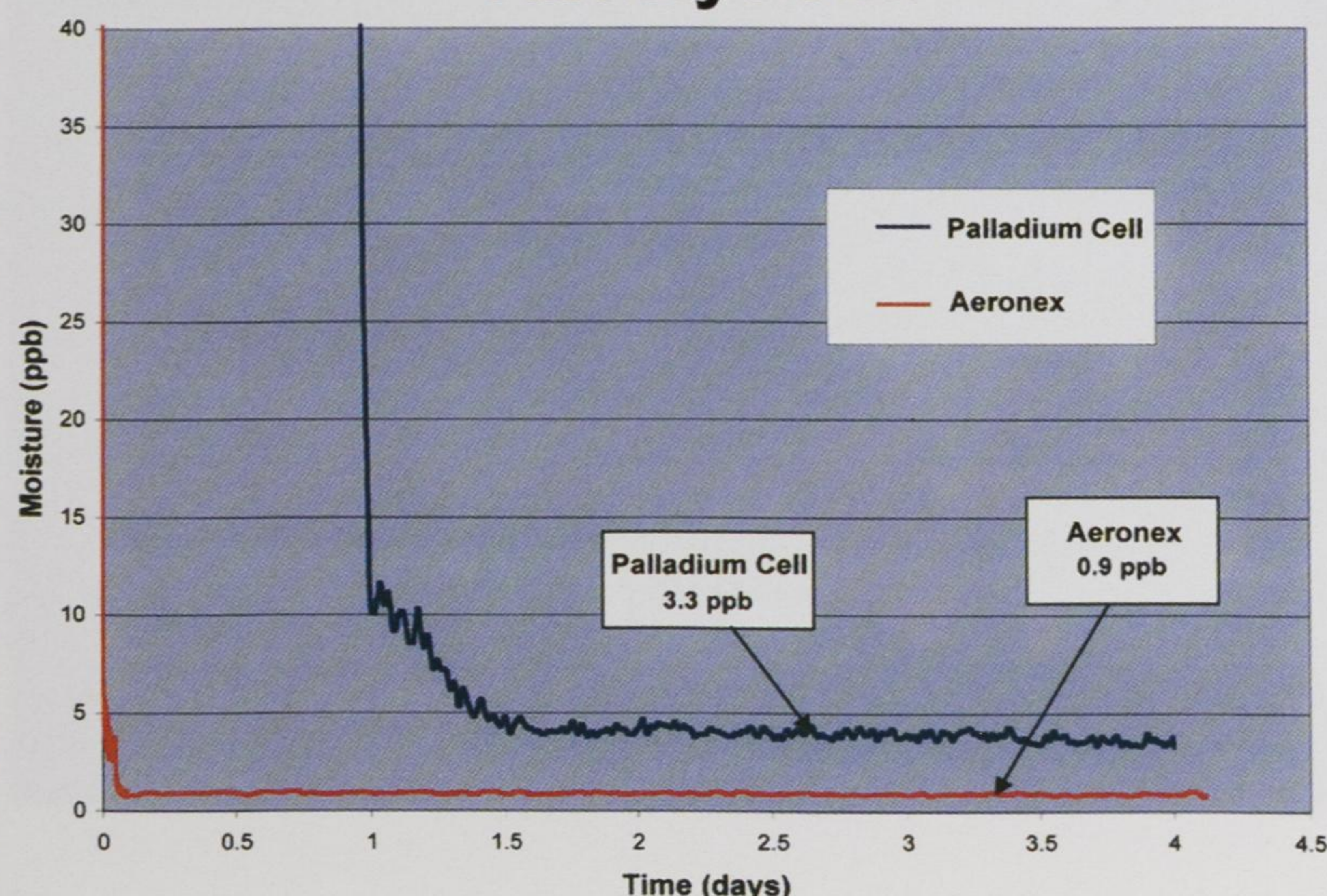
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In situ optical monitoring raises epi reactor productivity

Reflectance anisotropy spectroscopy has helped to improve the productivity of GaAs epitaxy.

Elisabeth Steimetz and colleagues describe how it is now being applied to InP-based structures.

Epitaxial growth is the first and often performance-determining step in the manufacturing of GaAs- and InP-based optoelectronic and RF devices. A steadily increasing number of device-grade single- and multi-wafer epitaxy systems are being equipped with real-time optical sensors for calibrating, monitoring and controlling the epitaxial growth process, thereby replacing, at least in part, conventional *ex situ* characterization techniques. The ability to measure layer parameters during growth, using real-time optical monitoring, can significantly improve the productivity of MBE and MOCVD systems.

Various types of sensors are available for almost any reactor, including such complex systems as multi-wafer production reactors. In combination with emission-corrected pyrometry measurements, even the surface temperature (or in the case of transparent materials, the susceptor) can be accurately measured *in situ*.

Optical *in situ* measurements involving reflectance and reflectance anisotropy spectroscopy (RAS) have been extensively applied to the MOCVD and MBE growth of GaAs-based device structures such as HBTs and 850 nm lasers. Efficient on-line reproducibility checks and faster device process developments have been made possible by a combination of *in situ* RAS, reflectance and pyrometry measurements.

To date there has been very little work on applying reflectance or RAS to the growth of InP-based materials such as InGaAsP. This is perhaps surprising given the increasing use of InP and its derivatives in high-speed microelectronics and optoelectronics, and the attendant demand for high-quality epiwafers. However, close co-operation between the

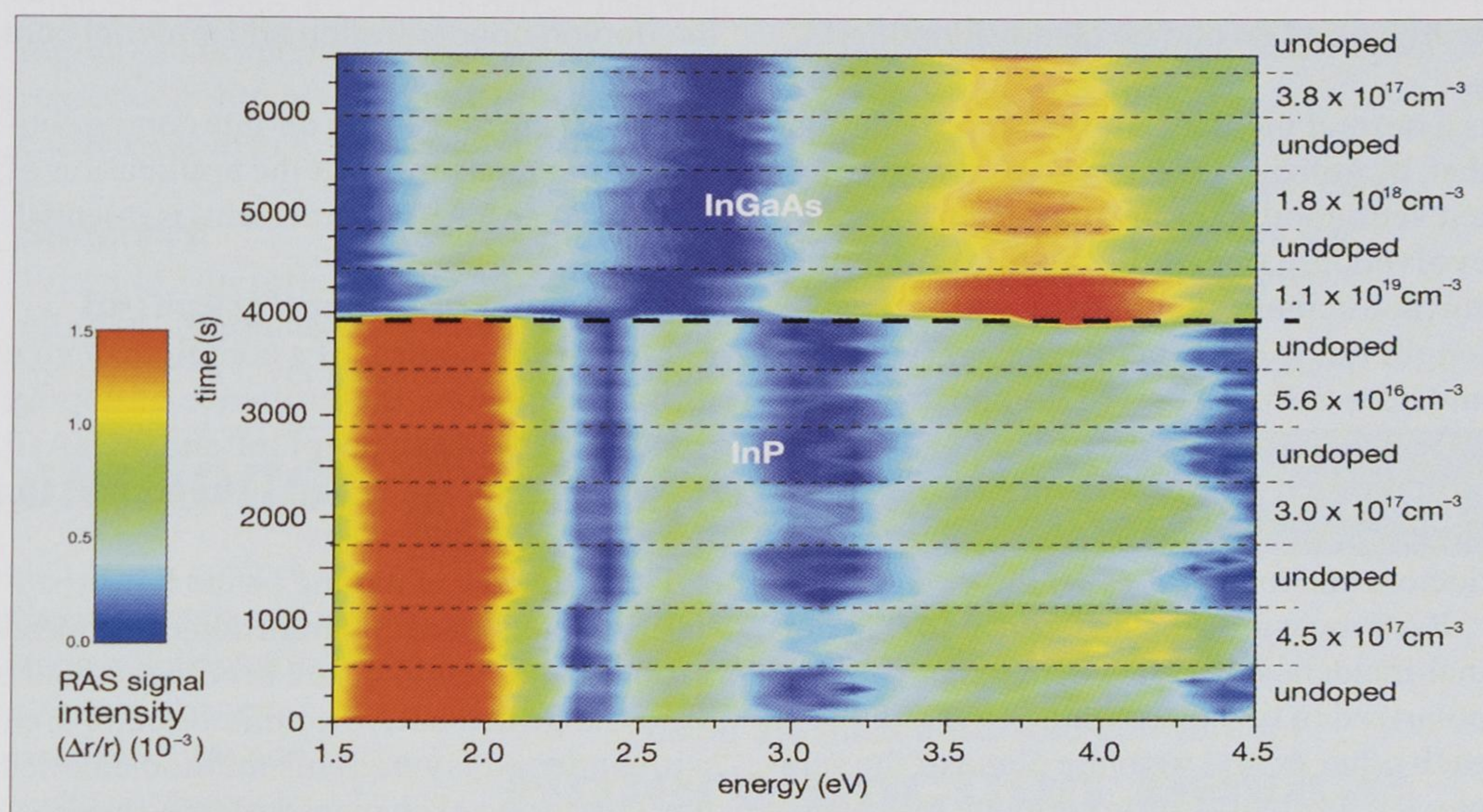


Fig. 1. RAS-fingerprint measurements of Zn-doping in InP and InGaAs. A comparison with the spectra measured for undoped material shows a resolution of doping effects down to $5 \times 10^{16} \text{ cm}^{-3}$ for InP and to low 10^{17} cm^{-3} levels for InGaAs.

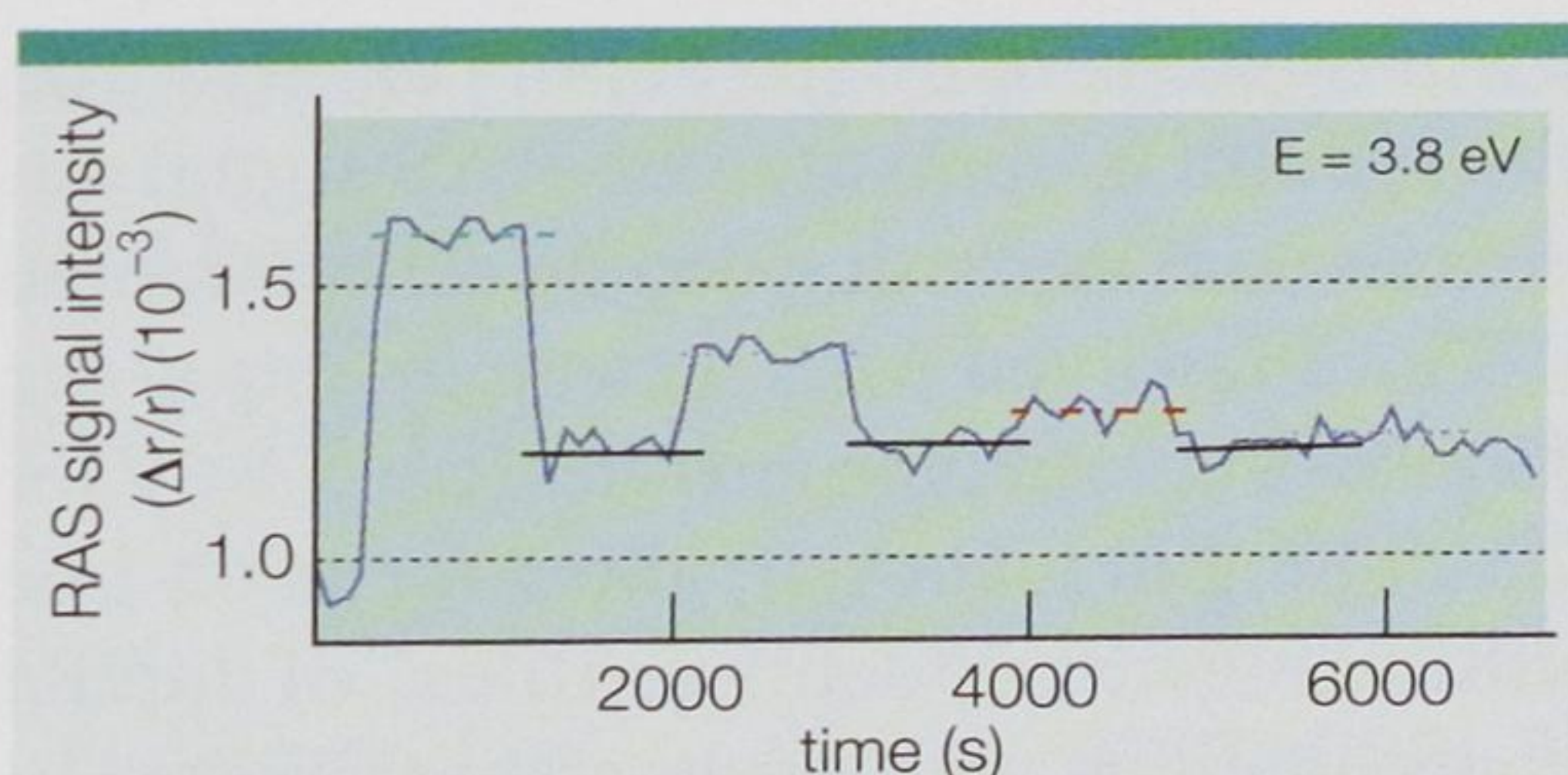


Fig. 2. A depth profile of Zn-doping in InGaAsP as generated from RAS measurements at 3.8 eV.

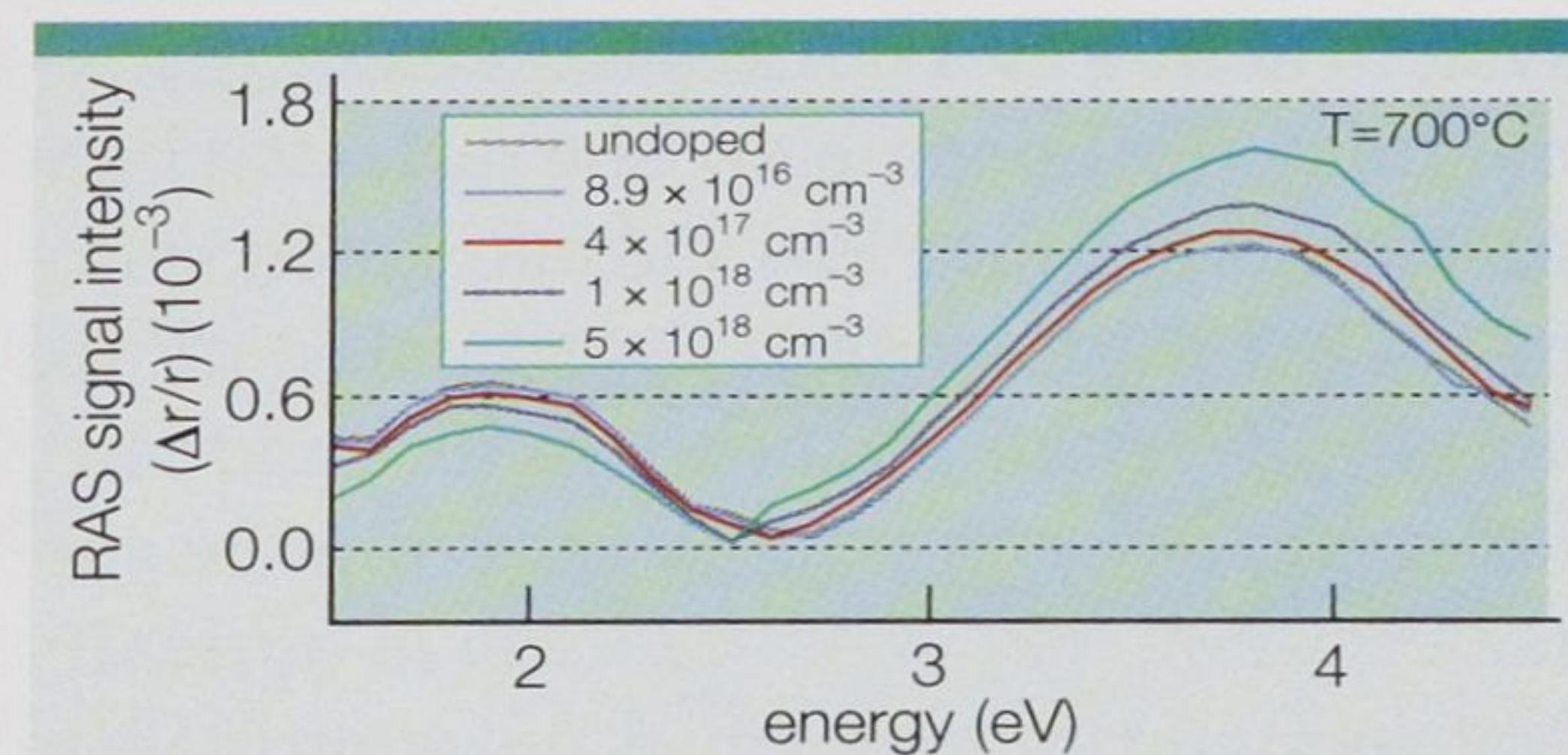


Fig. 3. During Zn doping of InGaAsP, the RAS signal intensity shows the largest variation for 3.8 eV photons.

