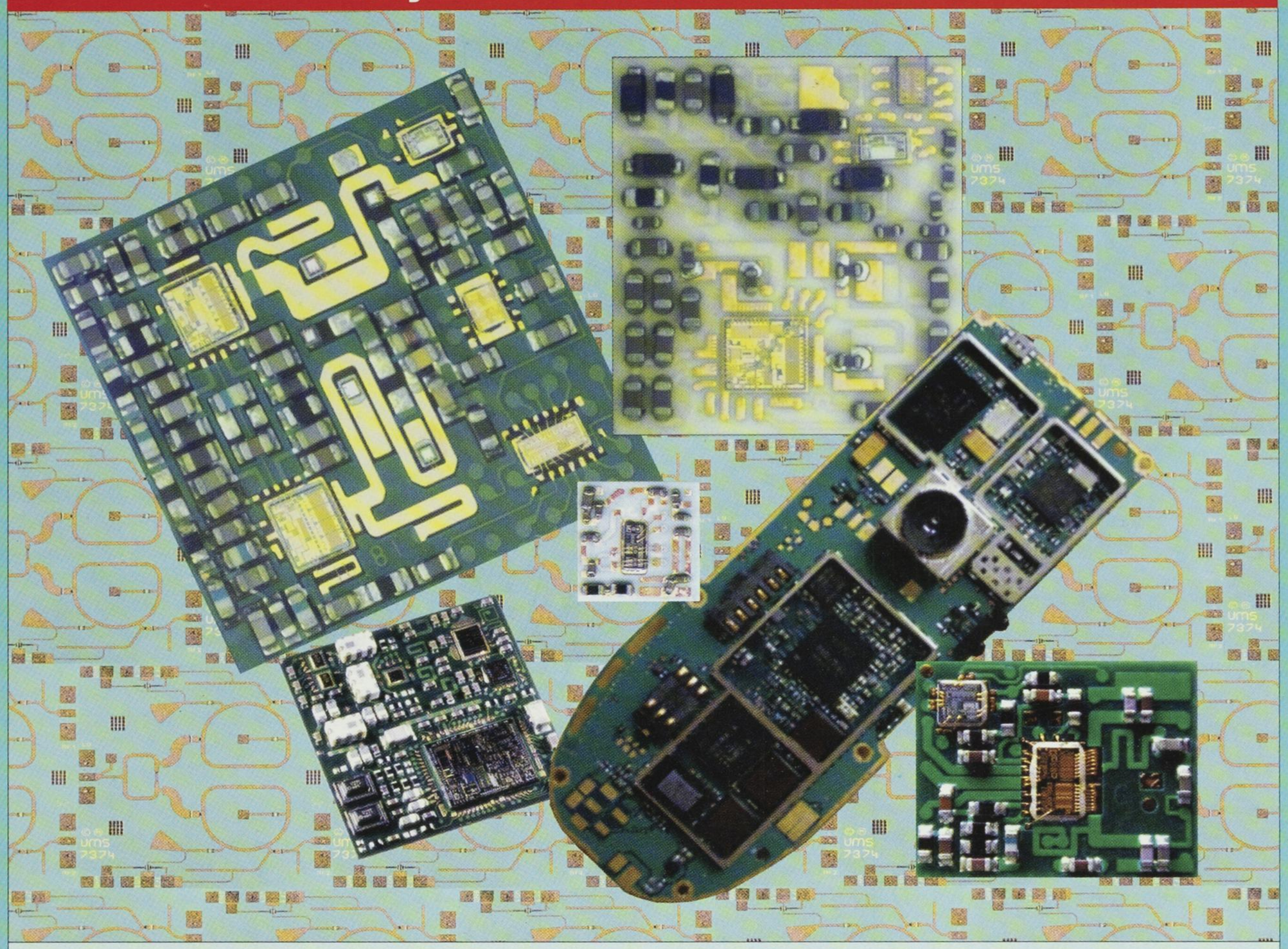
COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

May 2003 Volume 9 Number 4



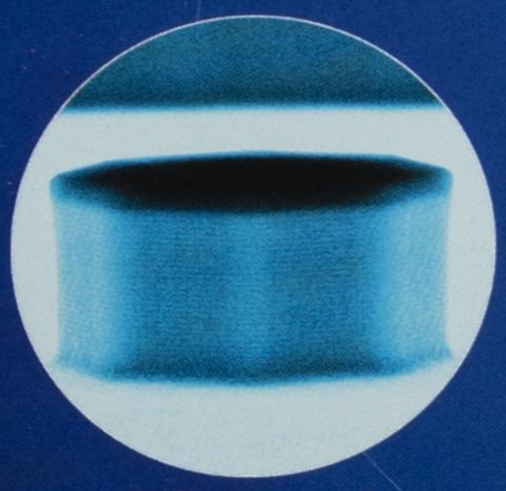
GALLIUM ARSENIDE

Modules and automotive radar drive GaAs market growth

ALSO INSIDE

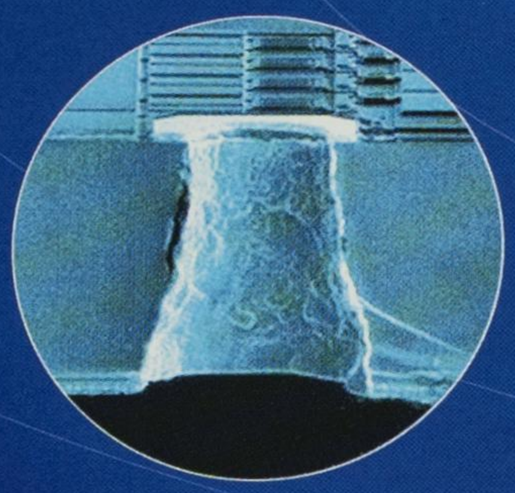
Purchases in GaAs epiwafer business	China emerges as a leading player	Growth predicted for gallium market

There's no substitute for experience.

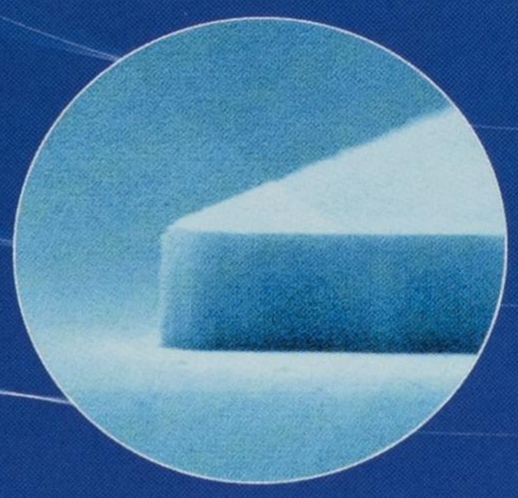


InP-based
VCSEL etch

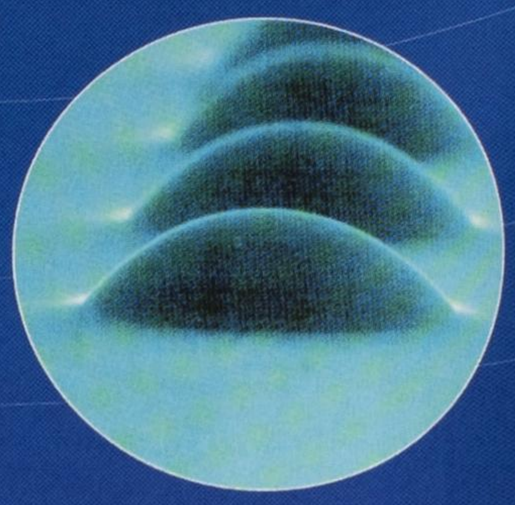
(Courtesy of Honeywell VCSEL Optical Products)



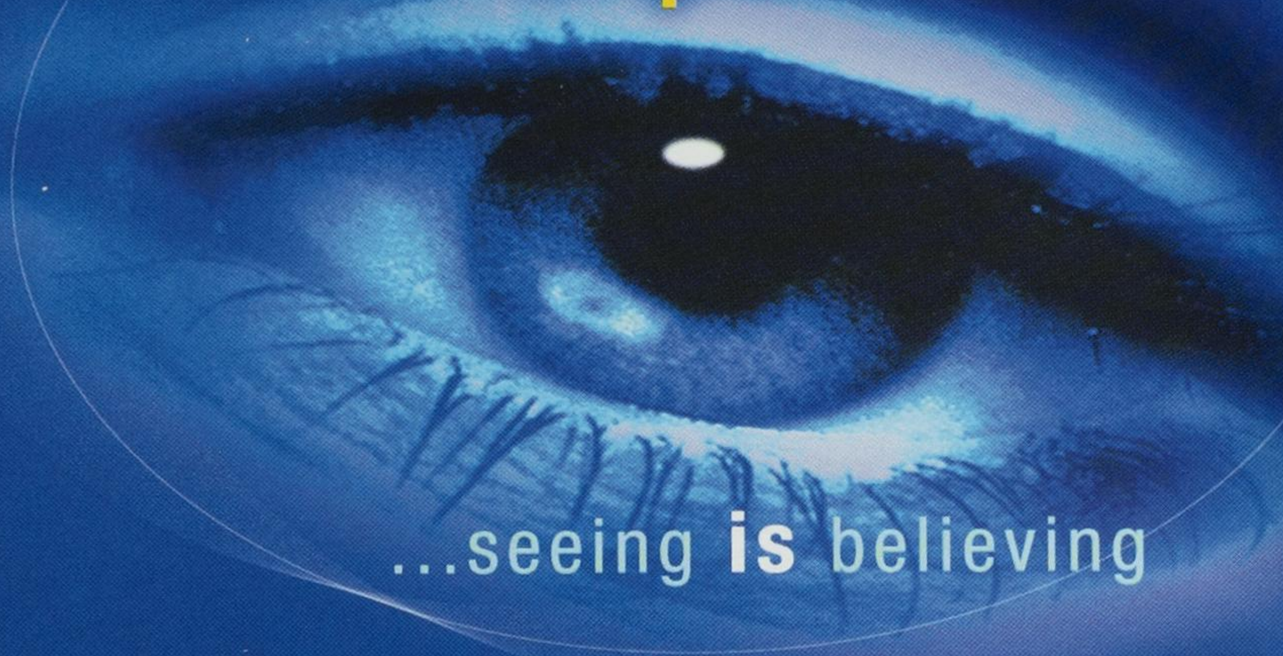
GaAs
via etch



GaN
facet etch



GaP
microlenses



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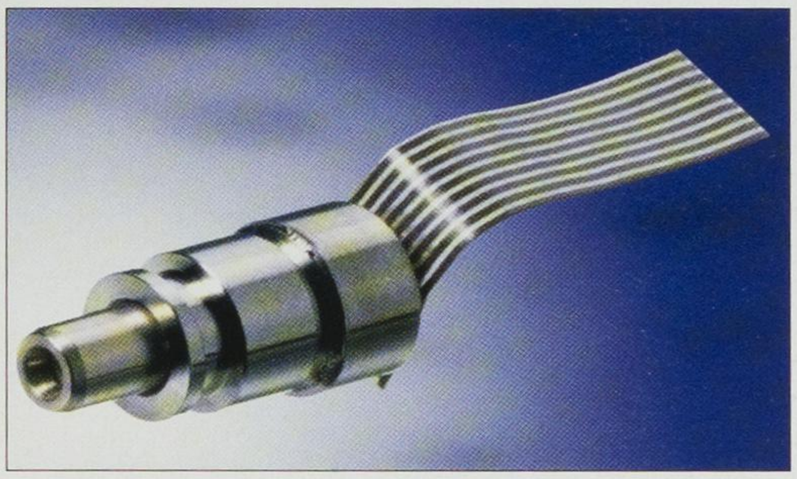
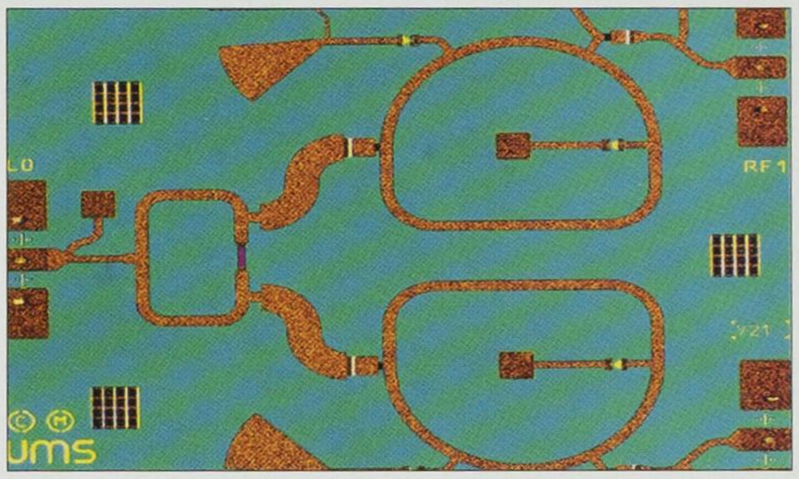


Infineon will begin volume manufacturing of 1310 nm VCSELs this year **p17**



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On the cover: *The migration to modules and sub-systems is a key driver in the GaAs industry (images courtesy of Motorola, CIBC, Skyworks) – see p24.*

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Three-Fives and Silicon Heterostructures

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Soitec buys Picogiga growth assets

Silicon-on-insulator (SOI) wafer manufacturer Soitec, based in Grenoble, France, has bought most of epiwafer vendor Picogiga's assets for €2.3 million ($2.5 million). The acquisition should mark the end of a turbulent year for Picogiga, which saw a potential takeover bid by Belgian company Umicore fall through (*Compound Semiconductor* December 2002 p7). At the end of November 2002, Picogiga declared itself bankrupt and then applied for the French equivalent of Chapter 11 protection in order to reorganize its financial affairs. However, the Court of Commerce rejected two separate proposals for ways in which Picogiga could continue as a company, and accepted the proposal from Soitec to acquire selected assets from Picogiga.

The acquired assets include most of Picogiga's MBE growth systems and 30 of its 55 staff. Soitec has assumed none of Picogiga's debt. The company has been rebranded as Picogiga International and will operate as a wholly owned subsidiary of Soitec. Linh Nuyen, Picogiga's president, has left the company and Soitec's managing director Jean-Michel Lamure has taken responsibility for running Picogiga.

"This purchase of some of Picogiga's assets represents an excellent opportunity for us to strengthen our position as a leading manufacturer of advanced materials and to meet the requirements for high-frequency devices and optoelectronics," said Lamure.

Soitec manufactures SOI wafers using its Smart Cut process, which transfers ultra-thin silicon layers from a handle wafer to another surface. During SOI wafer manufacturing using the process, a silicon wafer is oxidized, implanted with hydrogen ions and bonded to a second Si wafer. The wafers are then separated along the cleavage plane formed by the implanted ion, leaving an SOI substrate and a reusable Si wafer. Smart Cut technology can also be extended to other materials including silicon carbide, SiGe and sapphire, as well as III-V materials, and the development of such processes is now well under way (*Compound Semiconductor* January/February 2003 p32).

"We need epitaxy as a complementary technology for layer transfer and as a way to diversify our products," Lamure told *Compound Semiconductor*. "We can now perform transfer of thin layers of epitaxially grown compounds or grow onto layers transferred using Smart Cut."

While MBE is a technique that Soitec will use in its material developments, the company is keen to stress to customers that Picogiga International is a merchant MBE epiwafer supplier. The company says that the acquisition process will not affect its ability to meet Picogiga's customers' epiwafer demands and that a seamless transition can be expected.

● In related news, Sumitomo Chemical has bought ATMI's GaAs epiwafer business – see p6 for the full story.

Osram opens new opto chip factory in Germany

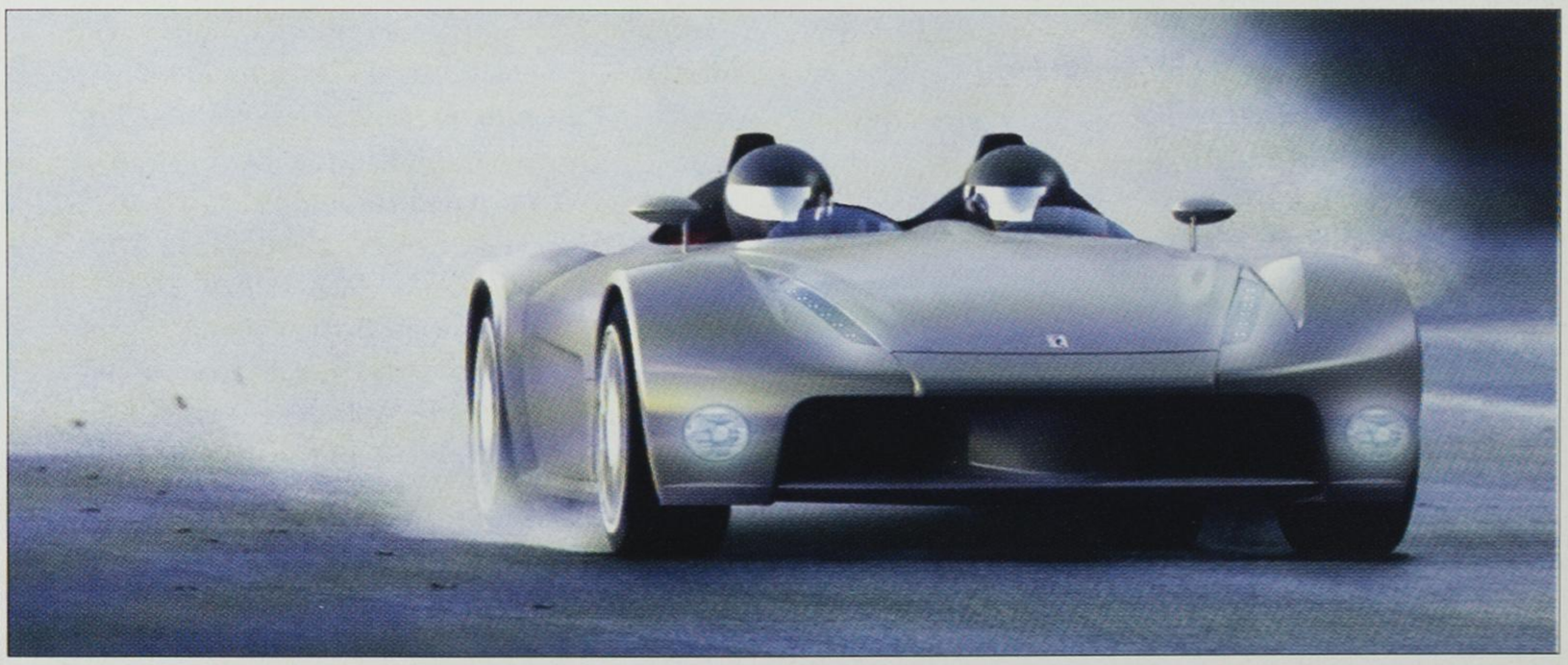
Osram has opened what it describes as "the world's most advanced optoelectronics chip factory" in Regensburg, Germany. The facility, which will manufacture LED chips, laser diodes and sensors, will enable Osram's subsidiary, Osram Opto Semiconductors, to double its production capacity of optoelectronic semiconductors by 2005.

Work began on the facility in July 2001. The fab, which has a cleanroom floor area of 3300 m^2 (35,500 sq. ft), is built on a 9 acre site with space for further expansion.

At the opening ceremony on April 7, Wolf-Dieter Bopst, president of Osram, said: "This will give us the platform to become number one [in optoelectronic semiconductors] in the medium term in this dynamic growth market." Market researchers expect optoelectronic semiconductors to register annual growth rates in double figures.

Osram has invested around €120 million ($129 million) in the new factory and will create about 500 new jobs in the medium term. The company already has a highly trained workforce in Regensburg engaged in the production of optoelectronic chips, and says that the region also has a good supply of well-trained workers.

Osram has an existing chip production facility in Regensburg-West, which was unable to cope with the company's plans for capacity expansion. The two factories will now work in parallel until the entire operation transfers to the new site in two years' time.



OSRAM OPTO SEMICONDUCTORS

White LEDs manufactured by Osram Opto Semiconductors were used to build the low-profile headlights of this futuristic sports car designed by Pininfarina of Italy.

Osram is the second largest lamp manufacturer in the world, and sees LEDs as a strategically important technology for the future of the lighting industry. Osram Opto Semiconductors has sites in San Jose, CA, and Penang, Malaysia, as well as Regensburg.

Osram Opto Semiconductors GmbH was founded in 1999 as a joint venture between Osram GmbH and the Siemens Semiconductor Division (now Infineon Technologies AG). In the summer of 2001, Osram GmbH took over all the shares of Osram Opto Semiconductors. Osram and Infineon continued to operate a joint venture to sell optoelectronic semiconductors.

On April 1, 2003, Osram Opto Semiconductors GmbH took over the worldwide sales activities for its optoelectronic semiconductor products from Infineon.

Sumitomo Chemical buys ATMI's GaAs business

Sumitomo Chemical Co, Ltd has purchased ATMI's GaAs epiwafer business and formed two new companies in Japan and the US to strengthen its position in this market.

ATMI announced in September 2002 that it planned to exit the GaAs epiwafer business, although it has retained its activities related to GaN and silicon epiwafers. In its annual report, the company stated that: "Effective January 31, 2003, certain assets of this business have been sold under an asset purchase agreement. The lease of the related facility in Phoenix, AZ, has been assumed by the buyer." The facility includes a number of MOVPE machines used to grow GaAs-based epiwafers, particularly HBTs.

It is now clear that the purchaser is Sumitomo Chemical, a Japanese company that already has a GaAs epiwafer manufacturing capability as well as being a supplier of metalorganic chemicals and high-purity gallium to the compound semiconductor industry. In order to concentrate on its epiwafer business (which it terms MOEPI, or metalorganic epitaxial), Sumitomo Chemical has formed two new companies to produce epiwafers for the cellular phone market and other mobile communication applications.

In Japan, Sumika Epi-Solution Co, Ltd will manufacture epiwafers at Sumitomo Chemical's Chiba works using epitaxial equipment designed in house. The recently upgraded facilities are designed to meet future growth in demand. In the US, Sumika Electronic Materials, Inc will produce epiwafers at the former ATMI facility and also market other relevant Sumitomo products.

Sumitomo says that the establishment of these wholly owned subsidiaries shows its commitment to providing flexible and well-timed responses to the changing needs of its customers in the Japanese and US markets, a commitment the company will underpin by synergistically linking technologies developed in Japan and the US.

Mitsubishi forms compound semiconductor division

Mitsubishi Electric & Electronic USA has established a new semiconductor division to provide compound semiconductors in discrete and module form for optoelectronic and microwave/RF customers based in North America. The new division will be headquartered in the Silicon Valley area and will provide marketing, sales and application engineering support for products manufactured in Japan.

Mitsubishi Electric manufactures a variety of GaAs-based devices for applications such as basestations, including satellite and terrestrial transmitters and receivers, mobile radios, cellular phones and subscriber units. CIBC World Markets placed Mitsubishi fifth in the list of leading analog GaAs suppliers in 2002 (see p24). The company also manufactures silicon RF power transistors and modules using MOS and LDMOS technologies for the industrial and consumer markets.

Mitsubishi Electric also offers a diverse range of optoelectronic products including electroabsorption modulators, Fabry–Perot and DFB lasers, pump laser diodes and electroabsorption modulated lasers. Other discrete products include avalanche and *pin* photodetectors, laser drivers and receiver pre-amplifiers. The company also manufactures integrated transceivers and transponders.

"We are establishing the new division to demonstrate our continued commitment to our optoelectronic and microwave/RF customers," said Kiyoshi Kawakami, president and CEO of Mitsubishi Electric & Electronic USA. "Although the overall high-technology market continues to go through challenging times, we believe that compound semiconductors will remain a strong and viable market over the long term. Our new division will enable us to continue offering world-class products to these customers."

VPEC to supply HBT epiwafers to Skyworks

Visual Photonics Epitaxy Co, Ltd (VPEC), a Taiwanese epiwafer supplier, has been selected by Skyworks Solutions as a second source for GaAs HBT wafers, which are used to manufacture a wide variety of wireless communications devices. Kopin is already established as a major supplier of such products to Skyworks.

"VPEC has proven to be a reliable, cost-effective resource for supplying Skyworks with the GaAs HBT wafers we need to build our industry-leading PA modules and RFICs," said Kevin Barber, senior VP of operations for Skyworks. "VPEC's record and experience in efficiently developing quality wafers makes them an ideal second source."

"VPEC's advantages in technology, quality, cost and speed will help sharpen Skyworks' competitive edge," added Michael Yang, VPEC's CEO.

TriQuint expands opto facility and product range

TriQuint has announced a wide range of new fiber-optic component products, as well as a capacity expansion in its manufacturing facility in Matamoros, Mexico. Matamoros is the primary location for low-cost assembly and test of TriQuint's existing line of optical transmitters, receivers, transceivers and transponders. The product lines and the Matamoros facility were acquired from Agere along with facilities in Pennsylvania.

"The expansion in Matamoros confirms our commitment to the industry and our dedication to providing customers with the most cost-effective manufacturing capability available," said Glen Riley, VP and general manager of the TriQuint Optoelectronics division.

Newly released optical components include two modulators, a 10 Gbit/s avalanche photodiode receiver, a transmitter and four laser sources. The extension of TriQuint's Netlight small-form-factor/small-form-factor-pluggable (SFF/SFP) product line will now provide a full range of transceivers for Gigabit Ethernet, SONET/SDH and Fiber Channel applications that are MSA-compliant and incorporate digital diagnostics. TriQuint also announced the development of a full line of low-cost, high-performance 10 Gbit/s uncooled and cooled transmit optical sub-assembly (TOSA) and receive optical sub-assembly (ROSA) optical engines to support all reach distance versions of the MSA standard XFP transceiver and X2 transponder modules.

