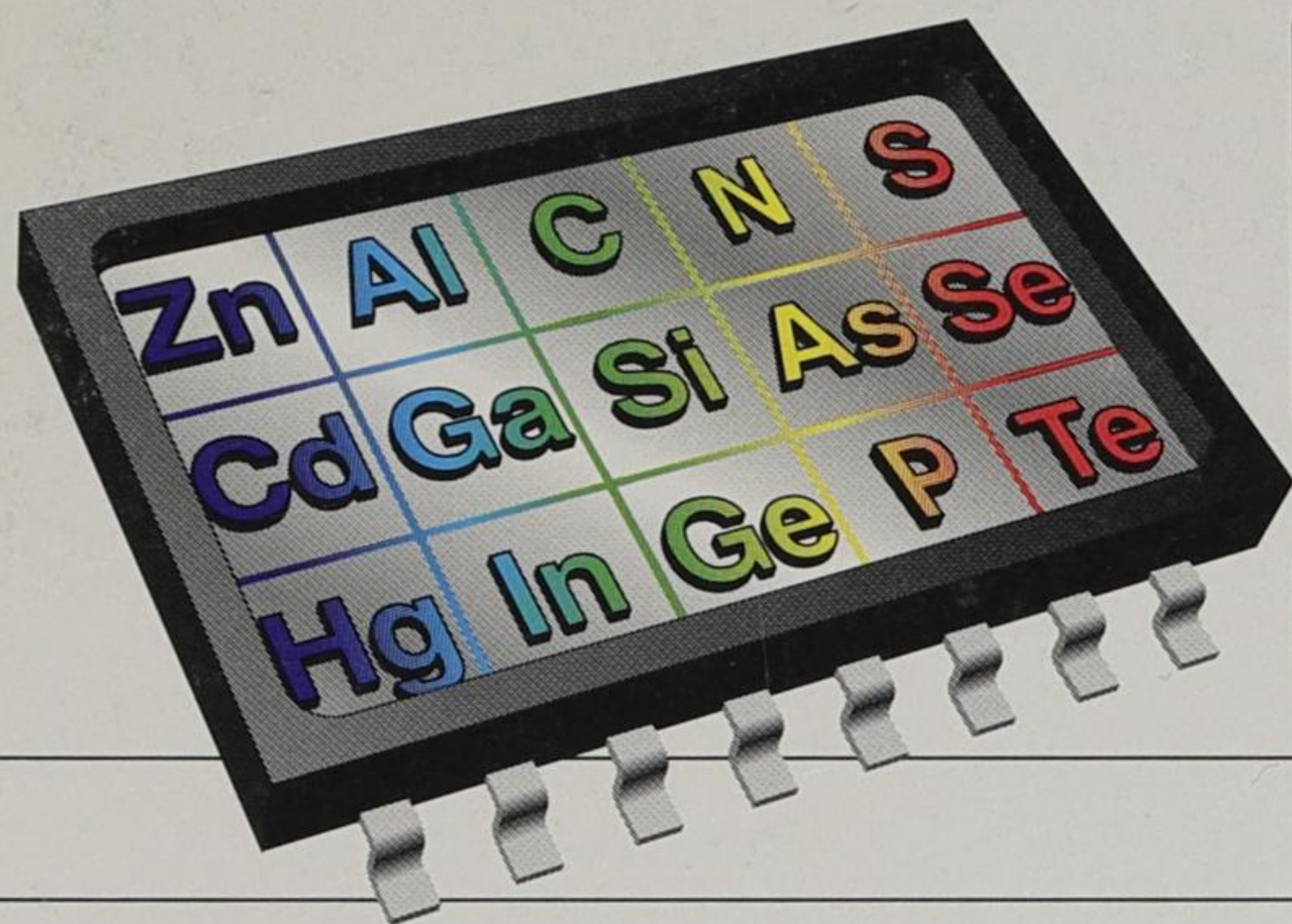


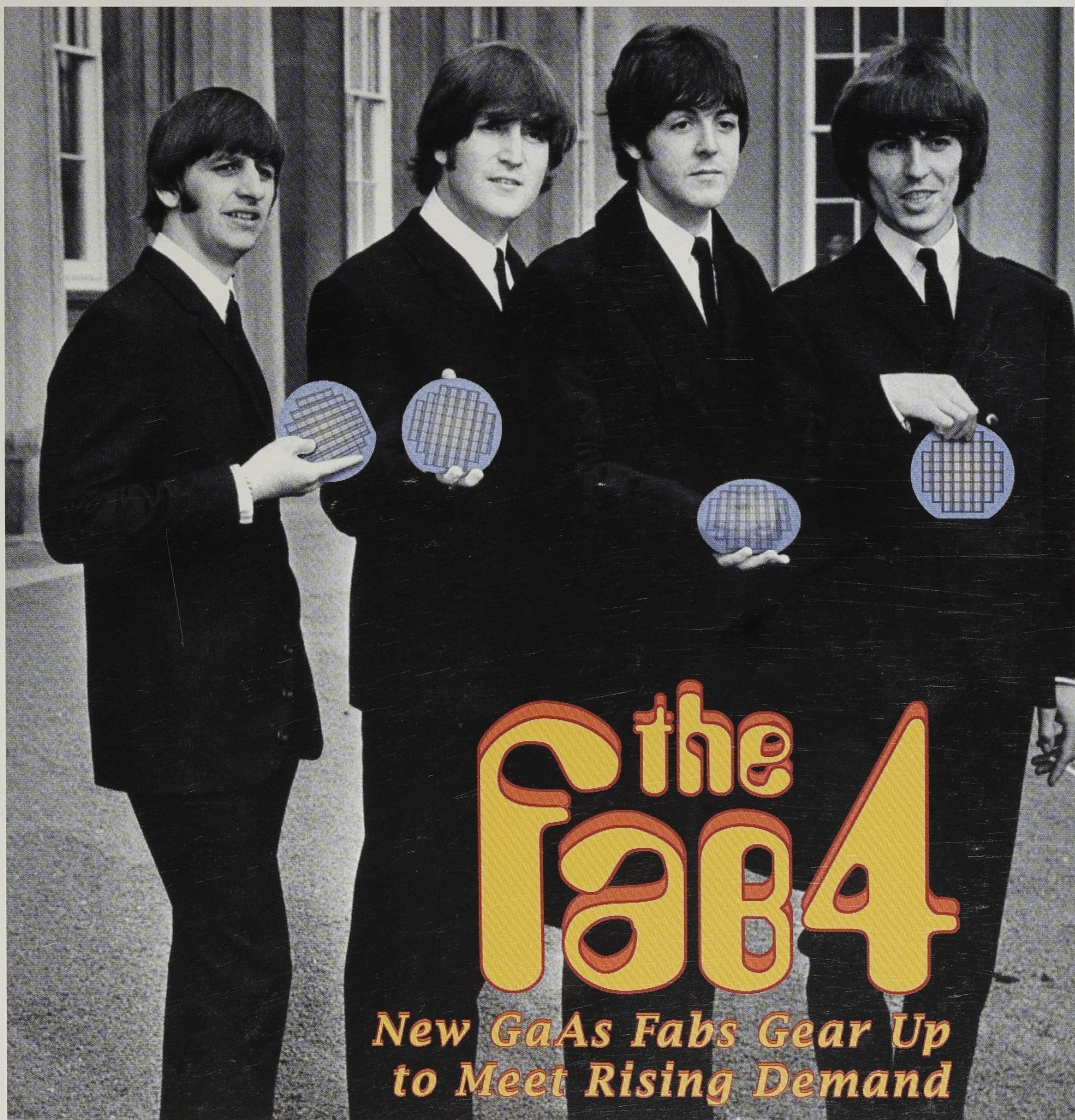


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SEMICONDUCTOR

May/June 2000

Volume 6 Number 4





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EMPLOYMENT ADS

Recruitment is one of the biggest issues in the compound semiconductor industry today. Therefore, we are reorganizing our Employment Section to make it more useful. Beginning with this issue, it now occupies a more prominent position in the magazine. And, for a limited time, we are also offering a free tie-in to the Employment section on our web site, CompoundSemiconductor.net (please note this is a dot-net, not a dot-com, address).

We have subscribers at more than 850 compound semiconductor facilities around the world, including virtually every fab and R&D center in the compound semiconductor field. We deliver a very targeted audience that you won't be able to reach using any other publication.

If you are interested in advertising your compound semiconductor-related job openings in this space in our next issue, we need to hear from you by June 16. The deadline for the subsequent issue is August 4. Interested parties should contact:

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mmeyer@compsem.com
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iv for rates

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VG Semicon, the world's largest supplier of production Molecular Beam Epitaxy systems, is seeking engineers to enhance its US Field Service team and to meet the challenges of the industry's rapid expansion. Applicants will need a solid background in electronics, mechanical engineering and computing. Experience working with Ultra High Vacuum systems would be an advantage. After training in the US and UK, duties will include system maintenance, customer training and installation of upgrades. A significant level of travel is required. Self motivation and the ability to work with minimal supervision is critical.

Interested parties should respond in writing to

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100 Cummings Center
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The position involves MBE growth and characterization of arsenide/antimonides. MBE experience is a requirement. Experience with antimonides is an advantage, but not a requirement.

DEVICE DESIGN, FABRICATION and TESTING

The position involves research on bipolar transistors in antimonide-based materials. Experience in design, fabrication and testing of RTD's, HEMT's or HBT's is desired. Experience with antimonides is an advantage, but not a requirement.

Contact:

Prof. Gary W. Wicks
The Institute of Optics
University of Rochester
Rochester, NY 14627
wicks@optics.rochester.edu

Opportunities at Picogiga

Picogiga, the first commercial MBE supplier and the quality leader, is seeking a professional to staff an East Coast sales office. The successful candidate for this job should be mature with several years' experience in semiconductor materials and sales. He/she should have good computer and communication skills both written and verbal. This position will primarily handle sales and customer service with Picogiga customers in the eastern United States, but will interact with customers throughout the country.

Salary and benefits will be commensurate with the candidate's experience and training and will be competitive with industry standards. Picogiga is an equal opportunity employer.

Persons interested in this position should contact
Frank J. Bruni

Picogiga, Inc.

4773 Sonoma Hwy. #62
Santa Rosa, CA 95409
Tel. (707) 539-2508
Fax (707) 539-4808
E-mail fjbruni@aol.com

KEY ACCOUNTS / PROJECT MANAGERS

VG Semicon is the world's leading manufacturer of Molecular Beam Epitaxy (MBE) equipment, which is used in the fabrication of electronic devices for the telecommunications industry. As part of our growth plans, we are looking for experienced individuals to fill the following senior positions:

KEY ACCOUNTS MANAGER

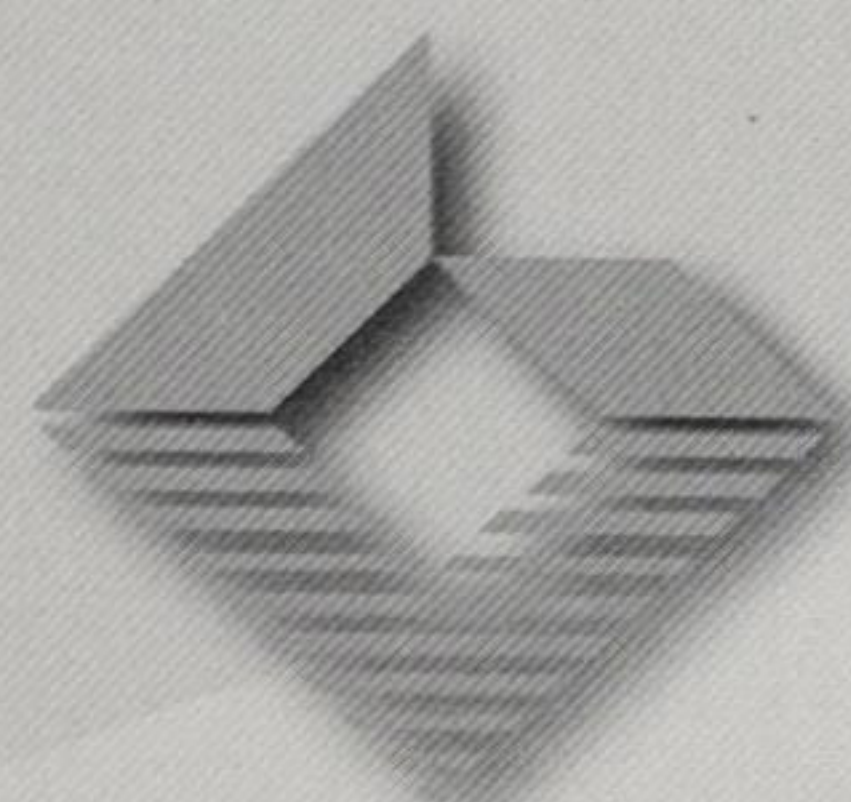
The Key Accounts Manager will be responsible for managing all aspects of our business interaction with a defined number of major international customers. The main responsibility is to fully understand customers' requirements and to effectively define and manage practical solutions. Applicants should have excellent communication skills and be able to demonstrate a successful track record in both the technical and commercial aspects of the telecommunications and/or semiconductor industry.

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The Senior Project Manager will define and manage major electro-mechanical and/or software development projects using a combination of internal and external resources. Applicants should be able to demonstrate excellent communication skills combined with a strong background in mechanical, electronic and software engineering.

These positions will be at a senior management level within the company. In addition to the skills noted above successful applicants will also require general skills and knowledge in the science and technology, commercial management, sales and marketing, and customer support aspects of the semiconductor equipment business. Successful candidates will probably have a PhD in a relevant scientific discipline. Direct knowledge of the MBE process will be a significant advantage. These positions will be based in the United Kingdom. We offer a highly competitive compensation package, including 25 vacation days per year.

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Senior position responsible for next generation VCSEL product development from device design to manufacturing implementation. You will work with our MOCVD engineers, process engineers, and customers to meet the company's aggressive technical and business objectives in the rapidly growing ≥ 10 Gbps and 1.3 micron data communications markets.

Requires a Ph.D. or equivalent in EE, physics, or related field and two or more years hands-on experience with GaAs or InP-based VCSEL devices.

■ ***Compound Semiconductor Device Development***

Senior position responsible for developing high-speed optoelectronic and electronic devices (GaAs and InGaAs detectors, laser diodes, high-speed LEDs, GaAs and InP RF devices) for advanced optical communications applications. Working with our MOCVD and process teams, you will lead all aspects of development, from device conception and epitaxial design through process development and product implementation.

Requires an M.S. or Ph.D. in EE, physics, or related field and five or more years experience in III-V device modeling and design.

■ ***Compound Semiconductor Process Engineering***

Responsible for developing and improving all aspects of III-V device process technology and yield, including mask design, photolithography, metallization, dielectric deposition, and wet/dry processing for a range of high speed and optoelectronic devices; this is a key technical leadership position.

Requires a B.S. or higher in EE, ChE, physics, or related field and three or more years experience in III-V materials and device processing.

■ ***Semiconductor Test and Reliability Engineering***

Responsible for all aspects of implementing and running a III-V device characterization and reliability facility, including GHz range and automated on-wafer and packaged device testing equipment. You will select equipment, design test procedures and fixtures, develop reliability and burn-in protocols, work closely with customers, and manage department operations.

Requires a B.S. or higher in EE, physics, or related field and two or more years experience with high-speed III-V optoelectronic devices. Familiarity with Bellcore standards is a plus

■ ***Advanced Optoelectronic Packaging Engineering***

Responsible for the development of advanced ≥ 10 GHz optoelectronics device packaging. Working with customers, in-house facilities, and outside vendors, you will develop and implement packaging for current and next generation devices, including high-volume, low cost packaging, and hermetic, hybrid, flip-chip, and novel configurations. You will manage packaging programs, select equipment for internal capacity, and qualify on-and off-shore vendors to ensure product reliability.

Requires a B.S. or higher in EE, physics, or related field and three or more years experience with high-speed III-V optoelectronic device packaging and reliability. Familiarity with Bellcore standards is a plus.

■ ***Semiconductor Production Manager***

Responsible for production control, materials, and scheduling to maintain costs and throughput in a high-growth, multi-product epitaxy and device fab. Your strong organizational skills and MRP/ MES system implementation experience will enable the company to meet customer expectations and attain its aggressive growth targets.

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Employment Opportunities at NOVA CRYSTALS, INC.