Heinrich-Hertz-Institute and LayTec in Berlin has enabled this gap to be closed using an EpiRAS *in situ* sensor.

RAS fingerprints of 1.3 μm laser structures have shown the great potential of this method for monitoring the growth of InP-based devices. Real-time doping concentration mea-

surements for all relevant dopants can be performed. In addition, real-time RAS measurements at characteristic photon energies provide composition monitoring of each quantum well in the active region of the laser.

Reflectance anisotropy spectroscopy, also known as reflectance difference spectroscopy,

CHARACTERIZATION

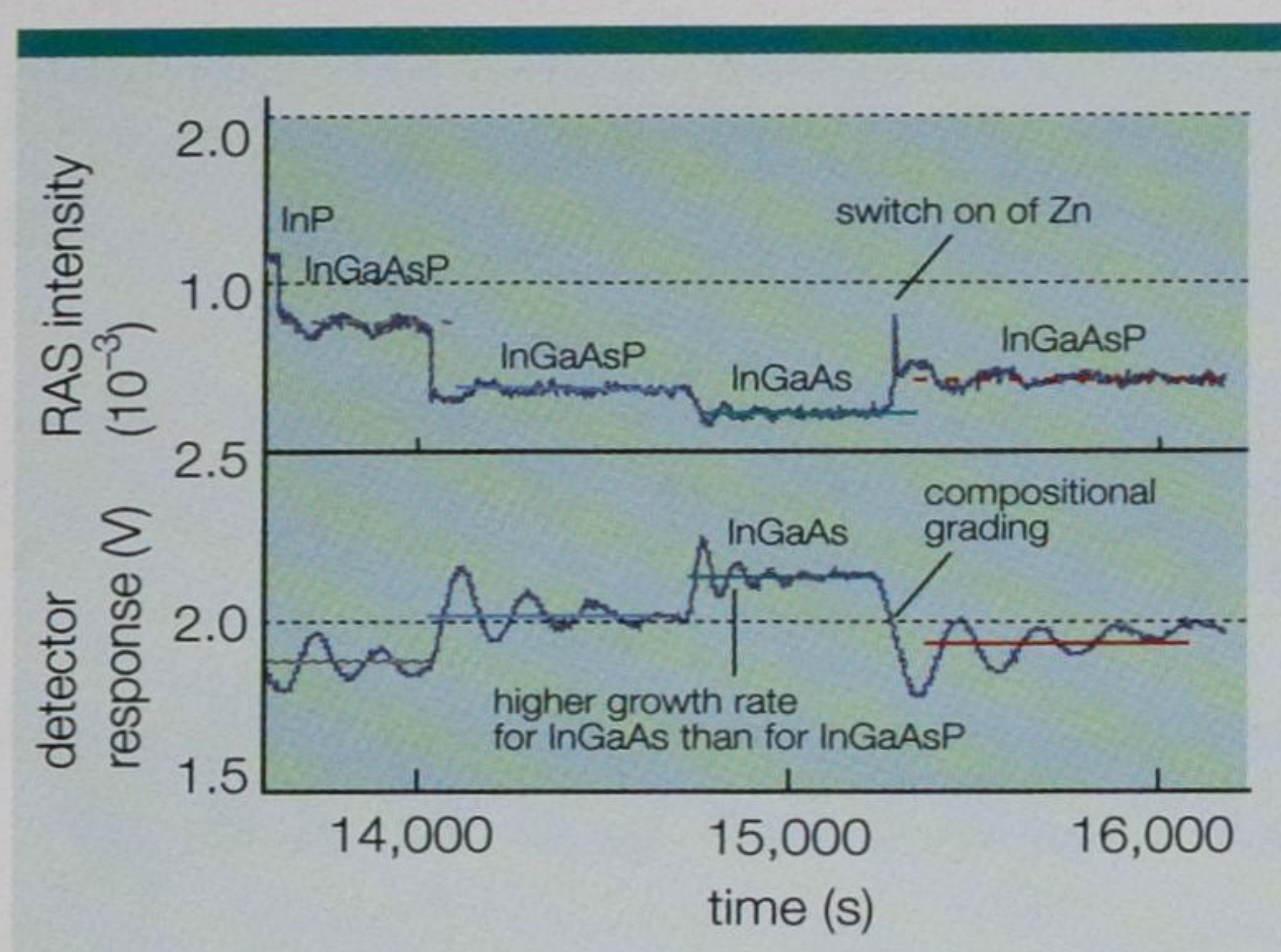


Fig. 4. Transient RAS and reflectance measurement for three different InGaAsP compositions, one InGaAs and one InP layer. The chemical sensitivity of RAS becomes evident by the fact that the switch on of Zn can be clearly identified.

is a normal incidence reflectance technique that, by utilizing the anisotropy of reconstructed semiconductor and metal surfaces, has evolved into one of the most useful optical surface science techniques. Using a wavelength range covering the near-UV, visible and near-infrared part of the spectrum (250 to 850 nm), RAS is capable of sensing the stoichiometry and symmetry of the uppermost atomic monolayers of cubic semiconductors and metals.

RAS measures the difference (Δr) in normal-incidence reflectances (r_x and r_y) for light polarized in two directions perpendicular to each other (x and y) in the plane of the sample. RAS calculates the complex reflectance anisotropy ($\Delta r/r$), where $r = (r_x + r_y)/2$, caused by the reduced symmetry at the surface of cubic crystals. The RAS set-up includes a photoelastic modulator (PEM)-based optical system acting as a normal-incidence phase-modulated ellipsometer. The reflected light passes through the PEM and into a monochromator before detection. The signals detected are usually of the order $(\Delta r/r) < 10^{-3}$, and carry information originating only from the surface region. The bulk beneath is optically isotropic and therefore does not contribute to the measured spectrum.

The RAS signal is normalized to the total reflectance measured under the same angle of incidence. This reflectance signal averages information over the material down to the wavelength-dependent penetration depth. As reflectance measurements are carried out with unpolarized light, the averaged reflectance signal is not surface-sensitive at all.

While reflectance measurements at a single wavelength give useful information on the

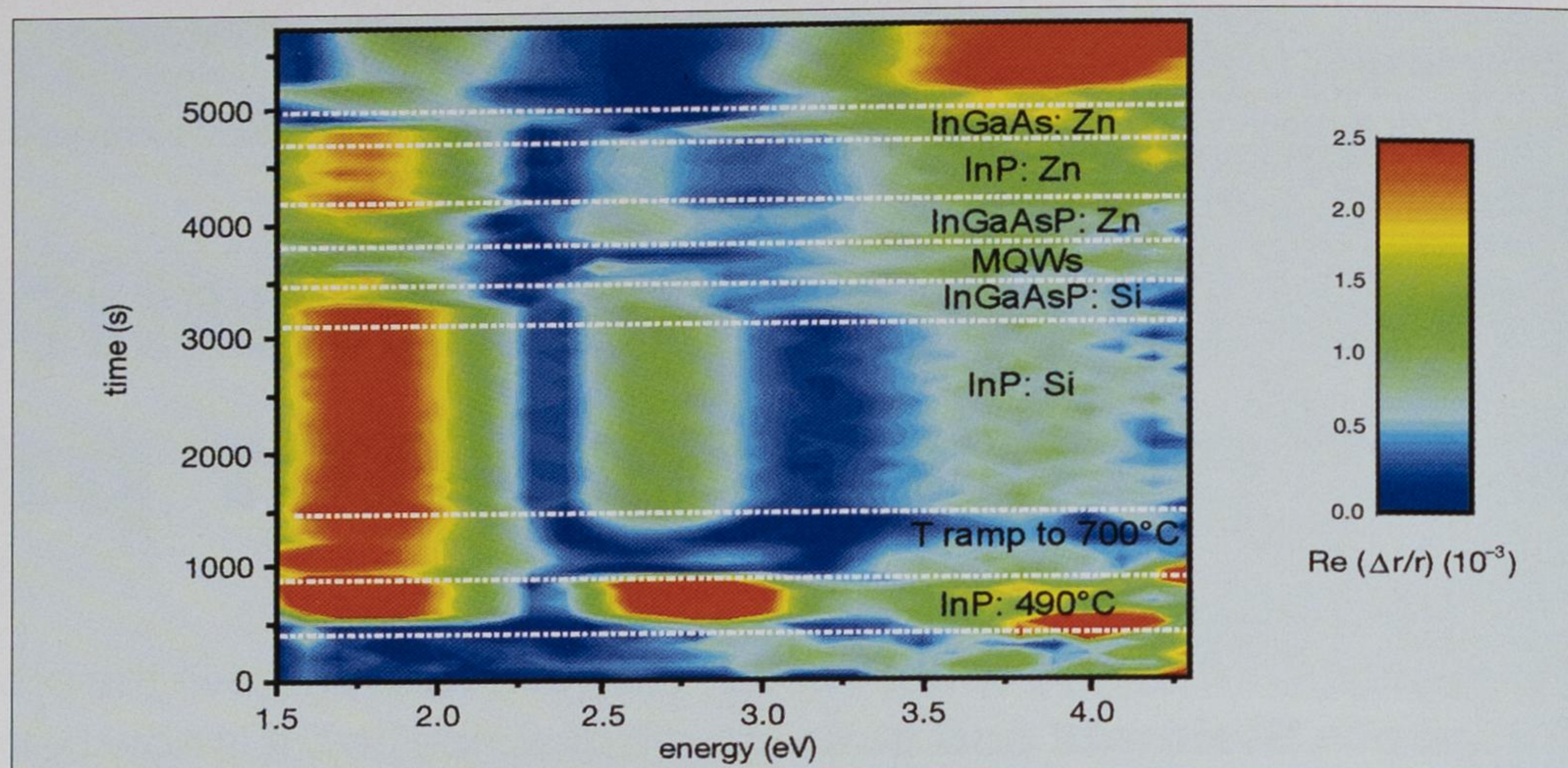


Fig. 5. Color-encoded RAS spectra of a complete 1.3 μm laser structure. Changes in the doping concentration and material composition are evident.

actual growth rate, for an on-line doping concentration measurement the application of spectroscopic RAS measurements is essential.

Doping measurements by EpiRAS

For the *in situ* control of a complete device growth sequence, the influence of doping (both n-type and p-type) of InP and InGaAsP on the optical data is highly important for all types of device.

The influence of doping on the RAS spectra arises predominantly from doping-induced surface band-bending, and becomes evident by a change in the RAS amplitude compared with undoped layers. This method enables the monitoring of changes in doping concentration almost instantaneously.

For p-type doping the RAS signal increases in the UV range of the spectral measurements, as shown in the false color-encoded RAS spectra in figure 1. In n-type doping the effect on the spectra is opposite: the RAS signal decreases with increasing doping concentration.

Time-resolved RAS measurements at the most sensitive photon energies (e.g. 3.8 eV for Zn-doping in InGaAsP) allow for an on-line measurement of “depth profiles” of doping concentrations, with results comparable to CV or SIMS measurements. In figure 2, a transient measurement taken from color-plot data for Zn-doped InGaAsP shows such a doping profile. As growth time is directly related to layer thickness, the effective depth resolution of this technique can be improved by increasing time resolution of the measurements.

Figure 3 shows how the RAS signal varies with photon energy for different Zn-doping concentrations. The largest variation in signal is seen at 3.8 eV. For Zn-doping in InP, the

sensitivity to doping concentration changes is even higher than for InGaAsP and InGaAs. For a wide range of concentrations and materials, a linear dependence of the RAS data on the doping concentration in a log-log diagram is seen. Calibration curves for *in situ* doping concentration measurements are generated by correlating the *in situ* signal changes with the *ex situ*-determined actual doping concentration. The resolution of *in situ* doping concentration measurements decreases from InP to InGaAsP to InGaAs. The more arsenic-rich the material, the lower the resolution of doping signatures from RAS measurements. The reason for this behavior is not yet understood and is under further investigation.

InGaAsP composition measurement

One of the most critical parameters for 1.3 μm lasers is the composition of the quaternary material in the MQW region, and the influence of intentional composition changes on the whole RAS spectra have been studied. Figure 4 shows RAS spectra for three different InGaAsP compositions. The composition influences the spectra mainly at surface dimer-related energies (1.8 and 2.5 eV), and at 3.8 eV, an energy thought to be influenced by the material's bulk properties. But for a quantitative analysis of the composition the reflectance data should be used instead of the RAS signal.

Both methods allow the detection of composition changes. However, the signal is easier to interpret and simulate using analysis software if the reflectance data is used. The period of the Fabry-Perot interference fringes can be used for an *in situ* calibration of the growth rate, while the amplitude of the reflectance (DC-signal) can be used for the deter-

mination of the composition. This kind of analysis has already been successfully performed for AlGaAs growth on GaAs.

Device-fingerprint measurements

With the information from systematic investigations on doping and composition measurements, the growth of a whole laser device can be analyzed. Figure 5 shows a color-encoded RAS measurement of a complete device structure. All growth steps show their characteristic features: changes in dopant; doping concentration; contrast between InP, InGaAsP and different quaternary compositions; temperature changes corresponding to deoxidation, cool down and switching sequences.