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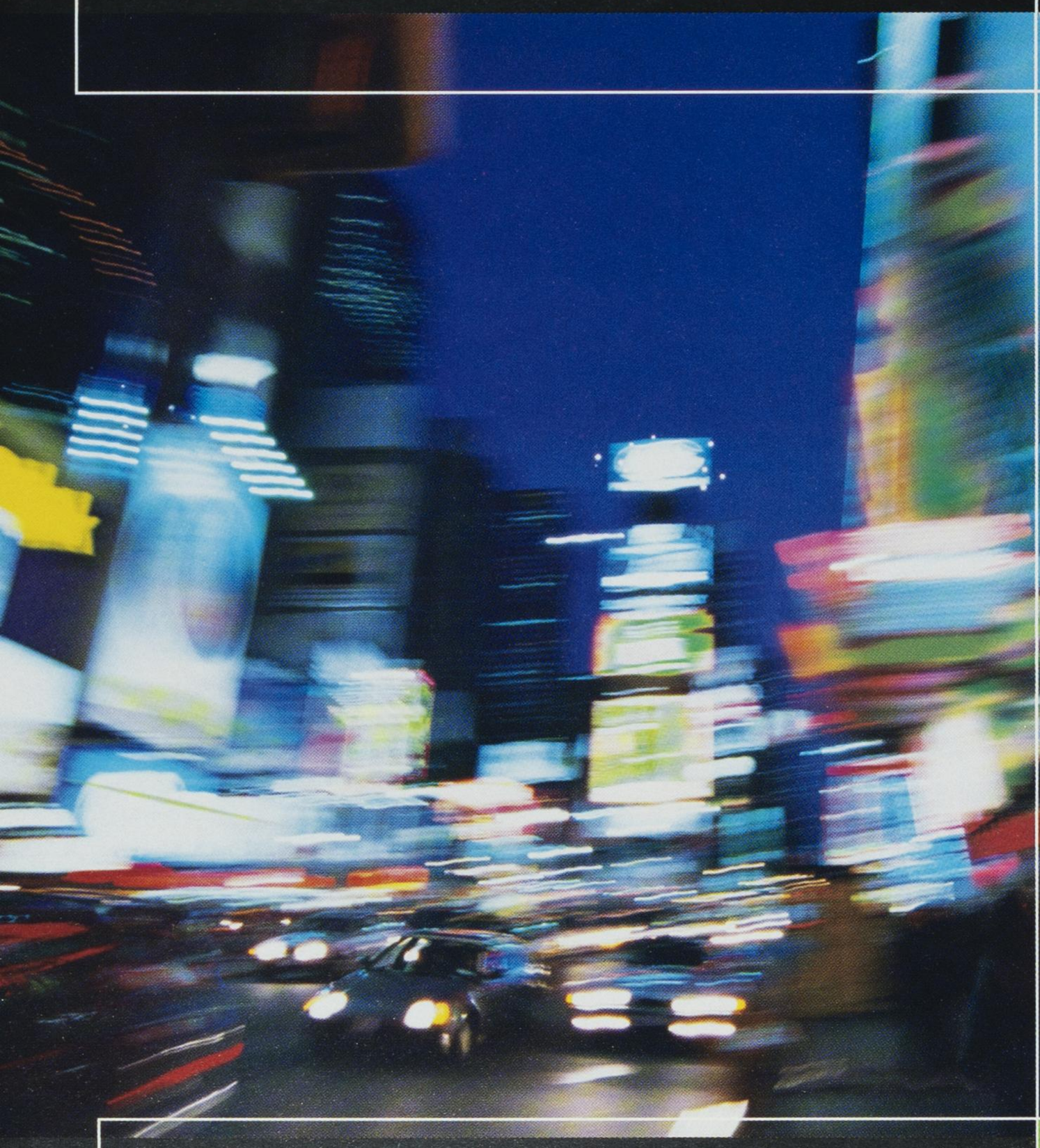

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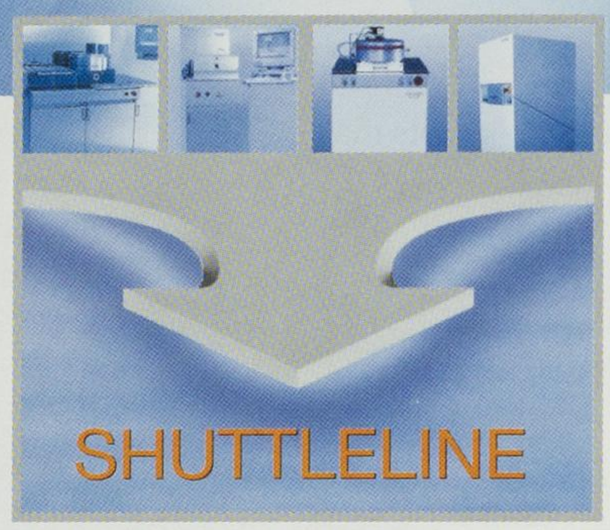

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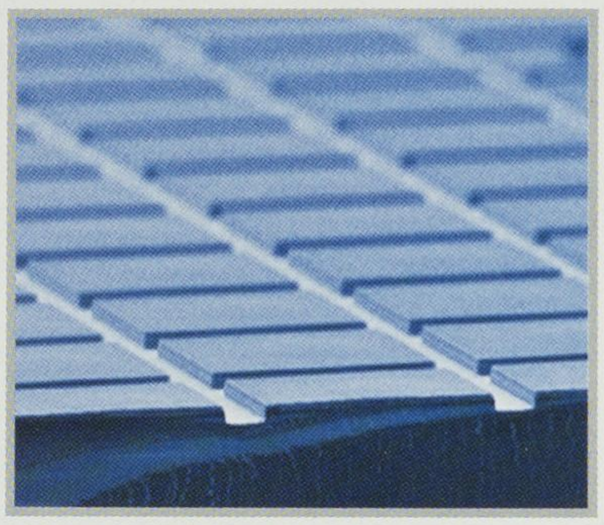

Etching of quantum well LEDs

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Anadigics buys RF Solutions' WLAN product lines

Anadigics has acquired the complete wireless local-area network (WLAN) power amplifier (PA) and module product lines from RF Solutions, a privately held fabless supplier of WLAN semiconductor products based in Atlanta, GA. The transaction is expected to broaden Anadigics' customer base and accelerate its penetration into the emerging WLAN market. The product line addresses the IEEE 802.11a, b and g WLAN standards.

The acquisition included RF Solutions' WLAN PA development operation and 16 employees comprising engineering, sales and marketing and operations personnel, as well as intellectual property concerning PA and module product design.

The deal will cost Anadigics $2.8 million in cash and up to 3 million common shares, currently valued at around $6.5 million, based on achievement of certain revenue targets over the next year. Anadigics is not the only GaAs IC manufacturer to have expanded into the market for WLAN chipsets. In 2002, RF Micro Devices acquired Resonext Communications, a fabless designer and supplier of CMOS chips for WLANs (*Compound Semiconductor* December 2002 p10).

"Our new WLAN PA team brings enormous value in terms of products, applications support, design talent, customer relationships and entrepreneurial spirit to help drive our growth in the WLAN market," said Bami Bastani, president and CEO of Anadigics.

RF Micro Devices opens design center in Boulder

RF Micro Devices has opened a new design center in Boulder, CO, after acquiring the assets and intellectual property of Channel Technology, a privately held RF and mixed-signal semiconductor company. Specific terms of the transaction were not disclosed. The Boulder office will focus on designing highly integrated products that support the convergence of multiple standards, such as cellular, wireless LAN, Bluetooth and GPS.

"The Boulder design center team should help us accelerate the trend toward these next-generation devices, through their expertise in DSP direct mixed-signal calibration and large mixed-signal system-on-a-chip integration optimized for multi-standard radios," said Bill Pratt, RF Micro Devices' CTO.

Anadigics develops lead-free packaging technology

Anadigics has developed an RF module packaging capability in support of customer efforts to produce lead-free products that meet European and Japanese environmental legislation. Lead reduction has meant that board assembly reflow processes require increased peak temperatures of 250 °C. Anadigics' new laminate-based packaging technology exceeds JEDEC (also known as the Solid State Technology Association) specifications that account for the added thermal and mechanical stresses involved in higher-temperature processing.

Celeritek unveils passive-free PA modules

CELERITEK

Removing passive components is allowing Celeritek to further shrink its modules.

The rapid changes in PA module technology took on another dimension recently when Celeritek announced a PA module that it describes as the world's first to use passive-free technology (PFT). This means that the module does not contain passive components within the matched module, and consists only of a molded lead frame and InGaP HBT die. According to Celeritek, its competitors use between four and seven passive components within their equivalent module packages. In compliance with the international directives for a reduction in hazardous materials in electronic manufacturing, all PFT-based modules are lead-free.

Celeritek's first PFT product is a W-CDMA module, the CHP2219-ML, which targets 3G applications. The module is offered in a compact, 4 × 4 mm^2 10-pin lead-frame package with a thickness of only 0.85 mm. The dimensions of the package provide handset customers with more space to add new features and functionality while at the same time significantly reducing the total bill of materials.

To enable longer handset talk and standby times, Celeritek has improved the efficiency of its modules. The CHP2219-ML has a PAE of 41% for W-CDMA operation at 1920–1980 MHz. Other characteristics include an output power of 27.0 dBm and gain of 27.0 dB.

Celeritek has begun to apply PFT to a broad range of frequencies and products in order to further reduce board space and cost when compared with alternative solutions. The company has also announced the availability of four new 3 × 3 × 1 mm PA modules using PFT for use in CDMA wireless handsets and other hand-held systems. The modules are now sampling to wireless handset OEMs and are priced at $1.75 in quantities of 100,000.

Spintronics Research

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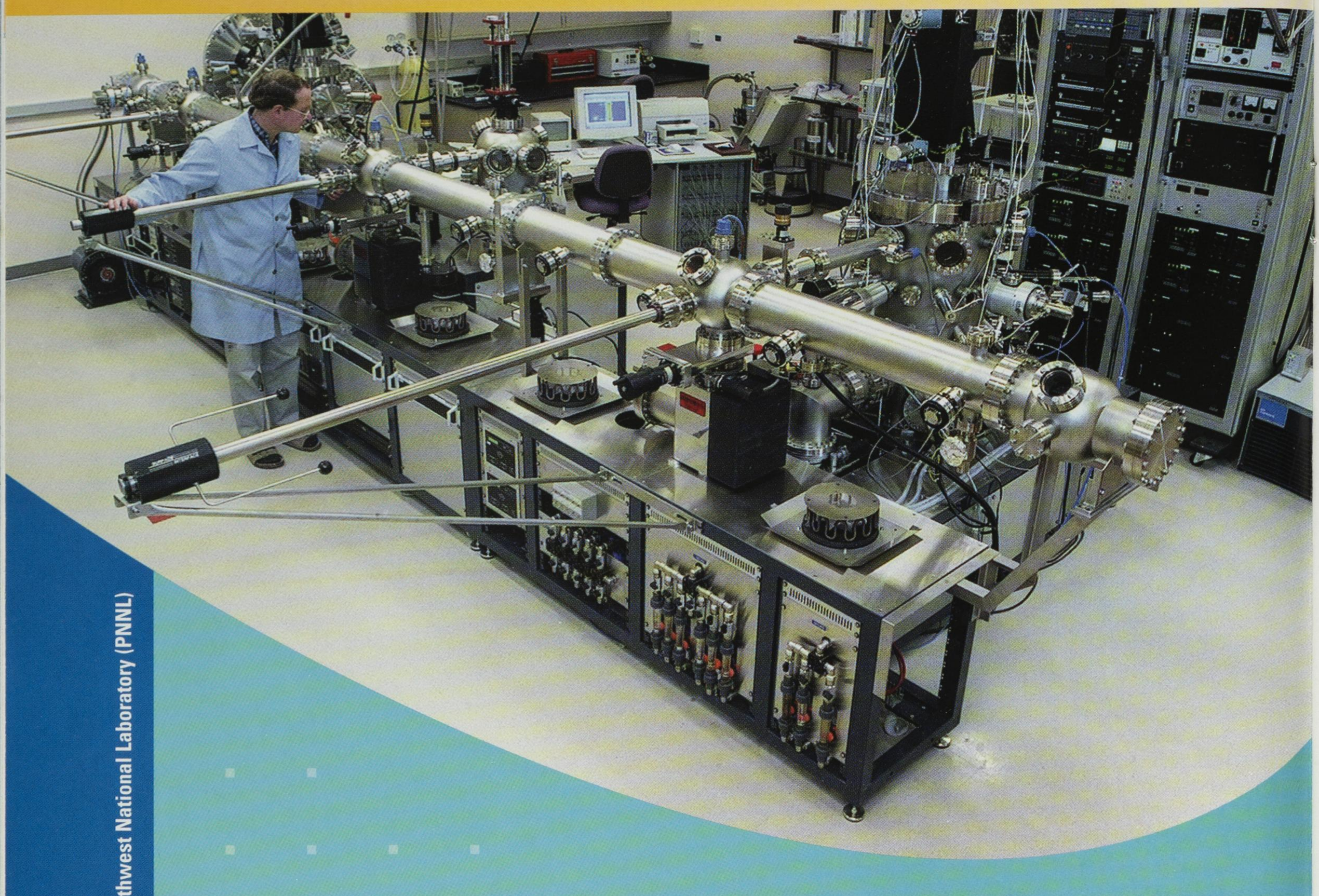

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DCA INSTRUMENTS

Cree receives $100 m LED order

Nitride LED manufacturer Cree has revealed that Sumitomo Corporation has agreed to purchase approximately $100 million of Cree's LED products during Cree's fiscal year ending June 30, 2004. Sumitomo sells Cree's LED chips to packaging customers in Japan.

This purchase commitment, which is the largest in Cree's history, is subject to end-customer demand and other terms and conditions. The amount of the agreement is four times larger than Sumitomo's commitment last year.

Cree and Sumitomo anticipate that the purchases will cover Cree's full line of LED products, including standard-brightness devices, MegaBright and other mid-brightness devices, and XBright LEDs.

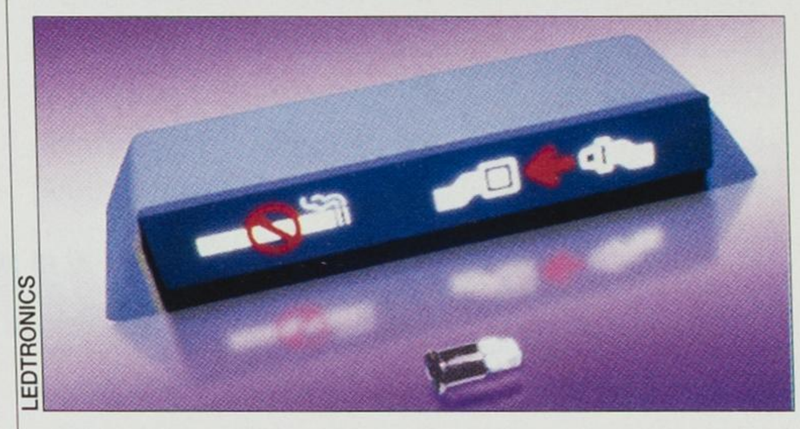
"This agreement is indicative of the growth we have experienced in Japan," said Chuck Swoboda, Cree's president and CEO. "We believe this is a direct result of our sales and engineering team at Cree Japan, Inc working closely with Sumitomo to support the major LED packagers in Japan."

"In the past year we have seen explosive growth in the market for Cree's LEDs in Japan," said Koichiro Kusano, general manager of Sumitomo's Electronic Materials & Equipment department. "We are excited that the business is spread across multiple applications among Japan's leading optoelectronic companies.

"Sumitomo sees continued growth in this segment, especially with the introduction of Cree's market-leading high-brightness products. This agreement represents our commitment to Cree's business in Japan as well as supporting the increasing customer demand for Cree's products."

The agreement reflects expected demand for the second year of the existing three-year distributorship agreement with Sumitomo, and ensures a continued local supply of Cree's LED chips for the Japanese market.

Ledtronics LED lamp lights aircraft signs


LEDTRONICS

Ledtronics, which manufactures a range of LED-based products, has received approval for one of its LED lamps to be used in DC-9 commercial aircraft. The aviation market offers significant opportunities for LEDs, in interior and exterior lighting on aircraft, and for airport lighting. The Federal Aviation Authority has approved Ledtronics' lamp for use in no smoking/fasten seatbelt signage (see photo), as well as indicators such as those marking the locations of lavatories and emergency exits.

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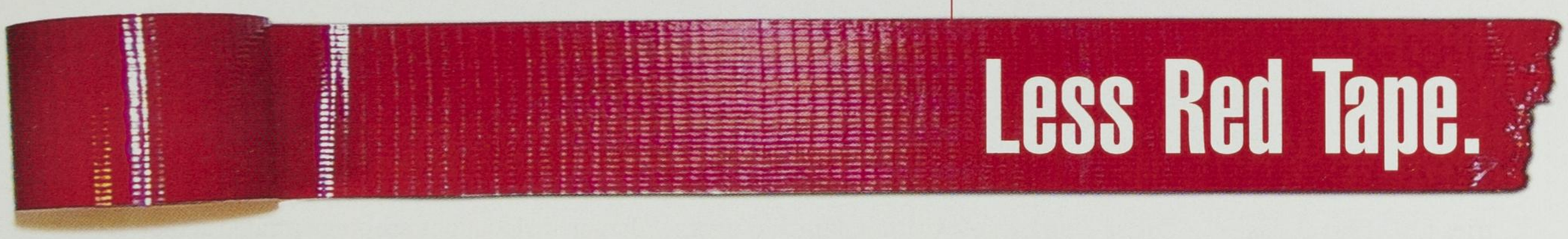

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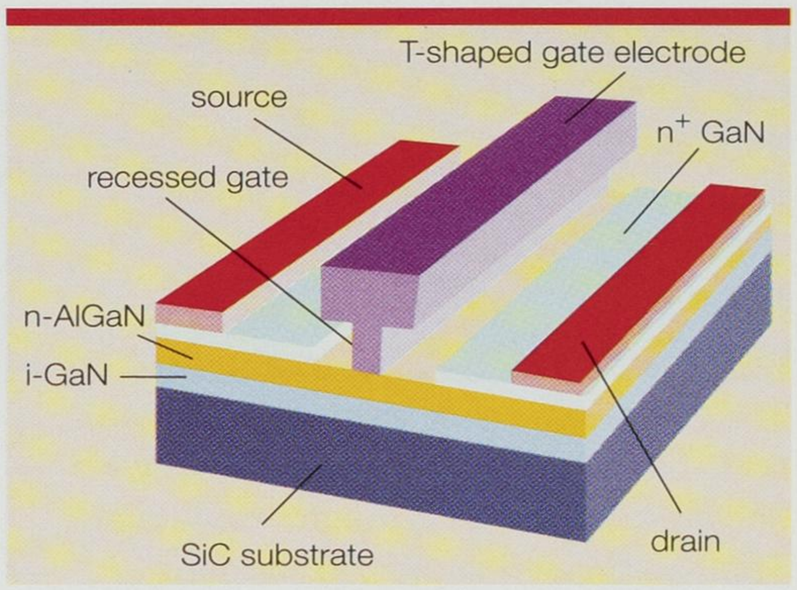
ELECTRONICS

Oki develops improved AlGaN HEMT

Oki Electric Industry Co, Ltd has developed a high-performance AlGaN/GaN HEMT grown on a SiC substrate. The device achieved a figure of 500 mS/mm for transconductance, compared with 327 mS/mm for previous Oki devices. To improve the amplification characteristics, Oki successfully fabricated T-shaped recessed gates, reduced the gate length, and optimized the device structure. The transistor had f_t and f_{max} values of 67 and 126 GHz, respectively.

"This development marks a critical step towards broadening the applicability of GaN HEMTs, which we expect to be an essential device in the next generation of wireless communications systems," said Harushige Sugimoto, general manager of the Corporate R&D Center at Oki Electric. "I believe this record high transconductance results from our R&D dedication to innovative technologies."

To achieve high power output using a conventional I-shaped gate, the gate must be made wider and longer, increasing its resistance and decreasing the operating frequency. A T-shaped gate electrode provides a larger cross-section and consequently a lower electrode resistance.



OKI ELECTRIC

Oki's AlGaN-on-SiC HEMT structure features a T-shaped recessed gate.

The use of a recessed gate dramatically reduces the parasitic resistance of the transistor, while improving amplification and high frequency characteristics. Recessed gates require very difficult, high-precision fabrication techniques rarely applied to GaN HEMTs.

The rapid increase of channels made necessary by growing communications volumes has increased the need to reduce power consumption and space per channel of mobile phone basestations and other wireless communications systems. With its improved amplification characteristics, Oki's new power transistor makes it possible to reduce the number of amplifier stages in transceiver equipment, providing a precise response to this market demand.

Oki intends to increase the power output and reduce the cost of the GaN-on-SiC HEMTs. It plans to begin sample shipments in late 2003 to customers building mobile phone basestations and wireless LANs.

Sumitomo Electric produces GaN wafers in volume

Sumitomo Electric Industries Ltd of Japan has commenced volume production of gallium nitride substrates for the fabrication of GaN-based violet lasers. The use of GaN as a substrate instead of sapphire or SiC is expected to significantly reduce defect formation during epitaxial growth. In turn, this will improve the performance and manufacturability of violet lasers, which will be used in next-generation optical disc drives.

Sumitomo Electric expects to produce the substrates, each of which can be used to make 10,000 lasers, at an initial rate of 200 units per month. It plans to boost output to 500 units per month in October and market the substrates to laser manufacturers.

Other Japanese wafer manufacturers including Hitachi Cable have plans to produce GaN substrates (*Compound Semiconductor* April 2003 p14). Furukawa also intends to start producing both GaN and sapphire substrates for the nitride market.

Sumitomo Electric first announced the development of GaN substrates in 2000. The company developed a process called DEEP, or Dislocation Elimination by Epitaxial growth with inverse-pyramidal Pits. GaN is grown by vapor-phase deposition on a carrier substrate, which is subsequently removed. The key to the technique is the formation of inverse-pyramidal pits on the surface of the GaN layer – as the layer grows and the pits get larger, dislocations are concentrated at the bottom of the pits. This reduces the dislocation density on the surface surrounding the pits to around $10^6/cm^2$, which is about 10^4 times less than the dislocation density of conventional GaN epitaxial layers on sapphire substrates.

Sumitomo Electric is also involved in a different approach to wide-bandgap optoelectronic components. The company recently formed a joint venture, Supra Opto, with Procomp Informatics to manufacture ZnSe white LEDs (*Compound Semiconductor* January/February 2003 p5). According to Der-Cherng Liu of Supra Opto, prototype versions of the new white LEDs will be available in the second quarter of 2003.

Lumilog introduces GaN-on-sapphire substrates

French company Lumilog has commenced production of a novel Fe-doped semi-insulating GaN substrate for the growth of AlGaN/GaN HEMTs and other nitride-based electronic devices. The product consists of a 4 μm thick GaN layer grown by MOVPE on a 2 inch sapphire substrate. The GaN exhibits a sheet resistance higher than 10^7 Ω at 300 K, as well as a low threading dislocation density. High-quality GaN substrates are required to fabricate long-lived, efficient and reliable devices such as lasers, LEDs and transistors.

Located in the Technological Park of Sophia Antipolis near Nice, Lumilog is a spin-off from the Centre National de la Recherche Scientifique (CNRS). The company also produces epitaxial lateral overgrown GaN on 2 inch sapphire with a very low dislocation density between stripes, and is developing free-standing bulk GaN substrates.

DVD Forum to ratify Blu-ray competitor

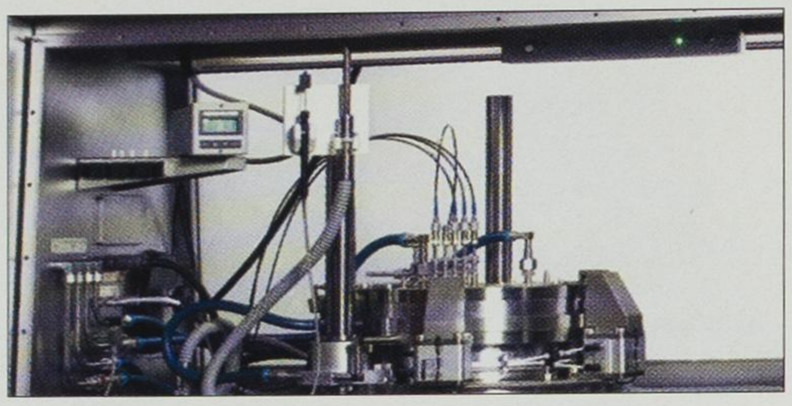
The DVD Forum, an international association of electronic manufacturers, is to release a new DVD standard later this year. Based on the Advanced Optical Disc format developed by Toshiba and NEC, the standard uses violet lasers to provide a recording capacity of 20 Gb for single-side, single-layer discs. It will compete with the Blu-ray standard developed by Sony and several other companies.

Cambridge University wins funding

The Materials Department of the University of Cambridge, UK, has received funding from the UK's Engineering and Physical Sciences Research Council (EPSRC) to continue its work on nitrides. The group, led by Professor Colin Humphreys, will conduct a three-year program starting in May and funded to the tune of £1.2 million ($1.9 million) to grow and characterize GaN-based materials and structures. The grant will also fund optical studies of GaN-based materials at UMIST, a university in Manchester, UK.

"I am delighted with the news of this major grant from EPSRC, which will enable us to make exciting advances in optimizing a wide range of GaN-based materials and structures," said Humphreys. Specific objectives include the demonstration of blue and green MQWs with an efficiency of 50%, and UV MQWs with an efficiency of 15%. The group will investigate a variety of other areas including epitaxial lateral overgrowth, GaN growth on silicon, dopant distributions, and energy levels of individual defect states. The department has expertise in a wide range of advanced electron microscopy techniques, as well as X-ray diffraction and AFM, to characterize materials and device structures.

Since beginning its nitrides work three years ago, the Cambridge group has achieved some impressive results. "We have grown InGaN QWs with a PL internal quantum efficiency of 43% at room temperature, and InGaN/GaN MQW LEDs with a power output of 4.8 mW at 500 nm," said Humphreys.



TSSE

The Cambridge University group grows GaN-based material on a close-coupled showerhead MOCVD reactor donated by Thomas Swan Scientific Equipment.

Results stem from collaboration

The group has also used electron holography to show that In clustering reduces the piezoelectric field across a single InGaN QW, and grown InGaN quantum dots with a lifetime of 1.8 ns at peak intensity (in collaboration with Oxford University). Other activities include the growth of semi-insulating GaN with a resistivity up to 10^{11} Ω.cm, as well as correlating growth conditions with dislocation type and electrical resistivity.

Humphreys' group grows GaN-based material using a 6 × 2 inch MOCVD system donated in 1999 by Thomas Swan Scientific Equipment (TSSE), which is located only 10 miles from Cambridge. TSSE maintains and upgrades the reactor and also provides 25% of the time of one of its growth experts, Ted Thrush, while the university obtained funding from EPSRC for installation and running costs. Outside the university's scientific programs, TSSE funds engineering investigations such as runs to prove uniformity and reproducibility, or testing of hardware modifications.

"The combination of excellent results and the ability to bring potential customers to the university to see our equipment in action has had a major impact on the performance of the company," said Thrush. For example, TSSE believes that its leading position in the nitride MOCVD equipment market in mainland China can be traced back to visits made by Chinese scientists to the Cambridge laboratory over the last two years.

Both TSSE and Cambridge University are keen to stress the benefits of their collaboration, and others agree. One of the referees of the recent grant application saw the relationship as "an excellent example of how industrial and academic groups can work together in a totally symbiotic way".

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Bookham streamlines its operations

By Susan Curtis

In November 2002, when Bookham Technology completed its purchase of Nortel Networks' Optical Components division, CEO Georgio Anania was certain that combining the Nortel operation with Bookham's previous acquisition of Marconi's optical components business would yield significant cost efficiencies. Now, just four months on, his strategy for streamlining Bookham's manufacturing facilities is becoming clear.

For a start, Nortel's former InP chip manufacturing plant in Ottawa, Canada, is being closed and the fab will be relocated over the next 12 months to the ex-Marconi facility in Caswell, UK. Also, Bookham's assembly and test operations are being consolidated at the former Nortel site in Paignton, UK.