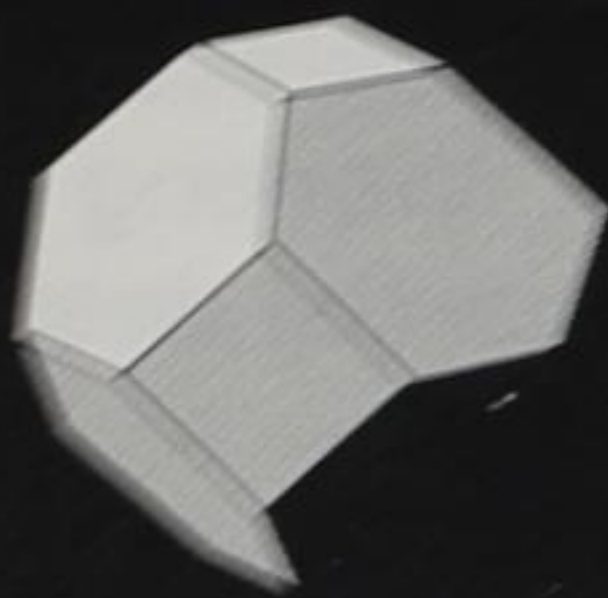
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- Manufacturing Engineers
- Foundry-Production Manager

Nova Crystals, Inc., (www.NovaCrystals.com), is a developer of high-performance opto-electronics components (VCSELs, LEDs, Receivers, etc.) for applications in fiber-optic data/telecommunications, solid-state lighting, and other applications. Nova's operations are based in San Jose CA. Founded in late-1998, Nova is backed by strategic and venture capital.

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Interested candidates should send cover letter and CV to:

Yolanda Deason
Nova Crystals, Inc.
 174 Component Drive
 San Jose, CA 95131
 Email: deason@novacrystals.com
 FAX: 408-434-6330



Engineering Career Opportunities

Spectrolab, Inc., A Hughes Electronics Company, the world's leading manufacturer of space and terrestrial photovoltaic systems, has career opportunities in its photonic devices division.

- **III-V Materials Growth Engineer** Epitaxial film deposition and characterization of III-V materials. BS required. Experience with MOVPE systems and materials characterization desirable.
- **III-V Solar Cell Project Engineer** Device design of III-V multijunction solar cells. PhD +1-2 yrs. or MS + 5 yrs. experience required. Must have strong understanding of physics of photovoltaic cells or detectors. Project management and proposal writing experience desirable.
- **Sensor Product Engineer** Design, fabricate and test III-V detectors, plus process documentation and proposal/report writing. BS required, MS preferred, plus 3-4 yrs. experience in III-V detectors required.
- **HBT Device Engineer** Develop III-V microelectronic devices (HBTs and HEMTs). Must be knowledgeable in electrical characterization and device processing. BS, MS, or PhD in EE, MatE, Physics, or related fields plus 1-2 yrs. experience required.
- **Thin-Film Process Engineer** for solar cell manufacturing. BS required and 1-4 yrs. experience preferred. Characterization of metals/dielectric films, SPC, DOE, and database management experience desirable.
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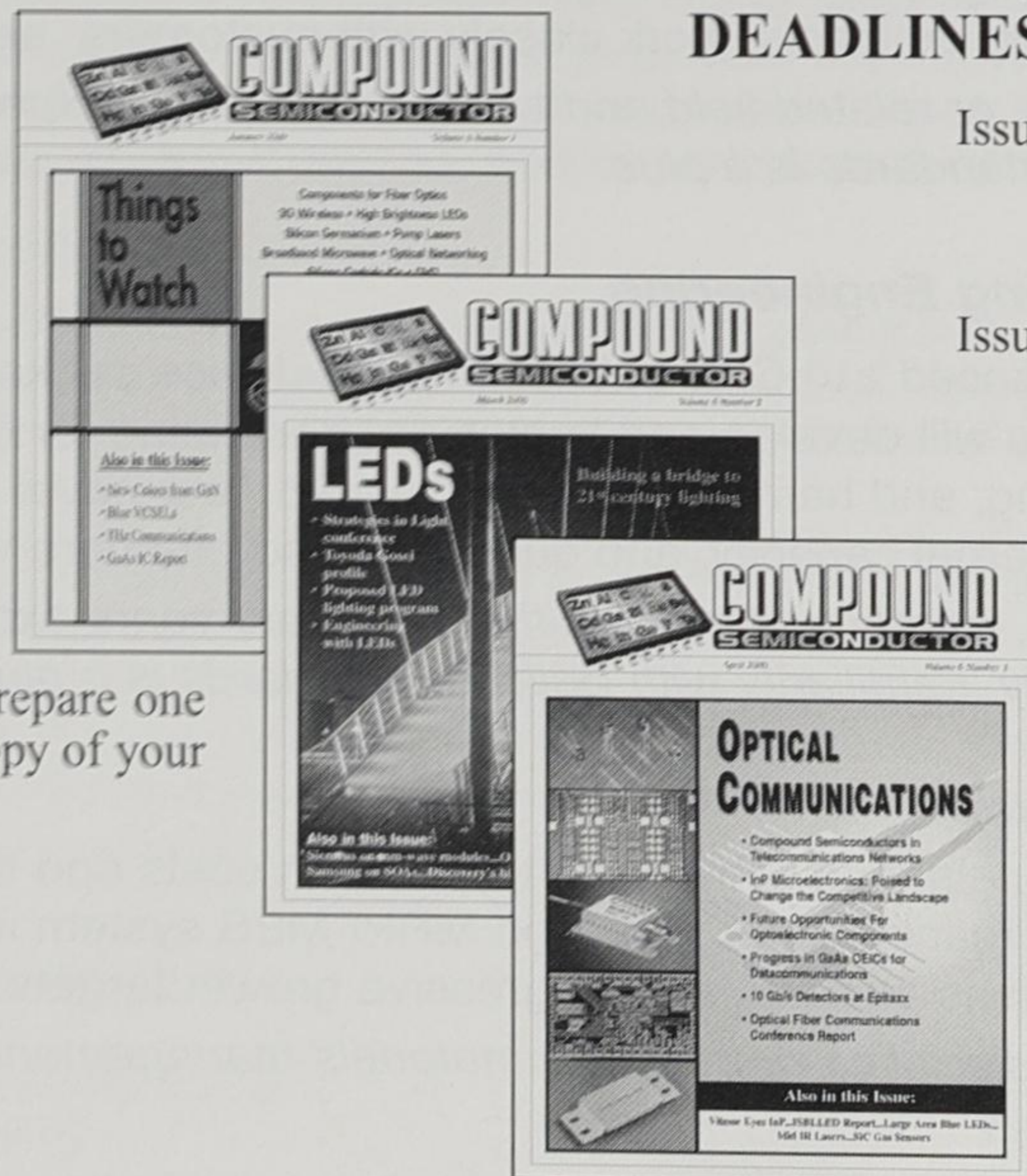
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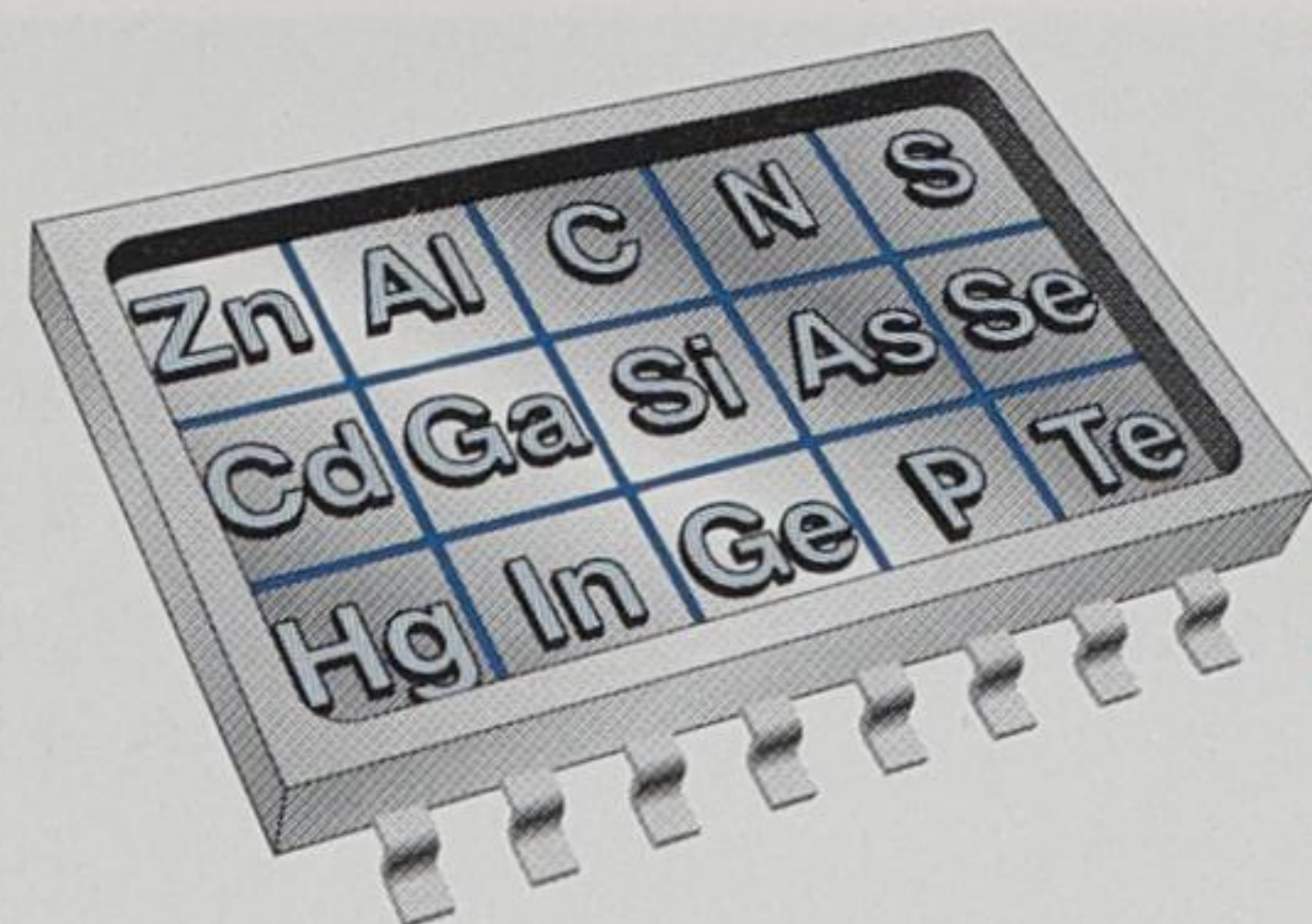
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<http://www.compoundsemiconductor.net>



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SEMICONDUCTOR

COVER STORY – THE FAB FOUR

42 Fab Four Address Growing GaAs Markets

All puns on the Beatles aside, we profile four new GaAs IC facilities currently under construction around the world, and detail the measures being taken by other companies to extend their capacity in the face of huge demand for GaAs products.

49 Trends in the Market for GaAs Devices

Continuing our series of articles from the Key Conference held in Key West recently, Stephen Entwistle of Strategy Analytics looks at current markets and future trends in the consumption of GaAs ICs.

GaAs ICs

27 GaAs IC News

SAL X-ray Lithography Printing 125 nm features at Sanders...Alpha Shipping GaAs PAs for LMDS...and more.

31 RF Requirements for 3G Mobile Systems

Raytheon's Sanjiv Shah throws light on device requirements for GaAs in next-generation mobile phones.

60 Applications of GaAs ICs to Communications

Rockwell Science Center's J. Aiden Higgins on how the enhanced performance of GaAs HBT and PHEMT devices will continue to enable penetration of communications markets.

FEATURE ARTICLES

36 Silicon Carbide and Gallium Nitride Circuits for Wireless Communications: Why, What and When

Raymond Pengelly of Cree notes that with 3-inch wafers now available and 4-inch at the lab stage, the size of SiC substrates is no longer an impediment to the commercialization of SiC and GaN ICs for wireless communications.

55 High Efficiency Surface Textured LEDs

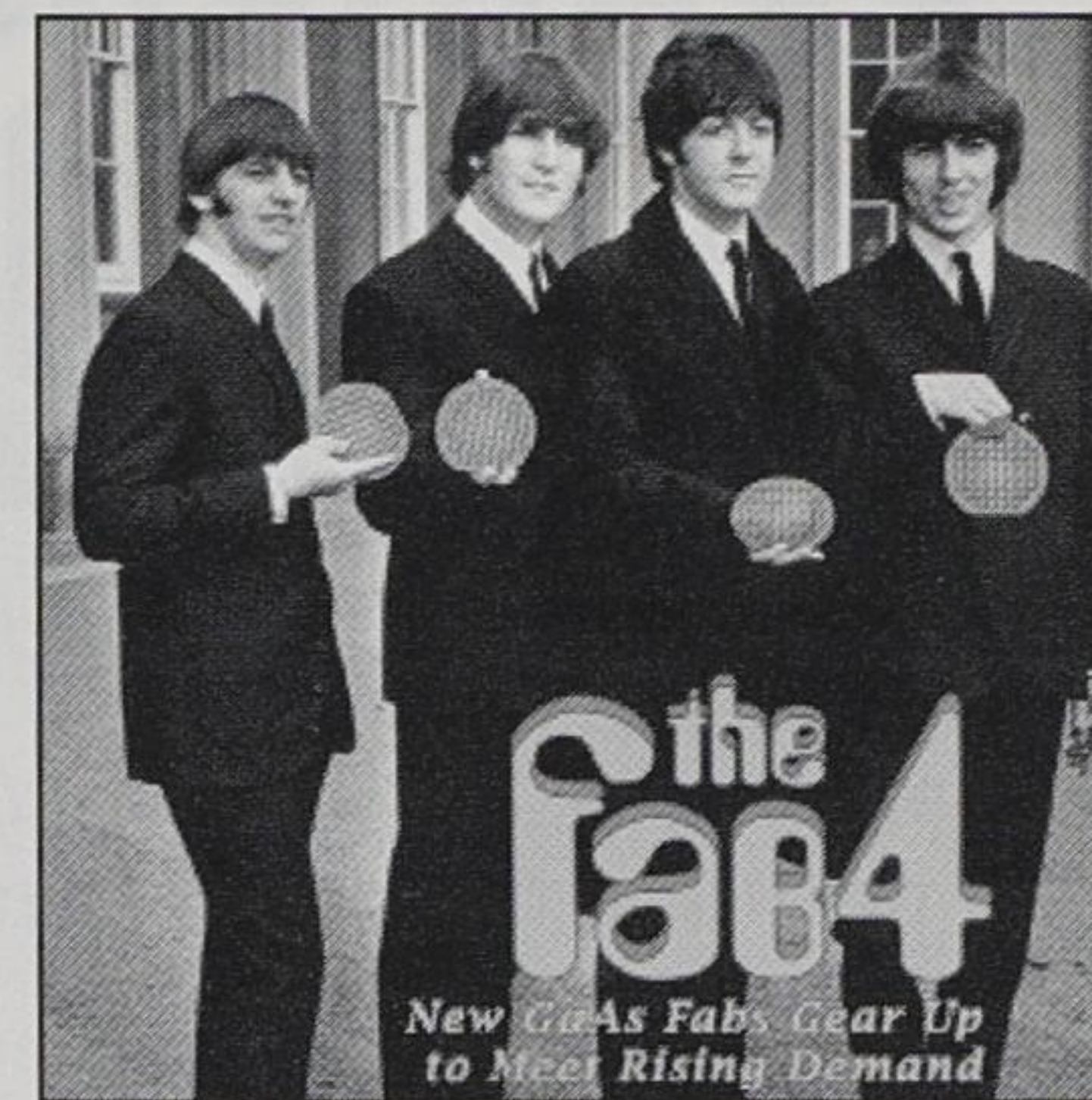
Reiner Windisch and colleagues from IMEC have used surface texturing to increase the efficiency of LEDs 20-fold compared to conventional devices.

68 Photon Recycling for High Brightness LEDs

Fred Schubert and co-workers at Boston University describe a novel LED device that "recycles" photons - and has the potential to change the face of light sources for future general illumination applications.

74 A Roadmap for Optoelectronics Interconnects for Integrated Circuits

The first part of a two-part article on the future role of III-V optoelectronics as interconnects for CMOS devices.



With GaAs IC manufacturers currently running almost "Eight Days a Week" to keep up with demand, we profile four fabs that are moving ahead with construction of 6-inch GaAs manufacturing facilities. The reasons for this big ramp are also outlined in further articles from the recent Key West conference on compound semiconductors.

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Cree buys Nitres...Uniroyal buys Sterling...AXT cyan, green LEDs, ships blue LEDs...and more.

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Nova Crystals relocates...LumiLeds new Business Unit, Products...and more.