For a more detailed investigation of the active region that includes the thin MQWs, transient RAS measurements at 1.8 eV are performed. A typical result is shown in figure 6. Due to the sensitivity of RAS to the surface stoichiometry, even the thin QWs could be resolved. As the well thickness is less than 10 nm, no complete Fabry-Perot interference is evident, and thus analysis of reflectance measurements is almost impossible. The

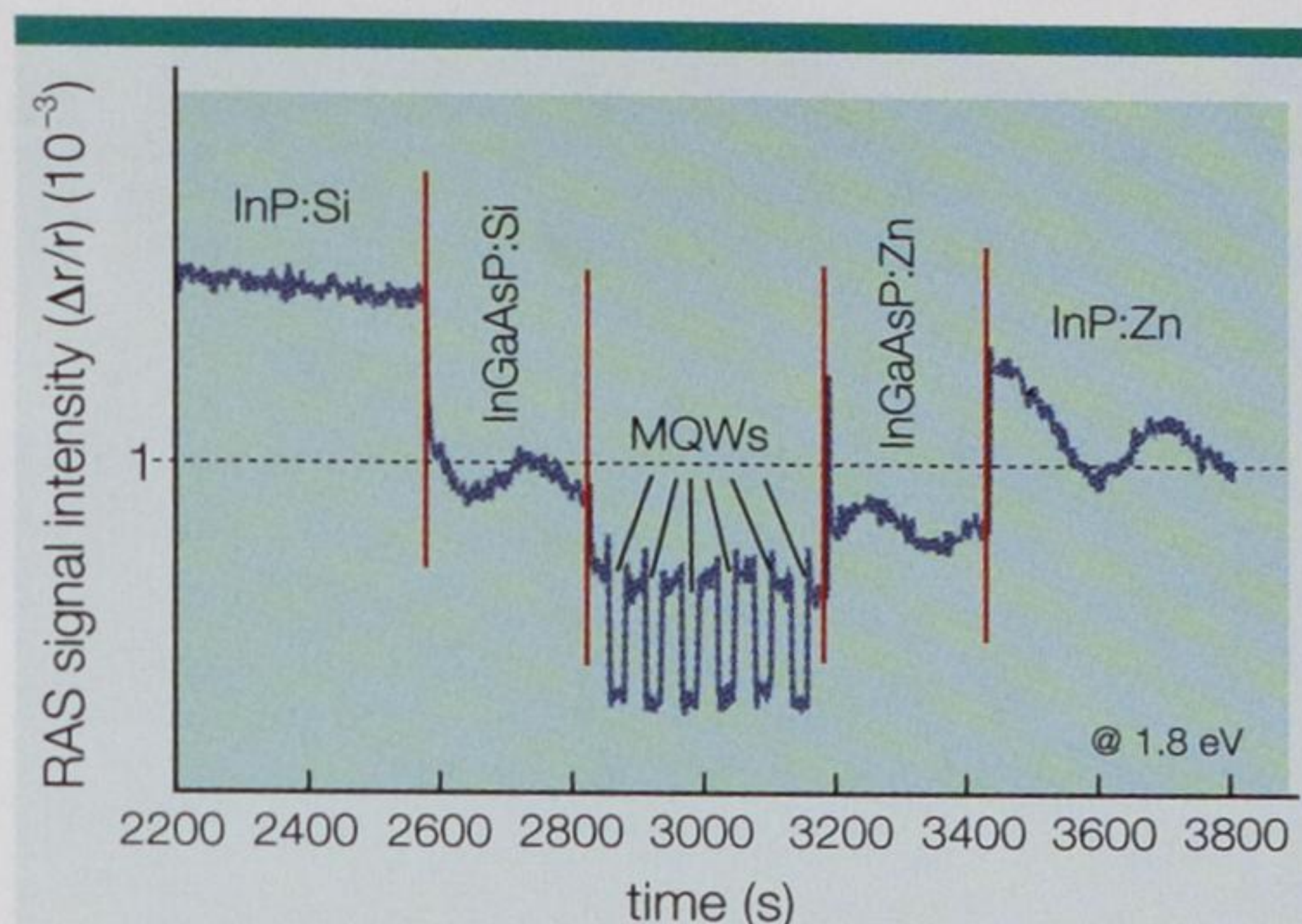


Fig. 6. Transient RAS measurement at 1.8 eV during deposition of the laser's active region. The growth of each QW can be monitored in real-time due to the sensitivity of RAS to the surface stoichiometry.

changing composition of the barrier and well region can be monitored by RAS, and so the reproducibility of switching sequences can easily be seen in RAS measurements.

Summary

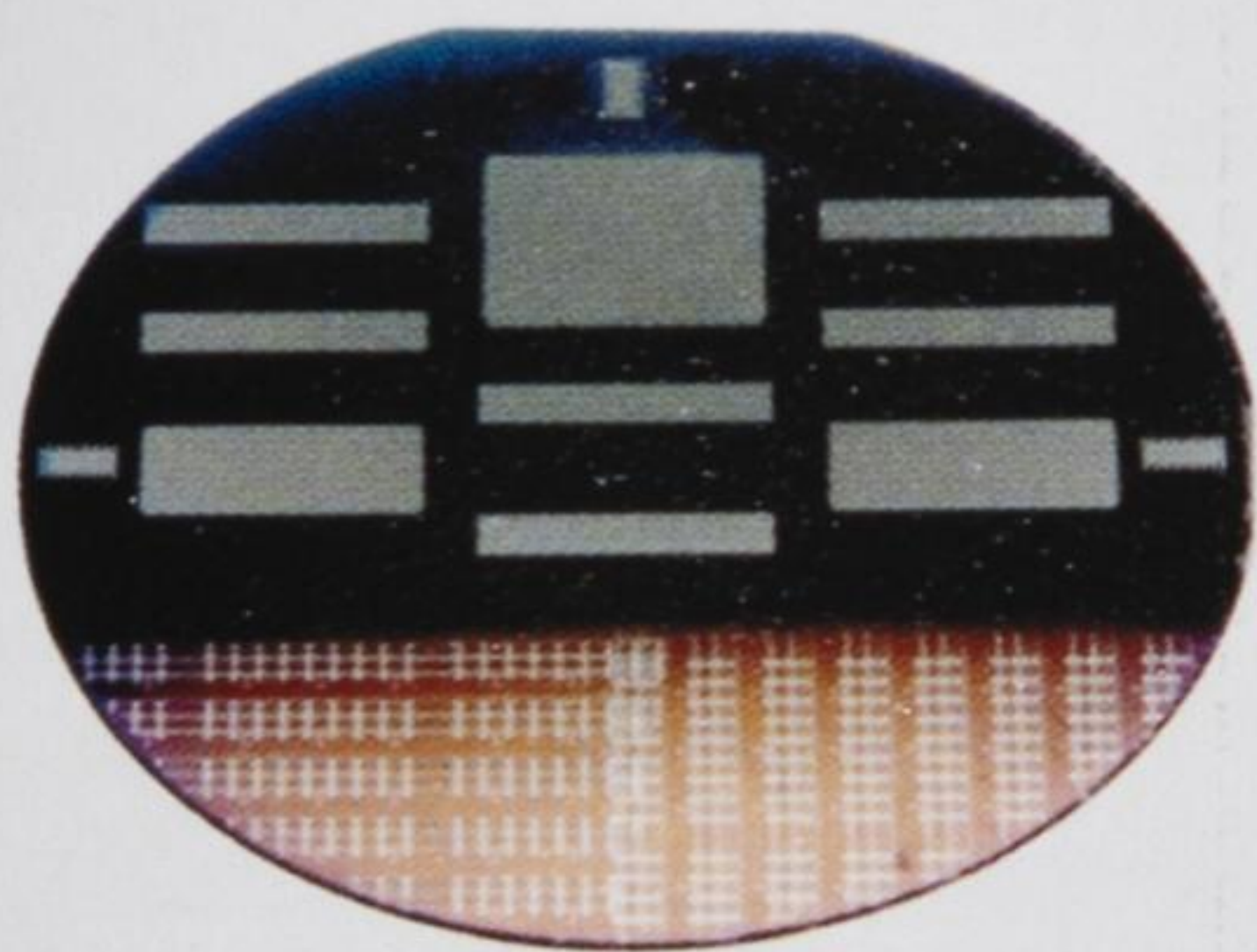
When *in situ* reflectance and RAS are applied to 1.3 μm laser-structure growth, the most crucial layer parameters can be deter-

mined during growth. For doping-related measurements, RAS is the only available *in situ* method, with great potential for on-line reproducibility checks, as shown by the data for Zn-doped InP-based material. Both spectroscopic RAS and reflectance measurements can be applied for on-line composition measurements. By using the obtained data with customized analysis software, this method can readily be used in a device production environment.

As the latest investigations have shown, RAS, due to its extreme surface sensitivity, is even able to resolve and optimize switching sequences and the growth of compositionally graded layers. With this basic knowledge of the growth process for InP-based materials, a stronger interaction between *in situ* optical measurement techniques and the epitaxial process is now possible.

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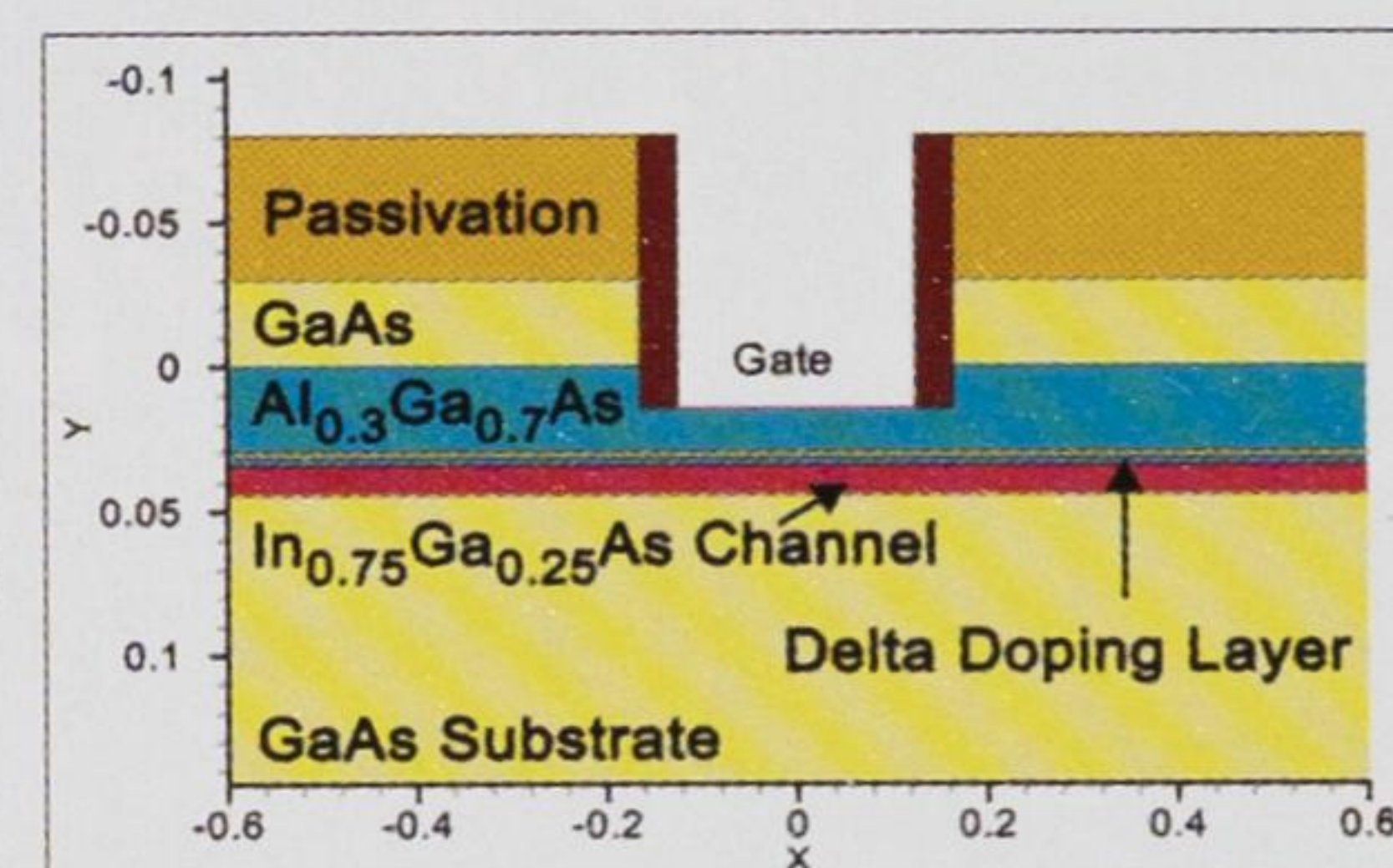
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Quantitative X-ray analysis provides production control

Peter Velling and colleagues from IPAG describe how a quantitative X-ray analysis technique is being used in the fab to provide SPC for epilayers.

Carbon-doped InP/InGaAs HBTs and InP/InGaAs HEMTs are the building blocks for many of the optoelectronic and RF integrated circuits that are needed for the OC-768 (40 Gbit/s) optical communication standard. For reliable fabrication of these often complex ICs, quantitative control of InP processing is necessary, even at the epiwafer level, before device processing can begin. Statistical process control (SPC) has become a cornerstone of compound semiconductor manufacturing, enabling rigid deviation limits to be put on a number of measurable variables from the start to the finish of a production process.

X-ray diffraction is an established non-destructive technique that enables the determination of layer parameters with high accuracy. Data on epilayer thickness and composition are required for SPC at the epitaxy stage of manufacturing. However, in practice X-ray diffraction analysis becomes qualitative for complex epitaxial structures because it relies on the comparison of fingerprints of "known good samples". While the analysis of these X-ray spectra is often complicated and time consuming, no calculations are done to determine specific layer parameters such as thickness and composition, which are necessary for SPC.

In order to gain quantitative information from InP-based HBT and HEMT epilayers, data from X-ray reflections from the 002 and 004 planes can be used to automatically calculate layer thickness and composition, providing valuable information for R&D and SPC in a production environment.