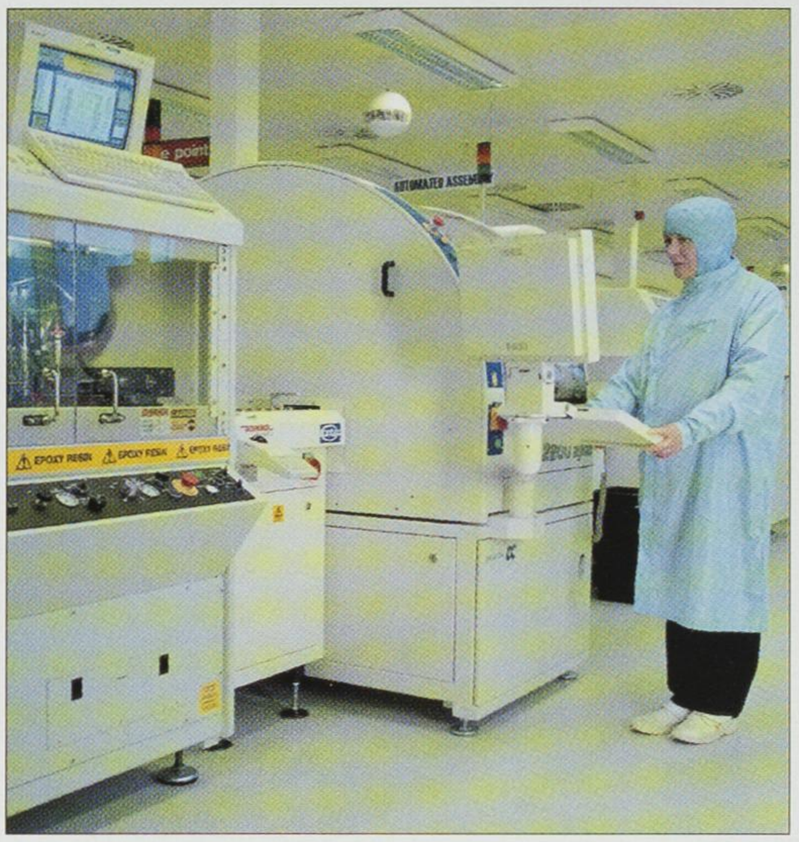
The Paignton facility transforms individual components – such as the optical chips made by Bookham's manufacturing plants at Caswell and Zurich, Switzerland – into packaged products that are ready to be installed into optical networking equipment. A quick tour of the site reveals the sheer range of products produced there, including a full range of transmitters, receivers, lasers, 980 nm pump modules and optical amplifiers. A new addition to the facility is a semi-automated line for laser assembly and test recently moved in from Caswell.

Shifting priorities

However, it is clear that the volume of products handled by the Paignton site has dropped dramatically over the last couple of years, in line with the precipitous decline in the optical components market. "In its heyday the plant was running 24 hours a day and seven days a week to keep pace with demand," says Tim Durrant, an operations manager at the site. At that time, some 7000 people were employed at Paignton, but now the headcount has dropped to 800, and many of the workstations stand idle.

But the decline in volume hasn't stopped innovation at the site. On the contrary, the telecom downturn is encouraging engineers to work more closely with their customers to deliver bespoke components that meet specific demands.

Furthermore, with systems houses cutting down on their own engineering resource, it is up to component makers like Bookham to design and manufacture value-added products, such as complete line-cards rather than discrete components. An on-site R&D lab allows engineers to modify designs and optimize device performance, while also ensuring that any new designs can be implemented on the production line.



Tough market conditions are slowing down Bookham's drive towards automation.

However, the difficult economic situation is putting the brakes on the drive towards automation. Although some assembly processes at Paignton have already been automated, Durrant explains that the volumes are now too low to justify investment in further labor-saving equipment.

Take the assembly of optical receivers as an example. A series of automatic machines has been installed to position and attach individual elements within the module package, but operators are still needed to physically move the product from one machine to another. "We have the building blocks here to fully automate the production line," says Durrant, "but we need greater volumes to warrant the expense."

Weighing up the cost

Durrant explains that automation is relatively straightforward for process steps that only involve chips, components and packaging. "However, automation remains a very expensive option for any process that involves fiber, and that's what makes the production of optical components so different from chip manufacturing," he says.

For example, the receivers and transmitters that zoom off the automated production line must be passed to skilled operators for fiber alignment, which remains a painstaking and time-consuming process. To prevent a bottleneck at this stage, the automatic line is switched between the assembly of several different products, allowing a number of alignment operators to work on those different products at the same time.

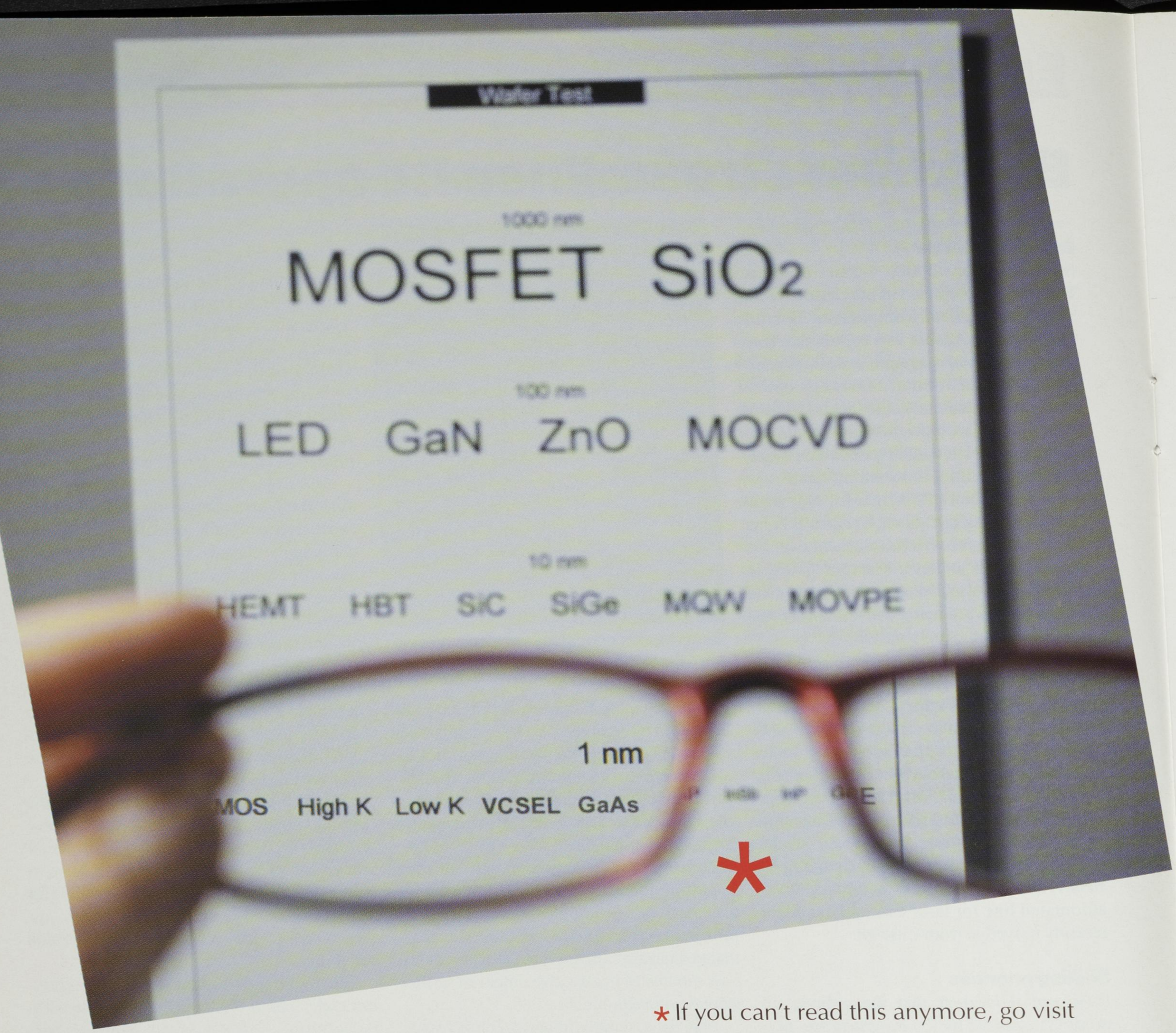
Automatic alignment systems are available, but Durrant says that they remain too expensive to be economically viable, particularly in the current climate. The continuing need for highly manual procedures makes process control an integral element of each assembly stage. After alignment, for example, the same operator measures the optical output of the device to ensure that it meets expectations. "The operator has control over the entire process, which provides an extra incentive to do the job well," says Durrant. "It also identifies any problems quickly to improve product yields."

The same approach is taken in all the assembly operations. And at final test, every effort is taken to replicate conditions in real networks. "This site was originally used to manufacture components for submerged cables, and we have the same mentality today when it comes to ensuring performance and reliability," says Durrant.

Meanwhile, Bookham is working fast to integrate operations at the Paignton site with its activities at Caswell and Milton, near Oxford, UK. "Nortel, Marconi and Bookham all had slightly different approaches to component manufacture," says Durrant. "We are having many exchanges of ideas that will help us to establish best practices across all our manufacturing facilities."

While it could be argued that the slack in the market offers the ideal opportunity to streamline and optimize operations, Durrant maintains that engineers at the site are just as busy as ever. "We are constantly working to improve the products and adapt the designs to meet specific customer requirements," he says. "In this market we have to work hard to win every contract."

Susan Curtis is contributing editor of FibreSystems Europe *magazine. This article originally appeared in* FibreSystems Europe *March 2003.*



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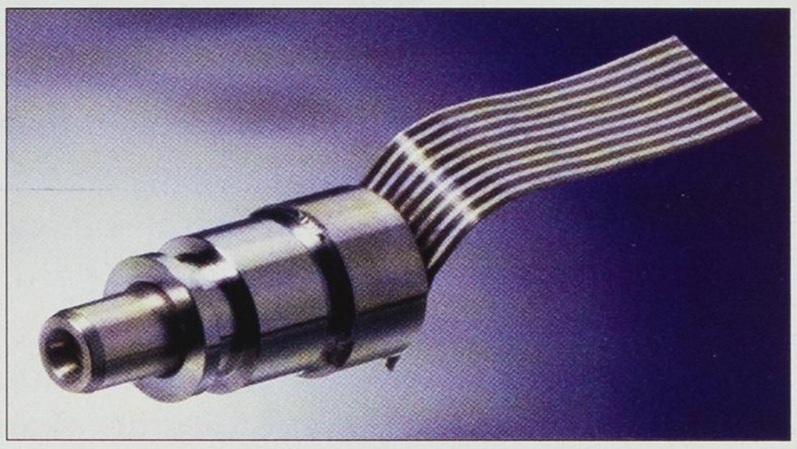
Infineon begins production of 1310 nm VCSELs

While several companies have demonstrated the capability to make long-wavelength VCSELs, Infineon looks set to become the first to commence high-volume manufacturing. In March, it announced the availability of 1310 nm VCSELs, which are now sampling to customers. High-volume production will begin in the second half of 2003.

Infineon has also demonstrated a 1310 nm VCSEL variant of its intelligent small-form factor pluggable (iSFP) transceiver module, which it will make commercially available in the second half of 2003.

Unlike the incumbent long-wavelength DFB and Fabry–Perot lasers, which emit light from the edge of the structure, VCSELs emit light from the surface, which simplifies packaging, allows on-wafer testing and results in a significant cost advantage. While 850 nm VCSELs dominate short-reach (up to 300 m) datacom applications, 1310 nm VCSELs allow transmission distances of up to 10 km.

Infineon has been producing 850 nm VCSELs in high volumes for several years, but like other manufacturers has been grappling with the problems of integrating the dissimilar materials that are required to implement the active and mirror regions of longer-wavelength VCSELs. So far, long-wavelength VCSELs have not had sufficient output power or reliability to replace edge-emitters for longer-reach applications.



INFINEON TECHNOLOGIES

Infineon intends to start high-volume manufacturing of 1310 nm VCSEL products.

Infineon's approach is to use a monolithic structure comprising GaAs-based epitaxial multilayer mirrors combined with a dilute nitride GaInAsN active region. This removes the need for complicated wafer-bonding procedures to integrate an InP-based active layer with GaAs-based mirrors.

The VCSEL's output power of 0.5 mW can be maintained up to 85 °C. The spectral line width and side-mode suppression performance of the 1310 nm single-mode VCSEL are equivalent to or better than a DFB laser. Low threshold and operating currents allow use in low-power consumption applications, and the heat dissipation is much less than that of a conventional edge-emitting laser. At present Infineon's 1310 nm VCSEL can be used for data rates of up to 2.5 Gbit/s, and a 10 Gbit/s version is in development.

In related news, Picolight has demonstrated SFP transceivers based on 1310 nm VCSELs with an operating speed of 2.5 Gbit/s. For a given data rate, 1310 nm VCSEL transceivers use 16–25% of the power of edge-emitter-based solutions, says the company.

Finisar acquires Genoa, relocates Demeter

Fiber-optic components manufacturer Finisar has continued with the acquisitions, disposals and business consolidation activities that began as it geared up for the telecom boom and are continuing as it reshapes for today's leaner environment. It has acquired optical amplifier manufacturer Genoa of Fremont, CA, in a stock-based deal valued at about $6.5 million. Genoa's CEO Fariba Danesh will become Finisar's new COO.

Genoa's linear optical amplifier (LOA) uses a single-chip design that incorporates a long-wavelength VCSEL. Finisar's interest is probably less driven by its desire to have an optical amplifier in its portfolio than by its interest in acquiring Genoa's 1310 and 1550 nm VCSEL technology. These VCSELs could be incorporated into Finisar's transceiver products, which are aimed at enterprise and metropolitan networks.

Like many similar-sized start-up companies in the fiber-optic components industry, Genoa has struggled with low demand, especially from DWDM applications where its LOA is targeted.

Finisar is also closing down its Demeter Technologies facility in El Monte, CA. Demeter produces long-wavelength Fabry–Perot and DFB lasers and was acquired by Finisar in 2000. Finisar is moving Demeter's activities to Genoa's site in Fremont. In October 2002, Finisar sold Sensors Unlimited, which it acquired for $700 million in 2000, back to the company's management team for $6.1 million (*Compound Semiconductor* November 2002 p30).

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Kamelian wins more funds, new investor

Semiconductor optical amplifier (SOA) manufacturer Kamelian has secured $6.3 million in the latest round of funding for its UK-based operations. The funding round included a new investor, Japanese company Hoya, which joined Kamelian's previous backers, including 3i Group, Goldman Sachs and Lightspeed Venture Partners. Hoya is well established in the optics industry, but in recent years has been diversifying into new areas, including SiC substrates (*Compound Semiconductor* August 2003 p13). Kamelian's total funding so far is now around $30 million.

To date, Kamelian's products have been relatively simple InP-based optical preamplifiers and optical power boosters. However, at OFC in March the company revealed an all-optical wavelength converter, the product towards which it has been working for some time.

The wavelength converter uses an SOA on each of the two silica waveguide arms of an interferometer. The arrangement is similar to that of a Mach–Zehnder modulator, except that there are two inputs, a tunable CW light source and the data signal. The wavelength of the output is set by changing the wavelength of the tunable CW input. If the tunable laser is set to the same wavelength as the data input, the device acts as a data signal regenerator, which reamplifies and reshapes the input. The product demonstrates Kamelian's technology for integrating its InP-based SOAs with silica passive components on a silicon platform, an integration system that it intends to extend to other devices for fiber-optic networks.

Picolight, IBM demonstrate 120 Gbit/s link

Picolight and IBM have demonstrated a 120 Gbit/s optical link using a single thumb-sized 12-channel module. Each channel operates at 10 Gbit/s and transmits over a standard 12-fiber ribbon. This enables seamless upgrades to existing systems, and more than triples the performance of current 12-channel transmit/receive modules. The demo combined Picolight's 12 × 10 Gbit/s parallel VCSEL optics with IBM's SiGe 12-channel VCSEL driver IC. The module occupies about one square inch of board space, the same as Picolight's 12-channel, 40 Gbit/s modules.

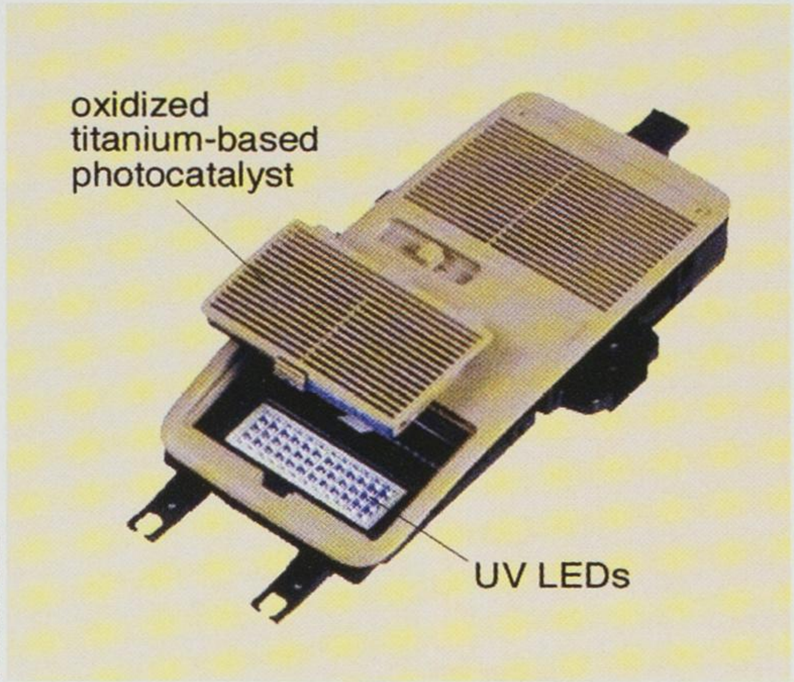
"This format is a more reliable alternative to low-speed, high-channel-count solutions using up to 48 channels [and 2D VCSEL arrays] to achieve the same throughput," said Jack Jewell, founder and CTO of Picolight.

Scotland gains opto packaging facility

A £4.2 million ($6.75 million) facility is to be established in Livingston, Scotland, in conjunction with the Scottish Optoelectronics Association, to commercialize packaging technology for complex optoelectronic chips. It will bridge the gap between design and manufacturing qualification of optoelectronic devices.

Toyoda UV LEDs power photocatalyst purifier

Koha and LED maker Toyoda Gosei have formed a joint venture, TG Opseed, to supply a photocatalyst system for deodorizing and sterilizing in hospitals, airplanes, refrigerators and freezers. The system uses 380 nm UV LEDs supplied by Toyoda Gosei to replace mercury-containing black lights. The photocatalyst material, developed by Koha, is made from titanium dioxide attached to silica gel rather than activated charcoal. The silica gel transmits light well, has a large surface area and readily absorbs organic materials. Systems using black lights need much higher power and cannot be used in low-temperature settings. Toyoda Gosei also supplies UV LEDs to Toyota Motor Company for use in photocatalyst-based air purifiers in cars.



TOYODA GOSEI

An photocatalyst purifier using Toyoda Gosei LEDs has been used in air conditioning systems in Toyota cars.

Taiwan R&D alliance officially established

In mid-March, the Ministry of Economic Affairs (MoEA) in Taiwan launched the III-V Semiconductor R&D Alliance. According to Huang Chong-Chiu, director of industrial technology at MoEA, the alliance will combine the R&D energy of industry, universities and research institutes with related government resources. The purpose is to improve the technological ability of the Taiwanese III-V semiconductor industry, and to make Taiwan a significant supplier of epitaxial and device wafers and equipment.

Furukawa develops 1300 nm VCSEL

Furukawa Electric has developed a 1300 nm VCSEL operating at up to 10 Gbit/s. The device is designed for short- to mid-range fiber-optic networks with a reach of 10 km or less. Edge-emitting lasers providing data rates of 10 Gbit/s cost around ¥10,000 ($85), while 2.5 Gbit/s devices cost around ¥4000. Furukawa estimates that the low-cost manufacturing techniques associated with VCSELs will allow the company to offer high-speed devices with a price tag of around ¥4000.

Latest LED news from Taiwan

Reports from Taiwan suggest that the price of blue LEDs has dropped considerably in recent months from about NTD 3 (8.5 cents) to NTD 2.5 (7 cents). As production capacity in the country continues to rise, further price reductions could occur.

Meanwhile, LED packaging company Lite-on Technology looks set to receive authorization from Toyoda Gosei to manufacture white LEDs under a patent license from the Japanese LED manufacturer.

Opto Tech plans to set up factory in China

Opto Tech plans to invest $5 million to set up an LED manufacturing plant in Suzhou, China, to compete for business opportunities arising from the 2008 Olympic Games in Beijing. Opto Tech (Suzhou) Co Ltd will manufacture products such as large-scale signboards and traffic lights. Construction of the plant began in mid-March, and trial production will start in the fourth quarter of 2003. Opto Tech will also invest $10 million in Jia Xing, a company set up in mainland China to manufacture low-brightness LED chips.

● Our feature article on compound semiconductors in China begins on p41.

Formosa Epitaxy goes public

Nitride LED manufacturer Formosa Epitaxy, located in the Lungtan Science Park, Taiwan, went public on April 11. Chien Feng-Jen, chairman of Formosa Epitaxy, points out that counterfeit money was widespread last year, and that UV LED-based systems for examining paper currency became very popular. As a result, the company received significant orders for UV LEDs, and recorded a sales volume of NTD 490 million ($14 million), and a net profit after tax of NTD 240 million. Formosa Epitaxy also produces LED backlights for mobile phones.

White LED source from Matsushita generates 120 lm

Using 64 blue LED chips combined with yellow fluorescent powder, Matsushita has produced a white LED source that generates 120 lm. Using a substrate with excellent heat-dissipation properties, the company was able to pack the chips into an area of just 2 cm^2. Matsushita says that the temperature of the package rises by only 1.2 °C for every 1 W of input power, allowing the LEDs to be driven by up to 8 W. Commercial versions of the device are likely to appear next year.

In brief...

Sanyo Electric develops 100 mW nitride laser

Sanyo Electric has developed a 100 mW violet laser and plans to start shipping samples by July. The device could double the capacity of Blu-ray optical drives by allowing the use of dual-layer discs.

Sumitomo expands GaP wafer production

Sumitomo Metal Mining plans to expand its output of GaP wafers by a factor of four, based on demand from transparent-substrate (TS) AlGaInP LED makers. Such LED structures are grown on GaAs wafers before being transferred to transparent GaP substrates.

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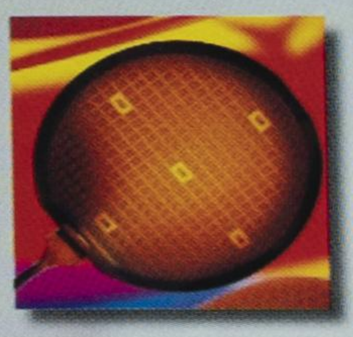

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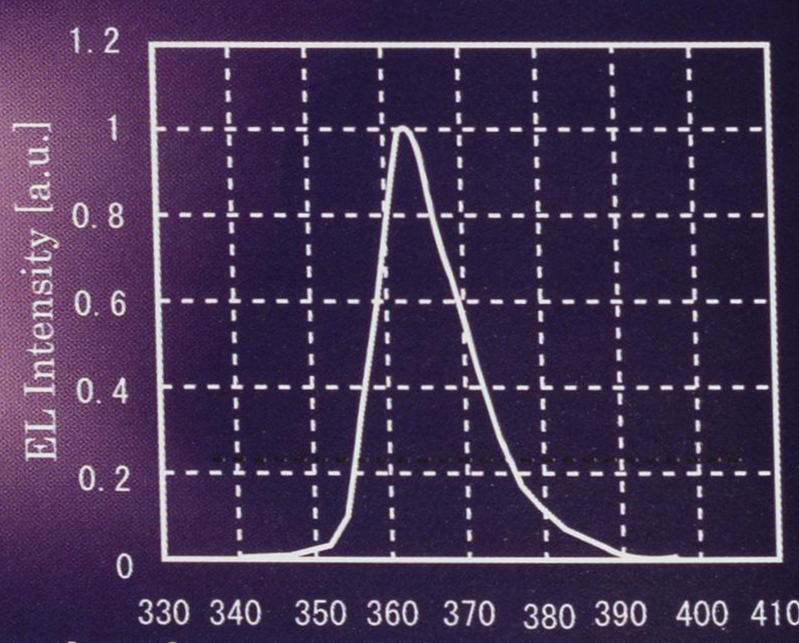

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Growth predicted for gallium market

By Tim Whitaker

After a huge spike in 2000, the demand for gallium appears to have stabilized and looks set to grow steadily for the next several years. According to a new report from Roskill Information Services, worldwide gallium demand peaked in 2000, but fell by one-third in 2001 to 141 tons (in this article "ton" refers to metric ton, or tonne, which is equal to 1000 kg). The market recovered to 162 tons in 2002, and Roskill predicts that demand will grow by 8–10% per year, reaching 280 tons by 2008 (figure 1). The market research firm says that growth will be driven by the recovering wireless market, particularly the advent of 3G services, and also by the LED market and notably a growing demand for white LEDs. Unlike other metals, such as indium, there are very few uses for gallium outside the compound semiconductor industry. Gallium is used to manufacture GaAs and GaP substrates, as an atomic source in MBE growth, and to make metalorganic precursors for MOVPE growth.

The fall-off in demand for gallium is attributed largely to the slump in the mobile phone handset market and the effect of this on the GaAs industry. In 2000 the prospect of continued rapid growth in demand, coupled with a real or perceived shortfall in supplies of starting materials, caused the GaAs IC makers to stockpile substrates. This affected the entire supply chain and caused gallium suppliers to expand their production capacity. At that stage, a demand level of 350 tons of gallium was forecast for 2008.

The apparent supply shortfall in early 2001 caused prices to skyrocket; by the end of March, spot prices reached $2250/kg, compared with around $550/kg two years earlier. (The spot price is the current price paid on the open market; large consumers will negotiate long-term contracts with significantly lower prices.) However, the slump in the GaAs IC industry in 2001 caused gallium consumption to fall dramatically, and prices did the same. According to the United States Geological Survey (USGS), prices for high-purity gallium (6N, or 99.9999% pure) were in the range of $400–500 per kg at the end of 2002 (figure 2).

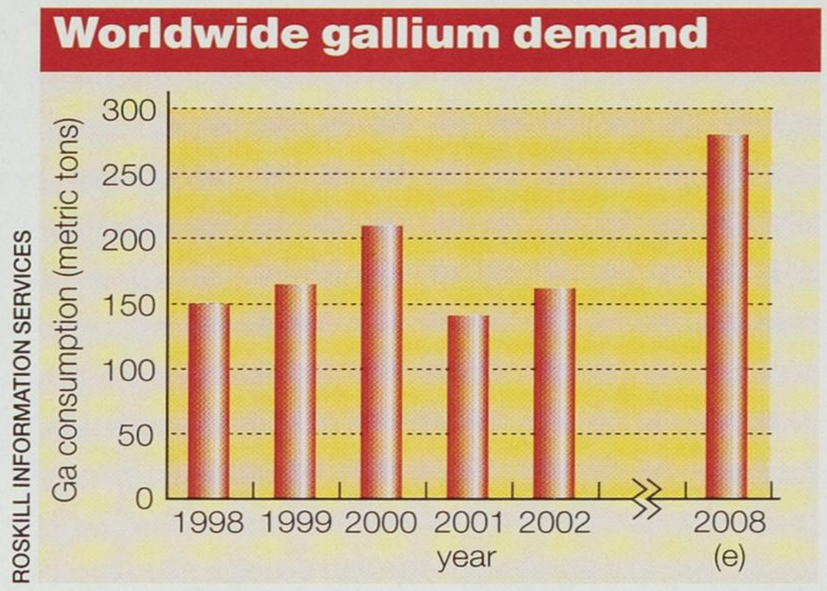

Fig. 1. After a spike in demand in 2000, the gallium market is expected to resume steady growth for the next several years.