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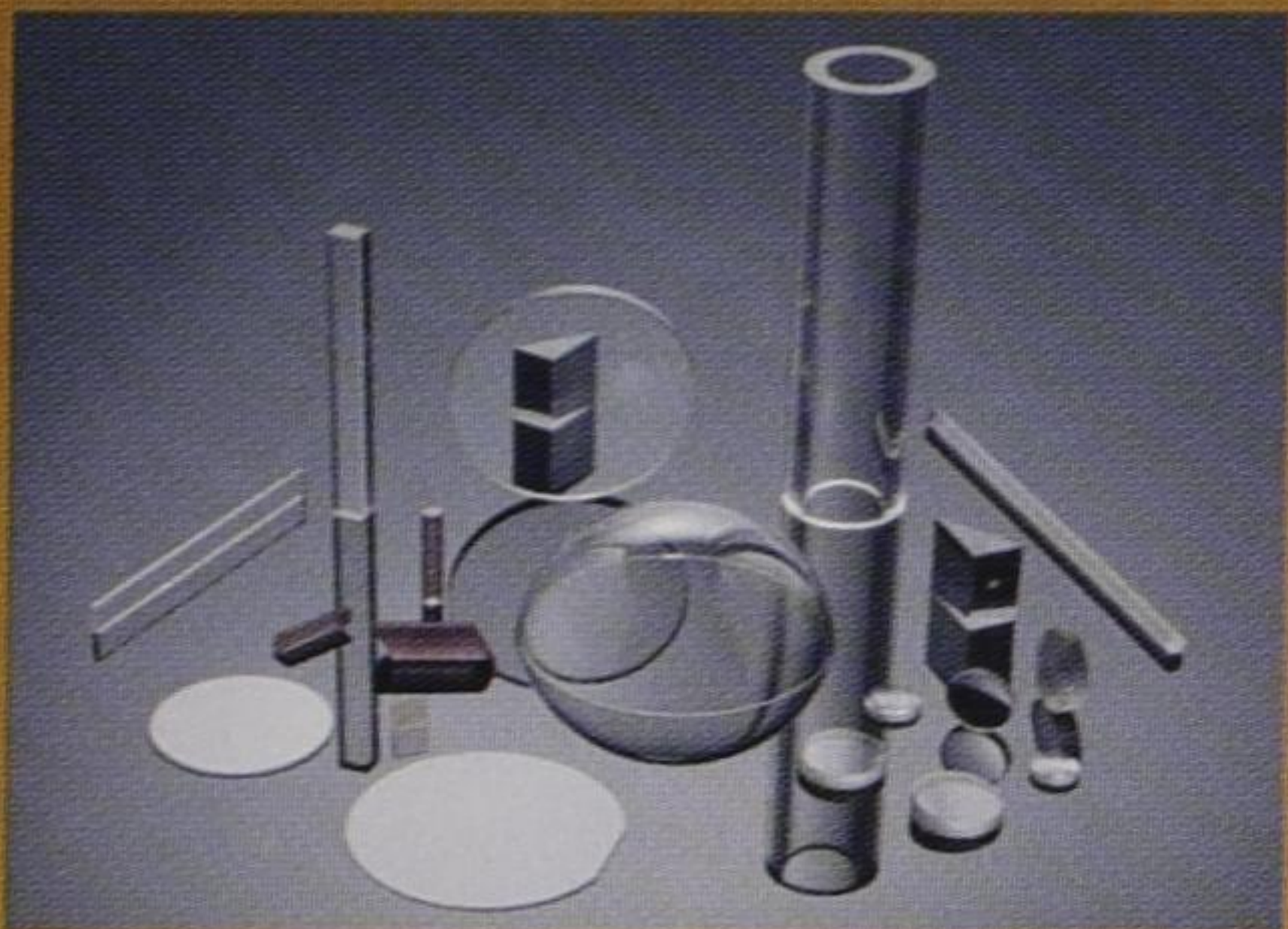
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Cree Acquires Nitres, Forms Solid State Lighting Subsidiary

Cree recently completed the acquisition of Nitres, combining two leaders in the field of wide bandgap materials and devices. Cree, based in Durham, NC, is one of the world's largest volume suppliers of nitride-based LEDs, and the leading manufacturer of SiC substrates. In addition, Cree manufactures commercial SiC MESFET-based RF transistors. Nitres (based in Westlake Village and Goleta, CA) has developed a range of advanced nitride-based devices including record efficiency blue/UV LEDs, and microwave devices with record power density. "The acquisition of Nitres, with its demonstrated performance and expertise in high brightness nitride LEDs, combined with Cree's low-cost manufacturing platform, should enable Cree to become the premier provider of high efficiency, low cost LEDs," says Neal Hunter, Cree's chairman and CEO. Nitres will now operate as Cree Lighting Company, a wholly owned subsidiary of Cree that will address the solid state lighting market. The acquisition was structured as a stock swap, valued at around \$195 million at current prices.

Addressing the Solid State Lighting Market

"The new company will continue with the same basic business strategy that we had at Nitres," says Fred Blum, former CEO of Nitres and now President of Cree Lighting Co. "We will develop high efficiency blue, UV and white emitters with a focus on the solid state lighting market."

"When Cree approached us to discuss the prospect of an acquisition, we were in the process of raising the investment capital required to bring our high brightness LED products to market," says Blum. "Our plan was to commence manufacturing later this year – we are still on course, but now we have a new source of capital."

Nitres has demonstrated nitride-based LEDs in the ultraviolet-to-blue range (400-410 nm peak wavelength) with a quantum efficiency of 20%, which is believed to be the highest ever reported [see CS 6(1), p. 16]. "The high efficiency of these devices is attributed to higher quality materials and advanced device structures," says Blum. "Although the record efficiency devices were grown on sapphire substrates, we have also done work using SiC substrates, and we will be expanding our device efforts on SiC under Cree."

Traditionally, GaN-based LEDs grown on SiC, as championed by Cree, have been lower cost and lower brightness products compared to those grown on sapphire. However, the performance of Cree's recently introduced InGaN-on-SiC LEDs [see CS 5(5), p. 11] is close to current devices grown on sapphire. Blum believes that the market is likely to choose between the two approaches – sapphire and SiC – depending on the specific application.

Cree Lighting will focus on the development and manufacture of white lamp products and UV LED chips for the solid state

lighting and illumination markets. At present, the company does not plan to manufacture lighting assemblies. Cree Optoelectronics, a separate business unit of Cree, will continue to manufacture GaN-based LED chips, primarily blue and green, for a wide variety of other markets. Blum envisages a great deal of synergy between the two units in the development of higher brightness and lower cost products.

Nitres' research to date has been funded under contracts by the U.S. Commerce Department (NIST), Air Force, AFOSR, BMDO, DARPA, and the Office of Naval Research. The contract with NIST provides funding for Nitres to participate in a research partnership with GE Lighting/GELcore to develop white LED lighting products. Nitres has focused on the development of UV LEDs while GE Lighting has funded its own complementary research to develop phosphor coatings. Nitres has corporate headquarters in Westlake Village, CA, and R&D facilities in Goleta, CA. Over time, Cree Lighting will consolidate these into a larger facility in Goleta that will carry out R&D, and MOCVD manufacturing. Device fabrication and back end processing is likely to be carried out at Cree's main facility in Durham, NC.

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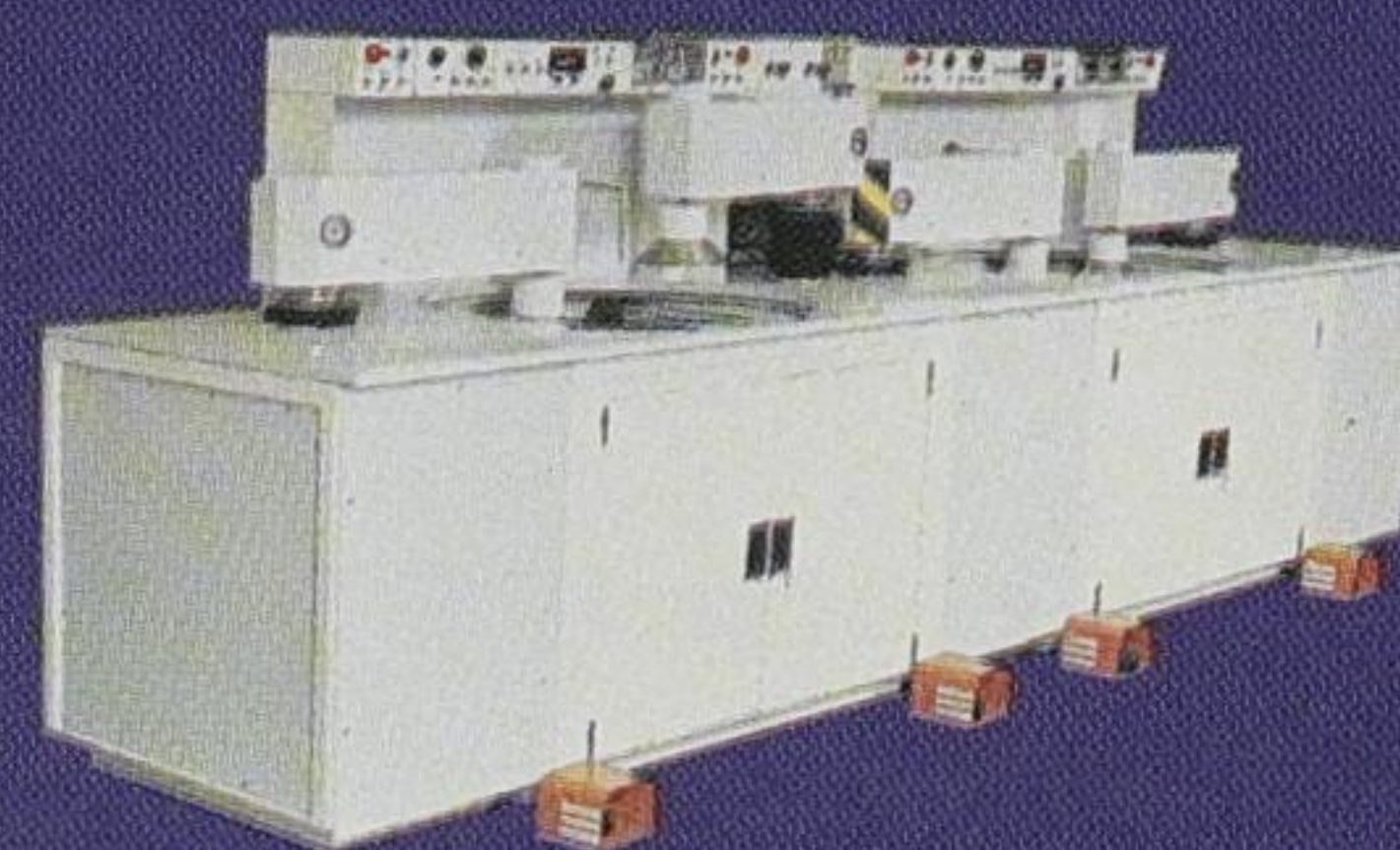
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Microwave Devices

The acquisition also brings together two of the world's leading developers of nitride-based microwave devices. Nitres has reported AlGaIn/GaN HEMTs with the world's highest reported power density [see CS 6(1), p. 13], complementing Cree's demonstration of the highest reported total power for nitride devices. Cree already manufactures commercial microwave products based on SiC MESFETs [see page 36]; the new resources provided by Nitres will help to expand Cree's future product line into higher frequencies.

"Nitres brings some of the world's premier nitride-based microwave device results and R&D talent to Cree," says Neal Hunter. "These resources will help with the acceleration of our commercialization of nitride-based microwave devices." According to Fred Blum, nitride device

development will continue in California under the direction of the Cree Microwave business unit centered in Durham, NC.

Patents

Cree/Nitres declined to comment on any matter concerning patents. However, various observers have suggested that the transaction would provide a route to commercialize Nitres' high efficiency LEDs without encountering problems due to other company's patents on GaN-on-sapphire devices including those of Nichia Chemical. Such patent portfolios appear to have deterred some companies from commercializing products in Japan. However, it is generally felt that many of these patents do not apply to devices grown on SiC; as a conducting substrate, SiC allows the use of top and bottom contacts while devices grown on sapphire

have a different configuration with two top contacts.

One theory doing the rounds of Internet chat rooms is that Cree will transfer Nitres' LED process from sapphire to SiC to avoid patent problems. However, it appears that Nitres was already well advanced towards commercializing its GaN-on-sapphire technology before the acquisition and Cree has indicated that for now it will pursue both sapphire and SiC approaches. These observations suggest that the patent question could be a non-issue.

One other interesting point is that Shuji Nakamura, who was responsible for Nichia's strong position in the nitride LED market, is now at the University of California at Santa Barbara (UCSB). Two other UCSB professors, Steve DenBaars and Umesh Mishra, are also part-time VPs at Nitres. It remains to be seen whether this has any significance.

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AXT Introduces Cyan and Green LEDs, Ships Blue LEDs

The Lyte Optonics subsidiary of AXT has introduced two new high-brightness cyan and green AlInGaIn LEDs, and is also shipping production quantities of its blue LEDs. These products are suitable for indoor and outdoor full-color displays, special purpose illumination, cell phone back lighting and traffic signals. The new 505 nm cyan LED, primarily used in traffic signals, has a minimum power output of 1.2 mW (at 20 mA) and 2.4 mW packaged. The new 525 nm green LED has a minimum power output of 0.75 mW (at 20 mA) and 1.5 mW packaged.

"This introduction comes at a time when the demand for high-brightness blue, green and cyan LEDs exceeds the supply," says Morris Young, AXT's president and CEO. "We are rapidly expanding our capacity in order to provide a shorter delivery window for the product. Our goal is to become a vertically integrated, full-color spectrum, high volume, high quality, high-brightness LED supplier."

AXT's new devices complement its current offering of red, amber, yellow and blue LEDs. The company also announced that after the successful customer trial of its previously introduced high-brightness blue LEDs, it is shipping these devices in production quantities.

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Uniroyal Technology Acquires Sterling Semiconductor

Just days after Cree announced that it was buying Nitres, high brightness LED manufacturer Uniroyal Technology Corp. (Sarasota, Florida) acquired silicon carbide specialist Sterling Semiconductor (Sterling, VA) in a stock transaction valued at around \$36 million. Sterling produces and sells single-crystal SiC substrates as well as epitaxial thin films on SiC, and is also involved in the development of advanced electronic SiC-based devices with Microsemi (see below). Uniroyal Technology manufactures high brightness InGaN and AlInGaP LEDs at its Uniroyal Optoelectronics facility in Tampa, Florida, which is a joint venture with Emcore. However, contrary to speculation, Uniroyal will continue to use sapphire substrates to grow its nitride-based LEDs rather than switching to SiC.

Instead, the acquisition of Sterling allows Uniroyal to broaden the base of technologies within the compound semiconductor field. "We are strategically positioned to increase Uniroyal's participation in the explosive compound semiconductor industry via internal growth as well as through acquisition," says Howard Curd, Chairman and CEO of Uniroyal Technology. "The addition of the SiC technology developed by Sterling creates a variety of opportunities for expansion into devices that solve common problems in the areas of high frequency communications, opto-

electronics, and high temperature, high power applications."

Under Uniroyal, Sterling's existing business plan to develop SiC substrates, epiwafers and devices will be accelerated by investment in the region of \$20-25 million. "As a subsidiary of Uniroyal, Sterling will be positioned to substantially increase its wafer, epitaxy and device production capacity," says Jim LeMunyon, President of Sterling. "We also see potential new market opportunities. For instance, our combined technologies of GaN epitaxy on SiC provides a platform to accelerate our product development of devices targeted at the rapidly growing wireless communications market."

Sterling has been the recipient of many U.S. government R&D grants and contracts to develop leading edge materials and device technologies for military and commercial applications. The company currently has a strong backlog of U.S. Government contracts, including a prestigious three year Title III contract to establish a 3-inch SiC wafer production line. Sterling's wafer R&D efforts and SiC epitaxy production are conducted at its facility in Sterling, Virginia, and wafer manufacturing and additional R&D is carried out in Danbury, Connecticut at a facility leased from ATMI. In time, Sterling will look to consolidate these activities at a single location.

Microsemi Launches 480 Volt SiC Schottky Diode

Microsemi Corp. has announced the first commercial SiC device to be developed through the company's alliance with Sterling Semiconductor [see CS 5(8), p. 16]. The UPSC148 is a 1 A, 480 V SiC Schottky diode packaged in Microsemi's patented low profile, 1-mm high Powermite package.

While Schottky devices are typically offered up to 100 V, the properties of SiC allow the manufacture of high voltage, efficient Schottky devices for high speed switching and power supply applications in telecommunications and implantable medical equipment. Microsemi has developed a product roadmap for SiC discrete semiconductors that explores the benefits in high frequency, high temperature, radiation resistant and high-density applications.

"We are quite pleased with our short product development cycle on our first SiC discrete semiconductor," commented Manuel Lynch, Microsemi's director of worldwide marketing. "We feel that we will be able to introduce several innovative discrete products based on SiC. Our broad product experience coupled with Sterling's expertise in SiC is a combination of talents that will produce several discrete solutions that will include Schottky diodes, PIN diodes, high speed switching transistors and MOSFETs."

High Power X-Band GaN PA from HRL Labs

HRL Laboratories (Malibu, CA) has demonstrated a high-efficiency 20 W GaN power amplifier operating at the X-band (8-12 GHz). This the first time a GaN PA has surpassed the performance of high-power (i.e. >10 W) GaAs PHEMT PAs at these frequencies.

Under the bias conditions required for high efficiency, the GaN PA produced 21.4 W with 43% PAE under CW operation. (The device has a total gate periphery of 4 mm.) When biased for high CW output power, the GaN PA produced 23.8 W with 35% PAE. HRL says that these are the highest CW power levels and efficiencies reported for a GaN PA at this frequency range.