HBT structure and data model

At IPAG a quantitative X-ray analysis technique is being used to provide SPC data on InP-based HBTs and HEMTs grown by low-

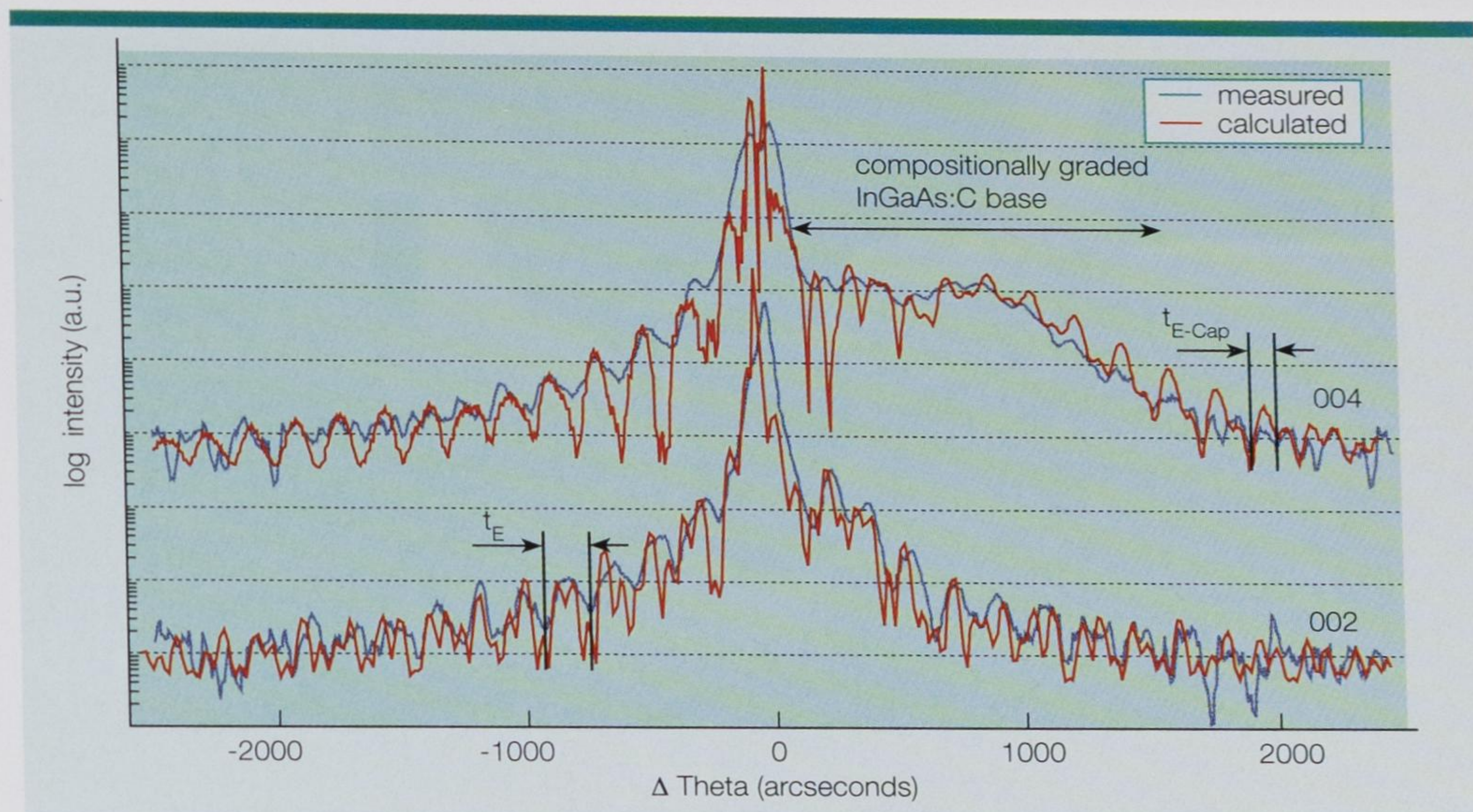


Fig. 1. Calculated X-ray and measured spectra from the 004 and 002 reflections of an InP/InGaAs:C HBT. The structure in figure 2 is used for the calculated curve.

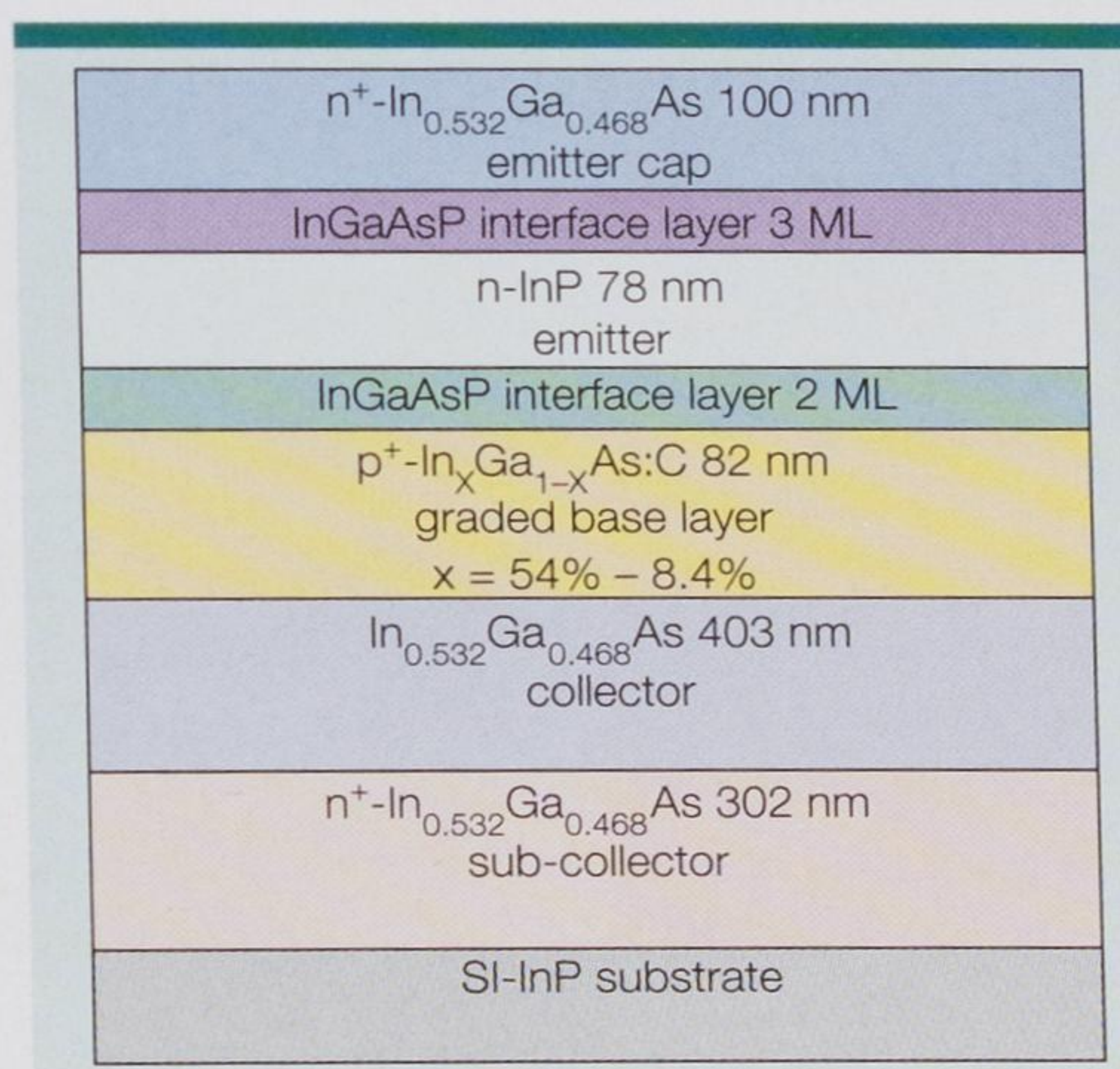


Fig. 2. The intended layer stack of the InP/InGaAs:C HBT structure, including the InGaAsP interface layers.

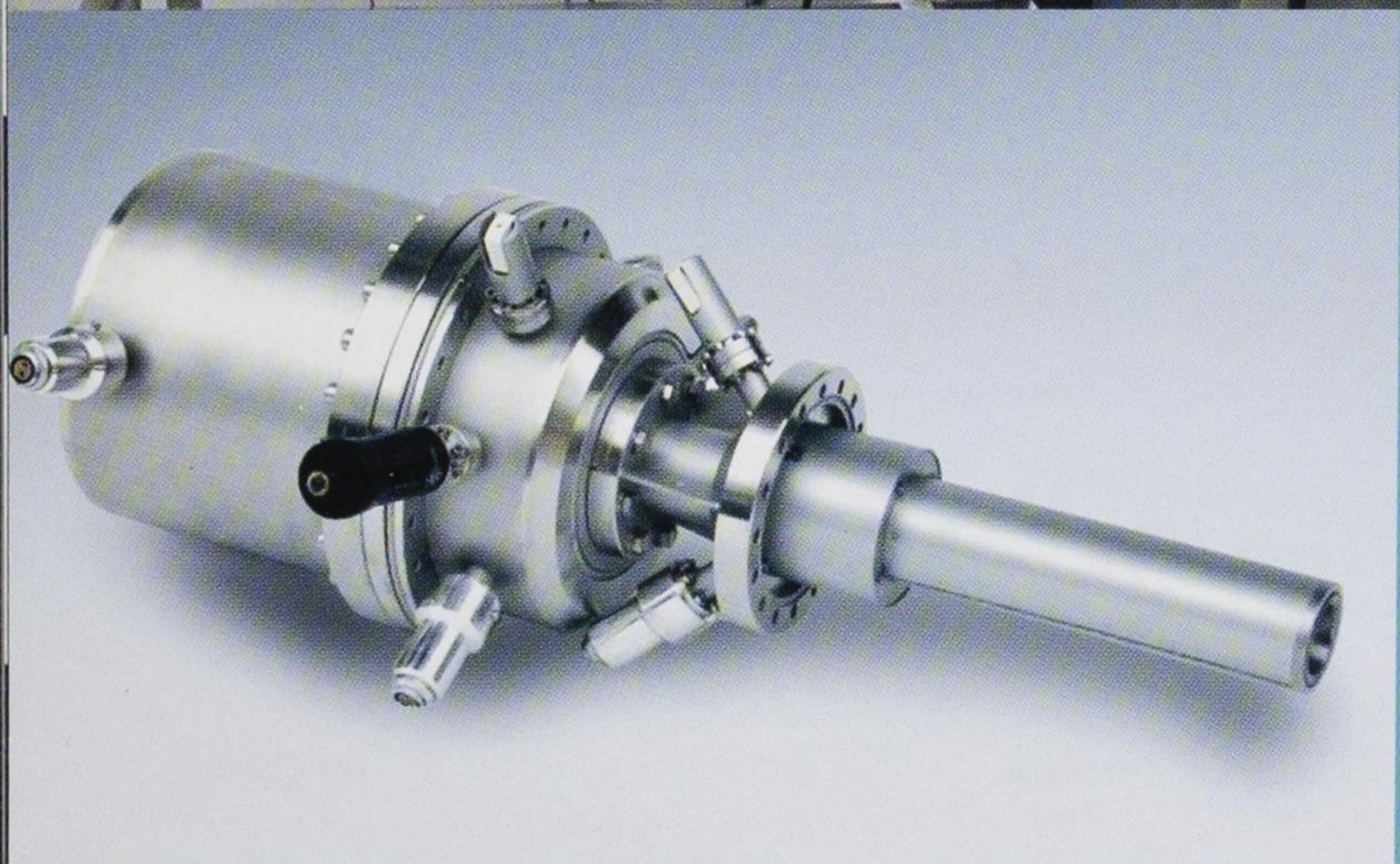
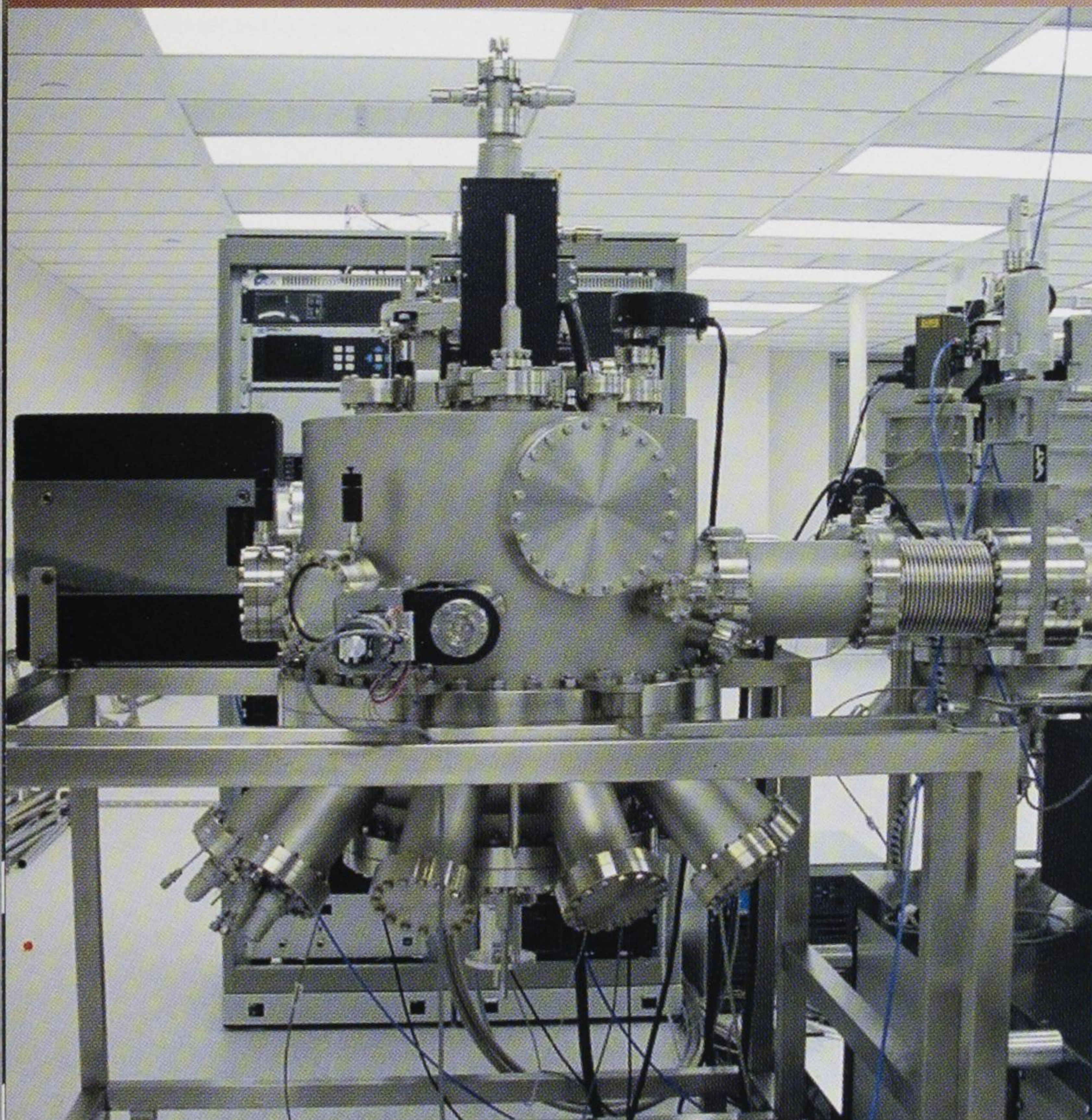
pressure MOVPE using a non-gaseous-source configuration (Velling, Velling *et al.*). The InP/InGaAs:C HBTs have a compositionally graded p-type InGaAs:C base and exhibit $f_t > 120$ GHz and $f_{max} > 190$ GHz. For X-ray diffraction data analysis, the commercial RADS Mercury software tool developed by Bede is used (Bowen, Bede Scientific Instruments). A high-resolution X-ray dif-

fractometer system with a double crystal monochromator setup is used for X-ray measurements in a coupled ω - 2θ mode (see *Compound Semiconductor* March 2001, p72).

Figure 1 shows the calculated X-ray rocking curve and measured curves for the 004 and 002 reflections. Figure 2 shows the intended InP/InGaAs:C HBT layer stack used by the model to create the calculated X-ray rocking curve. The excellent fit between the measured and calculated X-ray scans in figure 1 is achieved using the same layer model for both reflections. For the initial HBT layer model, a maximum variation in the composition and thickness of each layer of about $\pm 10\%$ around the intended values, is chosen to calculate the best fit to the X-ray spectra.

In order to take interface effects into account, two thin interlayers are included in the layer model between the InP emitter and the emitter cap above and the collector below. These interlayers enable the model to account for effects such as interface roughness and intermixing. It is important to reduce the number of free parameters in the model, as this makes the calculated curve parameters from a complex model more valid. To reduce the number of free parameters for the X-ray spec-

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trum analysis, the HBT layer parameters are coupled and scaled using the growth time.