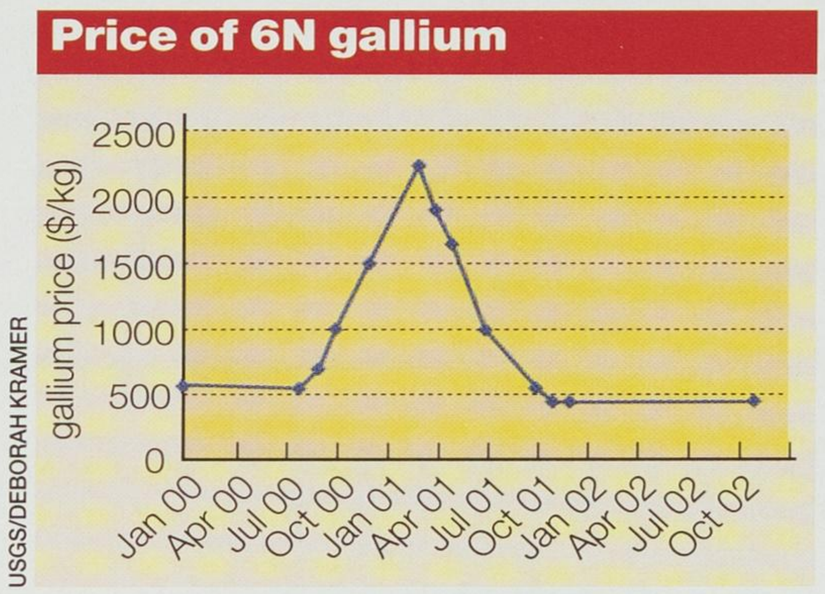

Fig. 2. Spot prices for 6N (99.9999% pure) gallium peaked in March 2001 and are now steady at around $450/kg.

Gallium production

In nature, gallium occurs in very small concentrations in rocks and ores of other metals. Most gallium is produced as a by-product of extracting aluminum from bauxite, while the remainder is extracted (principally by Dowa Mining in Japan) from by-products of zinc processing. Other leading primary producers include GEO Gallium, Pavlodar Alumina of Kazakhstan, and several companies in both Russia and China. Back in 2001, Canadian company Gold Canyon Resources said it was evaluating mineral deposits in Nevada to assess the feasibility of extracting gallium as a principal product (*Compound Semiconductor* June 2001 p4). CEO Robert Carrington recently said that Gold Canyon's Cordero gallium project was moving slowly at the moment, but production could start by the end of 2004 if the market picks up again.

While a small number of companies operate gallium extraction plants, others including Dowa Mining and Sumitomo Chemical in Japan and GEO Gallium purify the extracted gallium to make it suitable for semiconductor applications. According to USGS, primary production of crude gallium was about 61 tons in 2002, down from about 75 tons in 2001. Refined gallium production was about 81 tons, a figure that includes gallium produced by recycling scrap material. This comes from the production of GaAs and GaP substrates, as well as GaAs IC wafer processing and the LPE and VPE growth of LEDs. Dowa Mining, which has a subsidiary producing substrates and LEDs, is one of the world's largest gallium-refining companies. Recycling companies in Europe include Groupe Arnaud Electronics, MCP Group and PPM Pure Metals, which along with Furukawa is a major manufacturer of high-purity arsenic.

Recycling scrap material

Back in 2001, at the height of the gallium price boom, GaAs substrate maker Sumitomo Electric estimated that it was internally recycling 40% of the gallium used for crystal growth. A further 20% was retrieved from GaAs device makers in the form of broken wafers, sludge from wafer thinning and waste from epitaxial source material.

Clearly, now that gallium prices have fallen well below their pre-boom levels, there is much less incentive for recycling. Until last year, Eagle-Picher Technologies refined low-purity gallium, recycled GaAs scrap and manufactured gallium compounds in Quapaw, OK. However, at the end of November 2002, Eagle-Picher exited the gallium products business. According to marketing and sales manager Huey York, the decision was "based on continued soft demand from customers in the telecom and semiconductor markets as well as the downturn in the optical fiber industry."

A management group from Eagle-Picher has purchased the company's gallium assets and formed a spin-off. Greg Evans, vice-president and general manager of the new company, Gallium Compounds LLC, says that its product lines will remain the same. "However, we will not be recovering gallium from GaAs or other scrap material," he said.

Recapture Metals of Blanding, UT, also recovers gallium from scrap material. One of the company's owners, Dale Slade, says that it was badly hit by the sharp decrease in demand in 2001. "We had to lay off about half our staff," he said. "However, demand has been returning gradually in recent months, and we have taken some staff back." Slade says that Recapture Metals plans to recycle at least 20 tons of gallium during 2003.

GEO Gallium

One of the largest gallium producers, GEO Gallium, operates an extraction plant in Germany and a purification plant in France. At the start of 2001, the company announced plans to re-open a mothballed gallium extraction plant in Pinjarra, Australia, with the capacity to produce 100 tons of 99.99% (4N) pure gallium per year. In November 2001, GEO signed a supply agreement with Alcoa of Australia (an aluminum producer) to provide feedstock for the Pinjarra plant, but also announced that the plant's start-up would be delayed until at least the end of 2002.

In September 2002, GEO announced that it had exercised its purchase option agreement with Rhodia Chimie SA to take control of the Pinjarra plant. At the time of writing, GEO was unable to comment on whether it had started work to open up the facility.

Gallium in China

China is emerging as a large gallium producer, with a total nominal capacity of around 80 tons according to Roskill. Primary producer Great Wall Aluminum recently increased its capacity to 15 tons per year. In late 2001, Sumitomo Chemical announced the formation of a joint venture company in China that planned to build a factory capable of refining 40 tons of gallium per year.

In early 2002, US substrate maker AXT announced that it had created a joint venture, Beijing JiYa Semiconductor Material Co, Ltd, to produce 4N gallium in China. AXT's partners include Shanxi Aluminum Factory, China's largest aluminum producer, with an annual capacity of 1.2 million tons. Gallium is extracted as an impurity from a chemical mixture formed as an intermediate process in the manufacture of alumina. The concentration of gallium is among the highest available worldwide, making its extraction highly beneficial to both parties.

A spokesperson for AXT said that Beijing JiYa Semiconductor Material provided more than 10 metric tons of 4N gallium in 2002, and projects to exceed that volume in 2003. The 4N gallium is typically refined into 6N or 7N material by a third party, before being used in final applications including GaAs substrates.

Despite the large nominal capacity for gallium production in China, Roskill estimates that actual production was about 25 tons in 2001, and dropped still further in August 2002 owing to low prices and demand.

USGS estimates that the price of low-purity gallium (4N, or 99.99% pure) from China was around $250/kg in mid-2002. The cost to primary producers of extracting 4N gallium is thought to be around $400/kg. It now appears that the price of 4N gallium is currently rising back towards the levels where primary producers may restart their activities.

Although any short-term supply shortages could cause prices to rise suddenly, it seems that gallium suppliers have enough dormant capacity to prevent a repeat of the price spike in 2001.

The Economics of Gallium *(7th edition) is available from Roskill Information Services, London, UK. Tel: +44 20 8944 0066. Web: www.roskill.co.uk. USGS information is at http://minerals.usgs.gov/minerals.*

Aixtron opens Taiwan office

Aixtron Taiwan celebrated the opening of its new facility in the Science Based Industrial Park in Hsinchu, Taiwan, in April. Aixtron Taiwan's remit is to perform production-oriented research with its Taiwanese customers and to provide local support. "Whereas our other labs worldwide are aiming more at fundamental research, the clear orientation on production in Taiwan gives us the chance to concentrate our development work on manufacturing aspects," said Christian Geng, general manager of Aixtron Taiwan.

GET meets ISO standards

Giga Epitaxy Technology (GET), a Taiwanese subsidiary of Hitachi Cable that manufactures GaAs-based epitaxial wafers, has received ISO 9001 certification for its quality management system and ISO 14001 certification for its environmental management system.

GET, which produces MOVPE-grown HBTs, HEMTs and MESFETs, estimates that it has a production capacity of 3000 6 inch wafers per month. After several customers qualified its products in 2002, the company expects that sales will increase considerably during 2003.

Equipment sales

● **Emcore** has announced the sale of a GaNzilla MOCVD production tool to **Uni Light Technology**, in the Taoyuan Kuishan Industrial Zone in Taiwan. Uni Light will install the tool to expand its capacity for manufacturing GaN-based HB-LED materials.

Emcore has also sold an E300 GaNzilla MOCVD production tool to **Advanced Epitaxy Technology** (AET), headquartered in the Hsinchu Industrial Park, Taiwan. AET will primarily use its new tool for the high-volume manufacture of GaN-based UV, blue and green HB-LEDs.

● **Aixtron** has received an order for multiple AIX 2600G3 HT MOCVD systems with 24 × 2 inch configuration from China's **Shanghai LanBao Photoelectric Material Company**. The MOCVD reactors will be used for the mass production of GaN-based LEDs, and will be installed in LanBao's new production facilities in Shanghai.

● **Mitsubishi Electric** has started mass production of high-power lasers for DVD applications on Aixtron AIX 2400/2600G3 systems. The company's red (650 nm) lasers have output powers of 100 mW.

Mitsubishi now produces about 1 million units per month and plans to double its output.

● **NTT Advanced Technology Corp** in Japan has purchased a multiwafer close-coupled showerhead MOCVD system from **Thomas Swan Scientific Equipment**. The system will be used for the research and development of InP-based devices.

● **Humboldt University** in Berlin, Germany, has ordered a DCA MBE 450 machine for zinc oxide research studies from **DCA Instruments**. The new MBE machine has an extended linear transfer system, which allows it to be linked to an existing DCA MBE module as well as an AFM station.

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Opportunities still exist fo

The GaAs industry can look forward to modest growth, further migration from MMICs to modules and sub-systems, and challenges from silicon IC manufacturers, reports **Tim Whitaker**.

After a huge decline in 2001, the GaAs industry had a relatively good year in 2002 and looks set to grow again over the next few years, according to speakers at this year's Key Conference (held March 10–12 in Key West, Florida). Steve Entwistle, VP of the Strategic Technologies Practice at Strategy Analytics, said he was "very confident that the GaAs microelectronics markets will continue to grow". GaAs continues to be closely linked with the mobile handset market, although the relatively slow growth in handset shipments (10–15% annually) will be offset by the decline in average selling prices (ASPs) of semiconductor components.

In his talk entitled "What's hot and what's not", Entwistle identified automotive radar as a exciting future market for GaAs (see box on p26). Other opportunities exist in wireless local-area networks, according to Earl Lum, executive director of CIBC World Markets. "The best opportunities are for PA and switch sockets in the 802.11a band at 5 GHz," said Lum. "Standards are becoming fixed, and neither CMOS nor SiGe perform well to the specifications." He added that almost all chipset vendors use GaAs PAs, although pricing pressures are very intense. The market for digital radios in millimeter-wave communications suffered a serious setback in 2001/2, although there are signs of a possible recovery towards the second half of this year. Emerging millimeter-wave markets are one area where companies can succeed on performance, while cost is becoming a much more important factor for established markets such as wireless handsets.

Entwistle also said that InP won't directly compete with GaAs in mainstream markets. During the bubble, lots of companies said they were about to launch InP devices, and a great deal of R&D work was carried out. Now the markets have been pushed back three or four years. "InP looks likely to follow a similar path to GaAs," said Entwistle. "It will take 10 years to become an overnight success."

Market numbers

According to Entwistle, the total GaAs IC market (including MMICs, digital ICs and discretes) declined by about 6% in 2002 to a level of $2.72 billion, of which around 81% was merchant sales and the rest was for internal consumption. While the MMIC market showed 11% growth in 2002, the market for digital GaAs ICs declined by at least 50%. Facing stiff competition from both SiGe and CMOS, GaAs has already been largely driven out of 2.5 and 10 Gbit/s fiber-optic systems. "This marks the end of GaAs in mainstream consumer markets in the digital domain," said Entwistle.

Fortunately, despite the slump in 2001, the analog semiconductor market as a whole has not been subject to the cyclical behavior seen in the overall semiconductor market, which is dominated by digital ICs. Both Entwistle and Lum broadly agreed that the analog GaAs market was likely to grow at a fairly modest annual rate of about 15% over the next few years.

Lum presented figures for the analog GaAs market (table 1), showing a decline of 29% from 2000 to 2001, followed by a further drop of 13% in 2002. As shown in figure 1, the GaAs market is continuing to shift towards modules, which accounted for 35% of the entire market in 2002. Since modules can contain a range of technologies, not just GaAs, this makes accurate counting of the GaAs market increasingly difficult.

Lum also provided a run-down of the top analog GaAs suppliers, as shown in figure 2. Since 2001, Fujitsu Quantum Devices has been overtaken at the top of the list by both RFMD and Skyworks, which together accounted for over 36% of the analog GaAs market in 2002 (figures for Skyworks show combined Conexant and Alpha GaAs revenues). Fujitsu experienced a revenue drop of 47% in 2002, exceeded only by Motorola, which saw its sales fall by 65%. TriQuint's revenue fell by more than 28%, even though the numbers include Infineon's sales. The top 10 companies, 6 from the US and 4 from Japan, together accounted for more than 80% of the market.

GaAs market

($ billion)	2000	2001	2002
Total GaAs market (Strategy Analytics)		2.88	2.72
Analog GaAs market (CIBC World Markets)	3.46	2.44	2.13

Table 1. Different views of the GaAs market. The increasing prevalence of modules makes accurate assessment of GaAs content more difficult.

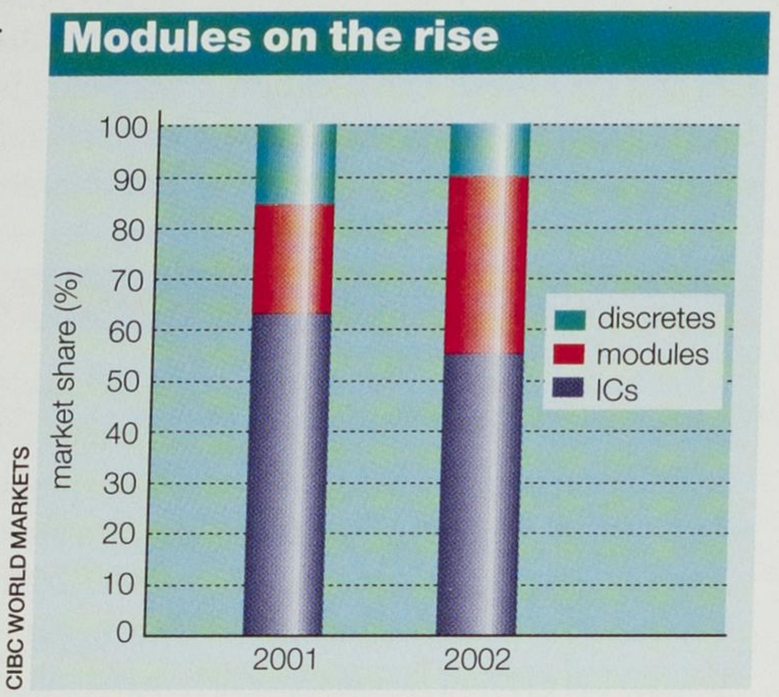


Fig. 1. The proportion of modules reached 35% of the analog GaAs market in 2002, as handset makers required more integration.

Entwistle made a further series of predictions about the market, one being that 4 inch GaAs for microelectronics will continue in the mainstream. This seems reasonable given the industry slowdown over the past couple of years, and the fact that two 6 inch fabs, at Vitesse and Infineon, are being closed. Also, the market for semi-insulating GaAs substrates will grow to around 23 million square inches by 2006, at least two-thirds of which will be used in epitaxial processes. Entwistle also predicted that MOCVD will overtake MBE as the dominant epitaxial technique for GaAs microelectronics.

The foundry model is still being tested in the GaAs industry, and a shake-out among the several "pure-play" foundries in Taiwan and Korea is likely. In the meantime, some of these companies are running other processes (e.g. SAW filters) instead of GaAs to boost revenue until the upturn comes. One problem with the

or GaAs industry to prosper

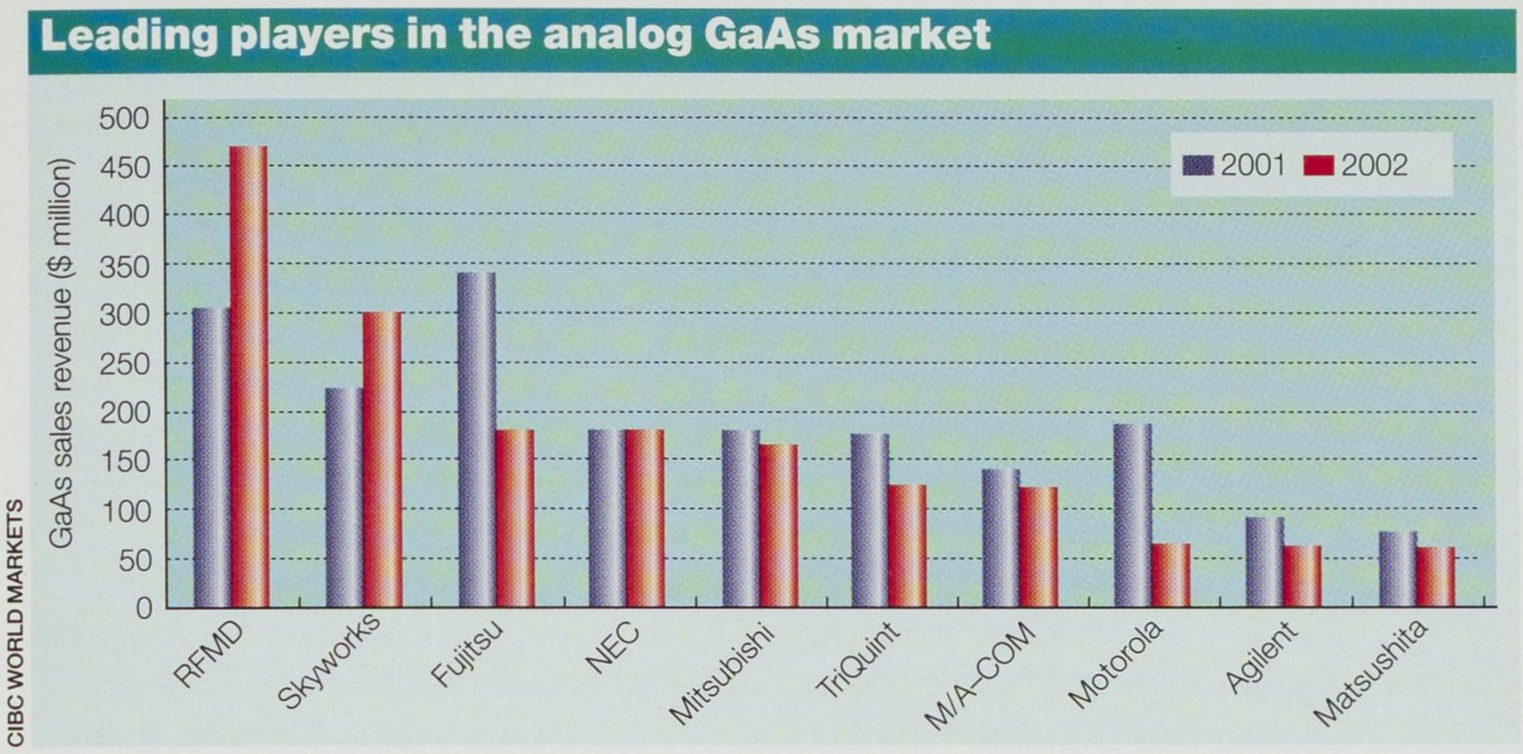


Fig. 2. The top 10 analog GaAs suppliers accounted for over 70% of the total market in 2002.

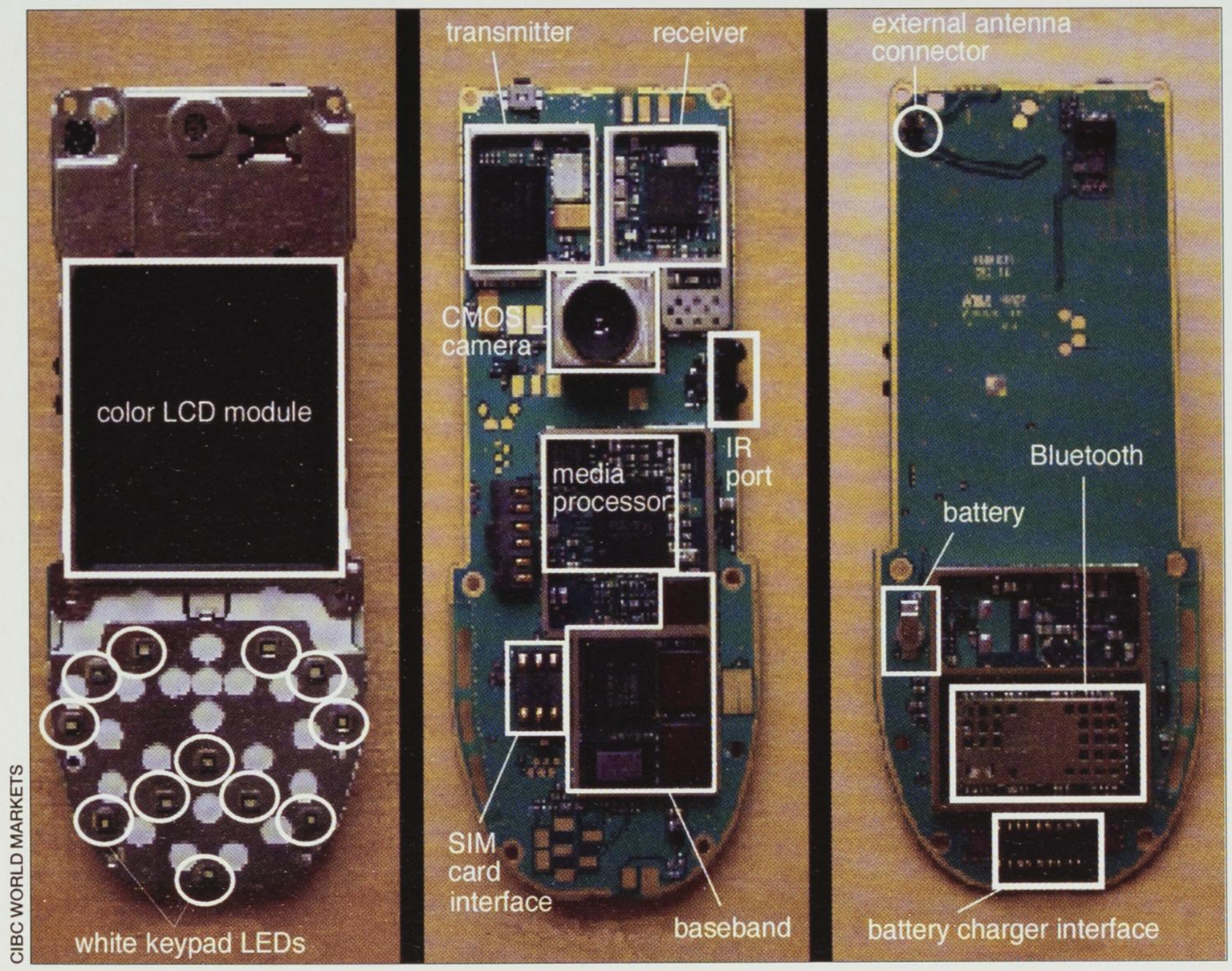


Fig. 3. The inside of a Nokia 3650 GSM handset, which contains 18 GaN-based LEDs, but no GaAs components. The handset has 256 Mbyte of memory.

GaAs foundry model is the lack of standards compared with the silicon CMOS world.

Opportunities in handsets

Sockets traditionally occupied by GaAs on the receive side of handsets, such as up- and down-converters, mixers and LNAs, are now being occupied by SiGe or silicon. However, GaAs will continue to have a dominant role on the transmit side, for PAs and switches. According to Lum, GaAs HBT is the technology of choice for CDMA, and there is a move away from E-mode HEMT towards HBT, at least for GSM. "However, E-mode won't go away completely," said Lum. "The move towards EDGE might cause an E-mode revival in 2004."

While SiGe has yet to make any progress in PAs, LDMOS continues to be successful. "Hitachi probably controls 50% of the GSM PA market in terms of unit volumes," said Lum. "Every time they move down a notch to smaller process dimensions, they open up a new market." Until last year, Hitachi had never participated in CDMA because it could not get the performance and efficiency out of its 0.18 μm LDMOS process. Now it has migrated to 0.13 μm, it has introduced its first CDMA products.

One of the key trends in the market for GaAs in handsets is integration. "We're no longer talking about a building-block solution, where companies can supply discrete LNAs, or mixers, or PAs," said Lum. "We're talking about a total system-level solution, and the companies that can supply that type of solution are the ones that will survive this downturn."

Lum gave an example of a GSM handset architecture from Skyworks that will soon consist of three modules: a tri-band antenna switch module; a direct conversion receiver; and a tri-band power amplifier module. Skyworks has also introduced its Single Package Radio solution, which consists of a complete radio front-end in a single package. Size reduction continues to be an issue; single-band PA modules have recently migrated from 6 × 6 mm to 3 × 3 mm packages. Thickness is also an issue, as more and more components such as camera modules are crammed into the phone.

Until now, CDMA handsets have experienced less integration: dual-band CDMA phones still have two PAs, whereas these are integrated into the same piece of GaAs for GSM. Now, PA modules for CDMA are starting to contain interstage SAW filters, duplexers and silicon control ICs. If you're a GaAs supplier, says Lum, this means you have to partner with a filter supplier who can provide these critical components. "The ability to supply a wide range of functionality is becoming more and more critical for any semiconductor supplier that wants to participate in the RF front-end," he said. Many GaAs manufacturers already have access to silicon technology, either internally or through foundry arrangements.

However, this works both ways: traditional

Short range radar and MMICs will help to increase shipments of automotive radar systems

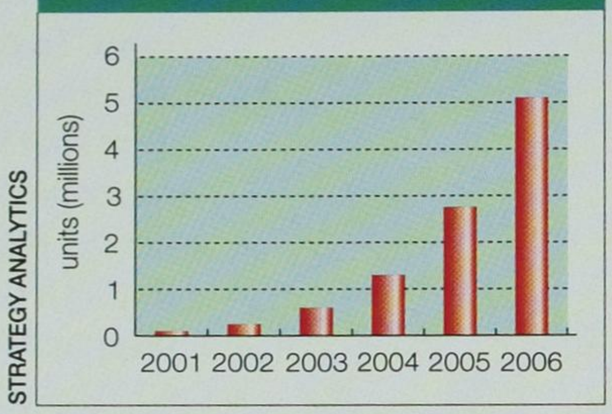
By Jon Newey

It is thought that 50% of car accidents happen because drivers fail to correctly predict the movement of vehicles in front or changes in road geometry. Another statistic says that 60% of front-end crashes would not occur if the driver could react 1 s sooner. These are just two of the figures that are commonly quoted by those involved in the effort to use radar for relieving drivers of at least some of the control of a vehicle.