"These results clearly show that GaN HFET technology is ready for the next step - the development of high performance MMICs," says Bill Stanchina, manager of HRL's Microelectronics Laboratory. HRL has developed a proprietary growth process using MBE that has significantly reduced material defects common to other reported GaN devices. MBE growth also produces device characteristics with less than 5% standard deviation over the 2-inch diameter SiC substrate, a six-fold improvement over previously reported results.

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Nova Crystals Relocates to Larger Facility

Nova Crystals has relocated from Ithaca, New York to a larger facility in San Jose, California. The new plant more than doubles the company's floor space to 14,000 sq. ft, and will house administrative research personnel and contain clean-room space for device development and pre-production. High-volume manufacturing of the company's products is performed at a fabrication facility in Taiwan.

"This new plant provides us with a complete, self-contained semiconductor laser R&D facility," says Felix Ejeckam, president and CEO. "Furthermore, the San Jose location gives us access to a very large labor pool of highly skilled individuals."

Nova Crystals was founded by researchers at Cornell University in September 1998 to develop and manufacture high efficiency LEDs for display and illumination applications, in

addition to fiber-optic communications components. The company's proprietary LEDs (known as "Nova Flares") are based on AlInGaP active layers on GaAs substrates, and feature high light extraction efficiency for applications such as outdoor signs, displays, cell-phone backlighting and PDAs. Nova's AlInGaP red and yellow LED lamps emit at 626 nm and 595 nm, respectively, and deliver over 20 lm/W.

Nova says it also has a number of fiber optic communications and lighting products under development, including short- and long-wavelength lasers and white LEDs. The company is also developing optical communications components with ultra-high gain and bandwidth for optical voice and data LANs and WANs, in addition to innovative laser and material technologies for optical intra-chip communications.

LumiLeds Announces New Components Business Unit, Lighting Products

LumiLeds Lighting (San Jose, CA) has created the Components Business Unit, a new division formed to pursue sales of the company's LED die and "light engine" products. The company says its light engine devices employ multiple high-power AlInGaP and InGaN LEDs fixed to a metal clad PC board, and are designed for applications traditionally addressed by fluorescent and neon light sources. The new unit will not encompass LumiLed's automotive and traffic signal activities.

New Lighting Products

Targeting specifically the fluorescent lighting market, LumiLeds has introduced new "edge-lit" LED signs. These signs consist of a housing that includes a driver and several high-brightness LEDs that light a 0.2-inch thick acrylic strip. In comparison to fluorescent displays, LumiLeds says these new LED systems can be used in outdoor daylight applications. This is a result of the high coupling efficiency of the LED light into the acrylic. The new signs feature much longer lifetimes and a myriad of colors variations and dynamic effects that are

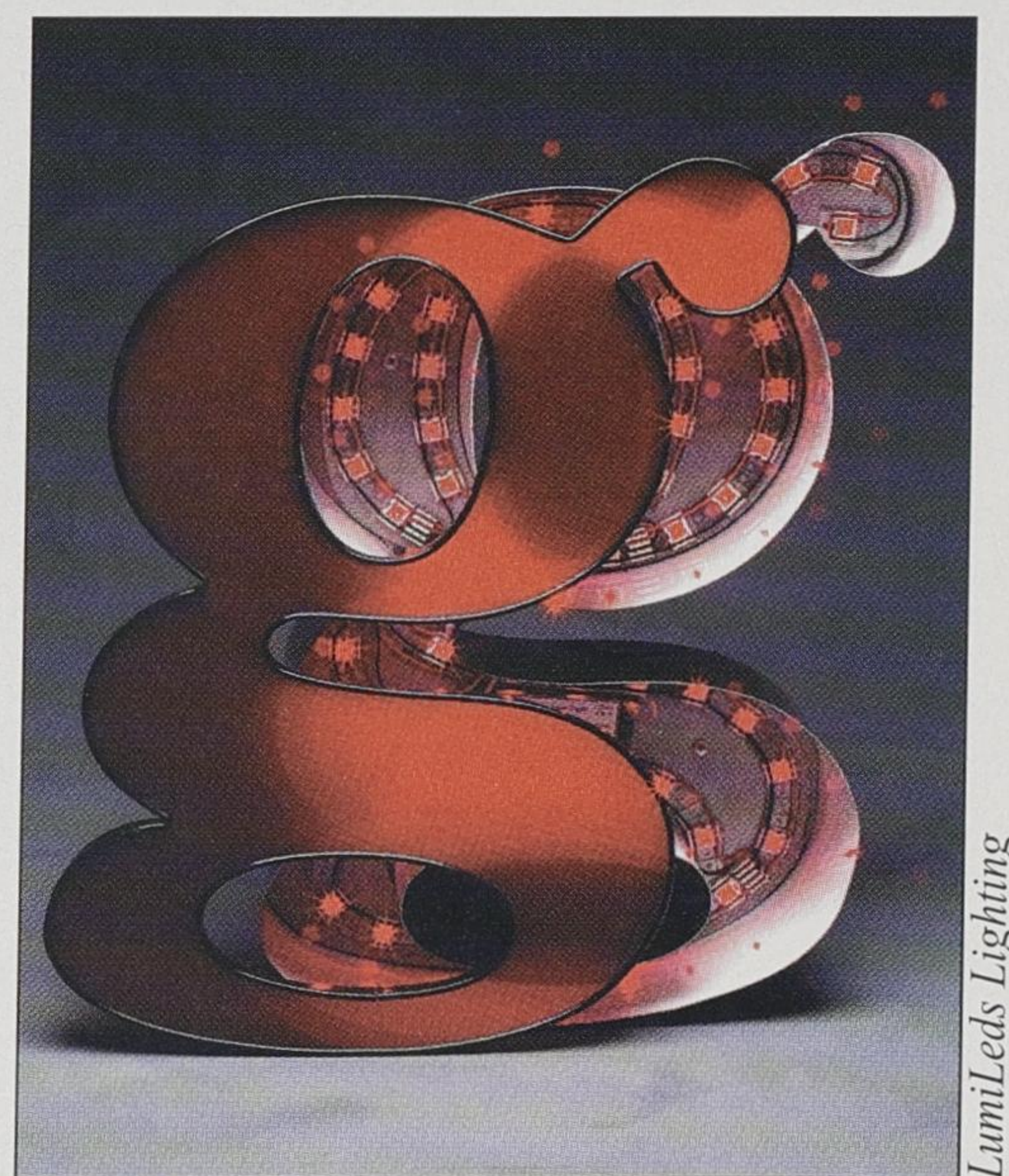
obtained with almost instantaneous switching, says the company. This product should be available in single colors by the summer and in multiple colors, including white, by the end of the year.

LumiLeds has also introduced the LED Rail, which consists of a string of LEDs mounted on a patented rail system that provide back-lighting for channel letter housings (see photo). The LED Rail is designed to replace neon lighting as the primary lighting source in channel letter lighting, not least because the LED efficiency allows for an 80% reduction in energy consumption. Because it contains no glass tubes, this device is resistance to breakage and is easy to install, says LumiLeds. The power supply system, developed by Philips, drives the rail at 24 V, leading to over 2 lumens of flux at 50 mA. The channel letter is currently available in red (630 nm) with additional colors available later this year.

Order for Automotive LED Products

In more news, LumiLeds has received an order worth \$3 million for its SnapLED high-brightness LEDs from a

major transportation manufacturer. The SnapLED, recently recognized for production innovation by the automotive industry [CS 6(3), p.13], uses high-brightness AlInGaP LEDs attached to a metal substrate, allowing manufacturers to use fewer LEDs in their lighting modules compared to traditional 5-mm devices.



The new LED Rail from LumiLeds Lighting is a string of LEDs mounted on a patented rail system for installation in standard channel letter housings.

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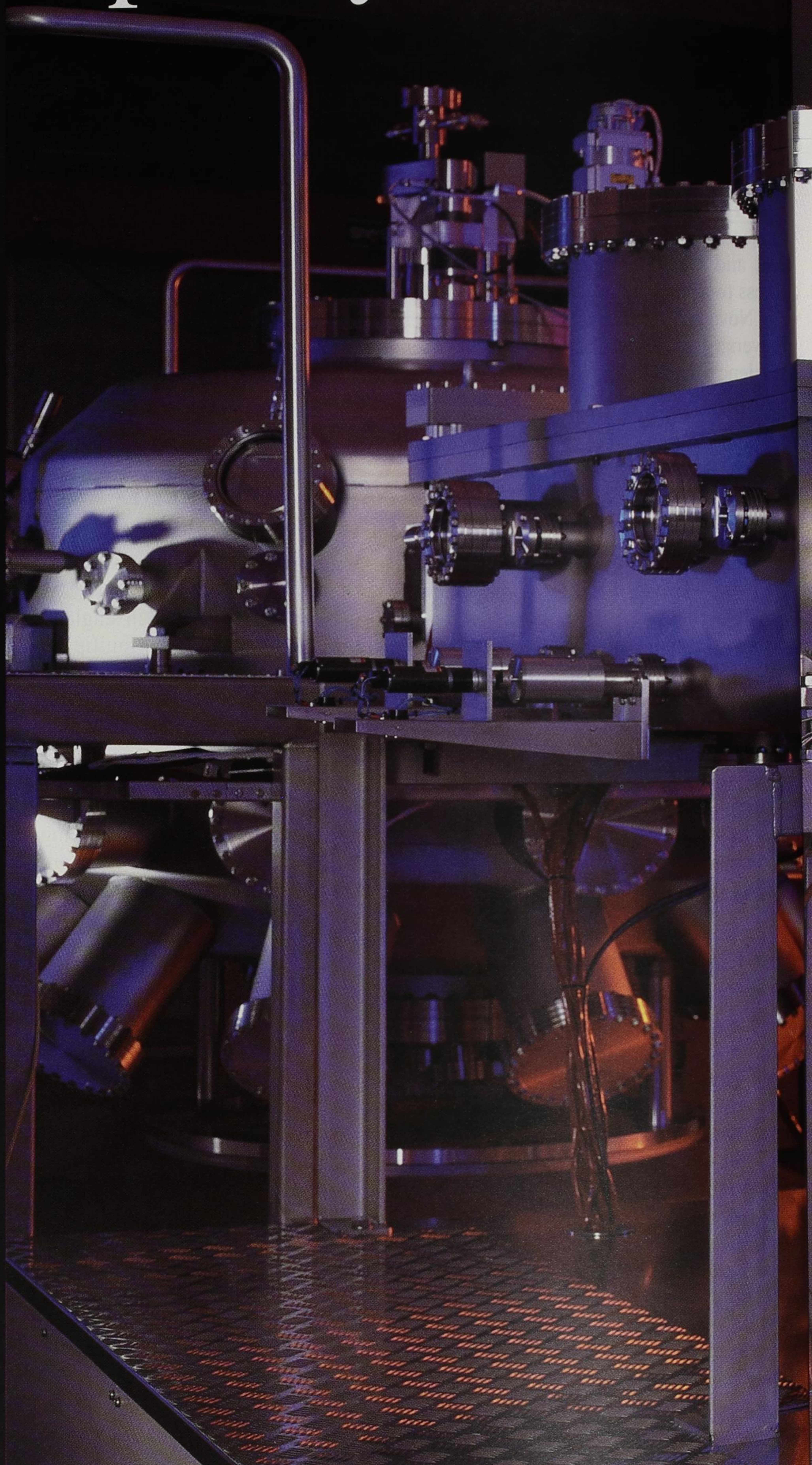
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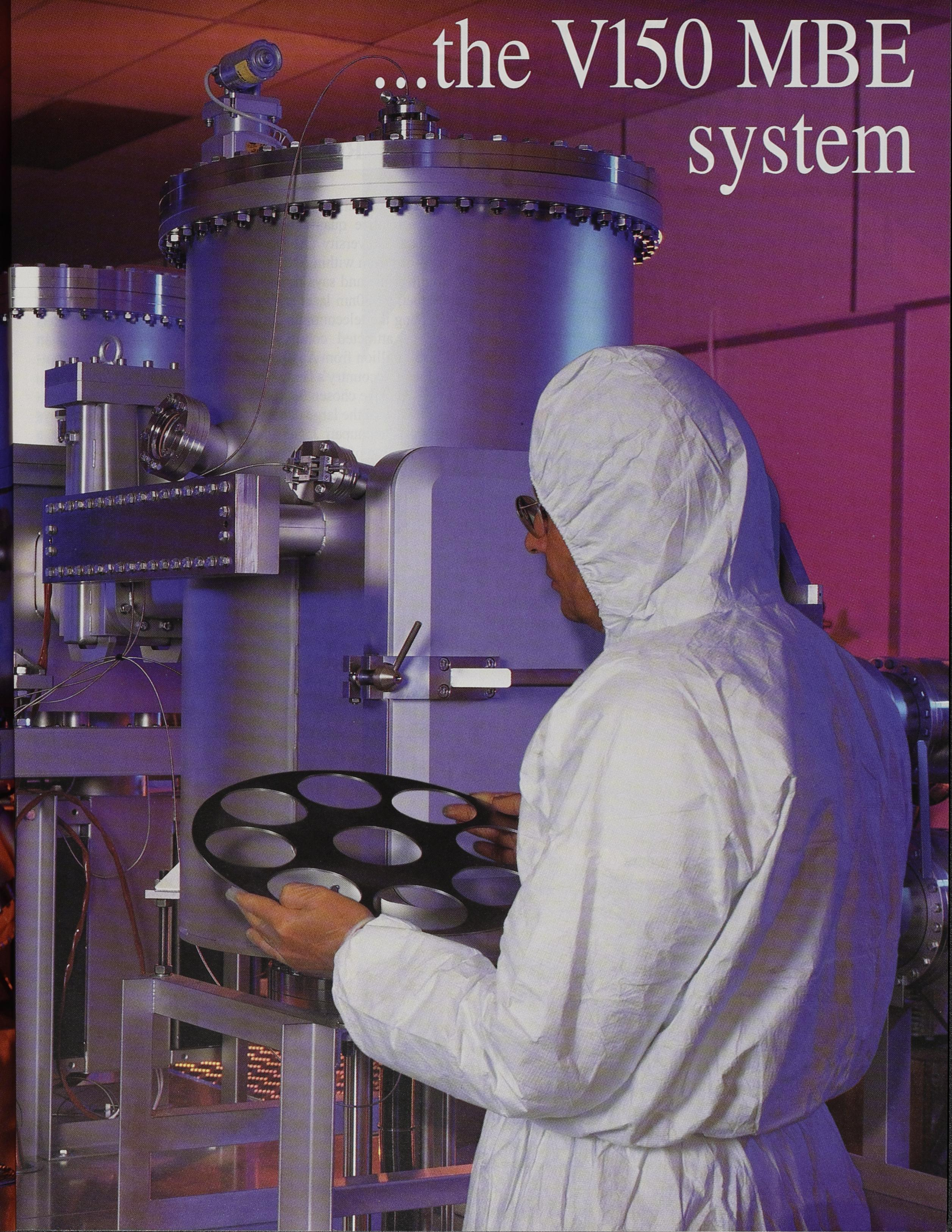
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Acton Lasers Born from Laser Research in Australia

A new company called Acton Lasers has been formed to commercialize quantum-well laser research at the Australian National University (ANU). Acton Lasers draws on photonics expertise from within ANU's Department of Electronic Materials Engineering, and says it has already received orders for its first product, a 980nm laser with a 50- μ m active stripe width that is targeting the telecommunications market. The ANU spin-off has already attracted commercial investments worth more than US\$50 million from Australian and overseas investors. The company is the country's first semiconductor production laboratory.

"We have chosen 980 nm lasers as a technology demonstrator in view of the large demand for pump lasers for EDFAs," says ANU's Chennupati Jagadish. "Currently, 980nm lasers have a market value of US \$300 million, and demand for these lasers is growing at a rate of 50% per annum or higher." Jagadish added that while the company will initially make use of ANU facilities, it will move to dedicated production facilities in due course.

ANU, Yuh Chen Group Collaborate on Blue-Green LEDs

In related news, the Australian National University (ANU) has reported that the Yuh Chen Group of Taiwan has decided to base its major optoelectronic development laboratory in Australia to tap into ANU's photonics expertise. The joint venture will focus on blue-green LEDs.

Rockwell Creates Technology Subsidiary

Rockwell has created Rockwell Technologies LLC, a subsidiary based in Thousand Oaks, CA that will promote the company's intellectual capital to the commercial marketplace. "In developing winning technologies for its businesses, Rockwell has produced innovations that we believe are valuable in the global technology marketplace," says Ted Izen, president of the new subsidiary. "Rockwell Technologies will seek to maximize the value of those innovations and seek partners for technology and product development when appropriate."

The new unit will license many of the technologies developed at the Rockwell Science Center (RSC), including some of the GaAs device work described in more detail on page 60 of this issue. RSC is also well known for its advanced imaging sensors, based on HgCdTe, which are used in most of the world's infrared telescopes.

Spectrolab Supplies Multi-Junction Solar Cells to NASA, Dornier

Multi-junction solar cells manufactured by Spectrolab (Sylmar, CA) are providing primary power to NASA's latest mission to explore Earth's magnetic field. The mission, designated IMAGE (or Imager for Magnetopause-to-Aurora Global Exploration), was launched on March 25th. IMAGE is a highly elliptical-orbit mission to study the global response of Earth's magnetosphere to changes in the solar wind.