For example, a ternary layer like $\text{In}_x\text{Ga}_{1-x}\text{As}$ is characterized by its thickness and composition. For $\text{In}_x\text{Ga}_{1-x}\text{As}$ layers such as the sub-collector, collector and emitter cap, this makes up to six separate layer parameters that need to be determined. It can be assumed that for the HBT structure discussed here, the three layers exhibit the same composition and growth rate. Consequently, the six free parameters corresponding to the three ternary layers can easily be reduced to two free layer parameters by fixing the compositions to the same value and scaling the thickness of each layer to the growth time. For the discussed HBT layer stack, the nine layer parameters for the ternary sub-collector, collector, base and emitter cap layers (two parameters each), and the binary InP emitter layer (one parameter, thickness only), are reduced to five parameters that need to be calculated from the measured X-ray spectra.

From data to epilayer parameters

Nonetheless, the period of the resolved fringes must be associated with an individual HBT layer. The fringe periods correspond to the thickness of the emitter (t_E) and the emitter cap ($t_{E\text{-Cap}}$) layers, as shown in figure 1. The calculated values of composition and thickness agree with the measured spectra. The relation between layer thickness (t_{layer}) and the width of the fringe ($\Theta_2 - \Theta_1$) is given by $t_{\text{layer}} = \lambda / 2 (\sin\Theta_2 - \sin\Theta_1)$, where λ is the X-ray wavelength, which for Cu $K\alpha$ X-rays is 0.154 nm.

The fringes in the 002 reflection are dominated by the InP emitter layer. The 002 reflection is quasi-forbidden for GaAs, and signal intensity is also strongly reduced in case of InGaAs. This is shown in figure 1, where the signal intensity corresponding to the emitter-cap, collector and sub-collector $\text{In}_{0.532}\text{Ga}_{0.468}\text{As}$ layers between $\Theta = 0$ and -200 arcseconds in the 004 reflection is strongly reduced in the 002 reflection. Consequently, the broad peak in the range of $0 < \Theta < 1500$ arcseconds, corresponding to the compositionally graded p-type InGaAs:C base, is suppressed in the 002 reflection.

Taking the 004 and 002 reflections into account in parallel enables a quantitative analysis of complex HBT layer stacks, while the fringe periods and signal intensities can be correlated to individual layers. This HBT layer analysis procedure has also been used at IPAG for InGaP/GaAs:C HBTs, InP-based resonant tunneling diodes (RTDs) and HBT/RTD combinations, resulting in very detailed material characterization. The quantitative X-ray analy-

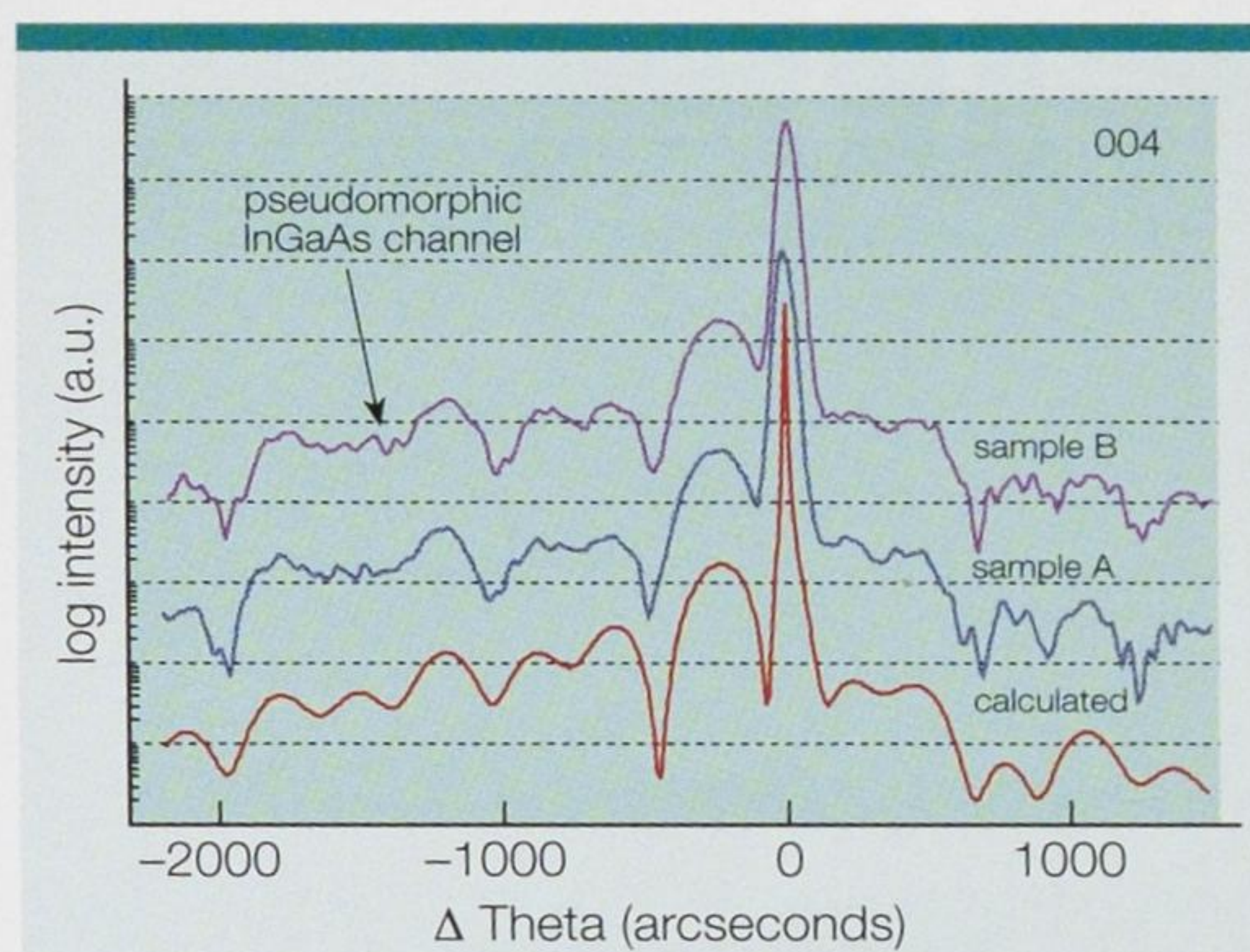


Fig. 3. Measured (samples A and B) and calculated 004 reflections from two nominally identical InP/InGaAs HEMTs.

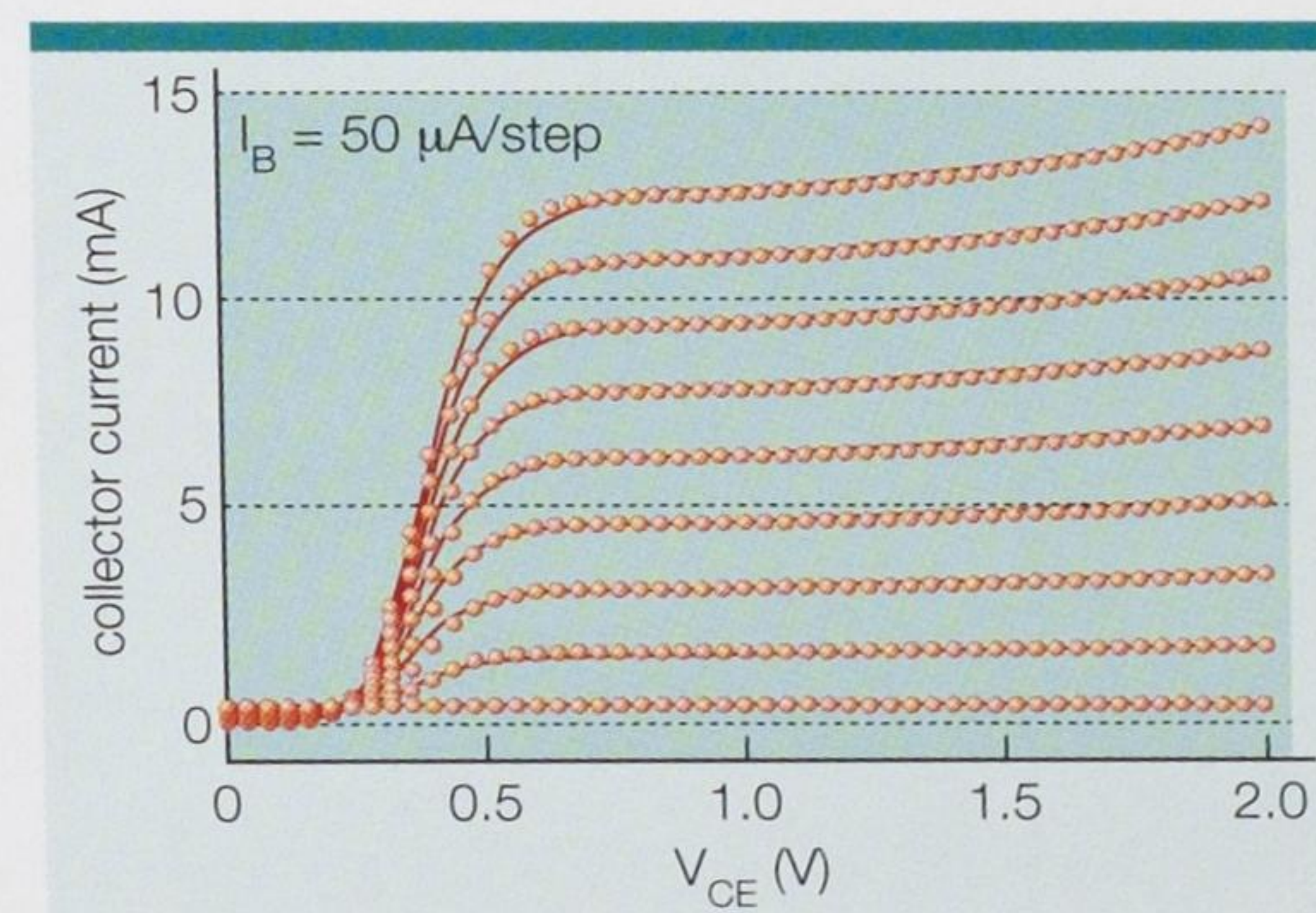


Fig. 4. Measured (balls) and modeled (solid lines) common emitter output characteristics of an InP/InGaAs:C SHBT.

sis of two intentionally identical HBT layer stacks indicates run-to-run variations of composition and thickness of less than 1% and 0.5%, respectively. These run-to-run variations are equal to the homogeneity variations across a full 2 inch wafer.

As discussed for the HBT structure in figure 2, an X-ray peak at $\Theta \approx -200$ arcseconds in the 004 reflection is clearly resolved, and corresponds to approximately 0.2% deviation of the indium content in $\text{In}_x\text{Ga}_{1-x}\text{As}$ from the composition required for lattice matching ($x = 53\%$). In other words lattice strain corresponding to compositional variations of much less than 1% is clearly resolved.

InP/InGaAs HEMTs

A good fit between the 004 rocking curves is also achieved for the HEMT structures shown in figure 3. Samples A and B represent two nominally identical HEMT structures, comprising a highly strained $\text{In}_{0.6}\text{Ga}_{0.4}\text{As}$ channel layer with an InP layer acting as a spacer, supply and Schottky barrier. The period of the fringes in the rocking curves from HEMTs A and B deviate from the calculated X-ray spectra by less than 10 arcseconds, and the

intensity modulation between A, B and the calculated curve are in agreement. Detailed X-ray analysis of the HEMT structures reveals the same excellent homogeneity characteristics as in the HBT structure.

Fabricated HEMT devices with a gate length of $0.25 \mu\text{m}$ exhibit f_t and f_{max} values of >100 GHz and a maximum transconductance of 550 mS/mm at $V_{\text{gs}} = 0 \text{ V}$. This clearly indicates that the HEMTs are not just test structures for X-ray analysis, but are also well suited for the production of front-end receiver chips operating up to 43 Gbit/s and higher.

Figure 4 shows a very good fit between the measured and modeled common emitter output characteristics of fabricated HBT devices with a $20 \mu\text{m}^2$ emitter area. A DC gain of up to 35 is reached for SHBT devices, and the extrapolated f_t and f_{max} values are 120 and 190 GHz, respectively, based on the as-measured s-parameters. The collector emitter breakdown voltage (BV_{ceo}) exceeds 7 V. These figures demonstrate the high-performance levels of the HBT and HEMT technologies that are the platform for 40 Gbit/s and higher optoelectronic and RF circuits in production and development at IPAG.

Conclusion

Since X-ray analysis revealed the excellent homogeneity of the epitaxial material, device homogeneity has also been investigated. While the thickness and compositional variations across the wafer are less than 1%, the variations of device parameters such as DC gain are less than 5%. This clearly demonstrates that the rapid and quantitative X-ray analysis described here is becoming an integral part of the technological platform for the production of high-speed optoelectronic and RF integrated circuits.

Further reading

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P Velling, D Keiper, A Brennemann, M Agethen, G Janssen and R Bertenburg are with Innovative Processing AG, Duisburg, Germany. Email velling@ipag35.com.

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Ellipsometry reveals epiwafer optical and physical properties

Spectroscopic ellipsometers have become an integral part of many thin-film manufacturing processes, and can measure the properties of semiconductor epilayers with great accuracy, write **Lianchao Sun, Jean-Claude Fouéré** and **Chris Pickering**.

There are many techniques for characterizing materials, each having its own advantages and disadvantages, and each revealing a different set of material properties. Spectroscopic ellipsometry (SE) is an optical technique that is particularly flexible because it can be used to determine the optical and physical properties of a wide variety of thin-film materials. Its ability to do this without contact or damage to the material has led to its routine use in R&D laboratories and within manufacturing facilities for monitoring thin-film growth and deposition processes.

SE is now implemented in a number of different configurations. Table-top instruments are mostly used for R&D applications where sample throughput is relatively low. Larger, automated tools are commonly found in semiconductor, flat-panel display and photonic device manufacturing facilities, where ease of use and measurement speed are essential. Automation usually includes wafer handling for complete hands-free operation, analyzing one full wafer batch at a time, and the ability to map an entire wafer.

What can SE reveal about a material?

SE relies on the determination of the polarization state of a beam of polarized light reflected from the sample under characterization. When performing SE measurements, the polarization state is determined at many discrete wavelengths over a broad wavelength range. The change in the polarization state can be traced to the physical properties of the thin film by means of a model. Material characteristics such as layer thickness, surface roughness, refractive index (n) and extinction coefficient (k) can be determined with excellent precision through regression analysis (Tompkins and McGahan).

The SE instrument determines two ellipsometry angles, Ψ and Δ , which describe the

plane of incidence (P) to the amplitude of the polarization perpendicular to the plane of incidence (S) is represented by Ψ . The phase retardation between the two polarization vectors P and S is represented by Δ . Changes in Ψ and Δ essentially depend upon the optical constants, n and k , of the layer materials and substrate, the physical thickness of the individual layers and the surface roughness.

For a given material, the magnitude of the change in Ψ and Δ is different at different angles of incidence. A larger change gives more accurate results, and for this reason data is taken at a number of incident angles to find the angle that gives the biggest change in Ψ and Δ . Data for 100 to 200 different wavelengths are acquired at each angle. SE instruments use a white light source, and individual wavelengths are selected for detection by either a motor-driven monochromator or a multichannel detector that can detect many wavelengths simultaneously.

Increasing the number of angles and wavelengths at which data are acquired improves analysis precision, especially for complicated epitaxial structures. In recent years SE has extended further into the vacuum ultraviolet (down to 140 nm) and infrared (up to 30 μm) regions of the spectrum, enabling the technique to provide more information on material properties (see *Compound Semiconductor* March 2001, p76).