So far only long-range forward-looking radar (FLR) operating at 77 GHz is in commercial use as part of intelligent cruise control systems in cars. FLR is offered as an option by luxury car makers including Mercedes, Jaguar and VW. However, the situation is slowly changing as car manufacturers look forward to the ultimate goal of constructing vehicles with the ability to evaluate and manage potentially dangerous situations. This will require the integration of FLR and 24 GHz short-range radar (SRR). A more complete control and safety solution will require fusion of the data from video and radar sensors, which could, in the distant future, result in a car that drives itself.

Although SRR is not yet in production for cars, it has been used on larger vehicles for some years now. Epsilon Lambda equipped the entire US fleet of 1700 Greyhound buses with 24 GHz antenna/transceiver subsystems in 1992. Automotive systems specialist Bosch will introduce a 24 GHz SRR product for cars later this year.

Automotive radar sales



The roll-out of SRR for cars is expected to boost radar sales significantly for two reasons. First, multiple SRR units will be required on each vehicle to give complete vehicle-surrounding SRR coverage. Second, SRR enables a number of different functions to be implemented, including reversing and parking aids, and the addition of a stop–go capability which will enable vehicles to move in queued traffic. Ultrasonic reversing aids are now included on many models, but the range of these is lower than that achievable with SRR. There are also aesthetic reasons for wanting to move away from ultrasonic sensors. "Many medium- to high-end cars are being shipped with ultrasonic parking aids operating through unsightly holes in the car's bumper," said Strategy Analytic's Steve Entwistle speaking at the Key Conference in March. "The motor industry is very keen to replace ultrasonic systems with a microwave-based system."

It is the cost of SRR systems that is mainly responsible for its slow implementation. "There is no technological reason why SRR is not available now," said Ken Lowe, product manager at TRW Automotive in Birmingham, UK. "It's just a matter of when customers are ready to pay for it." The electronic technology within the radar unit is an area that has a large impact on costs. Gunn diodes are the incumbent technology in automotive radar, but GaAs MMICs are making their presence felt as part of the effort to increase functionality and reduce costs.

TRW's second generation radar is taking full advantage of the advances in MMIC technology supplied to them by UMS (see p31). "The price of our second-generation unit will be dramatically lower [50% less] than the current one," said Colum McLaughlin-Greening, senior materials technologist at TRW Automotive. "This should help increase the pick-up of radar by OEMs."

TRW's current generation product is offered as an option on VW's Phaeton model, which is at the luxury end of the VW range. However, TRW has won a contract with VW to supply radar systems for a new model to replace its Passat, a less expensive vehicle. The use of radar lower down the model hierarchy will mean higher volumes and lower costs, but McLaughlin-Greening concedes that it is still unclear whether or when radar systems will appear at the compact car level where volumes will be maximized.

So far, the commercial uptake of automotive radar has largely been concentrated within Europe, as the US watches developments and addresses concerns over the legal implications that surround the further automation of vehicles. "Our perception is that the US has been watching the progression in Europe to see what sort of incidents might occur before launching such systems over there," said McLaughlin-Greening. "However, we are seeing increasing interest from those wanting to implement radar on American vehicles."

silicon houses are now starting to look at GaAs as they aim to provide complete RF chipsets. In February, for example, Analog Devices Inc (ADI) introduced an InGaP HBT PA with integrated control, manufactured by a GaAs foundry in Taiwan. The PA is designed to operate with ADI's Othello direct conversion RF transceiver. Both these products were part of a complete platform for EDGE, introduced by ADI in March, which also includes digital and mixed-signal analog baseband chips.

"Companies like TI and ADI have very strong traction in the handset market," said Entwistle. "They define the analog baseband part of the phone, and they could put severe pressure on the likes of RFMD and Skyworks."

Inside a Nokia 3650 handset

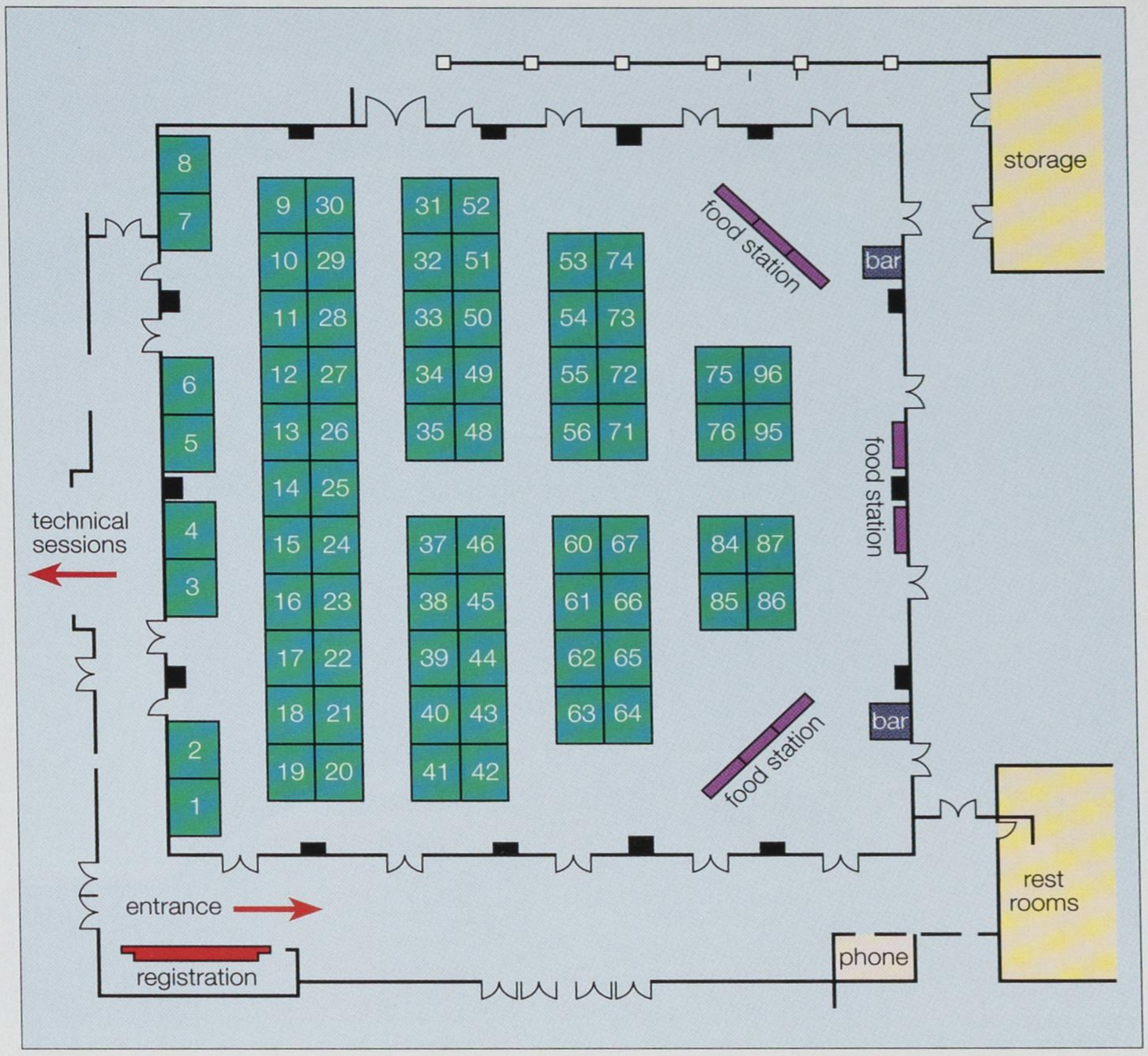
Lum also presented an analysis of the content of the Nokia 3650 GSM tri-band handset, which has a color screen and a camera among many other features. The phone contains a remarkably high number of white LEDs: there are 14 for the keypad and a further 4 for the color screen, all based on GaN-on-sapphire technology (figure 3). The entire GSM portion of the phone consists of a baseband section, containing 256 Mb of memory, a transmitter section based around a Hitachi LDMOS tri-band power amplifier, and a receiver section based around a direct conversion transceiver from Infineon. The phone doesn't contain any GaAs, although Lum believes that Nokia may decide to introduce GaAs-based switchplexers at some point. Silicon *pin* diodes are used at present, but the number of *pin* diodes required increases dramatically for tri- and quad-band phones, and GaAs PHEMTs become more viable. This could represent an opportunity worth $50–75 million for GaAs switch suppliers, just for Nokia, says Lum.

EXHIBITION GUIDE*

The Mantech Vendors' Exhibition is open as follows:

Monday, May 19: 6.00 p.m. to 9.00 p.m. (exhibits reception)

Tuesday, May 20: 7.00 a.m. to 8.00 a.m. (breakfast) and 9.50 a.m. to 4.00 p.m. (including lunch)



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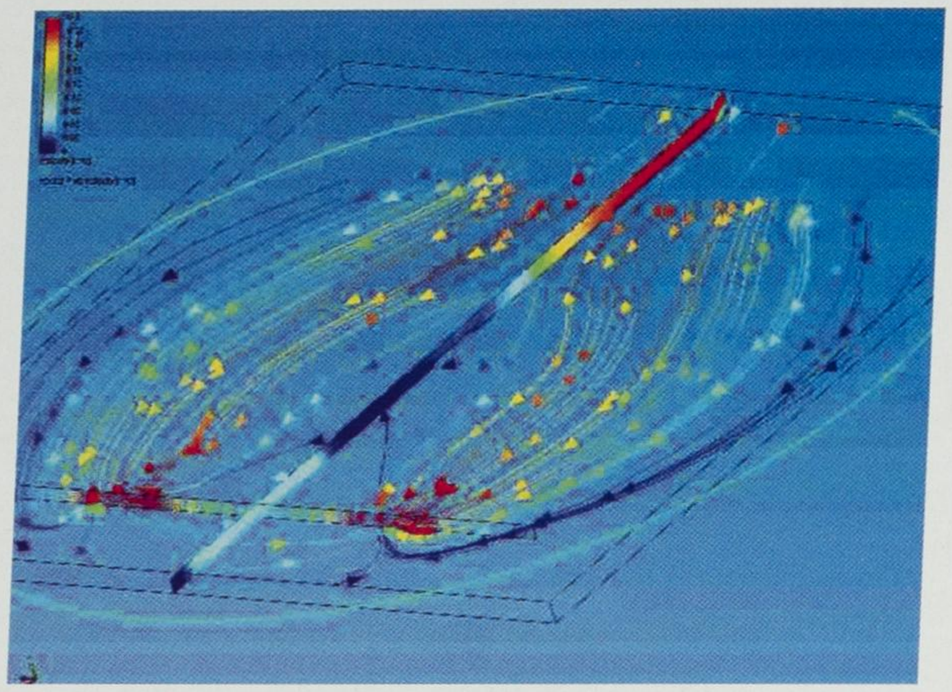

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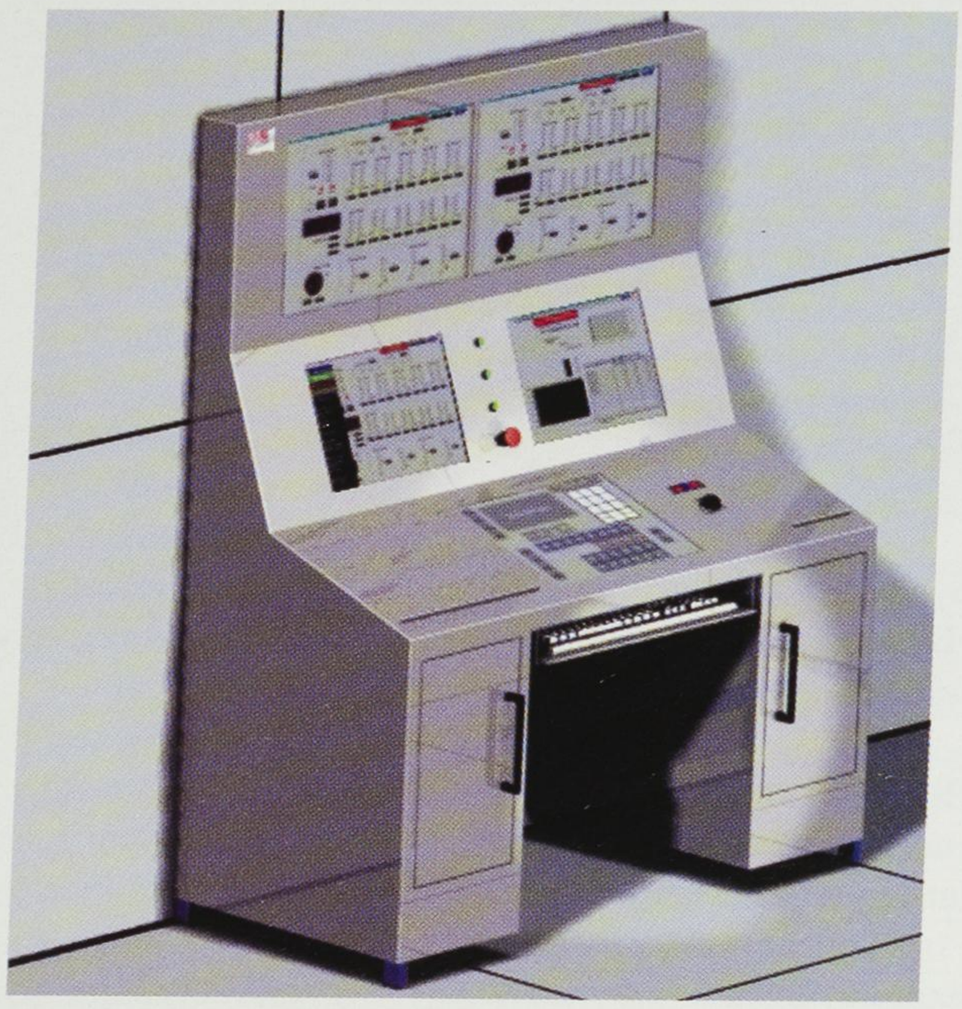

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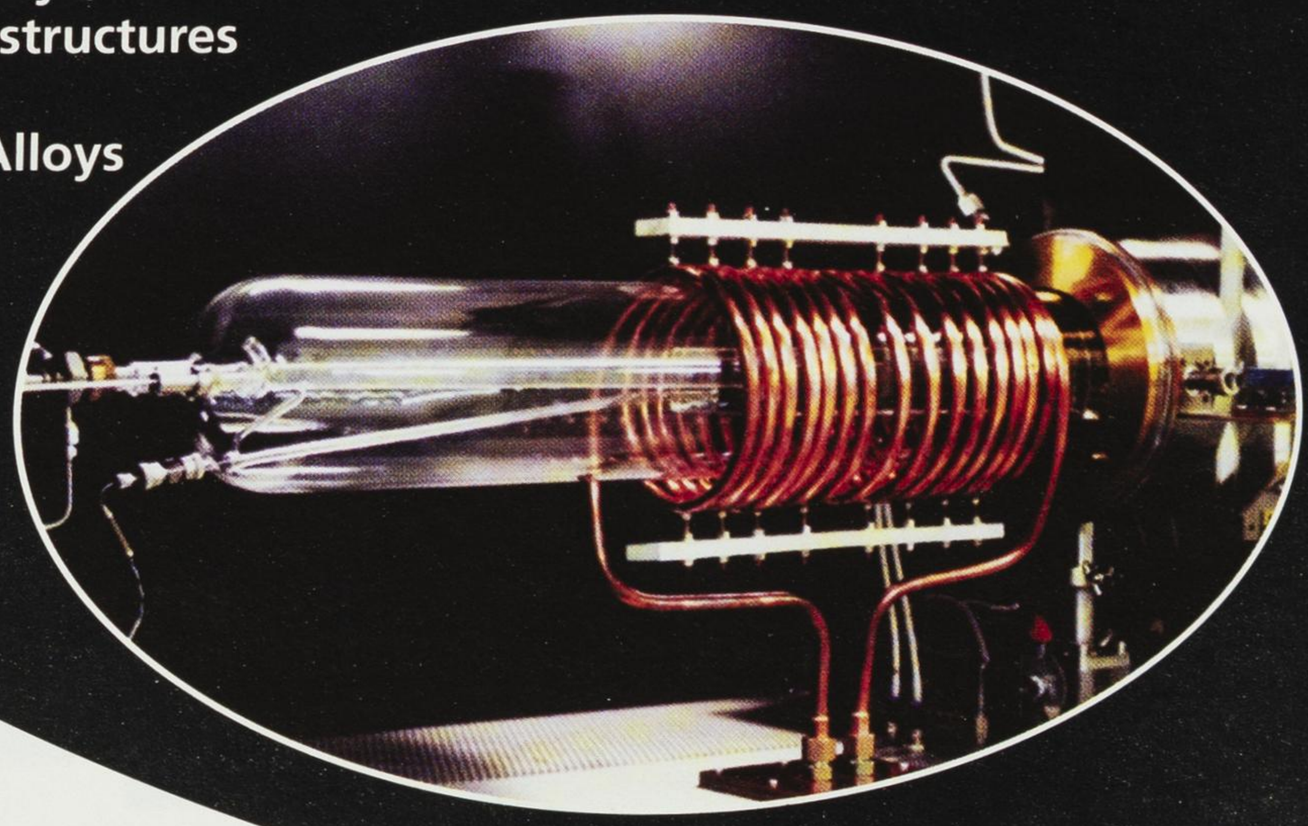

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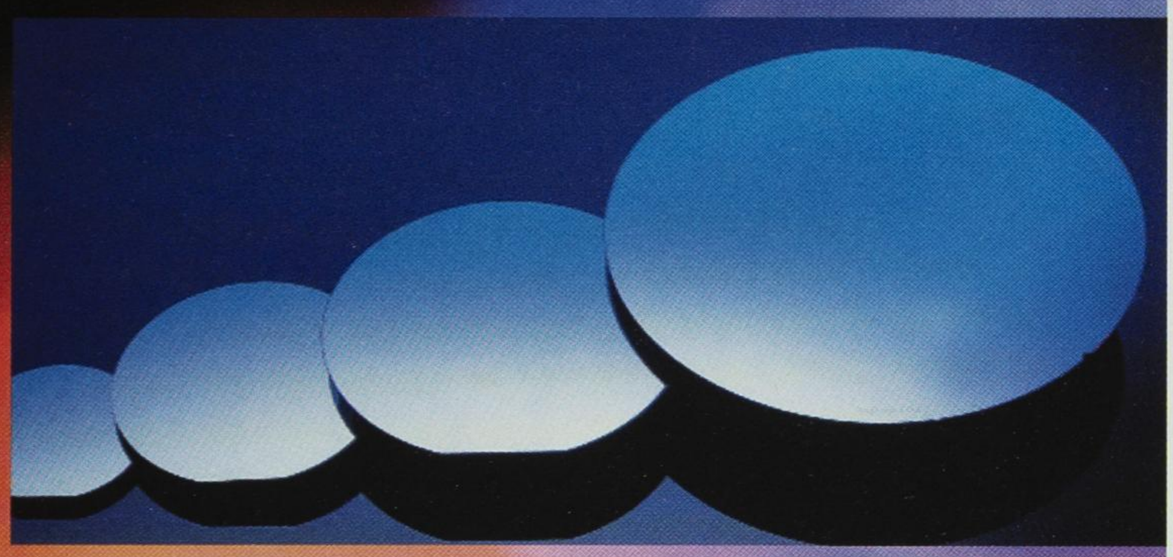

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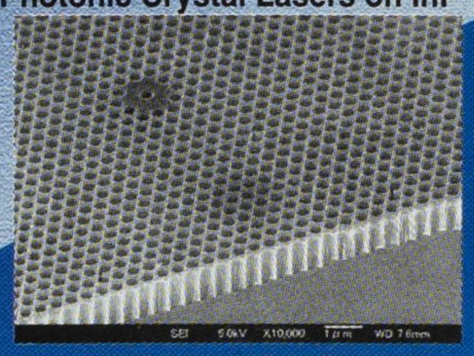

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MMICs provide the key for lower-cost automotive radar

Automotive radar has been heralded as the next big application for GaAs. **Marc Camiade** looks at this demanding area and the developments in MMIC technology that make GaAs the material of choice.

Many years have been spent on the development of automotive radar, with much of the progress based on knowledge gained during the evolution of defense radar. The objective is to increase safety by introducing sensors all around the vehicle that monitor the position of nearby objects. Medium-range detection in front of the car and short-range detection in all directions are required for automotive radar to be of most use. Millimeter-wave radar-based sensors are now a reality, and MMIC technology is helping to push the introduction of radar to more and more classes of vehicle. For several years, full MMIC solutions have been available, bringing the opportunity to increase the radar complexity and to move to real collision warning and avoidance systems (Camiade *et al.* 1999, 2000).

Car radar configuration

Among all of the future car accessories under development, the mm-wave radar-based sensor is now well advanced, and is becoming one of the main applications for GaAs-based MMICs. As shown in figure 1, the radar network configuration around the car is relatively complex, with more than eight sensors providing short- or medium-range detection.

The forward-looking radar system (FLRS) at 77 GHz allows a detection of objects 1–200 m in front of the car. The angular coverage is around ±5°. The commercially available versions are limited to the detection of moving objects. They are called autonomous cruise control (ACC) radars and are sold as comfort systems. The challenging next development steps consist of adding the detection and classification of fixed objects in order to build real collision warning and avoidance systems. These new generations require better performance including sensitivity and angular resolution, and higher architecture complexity to give multiple channels and fusion with different sensor technologies.

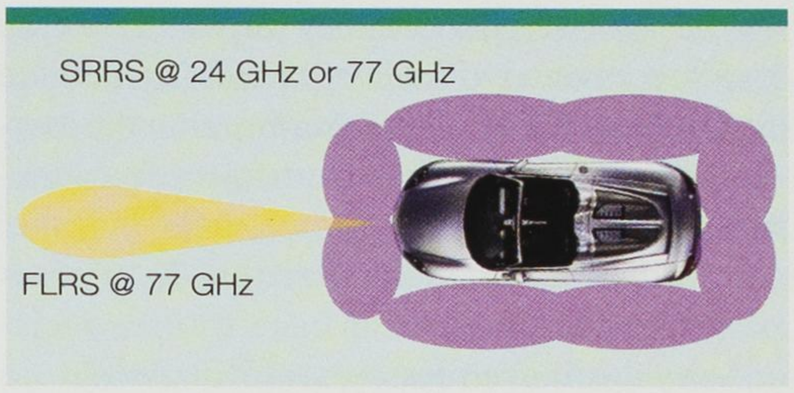

Fig. 1. FLRS has a range of up to 200 m, while multiple SRRS units provide detection of objects up to 20 m away.

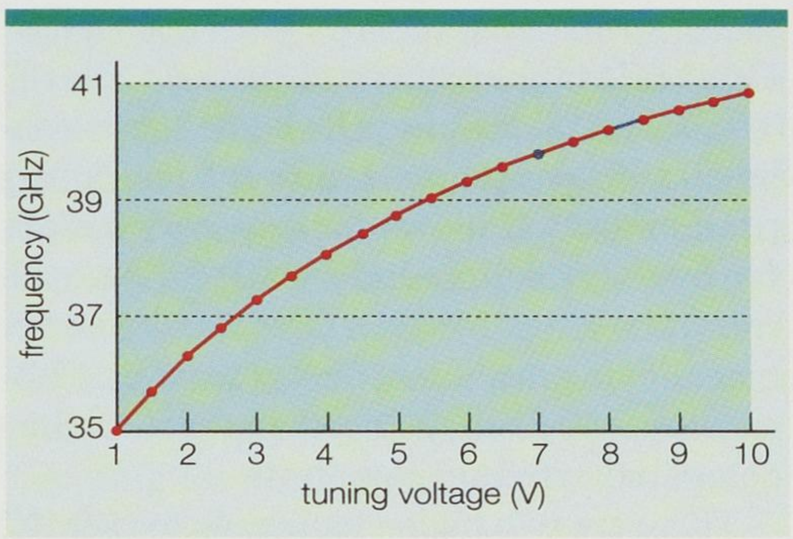

Fig. 2. Typical result obtained on fully integrated HBT-based VCO.

Short-range radar sensors (SRRS), also based on mm-wave radar, are put all around the car. The detection range is 0.1–20 m. The standard frequency for SRRS has yet to be decided due to important requirements on bandwidth (2–4 GHz). The most commonly used frequency is 24 GHz, but 77 GHz is also being considered. These sensors cover a range of applications such as parking and reversing aids (as fulfilled today by ultrasonic sensors), but also side object detection and the "stop and go" function for moving the vehicle forward in slow-moving traffic queues.

There are three main radar principles that can be applied to automotive radar: frequency shift keying (FSK) systems; frequency modulated continuous wave (FMCW) systems; and pulsed systems. Sensors based on these principles are "all-weather" solutions, providing very fast and accurate information on the speed, position and the size of detected objects. Thanks to continuing performance improvements such as radar sensitivity, multi-beam antennas, electronic scanning and sensor synchronization, more accurate and reliable information can be obtained, leading to many new possible functions.

GaAs MMIC-based solutions

The first generations of radar at 77 GHz were based on Gunn diodes. These are now being replaced in many systems by GaAs MMICs thanks to their wide availability, falling cost and high performance. This evolution is well advanced, and some MMIC-based radar versions are already in production for high-end cars. For a more widespread adoption of this concept by car manufacturers, MMIC technology has to show better performance at lower cost.

The main challenge to implementing MMIC-based automotive radar is to find a cost-effective solution fulfilling the following constraints:

- Operation at very high frequency;
- Solutions for high-volume production that do not need post-assembly tuning;
- Ability to withstand the harsh environmental conditions for automotive applications such as vibration, humidity and wide temperature variations;
- High integration level for building very small sensors;
- Relatively high level of performance.

All of these constraints when considered together define a tough set of boundaries for MMIC development, yet GaAs-based MMICs are helping to meet the performance criteria at acceptable costs. The existing processes (PHEMT, HBT and Schottky diode-based MMICs) are mature enough to provide high performance at the mandatory high-quality level for automotive radar. Due to the very high operating frequency of active and nonlin-

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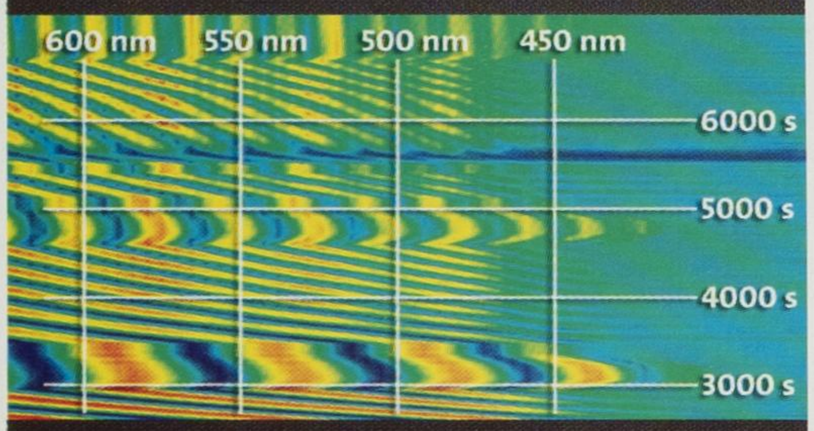

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ear devices, and the excellent quality factor of passive devices, many functions can be implemented. Silicon heterostructure technology is a candidate for future generations of automotive radar, but much development is needed to prove its feasibility in this application.