Lockheed Martin Missiles and Space (LMMS), which built the IMAGE observatory spacecraft, selected Spectrolab's multi-junction GaAs solar cells to power the satellite's scientific instrumentation and subsystems. Since the delivery of the IMAGE solar cells, Spectrolab has delivered more than 35,000 W of triple-junction GaAs solar cells with an average efficiency of 24.5% to multiple flight programs.

Spectrolab has also been chosen to supply solar cells to Dornier Satellitensysteme GmbH (DSS) of Germany for qualification testing in DSS' space solar array systems, under a technical assistance agreement between the two companies. This is the first European agreement for Spectrolab since its recent US government approval to provide solar cells, panels, and arrays to major European spacecraft manufacturers. The new agreement enables DSS to procure several hundred thousand multi-junction solar cells through 2002, as well as allowing DSS to insert multi-junction solar cells into existing designs.

Once qualified, Spectrolab's says its multi-junction GaAs solar cells can improve Dornier's solar array power performance by 40% compared with earlier designs using silicon cells. This significant performance boost supports spacecraft designs requiring total powers in excess of 20 kW.

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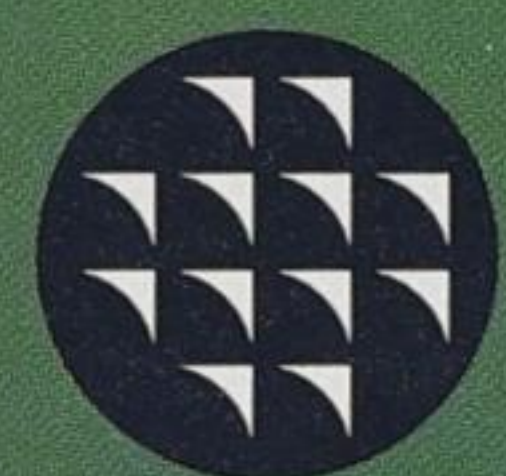


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ADC Buys Altitun

ADC Telecommunications has acquired Swedish tunable laser manufacturer Altitun for \$872 million. Tunable lasers are seen as critical components for routing signals and providing bandwidth on demand in future optical communications networks, and Altitun is arguably the leading developer of these components. The company's core technology is an InGaAsP/InP laser chip that can be tuned across the whole spectrum of an EDFA (1525-1565 nm). Altitun is in the process of expanding its production capacity with new facilities in Stockholm, where it expects to be mass-producing lasers by mid-year [see CS 6(2), p 8].

"Altitun brings ADC many significant strategic advantages to help our customers build next-generation, all-optical network equipment," said Lynn Davis, senior VP and president of ADC's Broadband Connectivity Group. Davis cites the wide tuning range of Altitun's lasers and its integrated package of laser, control electronics and software as key future technologies. ADC's takeover also benefits from Altitun's vertically integrated production and its ability to ramp production from current levels.

Minneapolis-based ADC, a supplier of network equipment, software and integration services for broadband, multi-service networks, has bought several optics companies in the last few years,

notably Spectracom, a manufacturer of 980 nm pump lasers. Most recently, ADC spent \$80 million to buy IBSEN Micro Structures, a developer of phase masks and fiber Bragg grating devices for DFB lasers and DWDM switch processors.

Corning Doubles Capacity at Lasertron

Corning is planning to double the manufacturing capacity for telecommunications lasers and receivers at its Lasertron plant in Bedford, MA. The expansion will be funded by a \$45 million capital expenditure and is expected to create more than 300 new jobs. Corning says it is experiencing unprecedented demand for its optical networking products, with first quarter sales in the company's Photonic Technologies Division up 90% on the previous year.

"Worldwide demand for active photonic devices has accelerated this year and is expected to continue to grow by more than 50% annually for at least the next two years," said Gerald Fine, VP and general manager for Corning's Photonic Technologies Division. "This expansion will allow us to better meet the needs of our customers as they strive to keep up with demand for additional bandwidth."

The Corning Lasertron announcement is the most recent in a series of plant expansions. Within the last four months, Corning said it would invest \$50 million to double its photonic module capacity by opening a second optical amplifier manufacturing facility at Benton Township in Pennsylvania, and increase by 10-fold the production of thin film optical filters at its Marlborough, MA facility.

Nortel Creates Optical Components Business Unit

Nortel Networks is to reorganize its optical components businesses into a single unit, to be known as High Performance Optical Components Solutions. The unit will incorporate 6,000 employees, located primarily in Harlow and Paignton (UK), Ottawa (Canada) and Research Triangle Park (North Carolina). "[This unit] will enable us to more fully leverage our recent acquisitions of Xros, a provider of fully photonic switching solutions, and CoreTek, a developer of tunable lasers, to redefine the Internet as we know it today," says Barbara Callaghan, who will head up the new group.

The new unit will combine Nortel's existing optical components group with other activities, including high-speed modules and IC design and development. It will develop lasers, high-bandwidth receivers and microelectronic components, including transmit/receive modules and optical chips for various internetworking functions. Emphasis will also be on integrating multiple functions onto a single chip, and module design.

Nortel will invest approximately \$143 million to create an additional 600,000 sq. ft. of space in 3 new buildings for 2,500 R&D staff at its site in Ottawa. This is part of a total investment of \$400 million that the company has allocated to its optical business in recent months — this will create about 5,000 jobs and is expected to triple production capacity.

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Wireless Optical Networks Take on Last Mile Bottleneck

Three companies - TeraBeam Networks, Airfiber and MRV - have announced wireless optical solutions designed to eliminate the last mile bottleneck between long distance networks operating in the Gb/s range, and Mb/s local area communications. These networks use eye safe near-infrared lasers to transmit data through free space, avoiding the costs of laying fiber and the problems of rooftop leasing and spectrum rights associated with microwave solutions.

Seattle-based TeraBeam Networks has a 70:30 joint venture with Lucent to push wireless optical network technology into commercial markets. TeraBeam says that its point-to-multipoint network can be deployed in days, and uses transceivers that are about the size of a small satellite dish and can be mounted in an office window. Despite the fact that fiberless networks are purported to suffer from outages or slow connection speeds - a result of attenuated laser signals caused by heavy rain, snow, air turbulence and fog - TeraBeam and Lucent are very confident that the technology will solve the data rate bottlenecks. Lucent plans to introduce its own OpticAir laser product line this summer.

Meanwhile, AirFiber of San Diego has developed OptiMesh, which operates at up to 622 Mb/s, and is based on a highly-redundant "mesh" or multiple point-to-point design that ensures reliability even in the harshest weather conditions. "At present, less than 5% of commercial buildings in the U.S. have direct high-bandwidth access, and that number is much lower in other parts of the world," says Jim Dunn, CEO and president of AirFiber. "We are aiming to dramatically increase the number of buildings with these capabilities in the next few years, making the last mile access bottleneck a thing of the past."

Finally, MRV Communications (Chatsworth, CA) recently acquired Jolt, a Jerusalem-based company that has developed wireless optical networking systems for 2 km links that operate in all weather conditions except heavy fog. MRV believes that Jolt's mesh architecture is more cost-effective, reliable and provides better performance than other point to multi-point wireless optical network systems.

MRV Communications Launches Luminent

MRV Communications (Chatsworth, CA) is to combine its optical component activities, including several recently acquired companies, to form a new company known as Luminent, Inc. MRV is an optical network components and systems company that integrates switching, routing, access servers and optical transmission systems.

Optronics International Corporation (OIC), a Taiwanese manufacturer of lasers, transceivers and detectors for optical networks, will become part of the new company. OIC is a fully vertically integrated manufacturer, with in-house MOCVD capability as well as complete facilities for chip fabrication, packaging and module assembly [see CS 6(2), p. 12].

Luminent will also incorporate Jolt, a Jerusalem-based manufacturer of wireless optical networks (see opposite); Quantum Optech, Inc (QOI), a thin film coating and DWDM filter manufacturer; and Fiber Optic Communications, Inc. (FOCI), which makes passive components.

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Lucent's Ortel Corp. Plans 16-Fold Capacity Expansion

Lucent Technologies is to spend \$40 million to augment the manufacturing capacity of Ortel Corp., a leading developer of optoelectronics components for cable TV networks acquired by Lucent for \$2.95 billion. The expansion is expected to increase the output of Ortel's facilities in California, at Alhambra and Irwindale, by at least 16 times and create around 450 manufacturing jobs over the next 18 months. Lucent recently completed a \$30 million expansion of its automated optoelectronics components operations in Pennsylvania.

The work includes the construction of a new 20,000 sq. ft. wafer fabrication and testing facility at Irwindale, which is expected to begin producing optoelectronics components for cable television networks in the summer of 2001. Lucent is also renovating an existing 166,000 sq. ft. building on the Irwindale campus that will house administration and some manufacturing operations. The company has also initiated enhancements to a 104,000 sq. ft. facility in Alhambra, which will be equipped with increased levels of automation and higher precision manufacturing processes.

"The upgrades to our Alhambra facility and the expansion into Irwindale will help us bring [optoelectronics components] to a capacity-constrained market faster through new and improved equipment and processes, including flexible production schedules, automated manufacturing capabilities, and reduced cycle times," says Jeff Rittichier, general manager of access products.

Lucent Announces 320-Channel Optical Networking System

Lucent Technologies has increased the number of wavelengths handled by its WaveStar OLS optical networking system from 80 to 320. The new WaveStar OLS 800G, which will be commercially available in the first quarter of 2001, transmits up to 320 wavelengths at a rate of 2.5 Gb/s each. Alternatively, the 320 wavelengths can be combined using a new wavelength-packing technology to provide a carrier with 80 channels, each transmitting information at a rate of 10 Gb/s. Lucent says its current 80-channel system has been shipped to more than 40 customers, six of which are carrying live network traffic across the system.

Methode Floats Stratos Lightwave

Methode Electronics has filed for an initial public offering (IPO) for its newly created optoelectronics subsidiary, Stratos Lightwave. The new company incorporates Bandwidth Semiconductor, which comprises the former optoelectronics activities of Spire Corp. [see CS 6(2), p. 11].

SDL Record Shipments Fuel Further Expansions

Driven by record results in the first quarter of 2000 (up 23% over the previous quarter), SDL plans to expand its numerous facilities to keep up with continued demand for its fiber optic communications products, which now make up 83% of its business. "In this quarter, we benefited from rising demand for Raman amplifiers, 980 nm pump products, LiNbO₃ modulators and drivers, and fiber gratings, among other products," said SDL's Chairman and CEO Don Scifres. "We are projecting a need for increased manufacturing facilities sooner than we had previously anticipated."

SDL's Santa Clara laser facility will be enlarged by 50,000 sq. ft. by the end of the year, and further expansion of SDL Optics in Victoria (BC, Canada), which manufactures pump modules, is also expected. The company will also enlarge the newly acquired SDL Veritech site (see below) from 18,000 to 60,000 sq. ft. and is looking at options for SDL Integrated Optics (Witham, UK), an optical modulator manufacturer which SDL bought last year.

Scifres added that the company's decision to move to 24 hour, 7-day shift work for its chip production and to increase automation at several sites has been at least as significant as increasing manufacturing capacity. This has been crucial to keeping up with demand for such products as the company's new 300 mW 980 nm pump lasers [see CS 6(3), p. 50].

SDL Builds a Fiber Optics Empire

SDL also recently embarked on a series of acquisitions aimed at providing it with technologies it perceives as key to this industry in future. At the end of February the company acquired Veritech Microwave (South Plainfield, NJ) in a deal worth \$590 million. Now SDL Veritech, the company manufactures high-speed electronic drivers for external light modulators, in addition to 10 Gb/s optical receivers for long-haul undersea and terrestrial fiber optic transmission systems. SDL says the addition of Veritech will further its position in 10 Gb/s module level transmitter and receiver products for DWDM.

SDL also acquired Queensgate Instruments (Bracknell, UK) for around \$210 million; the company produces network monitoring equipment employing precision tunable filters.