SE and compound semiconductors

SE has been used for the characterization of multilayer III-V compound semiconductor structures for several years. A review of the capability of the technique for characterizing such structures has been given by Pickering *et al.* SE is first used to establish reference spectra of n and k from material layers of different known compositions and thicknesses. For example, for an $\text{Al}_x\text{Ga}_{1-x}\text{As}$ sample of unknown x -value and layer thickness, a num-

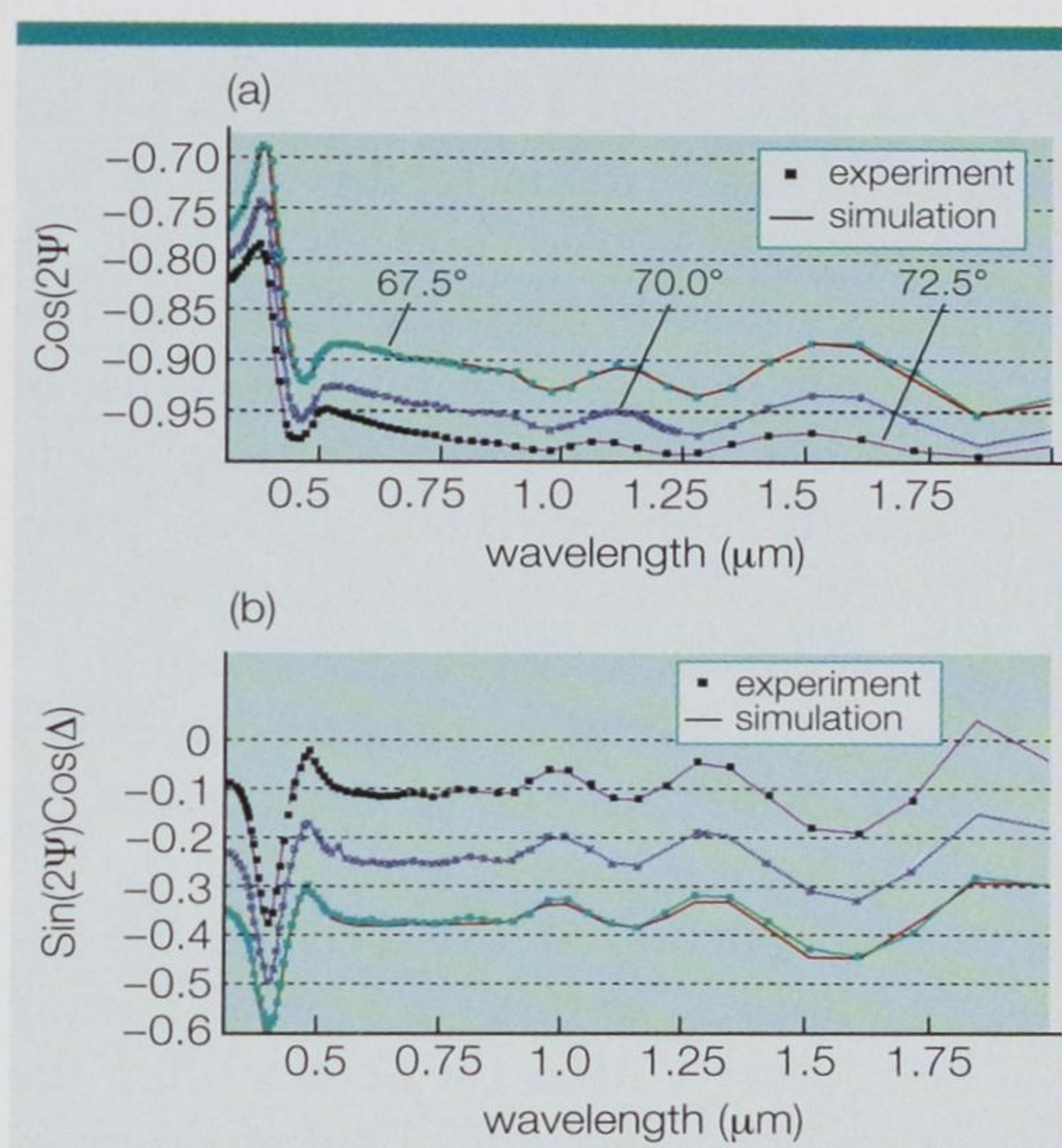


Fig. 1. Spectra for (a) $\text{Cos}(2\Psi)$ and (b) $\text{Sin}(2\Psi)\text{Cos}(\Delta)$ taken at three incident angles from the structure shown in figure 2 (below). These spectra illustrate how Ψ and Δ are different at different incident angles.

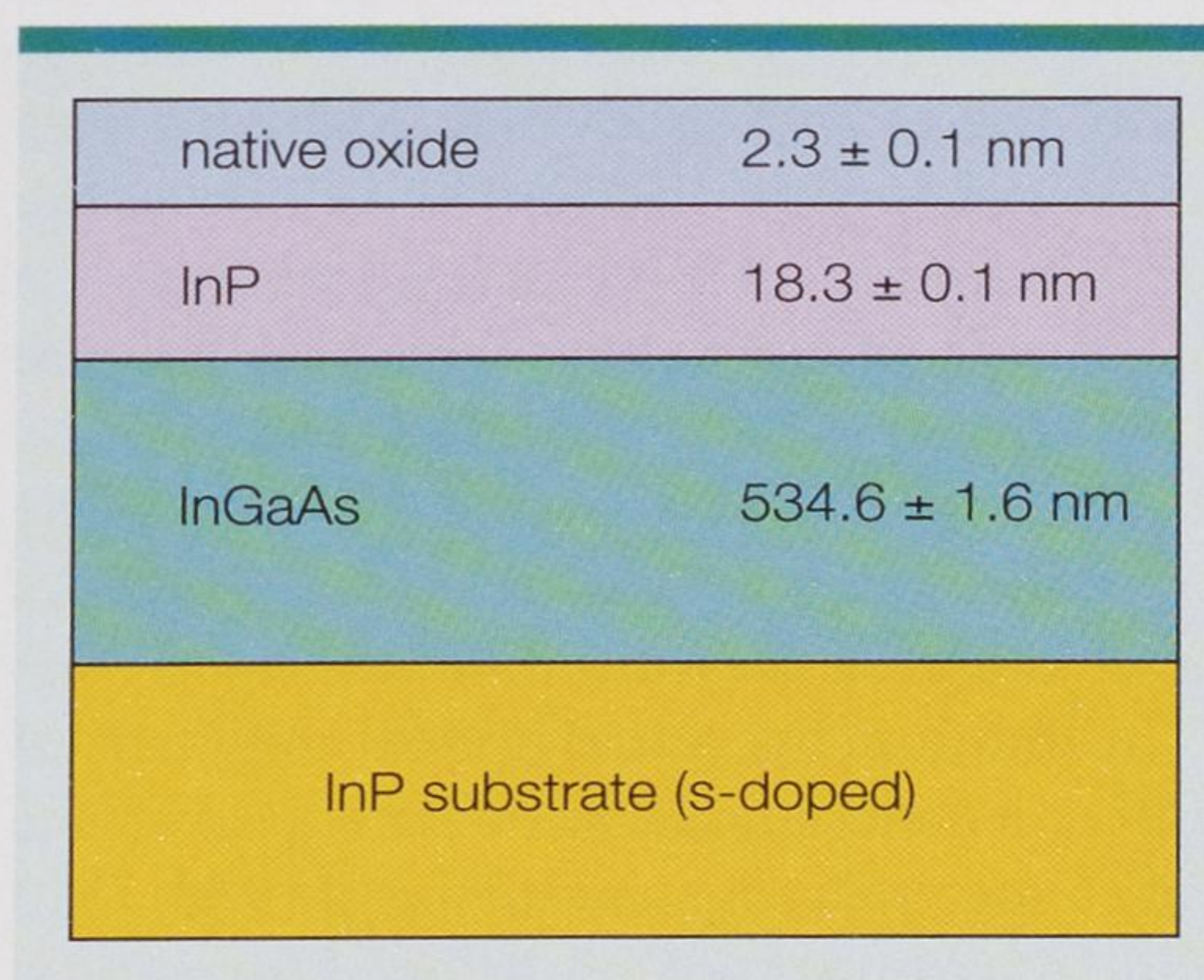
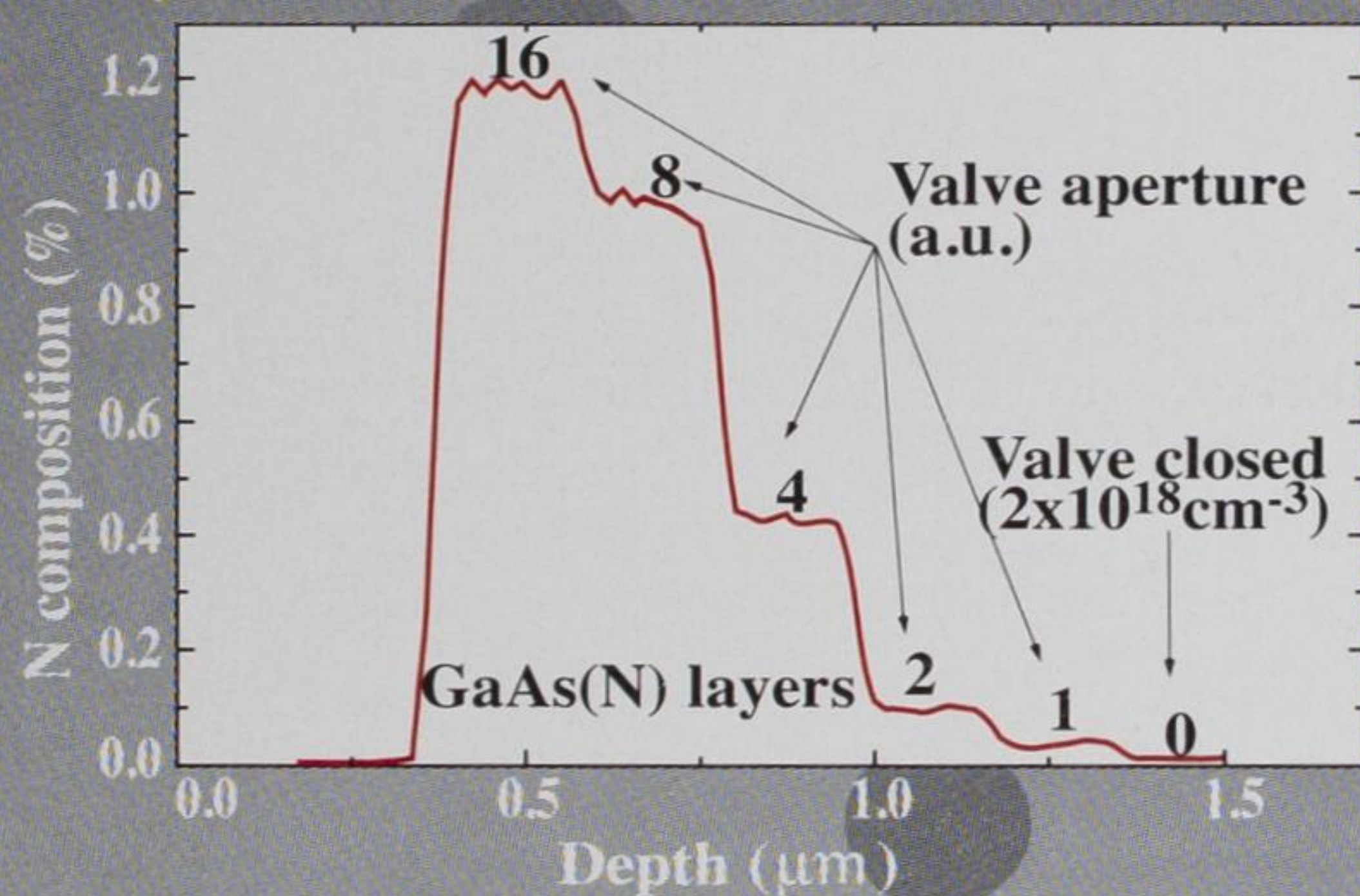


Fig. 2. The epilayer structure analyzed to give the spectra shown in figure 1 (above). The layer thicknesses derived by SE are shown with the measurement precision.

change in the polarization state of the beam upon reflection from the sample. The ratio of the amplitude of the polarization within the

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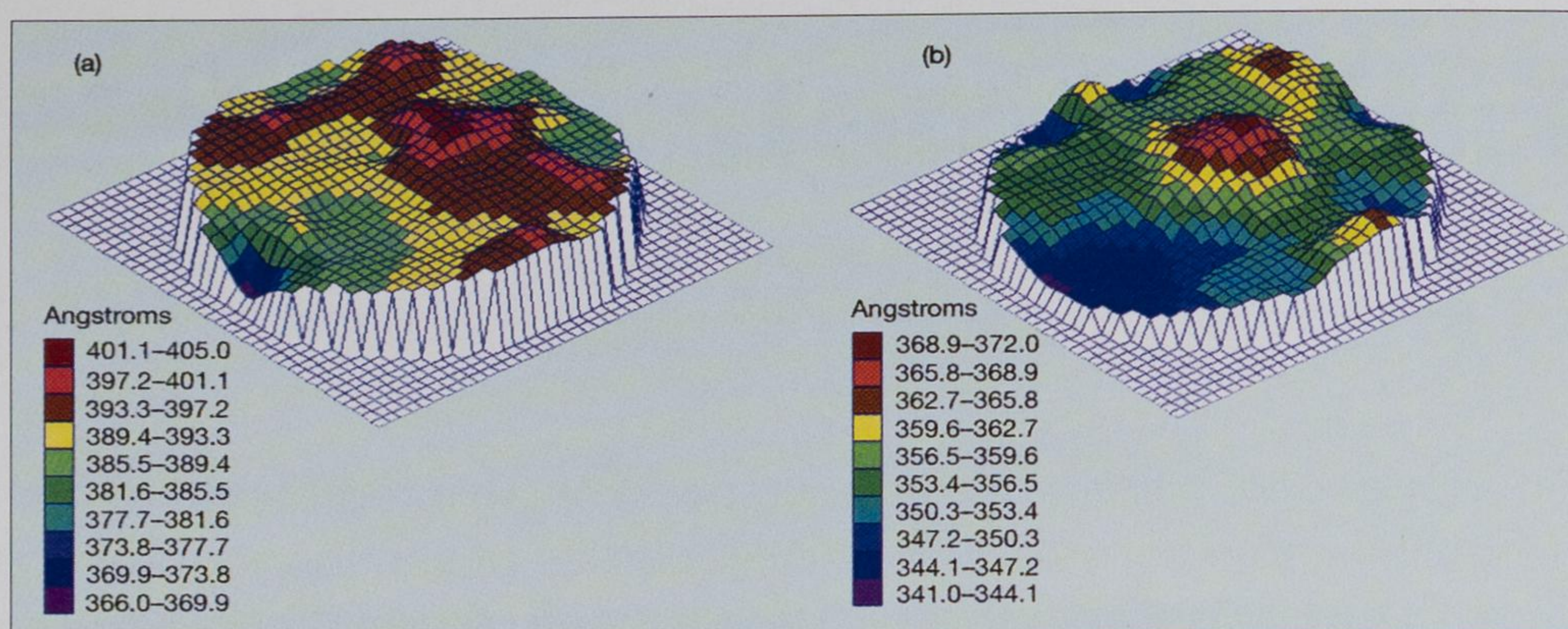


Fig. 3. Wafer maps of (a) SiGe layer and (b) Si-cap layer thickness taken across an 8 inch wafer.

ber of AlGaAs samples with known values are analyzed to build a model for the material. For commonly measured materials such as AlGaAs, libraries of reference data exist. The accuracy of these libraries relies on the use of state-of-the-art material for their compilation. Poor-quality reference material gives poor-quality data, and thus any model compiled will not give accurate results for real samples.