Considering the cost and the environmental constraints placed upon MMICs for automotive radar, the required performance level is relatively difficult to obtain. The key requirements can be summarized as follows:

- High sensitivity. This can be defined as the ratio between the output power and the noise figure. Noise is particularly important, as the radar receivers work at very low intermediate frequencies (IFs), and so minimizing the low-frequency noise and transmit-to-receive leakage is critical.
- A fully integrated VCO requires very low phase noise.
- Very-high-frequency stability when no phase locked loop (PLL) is used.
- Relatively high power at 77 GHz (12–17 dBm is required at the component level.)
- Very high switching speed for pulsed SRRS.

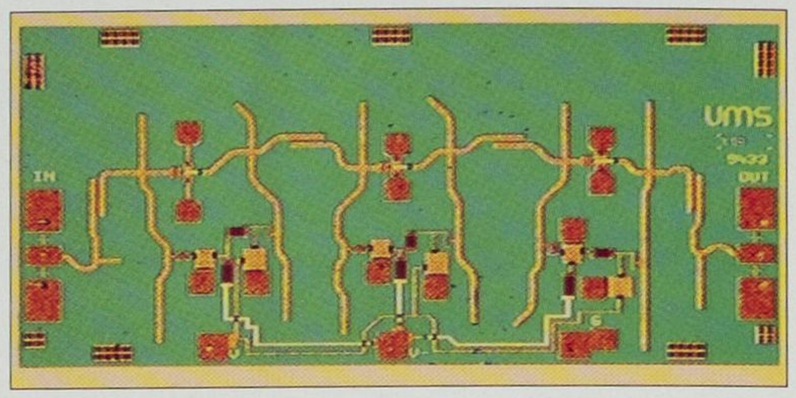

Fig. 3. A PHEMT-based three-stage LNA that forms part of a 77 GHz receiver.

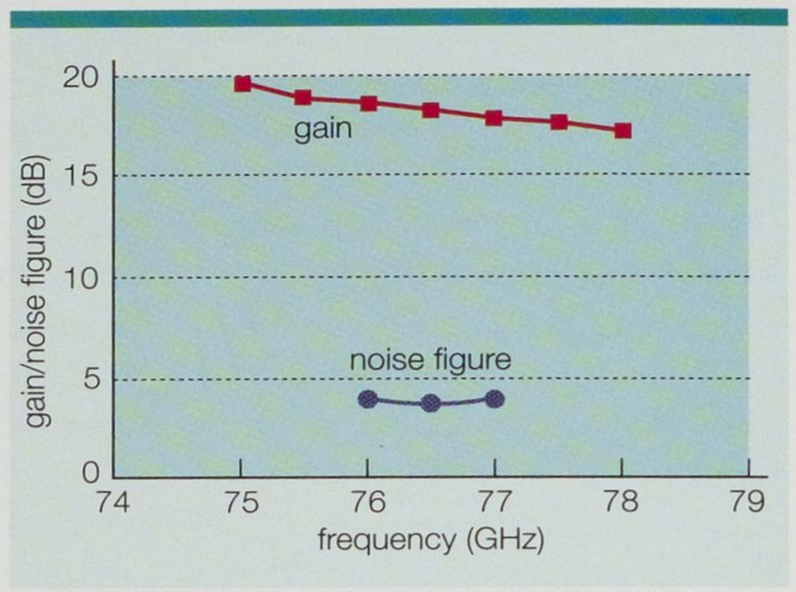

Fig. 4. The gain and noise figure from the low noise amplifier MMIC shown in figure 3.

Cost effective approaches

The cost of GaAs-based technologies is continually decreasing and is now at a few dollars per mm^2, which allows competitive solutions for trucks and high-end cars. It is now well recognized that MMICs have much to offer by removing the tuning during front-end fabrication, and also by improving yields when compared to hybrid solutions.

There are two main challenges for MMIC technology in this application. First, the chipset size must be minimized. This is a permanent objective of circuit designers, which begins with close co-operation with the radar designer in order to find the right architecture. It ends with a clever MMIC design done on the best technologies to optimize performance.

Second, the MMICs must be easily integrated into the front-end modules. This is not a trivial issue, due to the frequency range involved. Much work has already been done on interconnection techniques, allowing the MMICs to be assembled with automatic equipment (pick and place, and bonding). Also, in order to make MMIC solutions more attractive, a lot of emphasis is being placed on MMIC protection, such as passivation against humidity to avoid using expensive hermetically sealed modules. A number of packaging concepts are under test and evaluation. Surface mount technology is now practical at 24 GHz thanks to the latest developments in high-frequency plastic packages. However, at 77 GHz, packaging is still a challenging issue, despite the development at UMS of the multichip package in the W-band (MCPW) concept. This involves a package that integrates one or more MMICs where the W-band interconnects are performed using electromagnetic transitions. All other connections use standard microstrip or coaxial methods.

MMICs for frequency generation

The first generations of oscillators were fabricated using 0.25 μm gate length PHEMT processes. They were based on subharmonic generation and often used an external resonator. This was the only way to combine frequency stability, phase noise and good enough repeatability for production. The PHEMT-based VCOs developed at UMS for pulsed and FMCW systems operate at 12.75 GHz, are coupled to an external medium-Q resonator, and have a frequency tripler on the same chip. More than 300 MHz tuning range is obtained at 38 GHz with a phase noise in the range of –68 dBc/Hz at 100 kHz from carrier frequency.

Newer generations of oscillators are fabricated using HBT processes and give large improvements over the PHEMT-based VCOs, including better low-frequency noise characteristics and very high cut-off frequencies. VCOs can now be fully integrated, and pro-

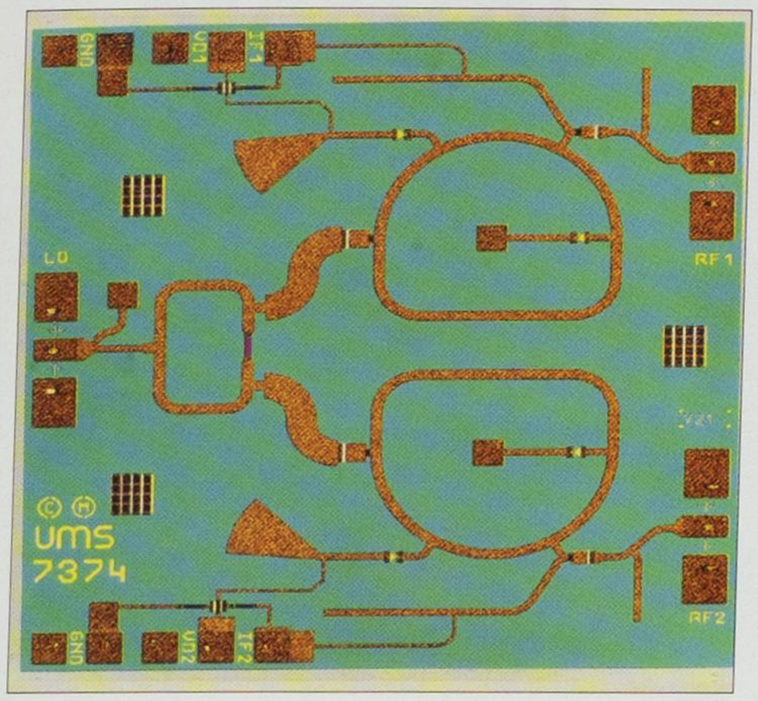

Fig. 5. The layout of a 77 GHz dual-channel mixer implemented using a MMIC with high-quality Schottky diodes.

vide better performance and the flexibility to include functions such as dual tuning ports and subharmonic output for PLL coupling. Figure 2 shows the results achieved on commercially available components. More than 5 GHz tuning range is obtained with a phase noise of about –85dBc/Hz at 100 kHz from the carrier frequency.

MMICs for reception

Low noise figures in the W-band are possible, thanks to PHEMT processes with gate lengths of 0.15 μm (0.25 μm is adequate for 24 GHz). As shown in figures 3 and 4, very good LNAs can be made at 77 GHz with a noise figure lower than 4 dB for an associated gain of 18 dB.

However, the limitation when using an LNA is the very low level of receiver saturation power. Indeed, there is no possible filtering between transmitter and receiver, and the leakage signal saturates the receiver if there is too much gain. Whatever the receiver principle, when a very low IF is needed, the main limitation is from the low-frequency noise of the devices. The three main contributors to low-frequency noise are: the AM noise of the source, the transfer of which to the IF depends on the AM rejection of the mixer and on the level of transmitter leakage; the low-frequency noise of the mixer; and the phase noise of the source in the presence of a high-level reflected signal with a long delay.

Mixers done on PHEMT processes, based on diodes or unbiased transistors, have very poor noise performance at very low IF (more than 30 dB at 100 kHz). Only MMIC processes providing high-quality Schottky diodes allow mixer noise figures in the same range as those obtained with Si-based diodes. Figure 5 shows the layout of a dual-channel mixer implemented using a MMIC with high-quality Schottky diodes. The result is a noise figure, at 77 GHz RF, of about 18 dB at 100 kHz IF.

MMICs for transmission

Today's PHEMT processes with 0.15 μm gate lengths give the necessary power in W-band with a reasonable chip size. MMICs for 77 GHz operation include a frequency multiplier and medium-power amplifier (MPA) with two outputs, one for the transmit antenna and the other for driving the receiver. Typical output power obtained with such a chip is 13 dBm. Power of up to 18 dBm is now proposed for transmit MMICs as standard products for Gunn diode replacement. Indeed, the most critical part of the first-generation automotive radar systems is the transmit function, and MMICs have already been demonstrated here as an efficient alternative to Gunn diodes.

New developments in this field include chip size reduction. MMICs that include the frequency multiplier have already been demonstrated in the development phase, with chip areas of approximately 4 mm^2 and 6 mm^2 for output powers of 13 dBm and 17 dBm, respectively. Another development is the optimization of the chip architecture for a better fit with front-end developments, such as new packaging concepts and an increase in the number of antenna beams. These new developments require changes to the frequency multiplier in the transmitter and the inclusion on the chip of part of the network for implementing the electromagnetic transitions for W-band interconnects.

Conclusion

Comfort and safety in vehicles are continually improving, and new systems such as mm-wave radars for cruise control and collision avoidance are proven concepts. Automotive radar provides a formidable volume market for GaAs MMICs, thanks to their already demonstrated potential to solve all of the main challenges such as cost, performance and integration level.

Further reading

Camiade *et al.* 1999 *IEEE MTT-S International Microwave Symposium Digest* volume 4.
Camiade *et al.* 2000 *European Microwave Week GaAs 2000 Proceedings* p280.

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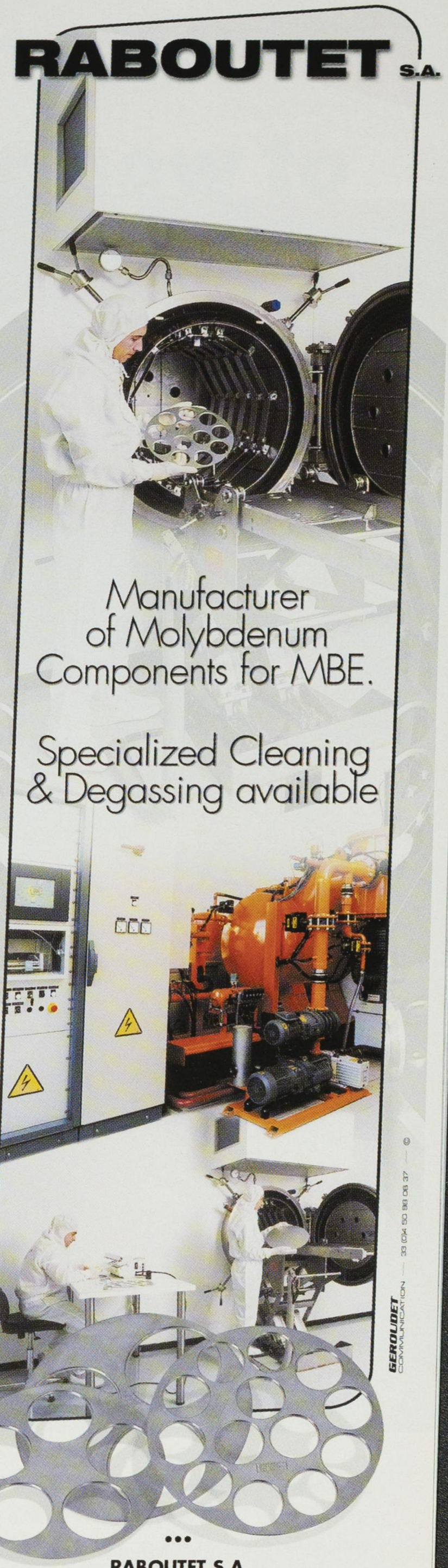

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GaAs-based devices: how to choose a suitable substrate

There are a number of companies that sell GaAs substrates grown by LEC or VGF, but what is the difference? **Russ Kremer** and **Steffen Teichert** provide some answers.

One of the more interesting questions that arises when considering the production of GaAs-based devices relates to the proper choice of substrate. Today's substrate suppliers currently mass-produce two types of wafer. These are based on two different crystal growth principles: the Czochralski process and the Bridgman process. With both methods it is possible to grow large-diameter, semi-insulating (as well as semiconducting) crystals for applications in micro- and optoelectronics.

The material is usually classified according to the crystal growth technology used in its manufacture. For the user, it is more meaningful to designate materials by their properties rather than by the production technology used. The two available substrate types are often called "low EPD" and "high EPD" material. The etch pit density (EPD) measures the dislocation density of the substrate. For semi-insulating GaAs, typical EPDs for material specified as high or low EPD are $<10^5/cm^2$ or $<10^4/cm^2$, respectively. However, EPD reflects only one of the properties of the materials. Other essential properties are also different, and these will be discussed below.

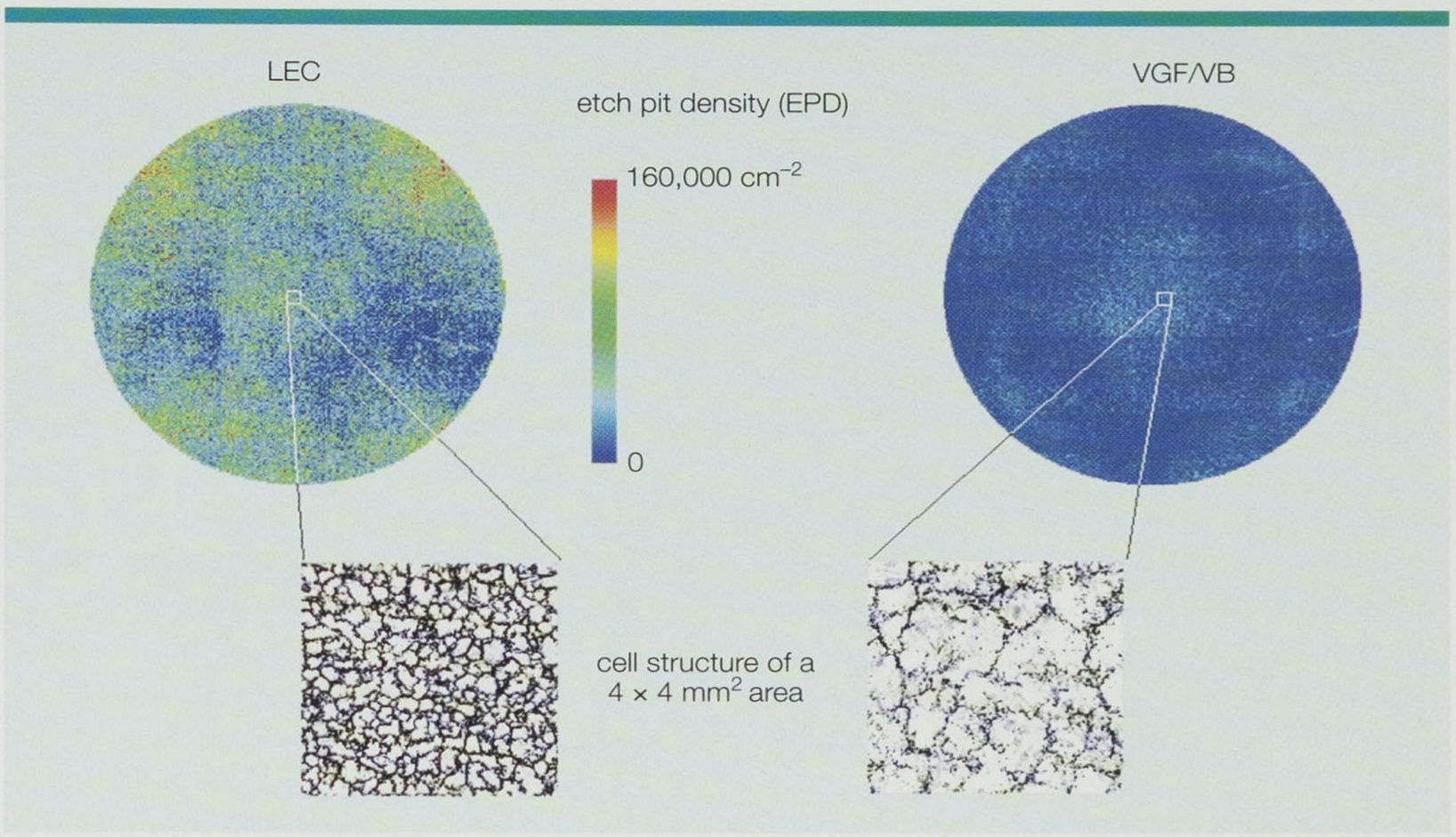

Fig. 1. Full wafer EPD mapping of LEC and VGF wafers (150 mm). The VGF/VB material has a lower, but less uniform, dislocation density than the LEC material.

Commercial production

As the only GaAs substrate producer with large-diameter production capacity in Czochralski and Bridgman processes, Freiberger Compound Materials (FCM) is uniquely positioned to compare and contrast the two types of material. Below is an analysis of the main differences and similarities of these substrate types. From knowledge of the properties of material produced using both methods, and additional commercial facts, it is possible to derive some conclusions for the proper choice of substrate material.

Before starting the technical discussion, some commercial issues should be mentioned. Today, over-capacity in the substrate supply chain tends to dictate wafer pricing. This results in average selling prices which are – for now – to some extent independent of the actual cost structure of wafer production. For each of the growth technologies, a reasonable volume of substrate production capacity for all diameters is available to the market. The return of a substrate shortage, as was seen in 2000, is not very likely in the near future. Only a complete switch of the industry to one or other of the crystal growth technologies would create a supply problem like the one seen in the past. The reason is simple: such a switch to a single technology would roughly halve the usable worldwide substrate capacity. However, the following discussion highlights the differences in the material properties with the consequence that there is a bright future for both Czochralski and Bridgman materials.

Crystal growth technology

In the Czochralski method, a seed crystal is placed over the melt held at a temperature close to the liquid–solid phase transition. After dipping the seed crystal in the melt, it is moved upwards under continuous rotation. The Bridgman method involves the directed solidification of a melt starting from the seed. The solidification direction can be vertical or horizontal. The movement of the liquid–solid interface can be accomplished in different ways: moving of the crucible in a static temperature field; or moving a temperature field with a static crucible. A typical Bridgman process is the vertical Bridgman (VB) technique, and the vertical gradient freeze (VGF) is a well known variant of the VB technique. Today, the actual processes used by the various companies that mass-produce substrates are mostly proprietary technologies based on modifications of the classical crystal growth techniques.

Based only on these short descriptions of the crystal growth methods, at first glance no limitations should be expected on the results obtainable by either of the technologies. The difference in the dislocation density, and

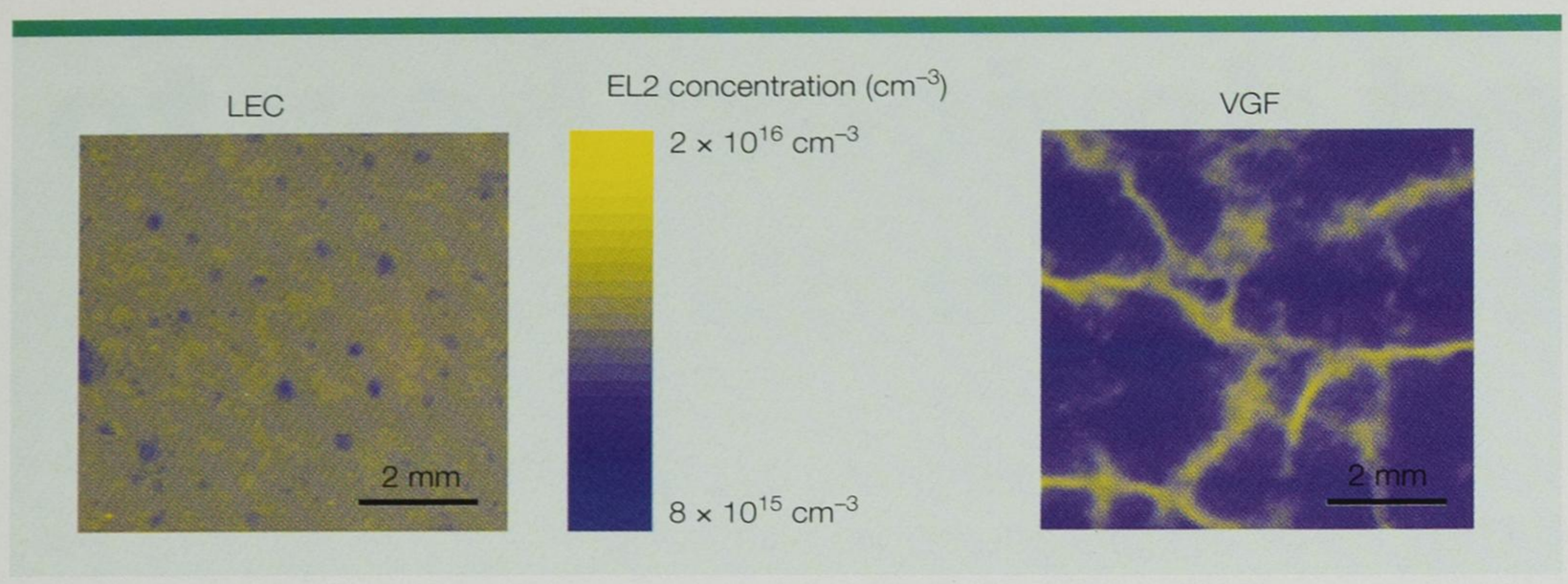

Fig. 2. Mesoscopic EL2 mapping of LEC and VGF wafers. The LEC wafers show a more uniform EL2 distribution and therefore more uniform electrical properties.

hence the EPD, seen in material grown by the two techniques is not an inherent result of the growth method itself, but is related to the method used to encapsulate the melt.

The vapor pressure of arsenic for a stoichiometric GaAs melt is roughly equal to 1 atm. Consequently, to ensure the stability of the melt, this arsenic pressure has to be maintained in the atmosphere surrounding the melt. There are two solutions: use of a closed hot wall system for the crystal growth; or encapsulation of the melt by boron oxide. In the case of the Czochralski method, boron oxide encapsulation is the best solution, resulting in the well known liquid-encapsulated Czochralski (LEC) process.

For the Bridgman process, both of the solutions mentioned above can be used. The crucial point for further discussion is the position of the encapsulating material in the case of LEC growth. The encapsulant, liquid boron oxide, is located on top of the melt surrounding the liquid–solid interface. This arrangement limits the minimum achievable temperature gradient close to this phase boundary. The temperature gradient is one of the main factors influencing the final dislocation density. For the Bridgman process, there is fundamentally no limit for the minimum temperature gradient. The EPD increases with increasing temperature gradient (or more precisely, with increasing curvature of the temperature field). However, the temperature gradient also influences the crystal growth rate, which must be kept in an acceptable range for economic and material quality reasons. The larger temperature gradient in the LEC process leads to a growth rate that is roughly twice that of Bridgman processes.

All other material properties that are not linked to the EPD are similar for both of the crystal growth technologies. For instance, the impurity concentration of semi-insulating GaAs is not determined by the crystal growth method, but by the equipment quality and knowledge of the production staff.

Beyond etch pit density

One remarkable consequence of the dislocation density in the crystal immediately after growth is the size of the parameter window that the dislocations make available for post-growth thermal treatments of the bulk crystal. The purpose of such annealing procedures is a further homogenization of the crystalline bulk properties. The presence of excess arsenic and the distribution of electrically active complexes like EL2, which is related to the electrical resistivity of the bulk material, are influenced by post-growth annealing.

The perfect result would be a crystal with an extremely narrow resistivity distribution on a mesoscopic size scale. One annealing condition that produces material close to the desired ideal result consists of a rather fast cooling of the crystal from some maximum temperature down to room temperature. However, fast cooling results in a situation similar to the case of rapid growth of the original crystal. Because of the high thermal capacity of the ingots and the limited thermal conductivity, a temperature gradient builds up inside the crystal, resulting in a strain field. In order to reduce this strain field, the material reacts with the formation of an appropriate dislocation density. High EPD material therefore allows a faster cooling speed than the low EPD material, as the strain-reducing dislocations are already present. Consequently, the mesoscopic homogeneity of the electrical properties is much better for high EPD than for low EPD material. To illustrate this behavior, the EPD and the corresponding EL2 defect concentration are plotted in figures 1 and 2, respectively. The EL2 distribution gives indirect information about the distribution of the electrical resistivity of the bulk material.

Although a detailed discussion will not be entered into here, in addition to the electrical properties, mechanical wafer properties are also sometimes discussed in connection with the EPD, especially the breakage strength and slip line generation. However, investigations using low and high EPD material at FCM have shown that the breakage strength is related only to the surface properties, and no correlation to the EPD was detected (Kleinwechter *et al.*). Slip line formation is often discussed as a result of residual strain in the wafers. Here, our experiments proved that the residual strain in LEC wafers is one order of magnitude less than the strain needed for the formation of slip lines.

To summarize this section, the two GaAs substrate types available on the market both have one significant advantage (and consequently one disadvantage). VGF/VB material has a lower dislocation density, but LEC wafers show more uniform, mesoscopic-scale electrical properties. All other properties of interest are more or less similar for the two growth techniques.

Substrates and devices

So, what is the impact of the above on the choice of semi-insulating material for different applications? Microelectronic circuits are typically designed using MESFET, HEMT or HBT structures on semi-insulating GaAs substrates. Semi-insulating substrates reduce parasitic losses in devices operating at high frequencies. MESFETs and HEMTs are both unipolar devices; there are no minority carriers, and recombination is not an issue. HBTs are bipolar, and contain *pn* junctions. According to most GaAs forecasts, MESFET technology will gradually lose significant market share to both HEMT and HBT devices.