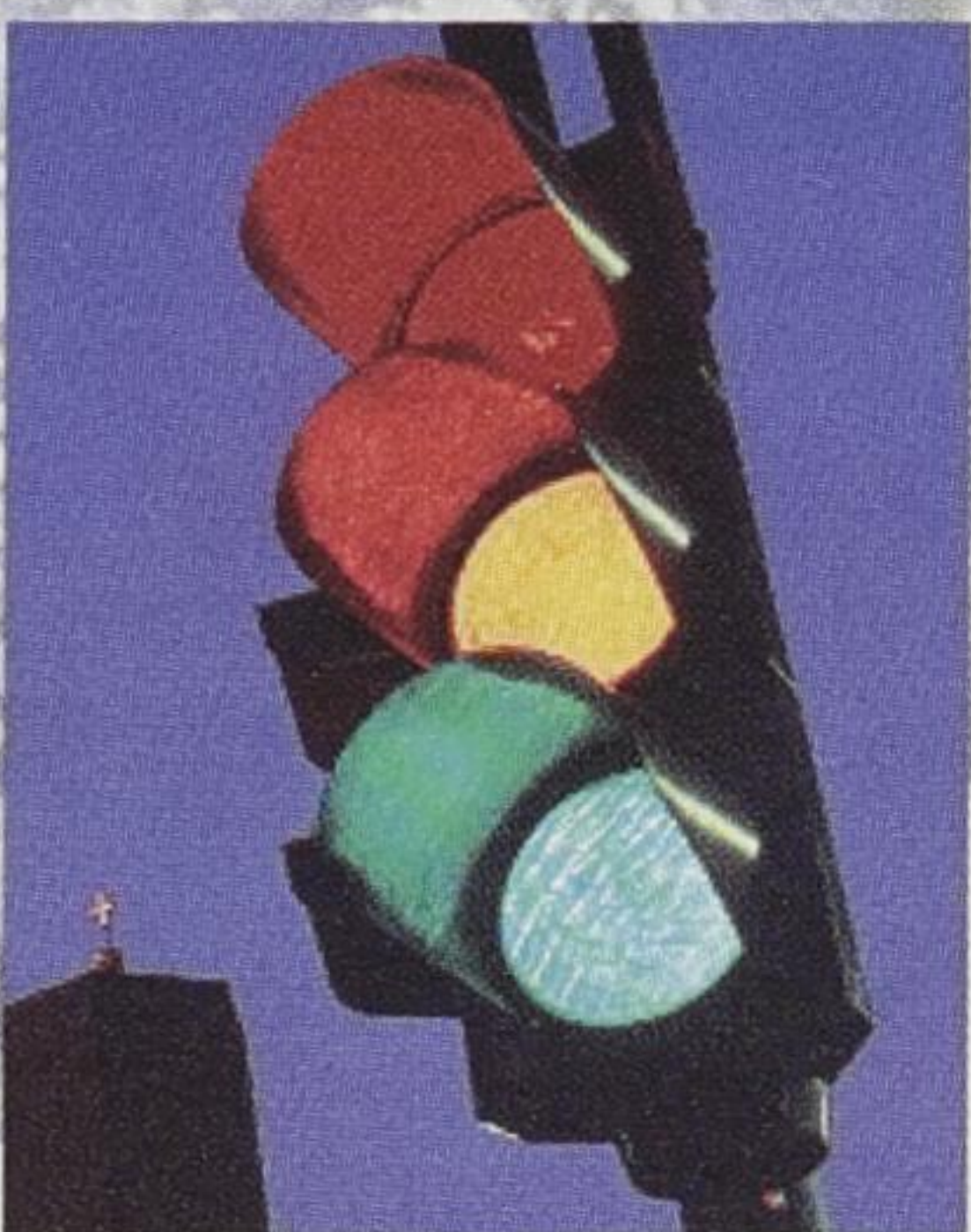
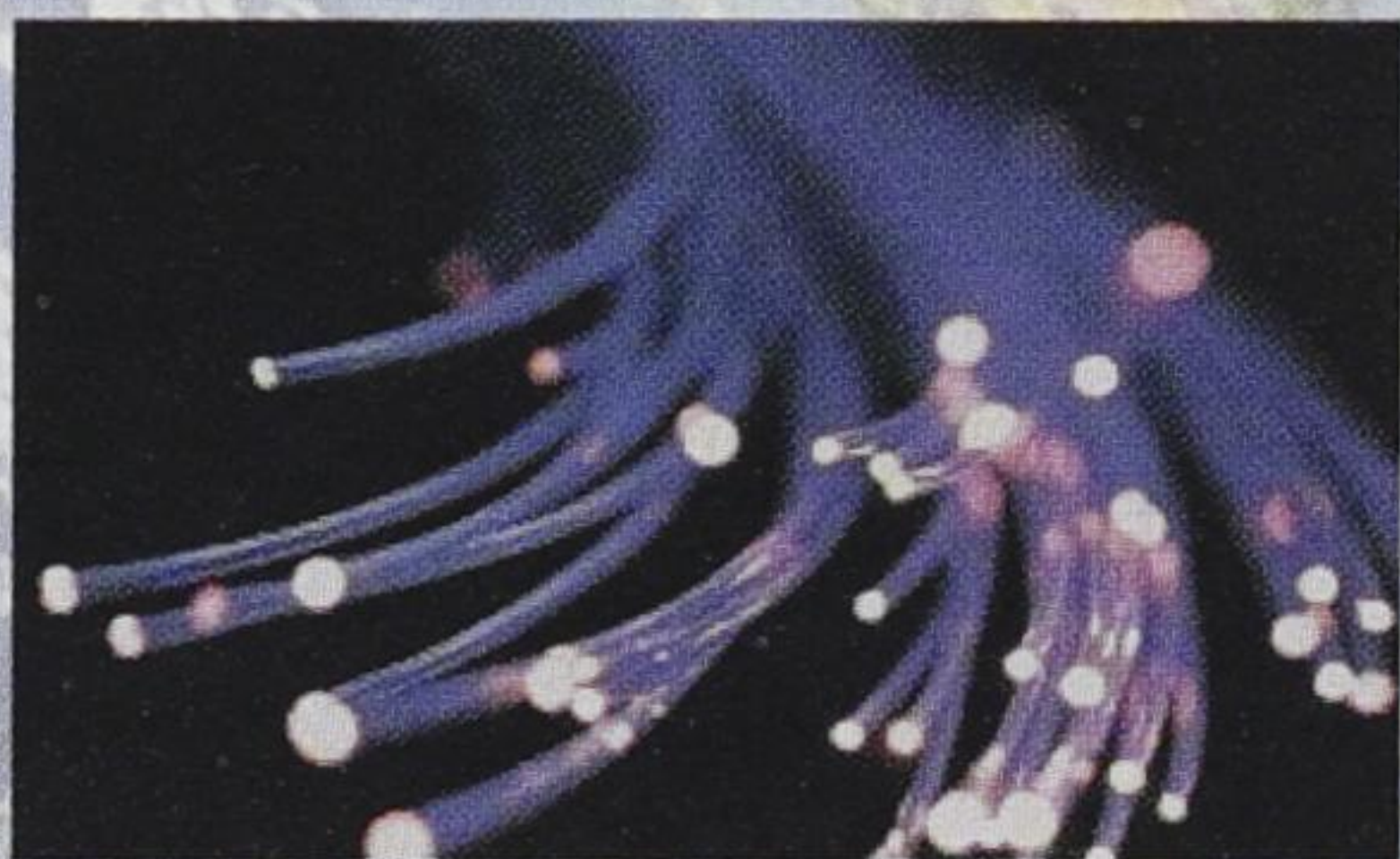
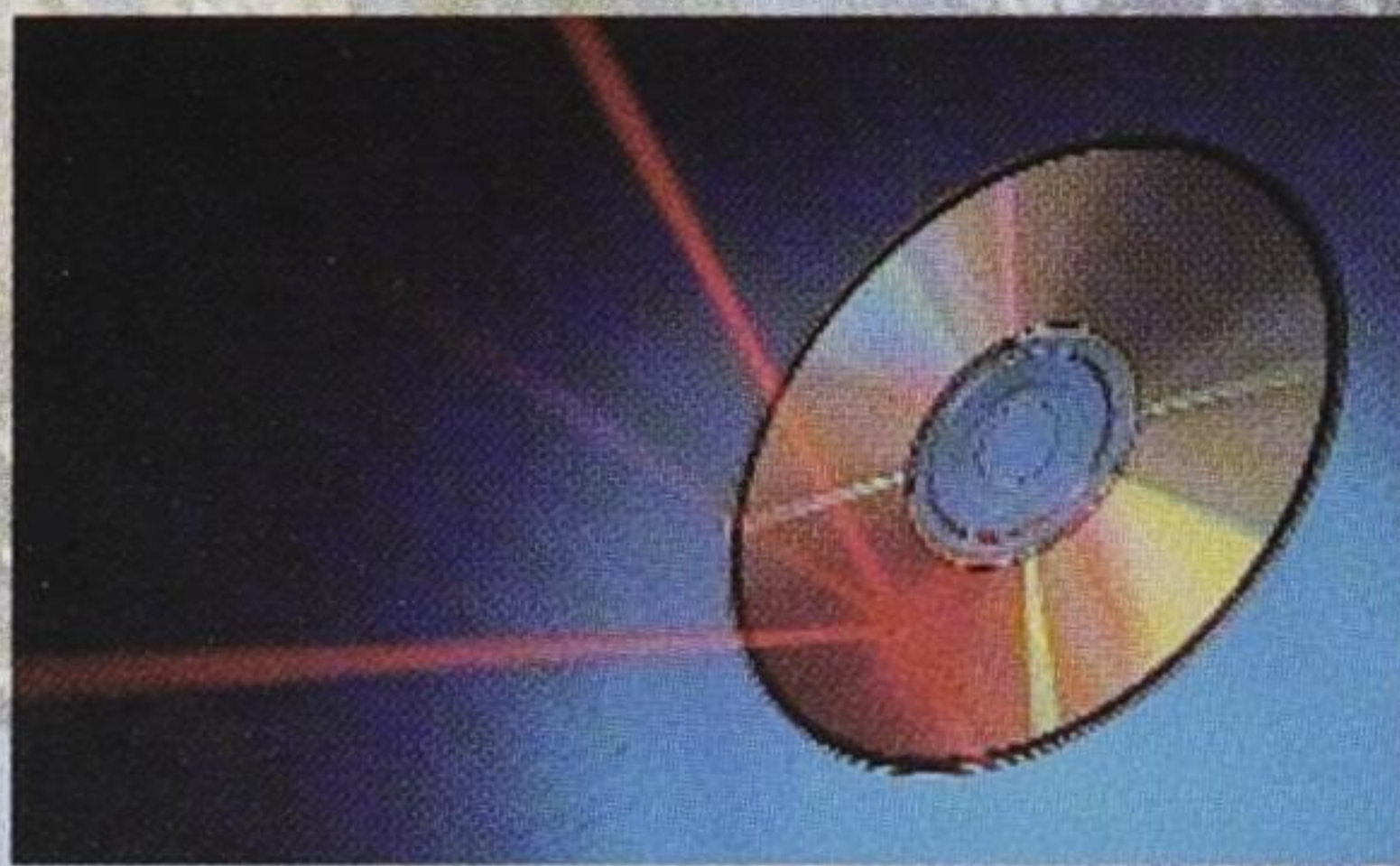
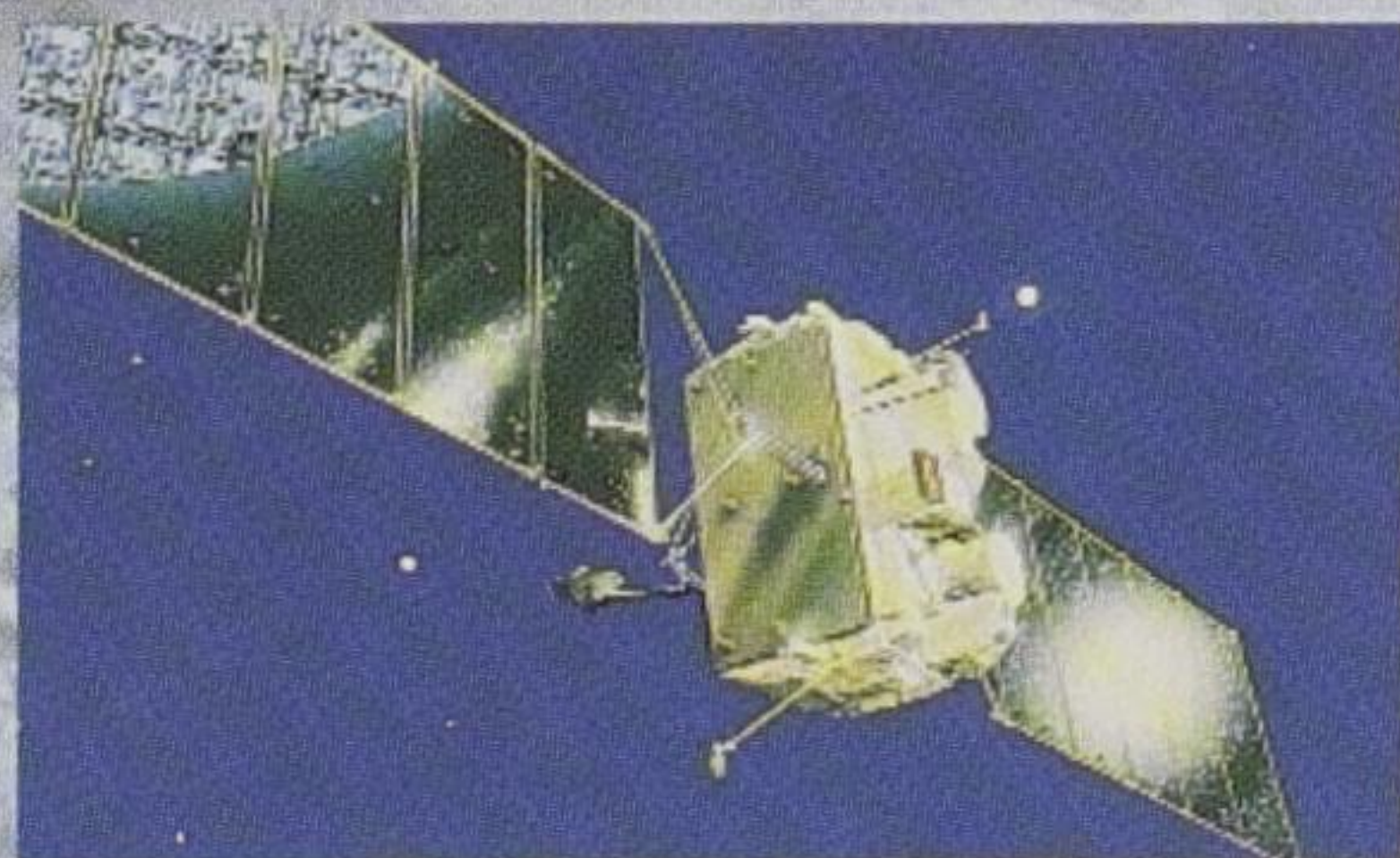
The company also recently signaled its move into the passives market by paying \$1.8 billion for Photonic Integration Research, Inc. (PIRI), a manufacturer of arrayed waveguide gratings (AWG) that enable the routing of individual wavelength channels in fiber optic mux/demux products. "SDL is also a strong believer in optical integration technologies," explained Scifres. "The power of IC-style manufacturing processes utilized in the silica waveguide technology available at PIRI is crucial for next generation product development."

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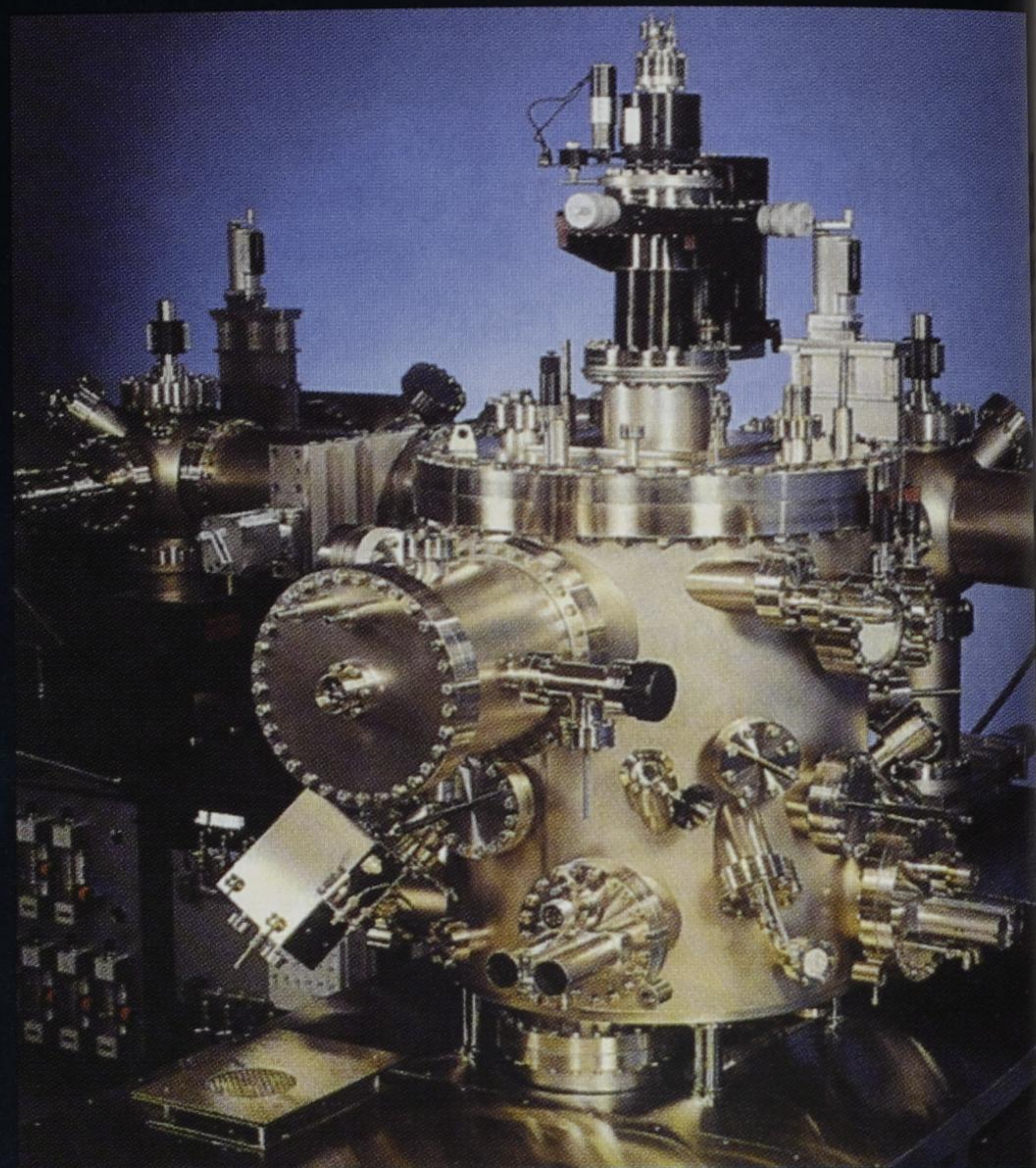
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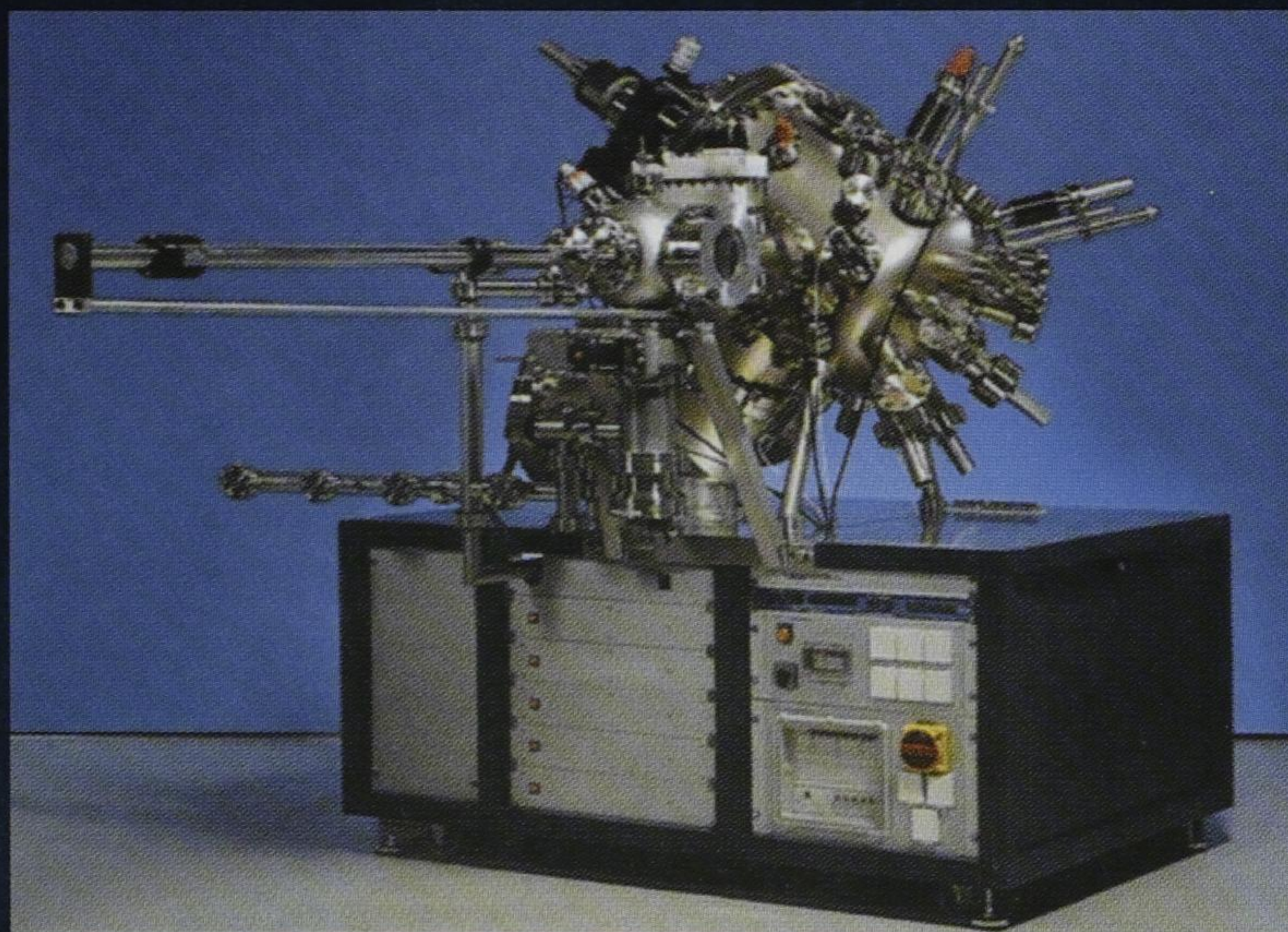