With a good model, n , k and the material's physical properties can be determined by matching the modeled Ψ and Δ with the experimentally acquired Ψ and Δ from the unknown samples. In this way the technique can be routinely used for determining the properties of compounds of unknown composition, as well as the thickness of the individual layers in multilayer stacks.

Spectra from an InGaAs/InP epilayer structure are shown in figure 1. The measurements have been performed at three discrete incident angles, and over a spectral range extending into the near infra-red at wavelengths up to 2 μm . These spectra show that different angles of incidence give different variations in the acquired values of Ψ and Δ . Typical thickness measurement precision is indicated in figure 2, which shows the structure derived from the data in figure 1. Analysis of the data gives the layer thicknesses for the InP layer, the InGaAs layer and even the InP native oxide.

In addition, the actual optical constants of different materials can be determined over the entire spectral range, including the 980, 1310 and 1550 nm wavelengths used for optical communications, an important application for compound semiconductors.

Characterization of SiGe epilayers

A very similar procedure can be applied for characterizing SiGe epilayer structures. Here the technique is successfully used for determining the thickness of the Si layer that

typically caps the SiGe layer, and the thickness and composition of the SiGe layer itself. The epilayer structure characteristics can be mapped out over an entire wafer.

Wafer mapping is performed by mounting the wafer on a motor-driven x-y stage and then scanning it through the ellipsometer beam. As well as characterizing a whole wafer, such systems can be programmed to acquire data from specific areas of the wafer. For batches of nominally identical wafers, the same critical points on each wafer can be automatically analyzed. Figure 3 shows maps of SiGe layer and Si-cap layer thickness for a 200 mm wafer with a Si-capped $\text{Si}_{0.92}\text{Ge}_{0.08}$ layer.

Summary

Spectroscopic ellipsometry is a powerful and versatile technique for characterizing a wide diversity of semiconductor and optical multilayer materials. Layer thickness and composition, together with the optical constants of the materials over a wide spectral range, can be determined with very good precision. SE is a non-contact technique that is also non-destructive. It is readily implemented using table-top instruments, or on industrial tools with substrate handling and mapping for hands-free automated operation, making it a popular characterization technique in many production facilities.

Further reading

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Email sopraappli@aol.com.

Chris Pickering is with QinetiQ, Malvern, UK.

Equipment and materials suppliers set for growth

The results from the infrastructure companies weren't pretty, but there may be hope on the horizon, as several firms in our portfolio cautiously predict that growth will return in the next quarter.



When the fab sneezes, the chip equipment company catches cold, so it isn't surprising that the 12 suppliers of semiconductor equipment and materials in our portfolio have seen their revenues slide 40% over the last 12 months. However, there are some hopeful signs that this past quarter might have been the bottom. Executives at AXT and Kopin are both predicting a 10% increase in sales in the June quarter; and a bit of reading between the lines of recent announcements from Aixtron, Riber and Picogiga leads to the conclusion that they are also expecting to show growth in the next quarter.

Epitaxy equipment

Aixtron reported revenues of €47.2 million (\$42.5 million) for the first quarter of 2002, down approximately 20% from both the year-ago period and the preceding quarter. Although Reuters reported that analysts had been expecting sales of €50.6 million, Aixtron's management indicated that this result was in line with their own expectations. Earnings before interest and taxes totaled €11.5 million, compared with €14.3 million for

the year-ago period. This is significantly better than the estimate of €9.9 million reported by Reuters.

New orders halved to €25 million, with a book-to-bill ratio of 0.63. Aixtron management said that "in view of the restrained global economy" this was in line with expectations. The company's total order backlog stood at €118.2 million at the end of the quarter, compared with €156.5 million in the year-ago period. However, Aixtron's executive board is standing by its earlier forecast of revenues of €210.0 million for the 2002 calendar year (see *Compound Semiconductor* April 2002, p75). That figure represents a 13% decline from 2001 sales, indicating that the company expects its business to improve over the next three quarters.

After two quarters of sharply declining sales, revenues at Emcore rose 21%, reaching \$23.1 million for the first quarter. However, the company reported a much larger loss than expected for the first quarter, due in part to major restructuring charges. The company posted a net loss of \$68.7 million, compared with break-even results in the year-ago quarter.

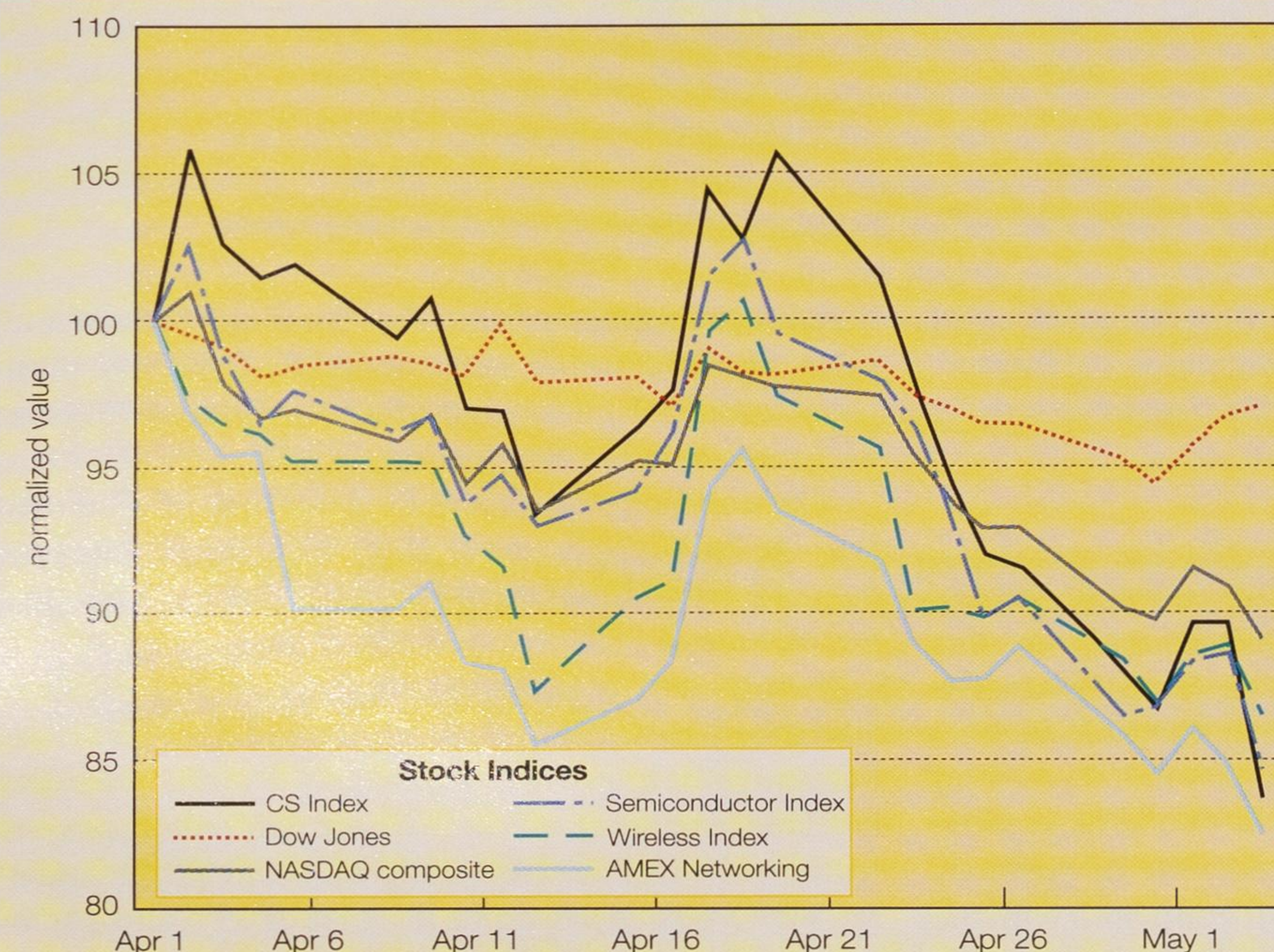
More than \$50 million of the loss was due to one-time charges for a company restructuring that was announced in early April. Write-downs in the value of property and equipment totaled \$35.1 million, and obsolete inventory accounted for another \$11.6 million. Also included was a \$1.1 million charge for workforce reduction; in recent months the company has laid off 180 employees, approximately 20% of its workforce. Excluding the one-time charges, the company lost \$0.50 a share; analysts had been expecting a loss of \$0.46 a share.

Revenues for the quarter showed a huge increase in materials-related sales, with revenues of \$18.7 million, an increase of \$9.9 million from the first quarter. Some 60% of materials-related shipments came from the photovoltaics area.

However, sales of MOCVD equipment declined sharply to \$4.34 million, down 57% from the previous quarter. This is the first time that materials sales have exceeded equipment sales (see chart, p53).

Commenting on these results, Reuben Richards, president and CEO, said that the company had made "significant strides" towards reducing its cost structure and streamlining operations during the quarter. He predicted that "substantial savings will materialize" beginning in the current quarter. He also said that the company had

Industry indices



Materials sales now exceed equipment sales at Emcore for the first time.

Market overview

Company	Symbol	Closing price on May 7	52-week low-high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha Industries	AHAA	9.90	9.90-41.45	437.8 m	N/A
Anadigics	ANAD	8.58	8.25-25.38	262.3 m	N/A
Celeritek	CLTK	9.66	8.95-16.91	117.6 m	N/A
Conexant	CNXT	7.50	6.57-18.11	1.917 bn	N/A
Endwave	ENWV	0.70	0.60-2.12	24.9 m	N/A
Multilink	MLTC	0.84	0.77-18.40	63.1 m	N/A
RF Microdevices	RFMD	15.75	13.40-37.50	2.636 bn	N/A
Sirenza Microdevices	SMDI	4.00	2.98-17.00	119.2 m	N/A
TriQuint	TQNT	8.88	8.80-32.00	1.165 bn	N/A
Vitesse	VTSS	4.77	4.28-37.00	955.1 m	N/A
Opto companies					
Agilent	A	27.81	18.00-41.18	12.900 bn	N/A
Agere	AGRa	3.75	2.50-9.50	6.133 bn	N/A
Alcatel Optronics	ALAO	4.55	4.04-28.68	75.1 m	N/A
Coherent	COHR	28.41	25.05-40.60	814.8 m	71.63
Cree	CREE	11.03	10.59-36.65	800.9 m	N/A
JDS Uniphase	JDSU	3.87	3.72-24.21	5.847 bn	N/A
Stratos Lightwave	STLW	2.42	2.37-14.25	162.8 m	N/A
Uniroyal Technology	UTCI	0.42	0.27-9.90	11.7 m	N/A
Semiconductor materials and equipment companies					
ATMI	ATMI	27.35	14.50-37.10	833.9 m	N/A
AXT	AXTI	9.50	8.55-41.65	212.7 m	N/A
Emcore	EMKR	8.04	7.59-40.30	294.1 m	N/A
Kopin	KOPN	7.00	6.61-19.05	483.8 m	N/A
Tegal	TGAL	1.03	0.95-3.45	14.7 m	N/A
Trikon	TRKN	12.90	6.96-16.72	166.3 m	N/A
Veeco	VECO	28.07	19.90-57.50	814.7 m	N/A
European companies (currency data in €)					
Aixtron	AIXG.F	14.80	15.55-30.00	957 m	N/A
Bede	BED.L	2.55	2.49-3.44	73.9 m	N/A
Bookham	BHM.L	1.47	1.22-2.97	208.5 m	N/A
Filtron	FTC.L	4.13	4.02-7.26	204.4 m	N/A
IQE	IQE.L	1.69	1.69-3.16	277.1 m	N/A
Picogiga	PGIG.LN	2.86	2.37-5.95	18.5 m	N/A
Riber	RIBE.LN	2.58	2.65-5.40	48.3 m	6.71
STS	SRTS.L	2.51	2.39-2.78	78.6 m	13.99

*Market capitalization = # shares x current share price.; **Price/Earnings ratio = current share price ÷ (income for the last four quarters ÷ # shares).

launched several new products during the quarter that are expected to “serve as growth engines in the future”. Recent product developments at Emcore have largely come from the optical devices area.

III-V materials

AXT’s revenues rose 9% from December to March, totaling \$16.8 million for the first quarter. However, this represents a decrease of 58% compared with the \$40.1 million reported in the first quarter of 2001.

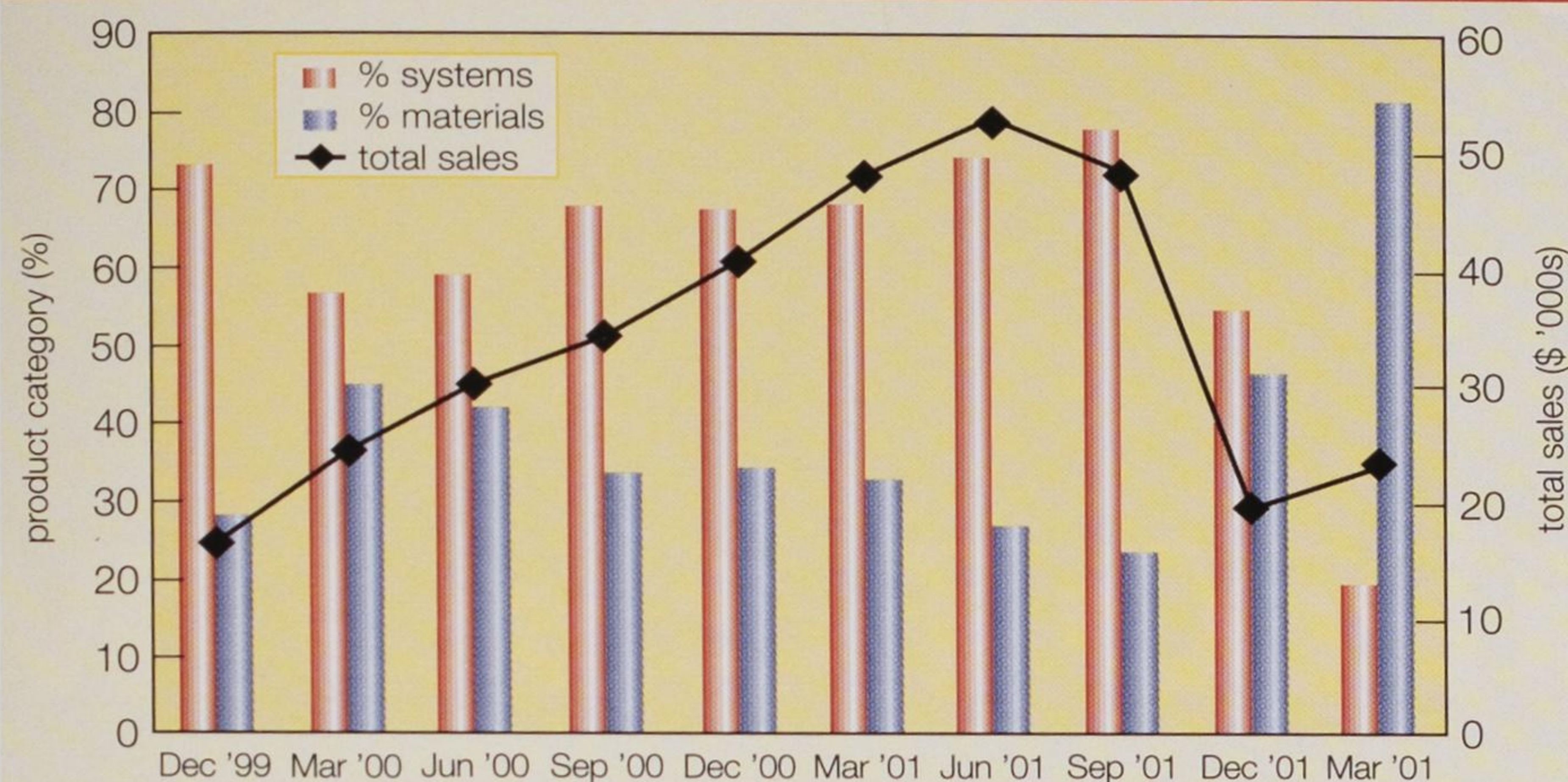
The substrate division accounted for 70% of total revenue for the quarter. Sales in this area totaled \$11.8 million, up slightly compared with the previous quarter, but down by more than half compared with the year-ago period. A bigger gain was reported by the LED

division, which contributed the remaining 30% of total sales. Optoelectronic sales totaled \$5.0 million, compared with \$3.9 million in the fourth quarter of 2001 and \$1.3 million in the first quarter of 2001.