While many of the substrate technical requirements are similar for these different types of devices, there are some significant differences. For example, since HEMTs and HBTs are epitaxial devices, both require very high quality, epi-ready surfaces, free of particles, and with well characterized and consistent oxide layers. For HEMTs, the resistivity of the substrate can influence the turn-on voltage of the device. As a result, fluctuations in the resistivity, either across a wafer or from wafer to wafer, can cause variations in the performance of the devices being produced. Thus for this family of structures, the stability and uniformity of the substrate electrical properties (on both microscopic and mesoscopic

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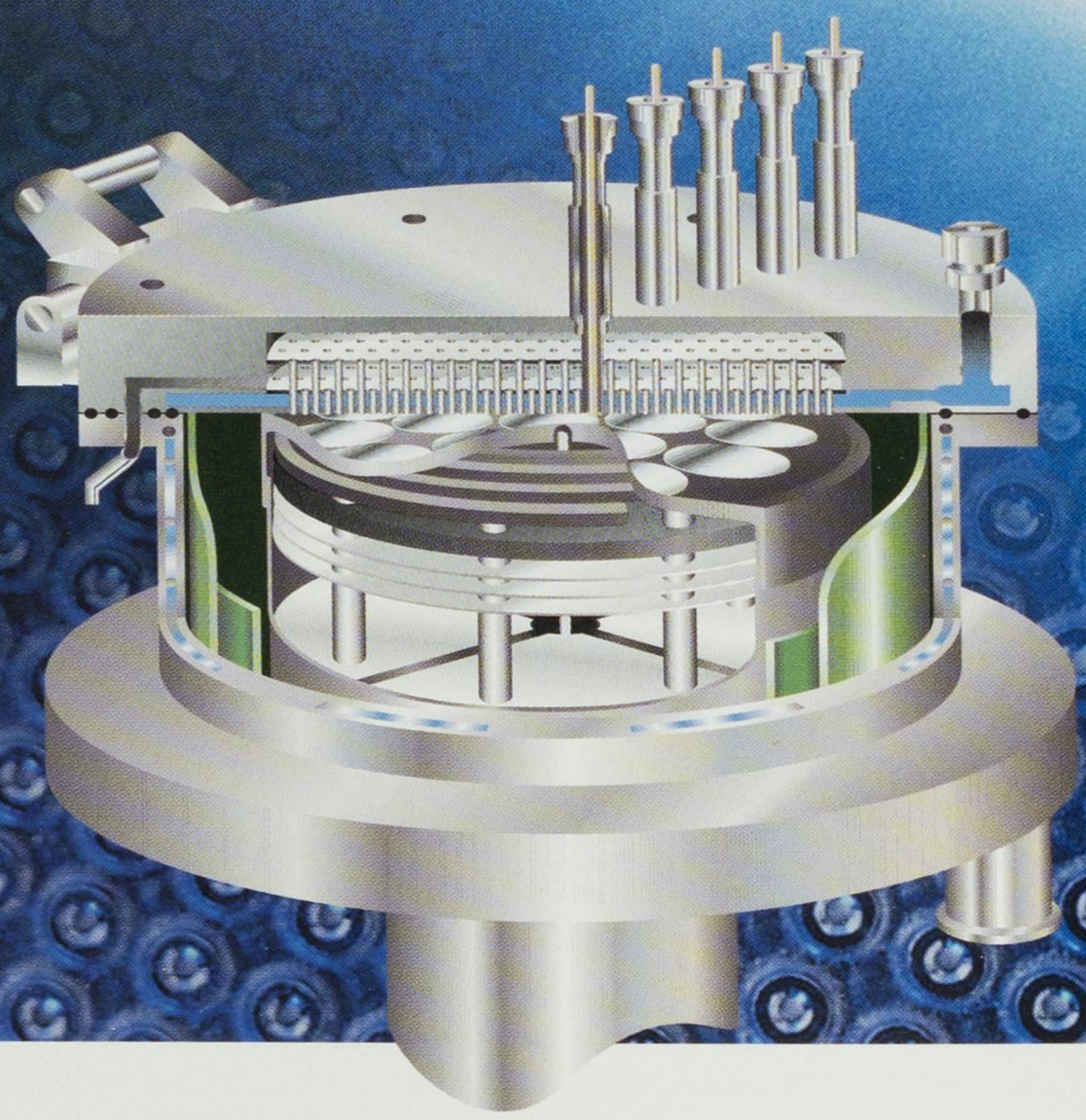

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Microelectronic devices			
Device	*Device mode*	*Characteristics/current density*	*Preferred substrate*
MESFET	unipolar	majority carrier	LEC
HEMT	unipolar	majority carrier	LEC
HBT	bipolar	minority carrier/medium	VGF/VB or LEC

Table 1. The uniform distribution of the EL2 defect (and therefore the resistivity) in LEC wafers makes them an obvious choice for HEMTs and MESFETs.

scales) are critically important.

Uniform substrates are also important for HBTs, but to a lesser extent. With HBTs, the most important substrate requirement is that the leakage through the substrate between different mesa-isolated devices must be extremely low. This is typically accomplished by using substrates with very high resistivity. For any bipolar device, it is important that the substrate does not contribute anything to the structure that can lead to device degradation through unwanted carrier recombination.

Device degradation mechanisms

It is useful to examine how various device structures degrade. For HBTs, recombination at the emitter-base junction can create defects. As the device ages, the number of these defects tends to grow, resulting in a gradual decay of the transistor gain. This process is driven by the current injection, and appears to be unrelated to any dislocations in the substrate. Note also that this gradual degradation is not the same as the sudden degradation, often referred to as the burn-in effect, that has occasionally been reported in HBTs (*Compound Semiconductor* April 2002 p69). There is no clear evidence or proposed mechanism that this sudden degradation is initiated by substrate dislocations either. However, there is a perception that HBTs grown on VGF/VB substrates are slightly better in this regard, especially in cases where the injection current is high. It should be noted that both LEC and VGF/VB materials are successfully used for HBT production.

For HEMTs and MESFETs, the degradation mechanisms are completely different from those in HBTs. Since the devices are unipolar, recombination at dislocations or other defects does not play a role. Thus for these devices, factors such as the uniformity of resistivity and the surface quality for epitaxy are the most important criteria for determining which type of substrate to use.

Therefore, the choice between LEC and VGF/VB substrates often depends on the details of the device to be built. For unipolar devices such as HEMTs and MESFETs, the better uniformity of LEC material might make it the preferred choice. For bipolar devices, either type of substrate may be used in cases where the injection current is low or moderate. Only for devices where the injection current is very high (for example, optoelectronic devices such as laser diodes) is it necessary to use VGF/VB substrates. These options are summarized in table 1.

GaAs wafers beyond 150 mm

Today the market is using a mixture of 100 mm and 150 mm (4 and 6 inch) GaAs wafers, with most major users either already at 150 mm, or moving to that diameter. In the future, there will be a need for even larger diameters. The growth of 200 mm (8 inch) wafers has already been demonstrated, and FCM has successfully grown 200 mm GaAs ingots by both the VGF and the LEC methods (Seidl *et al.*; Stenzenberger *et al.*). Evaluation of these initial 200 mm crystals indicates that the above discussion of the substrate properties will remain valid for the next generation of GaAs substrates. As with any significant advance, the processing technology required to produce 200 mm diameter wafers is again very challenging to the substrate suppliers. However, there appears to be no visible ultimate limit for either of the two main GaAs crystal growth processes. Therefore, the conclusion is straightforward: for the next-generation diameter as well, the users of GaAs substrates can expect to have a choice between LEC and VGF/VB material. They will also be able to select wafers based on the actual needs of their devices.

Further reading

A Kleinwechter *et al.* 2001 *GaAs Mantech Digest* p57.
A Seidl *et al.* 2001 *J. Cryst. Growth* **225** 561.
J Stenzenberger *et al.* 2003 *J. Cryst. Growth* **250** 57.

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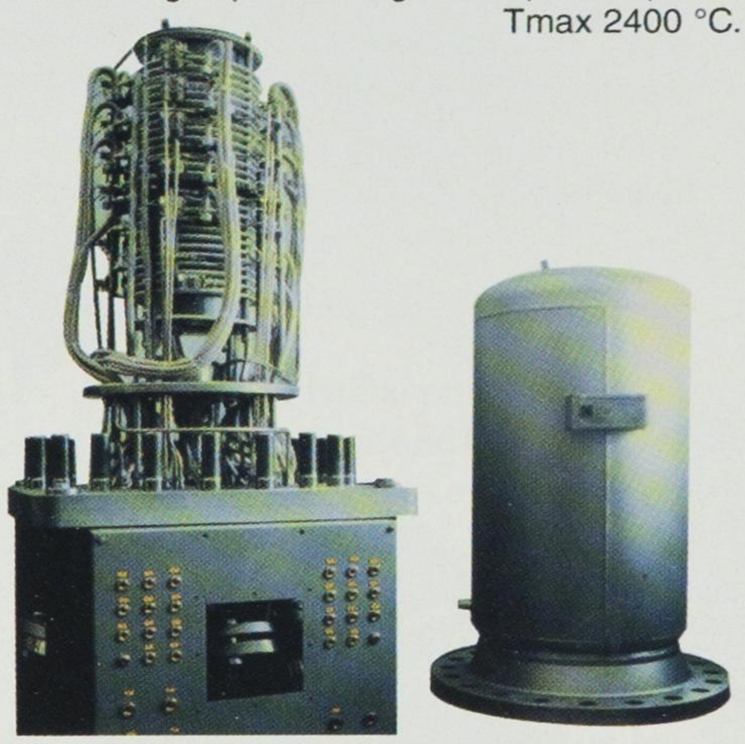

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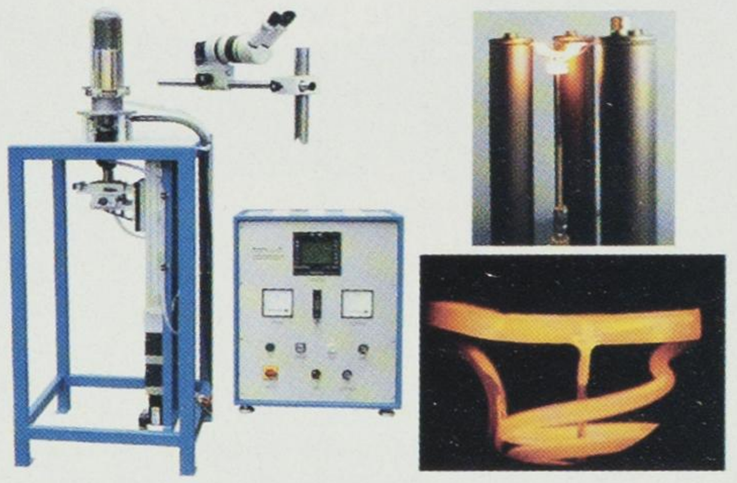

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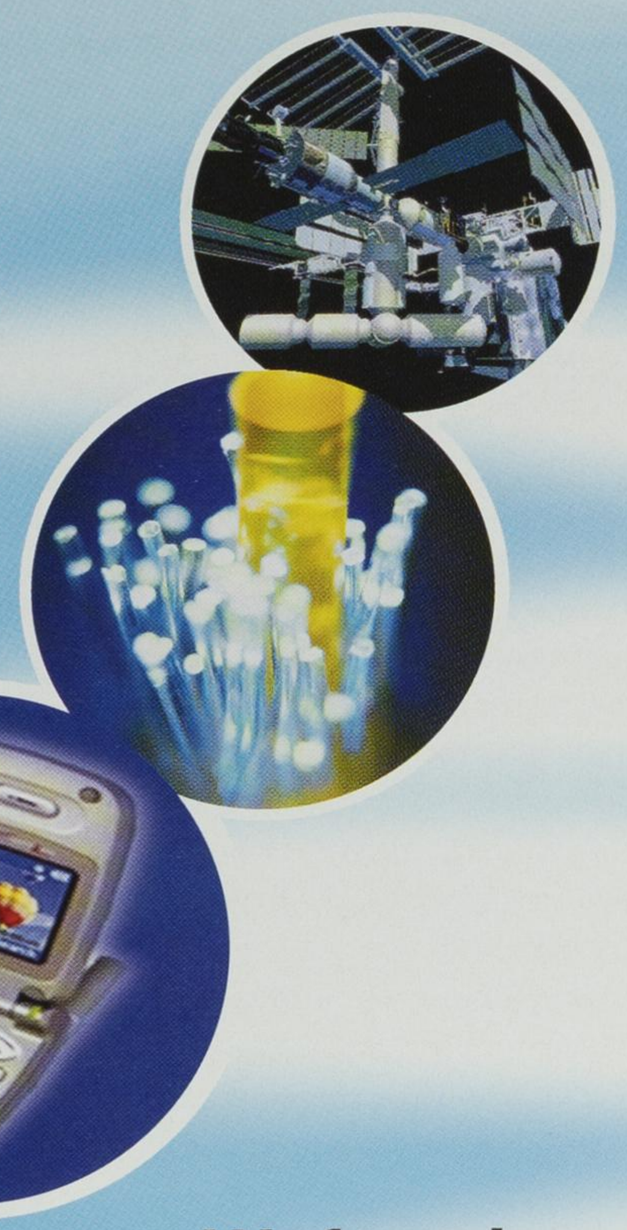

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China seeks rapid progress in electronics and photonics

In the first of a series of articles on the emerging compound semiconductor industry in the world's most populous country, **Sally Croft** takes a look at the prevailing business climate in China.

China today is increasingly determined to compete in the global technology market. Government targets for chip production alone are already set as 20 billion chips by 2005 and 50 billion chips by 2010. Large as these numbers are, they are expected to satisfy only around 30% of the domestic market and 2% of the international market in 2005, with the corresponding figures for 2010 being 50% and 5%.

However, unlike in the silicon industry, where both the Chinese government and commercial companies now seem to have accepted that the country's main role will lie in low-cost manufacturing, there is a strong determination that China will play a leading role in compound semiconductor research, development and production. As the information superhighway rolls out across this vast country, many of the traditional government-run research centers or their offspring are being positioned in a more commercial environment, and doors are opening for collaboration with foreign companies.

"We're currently seeing tremendous amounts of money going into the electronics and photonics industries, through government funding, direct inward investment, joint ventures and also domestic private venture capital," said Gary Ditmer, Asia and Japan business manager of Oxford Instruments Plasma Technology (see box on p42). "Our business has doubled in each of the last three years, and China is now our largest single-country customer in the Asia-Pacific region."

OPTO TECH CORPORATION

Giant LED screens are among the products manufactured by China's growing compound semiconductor industry.

Government programs

Research funding in China comes largely from government ministries. However, there is now growing investment from companies active in the marketplace, as well as other venture funding as companies decide to diversify.

The Ministry of Education funds the universities, and the Chinese Academy of Sciences (CAS) runs, for example, the Institute of Semiconductors, the Institute of Electronics and the Institute of Physics. Other funding sources include the Ministry of Information Industry (formerly the Ministry of Posts and Telecommunications) which has large institutes in Beijing and Wuhan, the Department of Commerce, and the Military Equipment Department.

Targeted government research programs are launched periodically and recent examples include:

- 863 program – a high-tech R&D program running from 1986 to 2010 with a broad remit including development in optoelectronics; some RMB 3.5 billion ($420 million) is allocated for 2001–2005.
- 973 program – a key basic research plan allocating RMB 2.5 billion for 2001–2005, with the main beneficiaries being CAS, Tsinghua University and Beijing University.
- 985 program – an information technology and nanotechnology initiative for 2001–2005, primarily directed into the universities.

Over the last decade, however, there has been distinct encouragement for research establishments to move more clearly into the commercial arena and to generate spin-off companies. An early, and very successful, example is Wuhan Telecom Devices Inc (WTD), established in 1980 as a joint venture between the Wuhan Research Institute of Posts and Telecommunications (WRI) – which had its origins in the national telephone company – and Corning Lasertron. New young companies such as Accelink Technologies, founded in January 2001 and located adjacent to WRI, and Wuhan Huagong Genuine Optics benefit from this clustering of skilled people and technology. China is now investing heavily in "Silicon Valley" style research clusters, such as the Optics Valley of China (OVC) in Wuhan.

Research clusters

Wuhan, the capital of Hubei province, is the largest city in central China and has a population of around 7 million. It has evolved into a major science and technology center, and today hosts 35 universities, 726 scientific R&D institutes and more than 30,000 industrial companies largely focused on high-tech and industrial sectors. Both WRI and a national optoelectronics technology center are located in the city.

The OVC initiative is intended to optimize the development of a firm base for the optoelectronics and information industries in Wuhan. Objectives set out in the State 10th five-year plan include establishing a dedicated 50 km^2 industrial zone; attracting relevant companies and promoting collaboration and/or mergers with Chinese or foreign optoelectronics companies or consortia; promoting quality products; and establishing first-class R&D and training facilities. Promoting fast technology transfer from academia to industry is also on the agenda.

OVC at Wuhan is focused primarily on optical communication and optoelectronics, with fiber-optic and compound semiconductor device manufacturing identified as key goals. At Changchun, located in the far north-east of China, an additional "Optical Valley" is being created, centered on compound semiconductor materials and devices, consumer optoelectronics, and monitor and display devices. In the region around Guangzhou and Shenzen, near Hong Kong, the Guangdong Photon Valley is becoming home to companies engaged in areas like high-volume LED man-

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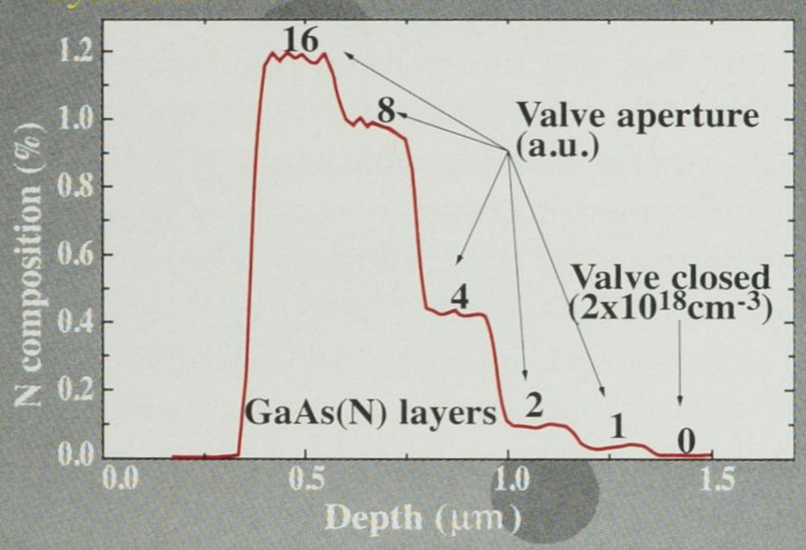

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An equipment supplier in China

Oxford Instruments Plasma Technology Ltd, based near Bristol, UK, began selling its range of plasma-processing equipment into China in 1983. In its first decade it sold about 40 systems through representative agents in the country. The company believes that the key to success in China involves having an array of access points to the market. While continuing to work through an agent for sales and service, the parent company Oxford Instruments opened its own representative office in Beijing in 1997. In 2001, the Plasma Technology division employed a direct sales manager, Mawson Meng.

"Our ability to install up-to-the-minute equipment and provide quality training for local staff is a key factor in our business," said Gary Ditmer, the company's Asia and Japan business manager, who is based in Shanghai. "Although customer service has always been important, we've really noticed in the last few years that it has become a much bigger factor in the purchasing decision. We have a small team of regionally based field support and process engineers, and customers also benefit from the local service provision undertaken by the company's agent, Silicon International. These resources are backed by technical support from the company's UK headquarters."

In 2000, Oxford Instruments Plasma Technology installed some £1.4 million ($2.2 million) worth of R&D and production systems in China. With the establishment of direct sales in 2001, 16 systems were installed and, despite a very challenging market, a similar level of sales was achieved in 2002. The company sells both to production users and to highly respected researchers and institutions, including Tsinghua University, WTD, Accelink, FangDa, and the Hebei Semiconductor Research Institute, which works on MMICs and wireless applications.

"One of the secrets of success in China is a multifaceted approach," said Ditmer. "As well as having good products and a prompt and efficient customer service operation, we've found the personal approach is critical. This is achieved through our strong relationship with our agent and through their and our own staff getting to know and developing mutual trust with our clients. Working closely with people is vital for success in China."

ufacturing and device packaging. Established local companies like Shenzhen Photon Technology, a fiber-optic components manufacturer, are already in place alongside significant inward investment from companies such as Philips and JDS Uniphase.

Promoting growth

These sponsored industrial initiatives encourage international investment through tax incentives and a readily available infrastructure. Their success demonstrates the attractiveness of China today as a manufacturing hub. A decade ago, Western companies setting up R&D operations in China were to a large extent going out on a limb – investing resources as "a gift to the government", as one leading player has described it. Equipment suppliers like Oxford Instruments Plasma Technology also found themselves advising on the necessary supporting infrastructures like cleanroom facilities and health and safety procedures, as well as helping researchers keep up to date with technical developments.

While some of these difficulties remain, the picture is changing rapidly. China today has a large number of highly skilled high-tech graduates and, while leaving for work or further studies in the US or elsewhere still exercises a strong pull for many, a significant proportion of those who do leave return to China a few years later. This growing pool of highly trained but relatively inexpensive employees (thanks to low local living costs), government tax incentives for foreign companies and a huge potential market means that the compound semiconductor industry is soaring.

"China is investing massively in compound semiconductors and the internal market is both large and highly competitive," said Ditmer. "I think it will be a few years before the country is a strong player in the global marketplace, but it's becoming increasingly clear that in technology terms, China is catching up fast and is probably now just a couple of years behind the West."

Sally Croft is a freelance writer based in the UK.

China exploits technology

With government support and private investment, commercial compound semiconductor ventures are becoming more common in China, writes **Tim Whitaker**.

The commercial compound semiconductor business in China is relatively immature, although its growth has accelerated in recent years. With extensive government support (see previous article), this trend seems set to continue. Due to its low labor costs, China has many packaging companies, particularly in the LED industry. Now, Chinese scientists and investors hope to exploit device-related technology.

Although commercial activity is just emerging, various research groups have experience dating back more than 25 years. However, the majority of the research work had been concentrated on material development rather than device optimization. Holger Juergensen of Aixtron estimates that there are more than 40 groups in China working in the field of compound semiconductors, with more than 50 MBE and 70 MOCVD systems (including around 40 commercial MOCVD reactors) installed throughout the country. Until recently, the lack of financial resources and production equipment made it quite difficult for the researchers to exploit their work.

In the past, work has concentrated on the development of laser devices for telecommunication or military applications. Today, however, most new companies are jumping into the high-brightness LED market, and are especially focusing on nitride LEDs. Juergensen says that the situation is similar to the status of Taiwan six or seven years ago when it entered the AlGaInP LED market (which it now dominates), but he feels that China will catch up with the rest of the world very quickly.

China already has a fledgling compound semiconductor supply chain, with companies manufacturing metalorganic precursors, and GaAs substrates and epiwafers. In addition, it is one of the world's leading suppliers of gallium (see p21).

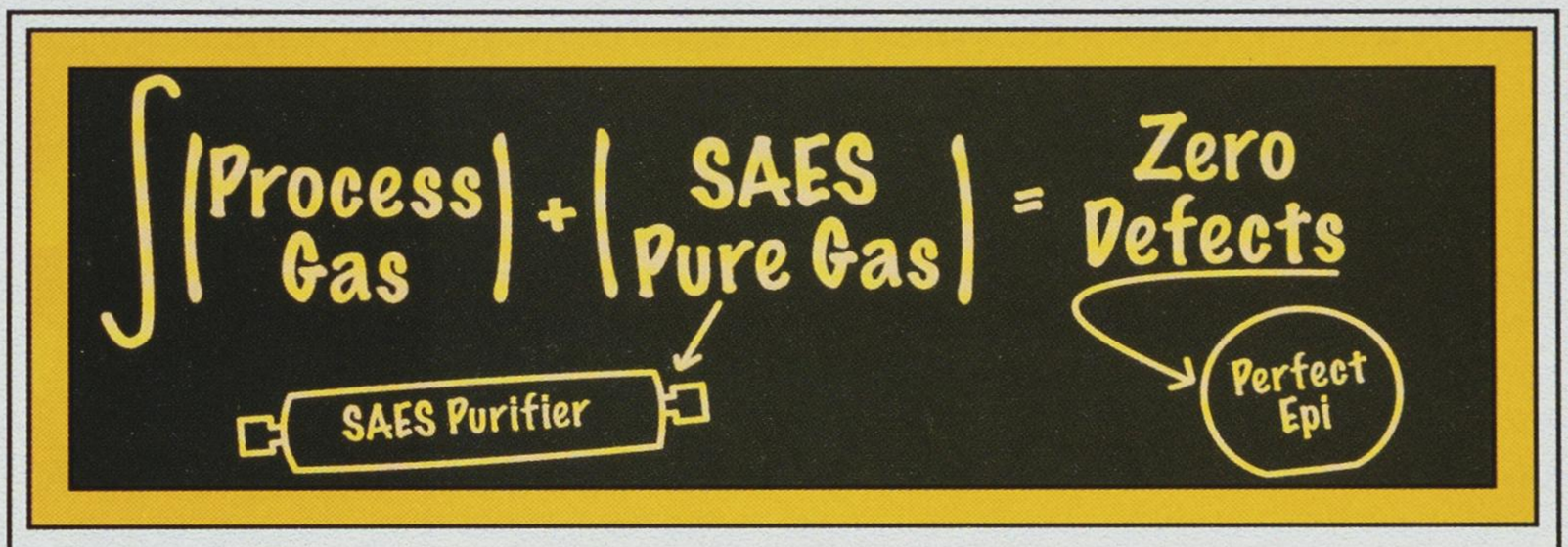
LED manufacturing

While Taiwan now dominates AlGaInP chip production, and is making rapid progress in the InGaN market, China has skipped the relatively mature AlGaInP field and is instead targeting GaN-based devices. Jiangxi Fangda Focus Information Material, a joint venture between China Fangda Group and Nanchang University, was formed in July 2000. Its main products are GaN-based epiwafers, and in late 2001 it ordered a series of MOCVD production systems from Thomas Swan for its facility in Nanchang. Shanghai LanBao Photoelectric Materials has ordered MOCVD machines from both Emcore and Aixtron. Established in September 2000, the company is a spin-off from the CAS Institute of Physics, and supplies blue and green GaN-based epiwafers and chips.

Shanghai Beida Blue Light is a spin-off company from Peking University supplying nitride epiwafers and UV, green and blue LED chips. The company is a customer of Aixtron and describes itself as the first specialized company for producing III-nitride semiconductors in China. Xiamen San'an Electronics plans to establish a large R&D and manufacturing site for high-brightness LEDs in Xiamen. Typical of some of the Chinese companies that become involved in compound semiconductors without prior experience, San'an Group is major producer of steel, pig iron and electricity.

Telecom and laser suppliers

A joint venture between Wuhan Research Institute (WRI) and Corning Lasertron, Wuhan Telecommunications Devices is the leading supplier of optoelectronic devices in China. Its products, which are almost all sold to Chinese telecom equipment manufacturers, include 850, 1310 and 1550 nm laser diodes; LEDs; detectors; transmitter, receiver and transceiver modules; and 980 nm pump lasers. The com-



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pany estimates it has an annual capacity of 5.5 million pairs of optoelectronic devices and 1.5 million optoelectronic modules.

Hi-Tech Optoelectronics was established in 1999, and is a spin-off from CAS Institute of Semiconductors in Beijing with investment from China Energy Conservation Investment Corp. It manufactures laser diodes at a range of wavelengths from 635 to 1650 nm, as well as fiber-coupled CW modules and photodetectors, and recently introduced 20 W laser diode arrays operating at 780–830 nm.

Tsinghua University

An example of one of the many academic facilities looking at compound semiconductors, the State Key Laboratory on Integrated Optoelectronics in Tsinghua University (established in 1991) carries out epitaxial growth using MBE and MOVPE. The group investigates integrated optoelectronic devices and their applications in fiber-optic networks, and recently developed a 2.5 Gbit/s gain-coupled DFB laser integrated with an EA modulator.