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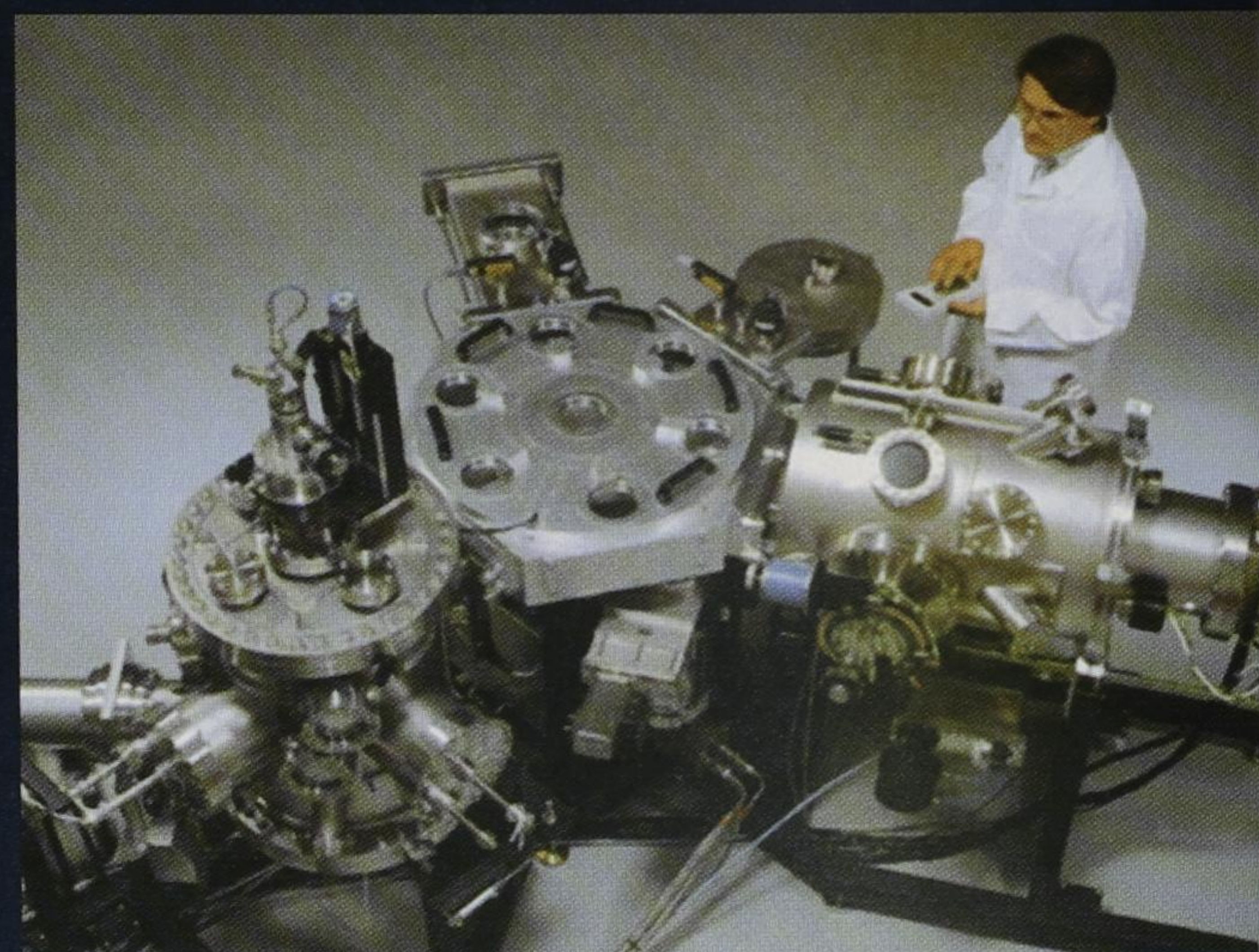
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Motorola to Employ Emcore MOCVD Tools, Epitaxy

Emcore has signed an agreement with Motorola to supply epitaxial process technology and multiple MOCVD reactors, in addition to purchase orders for electronic device epitaxial wafers. Emcore says its Electronic Materials (E2M) foundry division has been supplying production quantities of PHEMT epiwafers to Motorola's CS-1 fab for several months.

Mark Wilson, engineering manager for CS-1 said; "We have been impressed with Emcore's ability to provide high volumes of 100 mm PHEMT epitaxial wafers. We are also planning to work closely with them on other epitaxial technologies. Presently Emcore has been ramping up supply of 150 mm PHEMT wafers."

Motorola will place orders for two Emcore MOCVD production tools and has awarded Emcore the Standard Supplier Designation, making Emcore the only qualified supplier of MOCVD tools for Motorola's compound semiconductor factories. Emcore intends to transfer full PHEMT epiwafer technology from their E2M foundry division to Motorola in order to ensure full compatibility between the wafers supplied by E2M and Motorola's internal production on the Emcore reactors.

MOCVD Spending Spree in Taiwan

In a recent flurry of sales, two Taiwanese companies, United Epitaxy Company (UEC) and Epistar, have placed orders for a total of 25 MOCVD systems.

UEC has ordered 20 systems, 10 each from **Aixtron** and **Emcore**. The Aixtron 2400/2600G3 Planetary Systems will be used for the mass production of AlInGaP high brightness LEDs (using a 35 x 2-inch format) and 4- and 6-inch HBT epiwafers, as well as III-nitride LED manufacturing.

Emcore will deliver 10 TurboDisc Enterprise MOCVD systems to UEC over the next two years. The new systems are configured for the production of high brightness LEDs and electronic materials. UEC already has six Emcore systems, which are used for the production of AlInGaP LEDs.

Hsinchu-based **Epistar** has purchased five **Aixtron** 2400/2600G3 reactors as part of its new expansion scheme. The machines will be used for AlInGaP-based yellow, orange and red high-brightness LEDs, in addition to blue and green III-nitride wafer manufacturing.

Picopolish Opens New Wafer Reclaim Facility

Picopolish recently celebrated the opening and ISO 9002 certification of its new 65,000 sq.ft. wafer reclamation facility in Bevaix, Switzerland. Picopolish supplies reclaimed wafers that are used by manufacturers in monitoring, testing and various IC manufacturing steps, and has installed two separate production lines providing this service for both GaAs and Si.

AXT Aims For 3-Fold Expansion of GaAs Substrate Capacity

American Xtal Technology (AXT) plans to approximately triple its GaAs substrate production capacity by the end of the third quarter of 2001. The majority of the expansion is expected to take place at its Beijing, China facility. "We are experiencing a pressing demand for our GaAs substrates as several of our customers are substantially increasing their ordering patterns," says AXT's president and CEO Morris Young. "We believe that this demand is due in part to the strong growth in the wireless handset market and the increasing popularity of 6-inch GaAs substrates. Our capacity expansion will help relieve some of the near-term industry shortage, particularly for 6-inch substrates."

AXT plans to increase its manufacturing space in Beijing from the current level of 62,000 sq. ft. to around 160,000 sq. ft. by the end of the third quarter of 2001. The company also plans to add another 20,000 sq.ft. to its Californian facility in Fremont, which produces GaAs, InP, Ge and GaN substrates.

Kopin Establishes Second Site for HBT Production

Kopin has established a second high-volume production fab for HBT epiwafers, to be located close to the company's current 25,000 sq. ft HBT facility in Taunton (MA). The new 60,000 sq. ft plant is expected to be operational by October 2000. Known as the Hancock fab, the new facility is expected to generate approximately 40% of Kopin's HBT epiwafers by the first quarter of 2001. It also allows capacity for further expansion.

Kopin will invest up to \$20 million in clean room and production equipment and plans to increase its workforce, which has already doubled in the past 12 months. "In March 2000, we completed the first phase of our capacity expansion by installing six new HBT [epiwafer] machines," said Daily Hill, Kopin's VP of GaAs operations. "We plan to complete the next phase - the installation of eight additional HBT systems at our Taunton headquarters and Hancock fab - by the end of this year."

Riber Responds to EPI Patent Suit

As previously reported [see CS 6(3), p. 20], EPI MBE Products Group has filed suit against fellow MBE equipment manufacturer Riber, alleging infringement of a patent "which relates to effusion sources for MBE systems", according to EPI. Riber company officials recently issued a response, seeking to clarify the scope of the lawsuit. According to Mike Levy, Sales and Marketing Director, the lawsuit is limited to a relatively narrow product category, valved crackers, and is also limited to sales within the United States. "The lawsuit in no way affects other Riber effusion cells, or non-US valved cracker sales. Its potential impact on Riber's revenues is therefore very limited," Levy said.

Processing Equipment

Filtronic Compound Semiconductor has purchased a **KDF 643 GT** batch sputtering system, to be used in the volume production of GaAs PHEMT devices at the company's new GaAs fab in Northeast England. The 643 GT features a batch processing chamber that allows differing wafer sizes to be both front and backside processed.

Oxford Instruments Plasma Technology has reported that for the year leading up to March, it received over \$12m worth of orders from the compound semiconductor industry, an increase of more than 140% over last year. Almost three quarters of the orders came from optoelectronic communications companies for InP-based laser fabrication. The remaining contracts were received from the microelectronic sector for applications including through-wafer via hole processing and low-damage gate recess etching.

Tegal has received a follow-on order from a major East Coast USA customer for multiple 901e systems used to etch GaAs devices. Valued at over \$1 million, the order is scheduled to ship during this fiscal year.

Trikon Technologies has received multiple orders for processing equipment from a new GaAs facility in Asia, slated to manufacture wireless devices.

More Reactor Sales

VG Semicon has received contracts in excess of \$10 million from **RF MicroDevices** for multiple V100 MBE reactors. The V100 systems will be installed at RFMD's semiconductor fabrication facility in Greensboro, NC for the manufacture of HBT RFICs used in wireless communication applications such as GSM and PCS CDMA systems.

Aixtron has received orders for two reactors from Japanese companies. **Mitsubishi Electric Corporation** has ordered a further AIX 2400G3 reactor equipped with an automatic wafer handler for the mass production of lasers. Meanwhile, **Anritsu Corporation** has bought an AIX 200/4 (3 x 2-inch capacity) system for the production of long wavelength telecommunications lasers emitting at wavelengths of 1.3, 1.48 and 1.55 μm . Anritsu is a major supplier of high power EDFA pump lasers.

Riber has sold a MBE 49 (4 x 4-inch capacity) production system to **Global Communication Semiconductors**, a GaAs foundry based in Torrance (CA). Riber has also received an order for an MBE 6000 (9 x 4-inch or 4 x 6-inch) production reactor from **IntelliEPI**, a III-V epiwafer manufacturer.

SILICON UPDATE

Room at the Bottom

ROBERT A. METZGER



Shrinking the device dimensions in order to improve its performance is as old as the IC industry itself. In the III-V community, this approach has been taken to heart, and the gate lengths of high-performance HEMTs have been pushed into the sub-50 nm regime in order to optimize the characteristics of these III-V materials. But at some point, fundamental limits are reached. In future, the thickness of materials and the lengths of gates will no longer be measured in microns or even nanometers - a limit will be reached where this critical thickness is defined by the number of atomic spacings. And while current marketplace demands are keeping that final barrier fairly distant from most of the III-V community, the day will come when that final wall will be hit.

Fortunately, well before that impact, Si MOSFETs will have long since smashed into that wall, and perhaps from observation we can learn how distant that wall really is.

Just how small are these Si MOSFETs currently? On the commercial side, next generation Si CMOS gate lengths will soon migrate from 0.18 μm to 0.12 μm in size. These are dimensions with which high-performance HEMT and even MESFET workers are well familiar. But on the research side, CMOS gate lengths are

being pushed below the 0.02 μm level, that is, sub-20 nm gate lengths.

Researchers at LETI in France are investigating the characteristics of an implanted NMOSFET using a 20 nm physical gate length coupled with a gate oxide of only 1.2 nm [1]. After standard LOCOS oxidation and well implantation to form the active device region, the intended channel region is implanted with boron (5 keV and $1 \times 10^{13} \text{ cm}^{-2}$), and the 1.2 nm gate oxide is grown at 800°C by rapid thermal oxidation. In-situ doped polysilicon of 100 nm thickness is deposited on the gate oxide followed by 50 nm of TEOS, which will be used as a hard mask to define the polysilicon gate. A combination of E-beam, Deep-UV optical lithography and RIE etching defines a hard TEOS-based mask on the polysilicon layer. The polysilicon gate itself is then dry etched in an RIE reactor using HBr, Cl_2 and O_2 , in a highly-selective process so that the exposed gate oxide is not etched through during the gate over-etch.

Source and drain regions are formed by 3 kV As implantation ($1 \times 10^{14} \text{ cm}^{-2}$ flux), producing junction depths only 11 nm below the surface. These junctions need to be extremely shallow in order to reduce short channel effects; attaining this shallow depth is as

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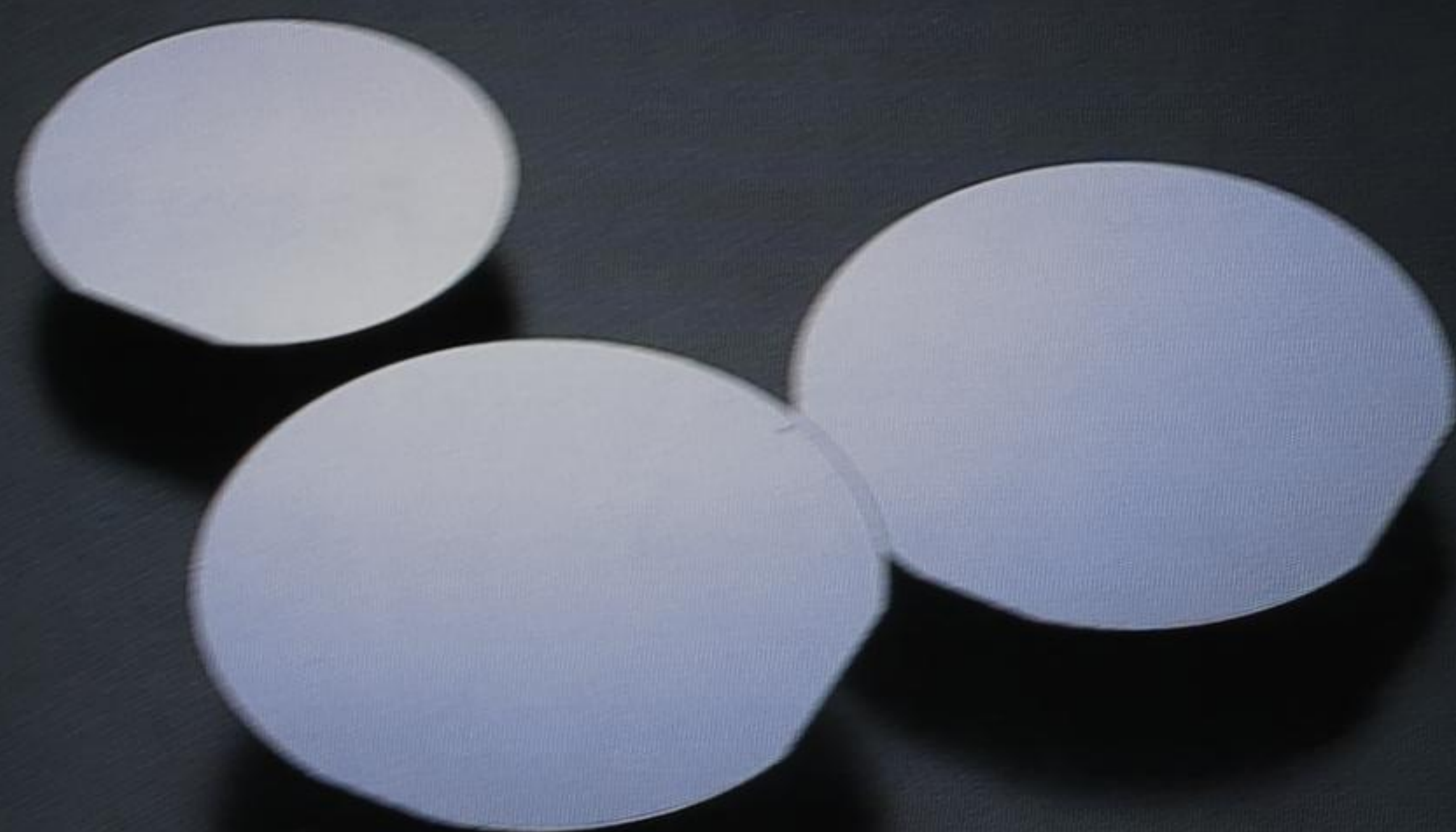
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SILICON UPDATE

large an experimental challenge as defining the narrow gate lengths. While the gate length of these devices is 20 nm, the metallurgical gate length is expected to be only 4 nm. Despite these incredibly small dimensions, these devices are formed using fairly standard Si CMOS processes, and the physical layout of the NMOSFET differs little from than production versions with gate lengths ten times larger.