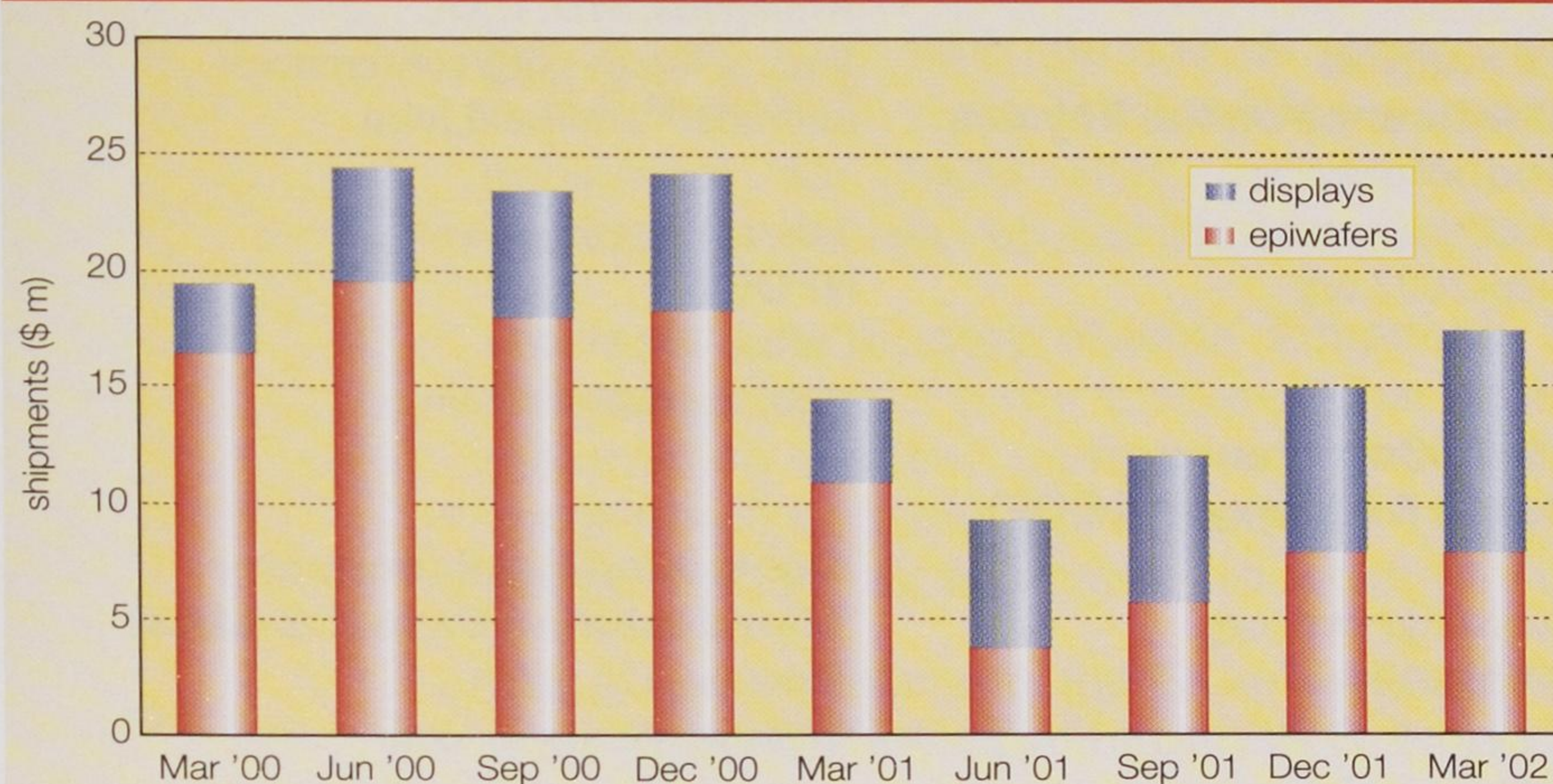
The company experienced a net loss of \$3.6 million for the first quarter of 2002, compared with a net loss of \$13.8 million for the fourth quarter of 2001, and net income of \$5.0 million in the year-ago period.

“Our financial results for the first quarter demonstrate that the difficult business conditions of 2001 are beginning to improve,” said Morris Young, president and chief executive officer. “We are particularly pleased by the growth of our LED division during the first quarter, which posted a revenue increase of 35% and, for the first time, a positive gross margin.”

Emcore revenues for the last 10 quarters



Kopin revenues for the last nine quarters



He went on to say that growth in AXT's substrate division is coming primarily from the wireless and LED device segments, suggesting that the fiber-optics market remains in the doldrums. AXT's management is predicting that second-quarter revenue will grow by 5–8%, pushed by both the LED and substrate product lines.

Kopin reported a 14% sequential increase in revenues in the first quarter. Sales were \$17.6 million compared with \$15.4 million in the fourth quarter of 2001 and \$15.0 million in the year-ago period. Revenue from

HBT epiwafers was roughly flat at \$7.7 million compared with \$7.8 million in the fourth quarter of 2001. CyberDisplay product revenue increased 39% sequentially to a record \$9.7 million. First-quarter net loss increased to \$3.2 million, from a net loss of \$7.1 million in the previous quarter.

Speaking on April 23, Kopin's president and CEO John C C Fan said that the near-term wireless handset outlook remains mixed, but Kopin had seen "something of a snap-back in recent weeks, driven by OEMs building new handset platforms with advanced features". Fan added, "Our III-V business managed to avoid the 5–10% seasonal decline that typically hits the semiconductor component industry in the March quarter. Orders in the beginning of January had a slow start as our customers assessed the inventory situation, but continued to steadily increase during the quarter from all of our major customers."

For the second quarter of 2002, Fan is predicting a 10% sequential increase in revenue, driven by both the III-V and CyberDisplay segments.

The view from Europe

Consistent with local practice, the two French companies in our portfolio made preliminary announcements about revenues in late April. Profitability figures will be announced at a later date.

Sales for Riber in the first quarter totaled €4.0 million, down 33% from the €6.0 million reported in the year-ago period. However, company executives said that the decrease was largely due to a slight delay in the shipment of one large order, which will now be reported in the second quarter. The company is forecasting a significant increase in revenues for the June quarter. The backlog on March 31 stood at €24.6 million. During the first quarter the company reported the receipt of several orders for its multi-4-inch machine for optoelectronic applications.

Picogiga announced sales of €2.5 million for the first quarter, down from €3.0 million in the fourth quarter of 2001. However, the company said that this was "the lowest point of activity", with a strong increase in order activity in April bringing the backlog to more than €6 million.

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Xi'an, China

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17-21 June

European MRS meeting

Strasbourg, France

Web: www-emrs.c-strasbourg.fr/

24-25 June

Semiconductor 2002

Edinburgh, UK

Web: www.semiconductor2k.com

24-26 June

Device Research Conference

Santa Barbara, CA, USA

Web: www.tms.org/Meetings/Specialty/DRC/2002/DRC-2002-home.html

26-28 June

Electronic Materials Conference

Santa Barbara, CA, USA

Web: www.tms.org/Meetings/Specialty/EMC02/EMC02.html

8-12 July

7th Optoelectronics and Communications Conference

Yokohama, Japan

Web: www.bcasj.or.jp/oecc2002

14-17 July

Optical Amplifiers and Their Applications

Vancouver, Canada

Web: www.osa.org/oaa

15-16 July

PhoPack 2002

Stanford University, Palo Alto, CA, USA

Web: www.cpmt.org/scv

17-24 July

Semicon West

San Jose, CA, USA

Web: www.semi.org/web/wexpositions.nsf

22-25 July

Int'l Workshop on Nitride Semiconductors (IWNS)

Aachen, Germany

Web: www.fz-juelich.de/iwn2002

29 July - 2 August

26th Int'l Conference on the Physics of Semiconductors

Edinburgh, UK

Web: www.icps2002.org

4-8 August

14th American Conference on Crystal Growth & Epitaxy (ACCGE)

Seattle, WA, USA

Web: www.crystalgrowth.org/conferences/acceg14

6-8 August

IEEE Lester Eastman Conference on High Performance Devices

Newark, DE, USA

Web: <http://nina.ecse.rpi.edu/shur/>

EastmanConference/

18-21 August

3rd Int'l Conference on Microwave and Millimeter Wave Technology

Beijing, China

Web: www.cie-china.org/icmmt2002/

1-5 September

European Conference on Silicon Carbide and Related Materials (ECSCRM-2002)

Linköping, Sweden

Web: www.ifm.liu.se/ecscrm2002

8-11 September

Int'l Conf. on Mid-IR optoelectronic materials and devices (MIOMD-V)

Annapolis, MD, USA

Web: www.avs.org/conferences/miomd2001/miomd.html

15-19 September

NFOEC

Dallas, TX, USA

Web: www.nfoec.com

11-13 November

Compound Semiconductor Manufacturing Expo (CS-MAX)

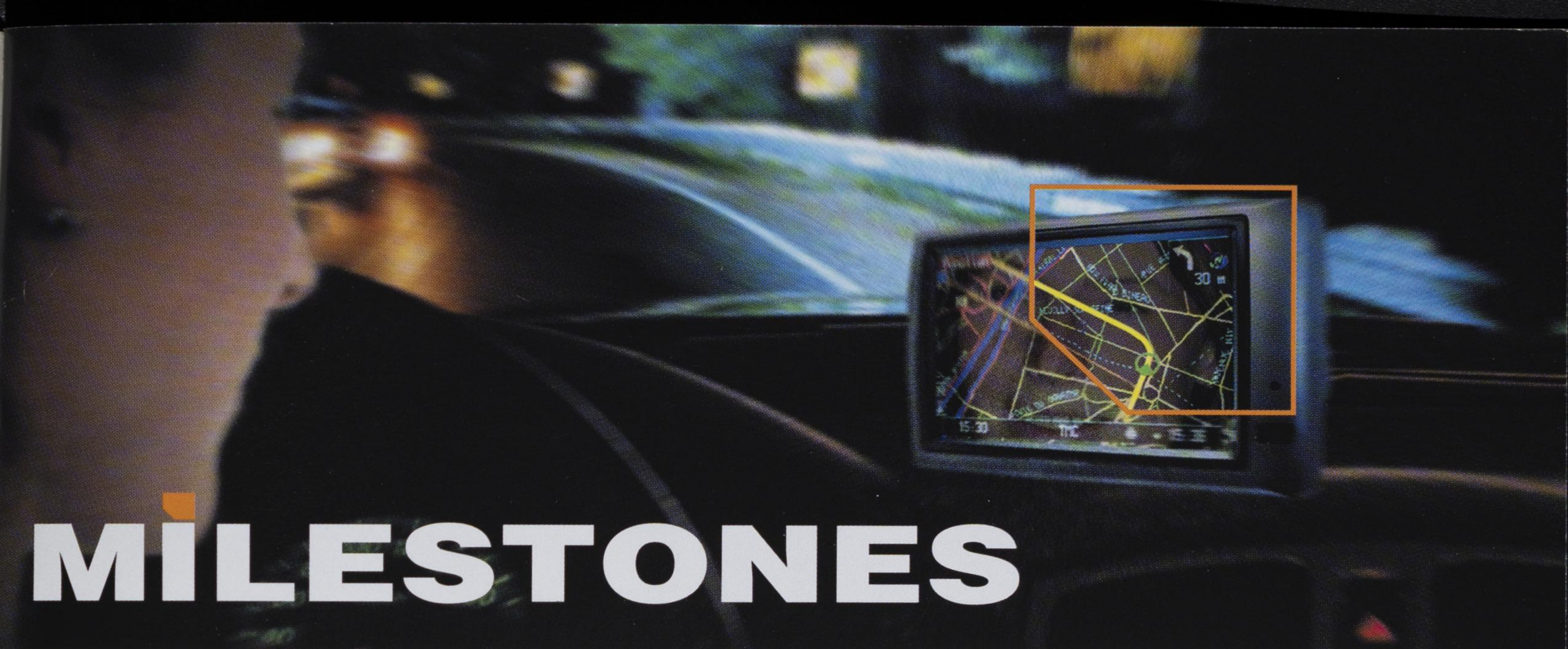
San Jose, CA, USA

Web: www.cs-max.com

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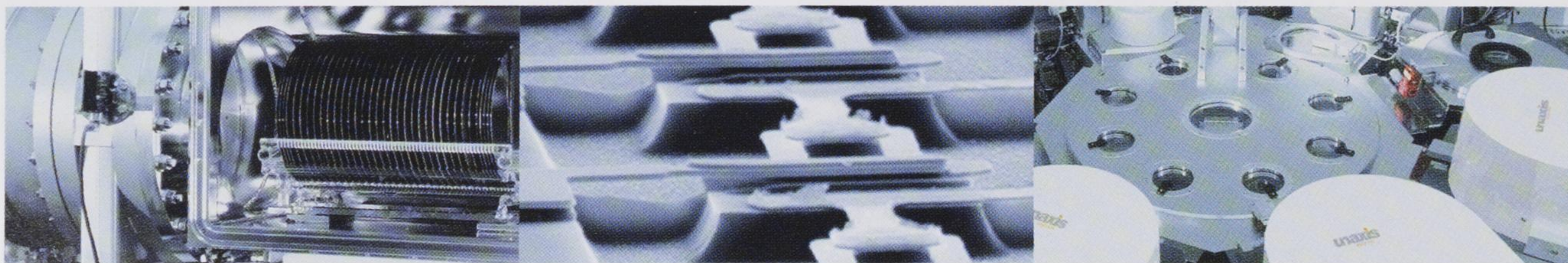
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