The lab has made lots of important research achievements and grown into a major research base for optoelectronic materials, devices and their applications in optical fiber communication systems and networks in the Chinese mainland. It is not yet involved with commercial manufacturing or spin-offs related to compound semiconductors.

The lab also has a nitride program investigating blue LEDs and HEMTs. With funding from Shandong Incalcu Group, the university's "high-brightness blue LED" project developed high-brightness InGaN/GaN MQW blue LEDs with an optical power of 1.5 mW at 470 nm (*Compound Semiconductor* March 2002 p9).

Material suppliers

As mentioned above, China has several commercial material suppliers. Jiangsu Nata Optoelectonic Material Co Ltd is a spin-off from Nanjing University, which began developing metalorganic precursors such as DEZn and TMI in 1986. The company was established at the end of 2000 and offers around 20 types of precursor, which are growth tested on the company's MOCVD system.

Also in late 2000, the CAS Institute of Semiconductors in Beijing announced plans to team up with four other investors to form Compound Crystal Technology to commercialize the institute's semi-insulating GaAs technology. The company has injected around RMB 540 million ($65 million) to establish a production line with a capacity of 100,000 wafers per year, and will also offer GaAs- and InP-based epiwafers.

A spin-off from the CAS Institute of Physics, Advanced Chinese Epitaxy is set to become the first company in China to offer GaAs-based epiwafers. The Beijing-based company, set up in partnership with Ningxia St Edenweiss, bought a V100 production MBE system from Thermo VG Semicon last year. "Our MBE work started here over 20 years ago," said Junming Zhou, head of the MBE laboratory at the Institute of Physics and president of Advanced Chinese Epitaxy. "Initially, the V100 will be used to prepare microwave device material for which there is an ever-increasing demand in our country."

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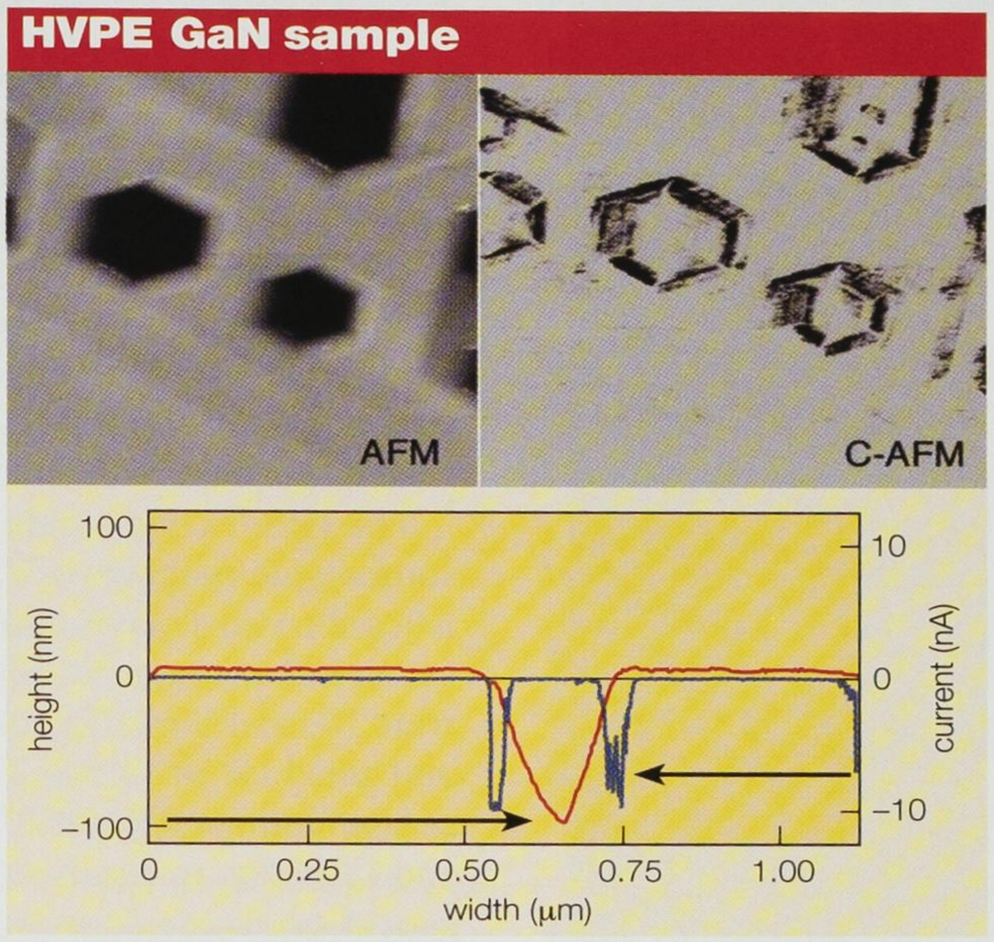
C-AFM exposes GaN's weaknesses

GaN-based devices still suffer from excessive current leakage, due in part to extended defects in the material, and point defects which are not well understood (*Compound Semiconductor* August 2001 p23). To take full advantage of GaN-based devices, a better understanding of this excessive leakage has become necessary. A team at Virginia Commonwealth University has used the technique of conductive atomic force microscopy (C-AFM) to investigate how the local conductivity of GaN films is related to morphology (*Appl. Phys. Lett.* 2003 **82(12)** 1890). They have observed enhanced conductivity for prismatic planes found around islands on as-grown samples, and on the edges of pits formed by post-growth chemical etching.

C-AFM correlates electrical properties with surface topography by simultaneously acquiring AFM and current images of a surface. The AFM is operated in contact mode with an electrically conductive probe, where current between the tip and sample is measured when a DC bias is applied. Typical currents range from 10 pA to 10 nA for voltages below 10 V.



AFM topography and C-AFM current images from a $1 \times 1\ \mu m^2$ area of an etched HVPE GaN sample. The linescan shows that current is measured at the edges of the pits.

In the case of etched HVPE-grown samples, AFM images show hexagonal pits produced by the etching of defect sites on c-plane GaN. Simultaneous C-AFM images show detectable current only at the edges of such pits for forward-bias voltages below 4 V. This indicates that crystallographic planes tilted with respect to the c-plane have a significantly higher conductivity than surrounding areas. Although still under investigation, possible mechanisms for this enhanced electrical activity include extended defects (which has been observed by others), surface states, and modified Schottky barrier heights on prismatic planes.

Texas Tech research group gets deeper into the UV

AlGaN is now considered the material of choice for light sources and photodetectors operating in the deep ultraviolet. Until now, device fabrication was limited by the difficulty of producing p-type layers of large-bandgap AlGaN. A number of papers by a research group at Texas Tech University show that this limitation can be overcome by the use of short period superlattices (SPSLs) consisting of AlN barriers 3–5 monolayers thick, and $Al_{0.06}GaN_{0.94}$ QWs 2–3 monolayers thick. SPSLs containing as many as 400 well-barrier pairs were grown reproducibly and with excellent structural and optical properties. When doped with Mg, hole concentrations as high as $1.1 \times 10^{18}\ cm^{-3}$ at room temperature were reported in superlattice layers with an average AlN content as high as 65% (*Appl. Phys. Lett.* 2002 **80(20)** 3682). In similar superlattices doped with Si, electron concentrations of $3 \times 10^{19}\ cm^{-3}$, with the room temperature mobility of 10–20 cm^2/Vs, were obtained (*J. Appl. Phys.* 2003 **93(3)** 1363).

SPSLs have been used to prepare LEDs with an emission wavelength as short as 260 nm. These UV sources exhibited low turn-on voltages of 3.5–4 V, low leakage currents of 20–30 μA for reverse voltages as high as 15 V, and could withstand DC current densities in excess of 500 A/cm^2 at room temperature (*Appl. Phys. Lett.* 2003 **82(9)** 1323). Photodiodes based on SPSLs showed state-of-the-art performance, with dark current densities below ~0.3 nA/cm^2 and high zero-bias resistance of $\sim 1 \times 10^{11}\ \Omega$. The sharp wavelength response cut-off obtained for these devices, with six orders of magnitude decrease in responsivity from 260 to 380 nm, makes them truly solar-blind.

Dilute nitrides reach longer wavelengths

The growth of telecom laser diode structures on cheap, large-area GaAs substrates has always sparked interest in developers of telecoms components who are keen to fabricate cost-effective devices for fiber-optic communications systems. The GaAs-based compound GaInNAs – also called "GINA" – is a member of a new class of narrow-gap dilute nitride semiconductors, and is attracting attention due to its possible application in long-wavelength telecom lasers. Impressive laser performances have been achieved at around 1300 nm by incorporating only ~1% N into GaInAs quantum wells (QWs).

The epitaxial growth of narrow-gap nitride semiconductors is extremely difficult to master, and the alloy quality rapidly degrades with increasing N-content. For this reason, it has often been suggested that GINA is not suited for emission in the 1500–1600 nm range needed for long-haul transmission, and that other systems, such as penternary alloys or quantum-dot structures, should be used.

A collaborative effort between researchers from CNRS in France, the Paul-Drude-Institut in Germany and ETSI in Spain has shown that careful optimization of the MBE growth conditions results in high-quality GINA QWs emitting at up to 1600 nm (*Appl. Phys. Lett.* 2003 **82(12)** 1845). The samples consisted of a 9 nm GINA single QW with ~37% In and as much as 3.5% N. Particular care was taken to preserve a perfect two-dimensional morphology of the QW even at this high N-content. This is the key to achieving a high radiative efficiency. In addition, TEM confirmed that no exchange/interdiffusion at the QW/barrier interface occurred during the post-growth annealing step which is traditionally used to enhance the radiative efficiency of GINA-based devices. These results show that GINA QWs are indeed suited for 1500 nm laser applications.

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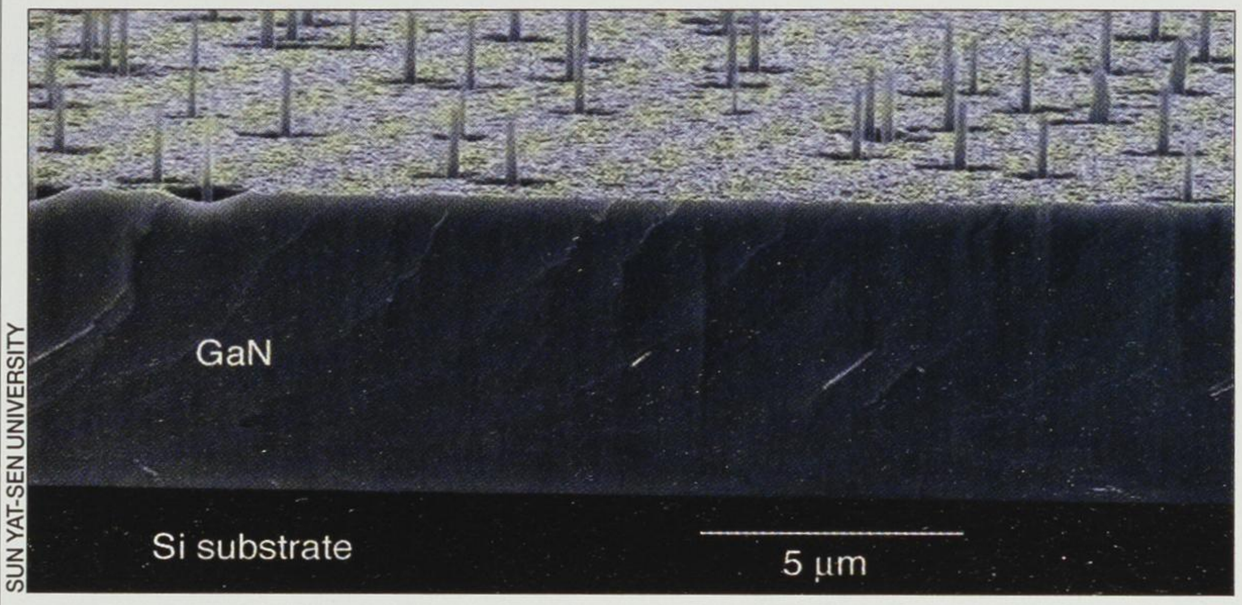
MBE-grown GaN HFETs reach 180 GHz

A group from the National Research Council in Ottawa, Canada, has reported AlGaN/GaN HFETs grown by ammonia MBE with some of the best high-frequency characteristics yet reported for MBE-grown devices (*Elec. Lett.* 2003 **39(6)** 564). The device layers, grown onto 4H-SiC substrates, consisted of a 20 nm AlN buffer layer deposited by magnetron sputter epitaxy, followed by a series of layers grown by ammonia MBE. These were a 2 μm insulating GaN layer, a 0.2 μm undoped GaN channel layer and a 14 nm AlGaN layer consisting of a 4 nm spacer, a 4 nm donor layer and a 6 nm cap.

The HFETs had a gate length of 0.13 μm and source-drain and source-gate spacings of 2.1 and 0.7 μm, respectively. DC characteristics showed a maximum drain current of over 1.25 A/mm and peak transconductance was 250 mS/mm. Extrapolated values for f_t and f_{max} were 103 and 170 GHz, respectively, at a source-drain voltage of 10 V and gate bias of –2.5 V. The RF characteristics were tested out to a source-drain voltage of 20 V where the f_t and f_{max} values were 75 GHz and 180 GHz, respectively.

Self-assembled GaN nanorods grown by MBE



SUN YAT-SEN UNIVERSITY

A field-emission SEM image of GaN nanorods with the c-axis along the rod length and with hexagonal cross-section.

A group headed by Professor Li-Wei at the National Sun Yat-Sen University in Taiwan has reported the growth of nanosize GaN pillars by nitrogen plasma MBE (*Appl. Phys. Lett.* 2003 **82(10)** 1601). These wurtzite GaN nanorods were vertical to the Si (111) substrate wafer and were aligned along the crystallographic c-axis with a hexagonal cross-section. The top surfaces of the nanorods were flat and parallel to the substrate, and TEM showed the rods to be dislocation-free.

By tuning various growth parameters the team were able to vary the size and the distribution density of the nanorods. The smallest GaN rod diameter was around 10 nm, the greatest rod height was over 3 μm and rod densities ranged from 10^6 to 10^9 cm^{-2}. Low-temperature photoluminescence showed an emission peak at 363 nm. An N_2 plasma treatment to passivate the surface eliminated this peak, demonstrating that its origin was in rod surface states, which are known to play an important role in structures with large surface/volume ratios.

The group is now investigating nanorods that incorporate heterojunctions with multiple InGaN/GaN quantum wells.

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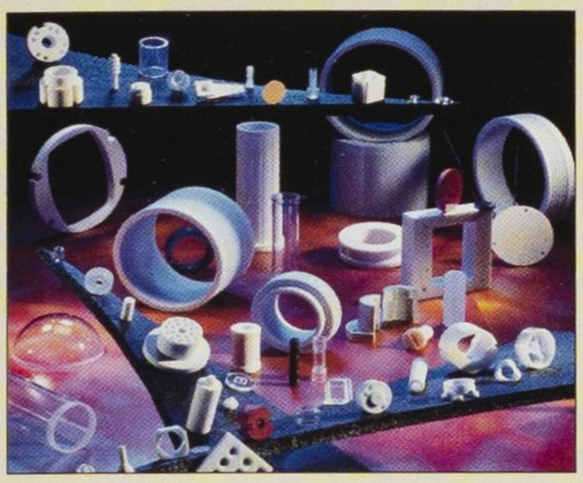

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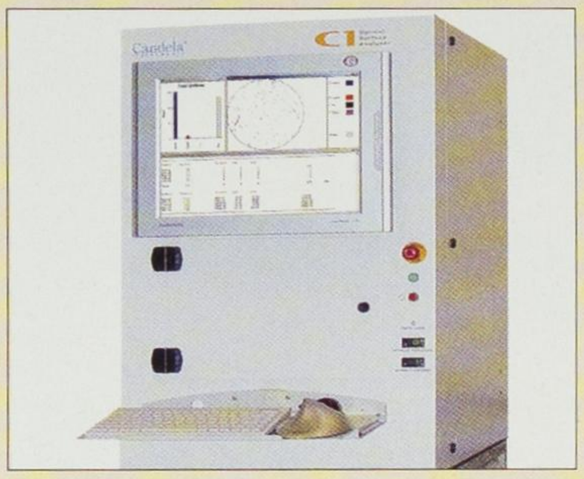

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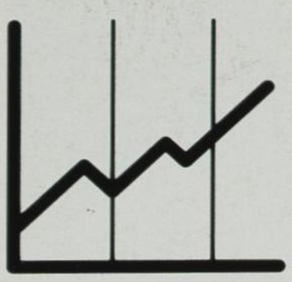
The brakes go on at RFIC makers

After a run of impressive revenue growth, things seem to be slowing up for the GaAs giants, but it's full steam ahead for Cree's LED business as it brings more production capacity on line.



As the figures began to roll in for the March 2003 quarter, it was clear that RFIC manufacturers are now fighting to maintain revenues and profitability. Skyworks Solutions announced revenues of $157.4 m for the March quarter, up 22% from the same period last year, but down nearly 2% compared with the December 2002 quarter. After reaching its goal of operating profitability in the September 2002 quarter, Skyworks has continued to build on this through improvements in its margins, which are now at 44%. The company reported an operating income of $4 m in the March quarter, up slightly compared with $3.7 m in the previous quarter.

Market overview

Company	*Symbol*	*Closing price on Apr 22*	*52-week low–high*	*Market cap**
GaAs IC companies				
Anadigics	ANAD	1.98	1.59–12.27	60.7 m
Celeritek	CLTK	7.59	5.01–11.16	93.7 m
Endwave	ENWV	1.18	0.32–3.80	10.5 m
RF Micro Devices	RFMD	5.48	4.97–19.38	1.003 bn
Sirenza Microdevices	SMDI	1.62	1.05–5.40	48.6 m
Skyworks Solutions	SWKS	5.59	2.89–14.96	771.9 m
TriQuint	TQNT	3.68	2.55–11.41	490.0 m
Vitesse	VTSS	2.70	0.62–7.59	552.1 m
Opto companies				
Agilent	A	15.52	10.50–34.65	7.314 bn
Alcatel Optronics	ALAO	8.25	1.50–8.30	896.0 m
Cree	CREE	21.36	8.989–25.42	1.564 bn
JDS Uniphase	JDSU	3.24	1.58–5.45	4.586 bn
Semiconductor materials and equipment companies				
ATMI	ATMI	22.70	11.75–34.15	697.5 m
AXT	AXTI	0.94	0.66–12.00	21.1 m
Emcore	EMKR	1.95	0.98–9.74	72.0 m
Kopin	KOPN	5.76	1.93–9.40	399.7 m
Tegal	TGAL	0.39	0.13–1.40	6.3 m
Trikon	TRKN	3.43	3.02–15.02	48.1 m
Veeco	VECO	15.67	9.14–34.30	458.0 m
European companies (currency data in €)				
Aixtron	AIXG.F	3.22	2.06–18.00	226.1 m
Bede	BED.L	0.13	0.12–0.44	3.6 m
Bookham	BHM.L	1.05	0.92–1.25	229.5 m
IQE	IQE.L	0.04	1.44–9.36	7.5 m
Riber	RIBE.LN	0.79	0.58–1.14	14.9 m
Soitec	SOIT.LN	3.37	2.22–3.80	201 m
STS	SRTS.L	0.11	0.06–0.16	3.4 m
Unaxis	UNAXZN.VX	68.60	42.2–136.1	915 m

**Market capitalization = # shares × current share price.*

A boost to margins has come from the completion during the quarter of the company's facility consolidations, which have been ongoing since the Alpha/Conexant Wireless merger. GaAs HBT production has moved from the former NDI/Alpha fab in Sunnyvale, CA, to Newbury Park, CA, and module manufacturing from Haverhill, MA, to Mexicali, Mexico.

Looking ahead, Skyworks expects its revenue for the June quarter to be in the range of flat to down 5% sequentially, despite new design wins. This is due to the current economic environment, coupled with reported softness in its Chinese, Korean and Indian markets.

Skyworks' rival, RF Micro Devices, reported revenue for the March quarter of $138.3 m, a sequential decrease of 5.1%, but a 37.7% increase over the figure of $100.4 m for the year-ago quarter. Net loss was $13 m, or $0.07 per share, which was in line with revised guidance given on April 7. In the December 2002 quarter the company had a net income of $2.8 m. Originally RF Micro Devices had forecast a net loss of about $0.01 per share, but was forced to revise this figure when its sales mix shifted during the quarter towards lower margin products for GSM handsets.

The shift in its product mix looks set to continue as evidenced in the company's guidance for a loss of between $9 m and $11 m (5–6 cents per share) for the June quarter. However, efforts to improve margins and profitability are expected to bear fruit in the June quarter. These include improved yields and the conversion to 6 inch wafer manufacturing.

Anadigics posted lower sales and wider losses for the March quarter than analysts had been expecting. Its loss stood at $12.2 m, compared with $7 m in the previous quarter and analysts' expectations of a $9 m loss. Sales declined by 15% sequentially to $16.1 m, $1.1 m below expectations.

Cree breaks another revenue record

Cree posted its second successive record quarterly revenue figure of $60.2 m, a 6% sequential rise. The figure was an impressive 80% higher than the $33.4 m reported in the year-ago quarter, thanks to continued strength in demand for the company's LEDs. Net income for the quarter increased to $10.6 m, compared with a loss of $68.3 m in the year-ago period.

The demand for Cree's LED products has necessitated a rapid expansion in manufacturing capacity. This is now coming on line, and the company expects to be able to pursue new business that will add to its revenues in the coming quarters.

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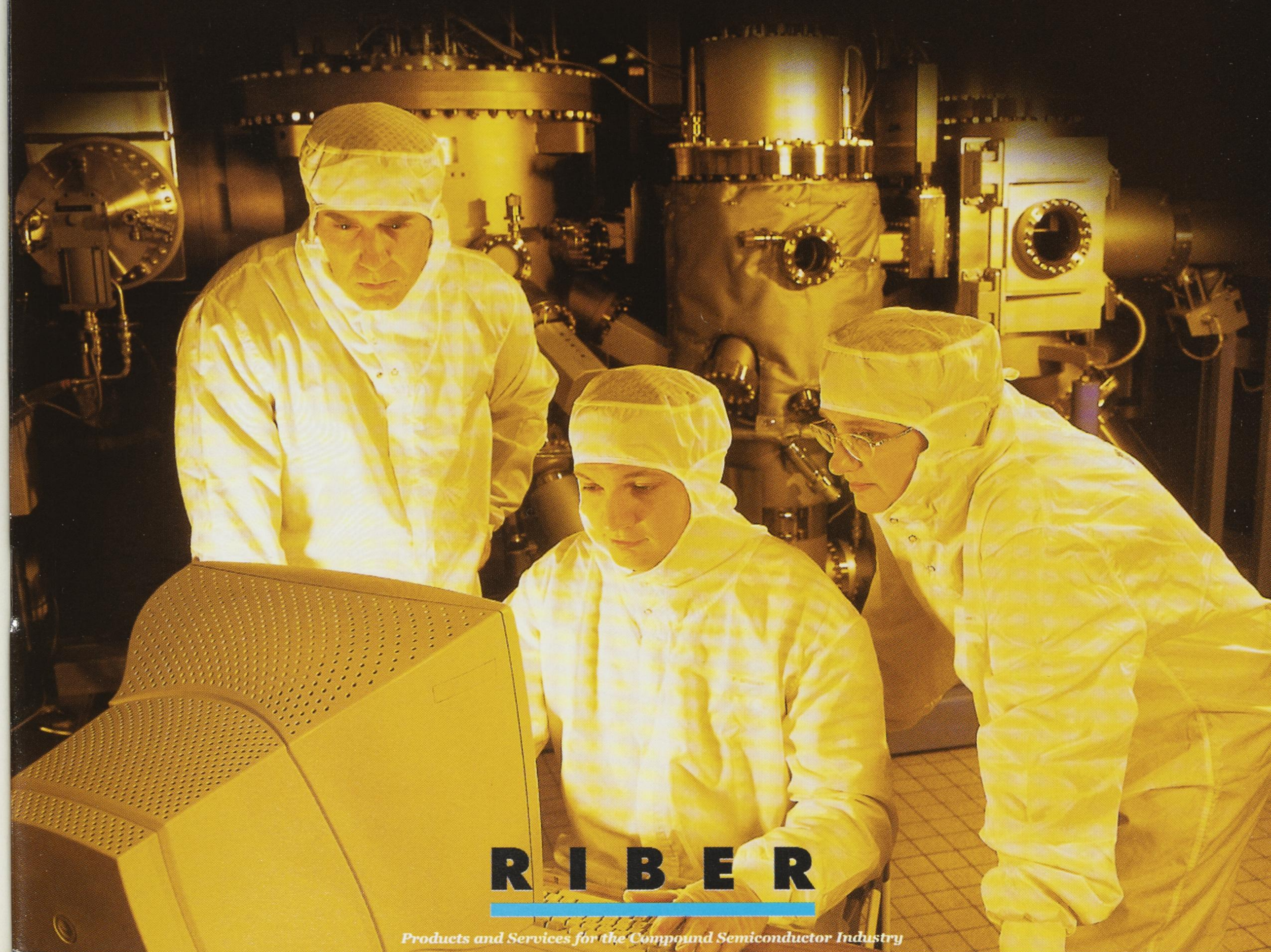

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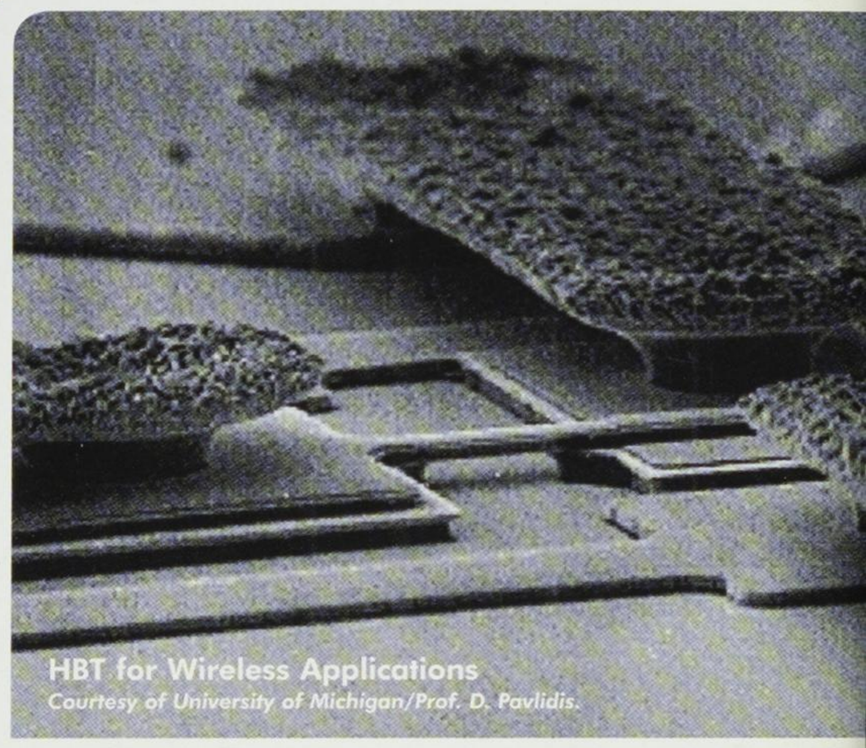

HBT for Wireless Applications
Courtesy of University of Michigan/Prof. D. Pavlidis.

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