For gates as small as 20 nm (gate lengths were varied from 20 to 30 nm), the channel conduction could be controlled from accumulation to inversion by sweeping the gate voltage from negative to positive bias. For slightly larger gates of 25 to 30 nm, significant on/off ratios up to 1×10^8 could be obtained with 1.5 V drain bias. A maximum transconductance of $380 \mu\text{S}/\mu\text{m}$ was obtained, along with threshold voltages of approximately 0.45 V. These devices are certainly the smallest ever made using conventional processing techniques, and clearly demonstrate that sub-20 nm gate length devices are possible experimentally.

In order to define the even shallower source/drain junctions needed to minimize short channel effects, researchers at NEC Japan are not relying on ion implantation or solid state diffusion to define these junctions. Instead they use an inversion layer generated by a second gate to effectively generate the source/drain regions by electrical means [2]. This device, called an electrically-variable shallow junction MOSFET or EJ-MOSFET, can induce source/drain junction depths of only 5 nm. While the resistance of these electrically-generated regions is too great to produce MOSFETs suitable for large scale integration, it is sufficient to study transistor behavior for very short gate lengths - in this case, for E-beam-defined gates as short as 14 nm. Other than the novel formation approach used to form the source/drain regions, the remainder of the device was made with conventional NMOS processing techniques, with E-beam-defined gates and a relatively thick gate oxide of 8 nm.

A range of different gate length devices were fabricated and analyzed. These devices showed relatively small saturation currents of only 10^{-6} A/mm, due to the high resistance of the electrically induced source/drain regions. With a drain voltage of 0.5 V, devices with gate lengths greater than 49 nm exhibited leakage currents of less than 1 pA/mm, resulting in a device with an on/off ratio of 10^6 . For gate lengths less than 30 nm, sub-threshold leakage began to increase. By evaluating transistor characteristics as a function of temperature (as low as 10 K), the authors were able to determine that even for the smallest gate lengths of 14 nm, this leakage was caused by classical thermal processes. In addition, they found that during room temperature operation, quantum-induced tunneling effects did not play an important role in device performance.

If a lesson can be learned from these ultra-small gate length MOSFETs, it is that there is still a great deal of room at the bottom. For III-V devices, conventional structures and relatively conventional processes can still be used for quite some time to come as device dimensions continue to be reduced in the drive for improved performance.

References

- [1] S. Deleonibus et al, *IEEE Elec. Dev. Lett.*, 2000, 21(4), p. 173
- [2] H. Kawaura et al, *IEEE Trans. Elec. Dev.*, 2000, 47(4), p. 856

SAL X-ray Lithography System Printing 125 nm Features at Sanders

The GaAs industry's first point source X-ray lithography (XRL) system has been installed at Sanders' Microwave Electronics Center (MEC) in Nashua, NH, where it will ultimately support Sanders' 6-inch manufacturing line. The development and installation of the tool has been supported by DARPA funding and will allow Sanders to fabricate high frequency MMICs for projects such as the F22 fighter aircraft and Longbow missile seekers.

"X-ray lithography was essential to our plans to upgrade to 6-inch operation," says Paul Hoff, director of Sanders' MEC. "The system offers a significantly higher throughput than e-beam systems, along with the necessary resolution to fabricate very high performance millimeter-wave devices." Initial exposures have shown resolution to 125 nm (see Figure 1). "X-ray allows tight control of the gate footprint and recess, without introducing additional undercut that will degrade performance," adds Hoff. The system will initially provide a throughput of five 6-inch wafers per hour, and has the scope to increase this to around thirty wafers per hour.

As a straightforward technique in which patterns are transferred directly, using a 1:1 mask-to-wafer arrangement, XRL is relatively insensitive to minimum

feature scaling issues. In contrast, Sanders has calculated that the throughput of a direct write e-beam system could decrease by as much as 50% when the resolution is reduced from 250 nm to 150 nm. Deep UV optical lithography, the other contending approach, suffers from an upward spiral of complexity and cost as resolution diminishes. Perhaps most importantly, XRL is extendible over multiple generations (from 180 nm down to at least 50 nm), potentially saving large sums of money and time for tool and process development for each generation of device.

System Details

The XRS2000 NanoPulsar System comprises SAL's XRS2000 stepper, a dense plasma focus X-ray point source manufactured by Science Research Laboratory (SRL) of Somerville, MA, and a beamline from The Center for Nano Technology (CNTech) at the University of Wisconsin (see Figure 2). The system also includes a fully automated material handling system with process modules and a Class 1 mini-environment.

The point source is a crucial feature of the system. Most X-ray steppers use a compact storage ring (synchrotron) as the X-ray source. A single synchrotron supporting up to 18 steppers and costing about \$20 million is a cost-effective source for volume production in the silicon industry. However, for a GaAs fab processing in the region of 3,000-10,000 wafers per year, the space and funding requirements of a synchrotron are out of the question.

"This tool – with one source and one stepper – makes X-ray lithography available to a greater number of companies, and an attractive economic choice," says Bob Selzer, SAL's Senior VP of Technology. "The physical size of the

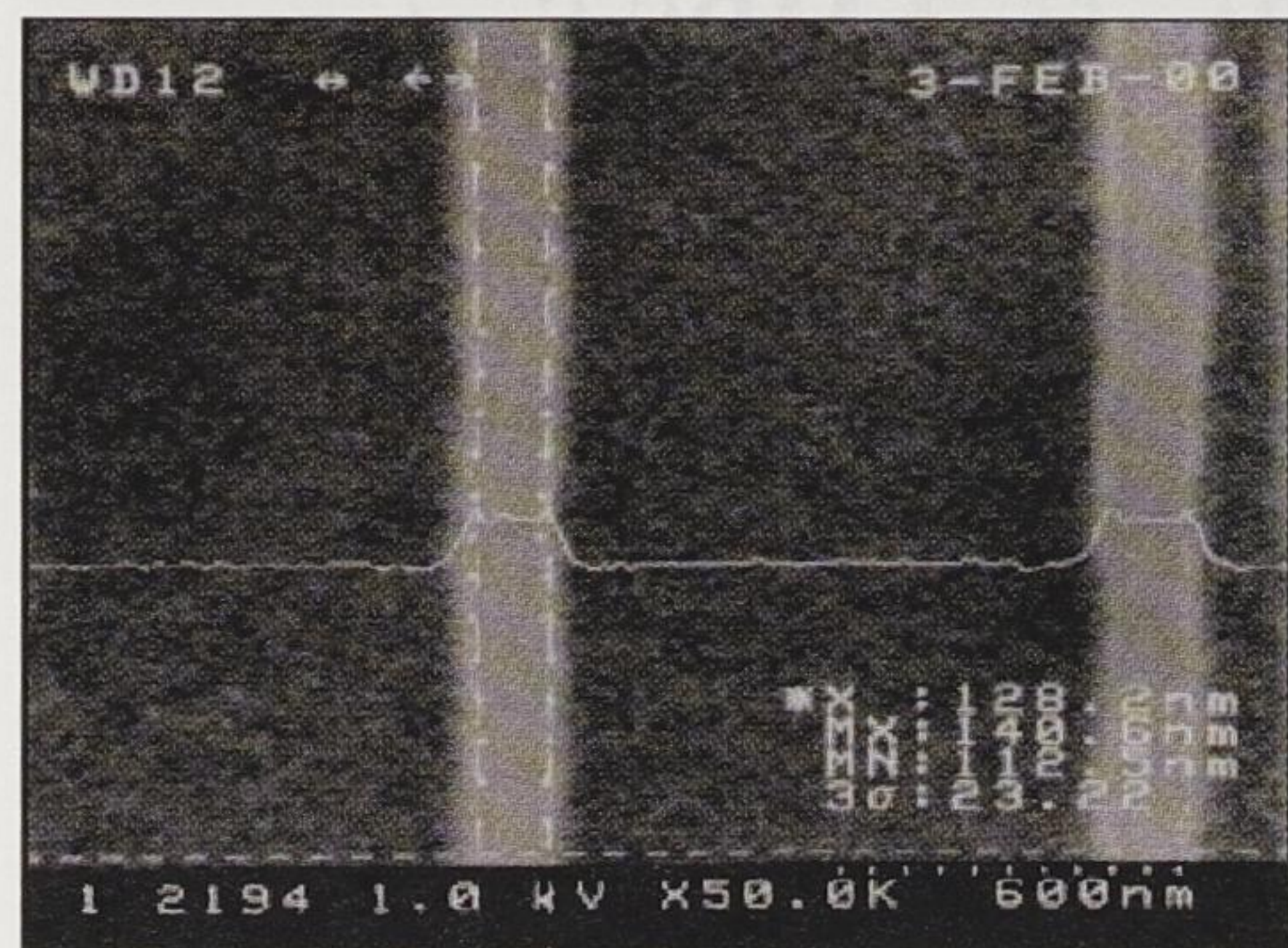


Figure 1. SEM top view of a 128 nm gate footprint, defined by point source X-ray lithography, prior to T-gate formation.

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point source XRL system is the same as the familiar deep-UV optical systems." The cost of the XRL system – in the region of \$8 million – is less than comparable deep UV systems.

Installation at Sanders

Sanders has begun characterization tests with GaAs wafers and X-ray masks with MMIC gate patterns. "The system performance to date is very encouraging since many pundits believed that point source X-ray lithography could not be fully realized," says John Heaton, Program Manager for Sanders. "The system is meeting its resolution goals already, even this early in the program." Sanders is now focussing on demonstrating system reliability to support multiple manufacturing shifts.

Initial exposures have shown resolution to 125 nm. These exposures show similar results to process development work that Sanders carried out at CNTech on a SAL XRS200 stepper with a synchrotron source. Sanders intends to qualify a 150 nm process on the integrated point source system by midyear and begin volume production of GaAs MMICs on 150 mm wafers in 2001.

During the qualification phase, Sanders will support visits by SAL's customers to see the XRL system at the New Hampshire facility. "The cooperation of the Sanders staff is key to our ability to demonstrate the performance of the XRS2000 in the manu-

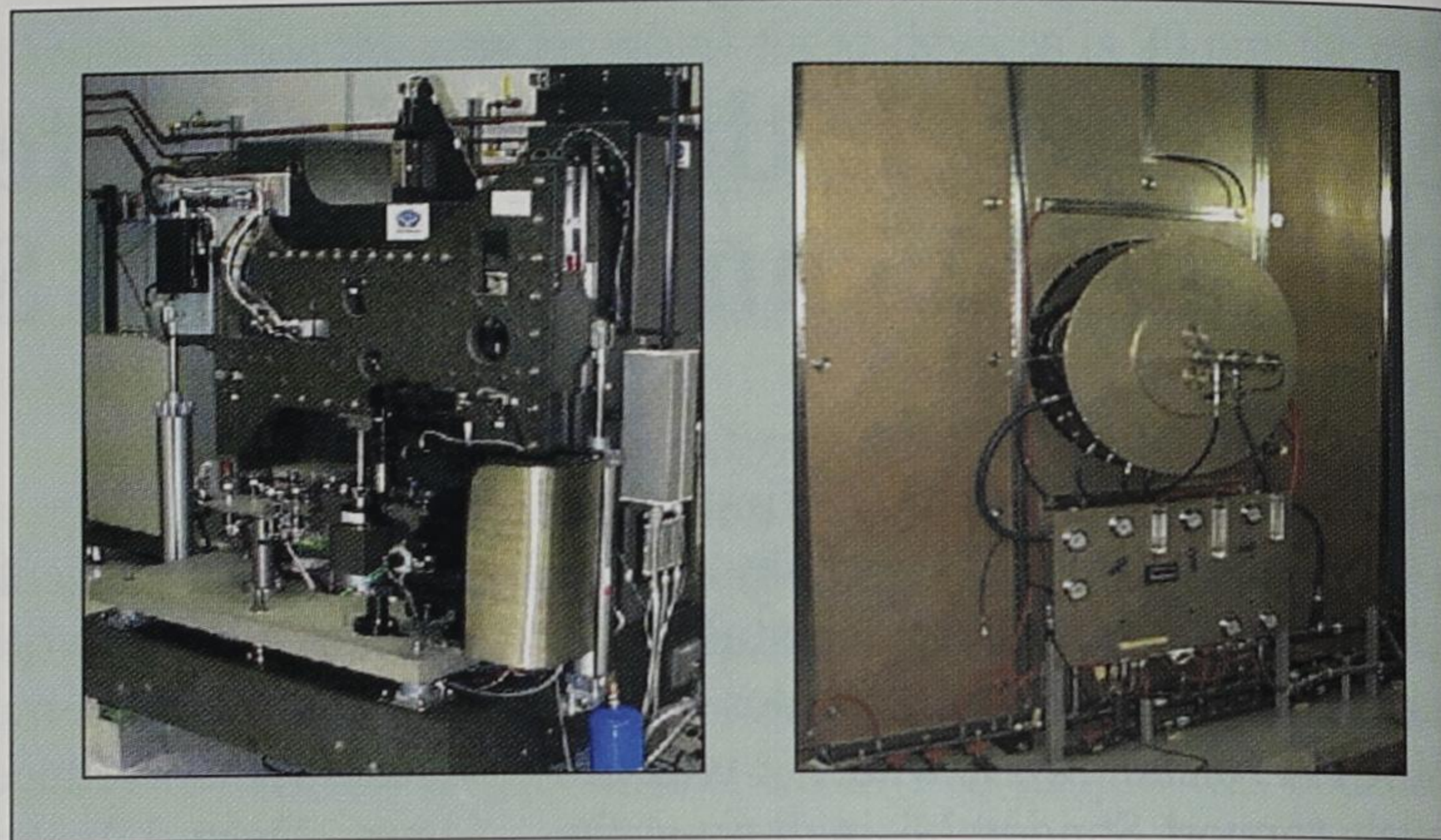


Figure 2. Building blocks of the X-ray system are (left) the X-ray stepper manufactured by SAL, and (right) the X-ray point source from SRL.

facturing environment," says Ken Mason, VP Sales and Marketing at SAL. "This installation allows SAL to highlight the advantages of the XRS2000 and the maturity of the industry's XRL infrastructure including masks, materials, and process knowledge." SAL, Inc. (South Burlington, VT) is a privately held, U.S. majority-owned company, formed in 1994 as a spin-off from Karl Suss.

RFMD Supplies HBT ICs to Motorola, Opens Phoenix Design Center

RF Micro Devices has received production orders for GaAs HBT ICs for use in Motorola's iDEN handsets. These devices include the RF2138 PA and RF2361 and RF2442 LNAs, which provide a high dynamic range and makes them suitable for digital cellular applications.

"The iDEN phones are the first of Motorola's high-volume production handsets to use our GaAs HBT power amplifiers," says Greg Thompson, RFMD's director of sales. "With the ongoing expansion of our wafer fab operations in Greensboro, we believe we will be in a good position to grow our sales with Motorola."

RFMD has also opened a new 6,000 sq. ft engineering design center in Chandler, AZ for the design of GaAs HBTs, Si and SiGe technologies for the development of high-efficiency linear PAs, Bluetooth circuits and other RFICs used in cellular and PCS telephones. The company also has design centers in Scotts Valley, CA, Cedar Rapids, IN and Boston, MA.

Anadigics Ships PAs for Ericsson's Tri-Mode Phones

Anadigics has begun production volume shipments of two PAs to support Ericsson's A1228d TDMA mobile phone. This tri-mode (analog 800 MHz, digital TDMA 800/1900 MHz) wireless handset employs Anadigics' high-efficiency PAs, enabling the delivery of up to 4 hours of talk time with broad geographic coverage. "As a result of our close relationship with Ericsson, we continue to gain important design wins in industry-leading digital phones such as the A1228d," remarks Bami Bastani, president and CEO.

Alpha Ships GaAs PAs for LMDS System

Alpha Industries is shipping production volumes of 28 GHz GaAs MMIC power amplifiers for use in Local Multipoint Distribution System (LMDS) equipment manufactured by Newbridge Networks. LMDS offers very high-speed broadband data, Internet and telecommunications access, with data rates of up to 150 Mb/s and lower installation costs than other broadband data systems. A compact base station and simple customer premises equipment provides direct wireless links to businesses and homes.

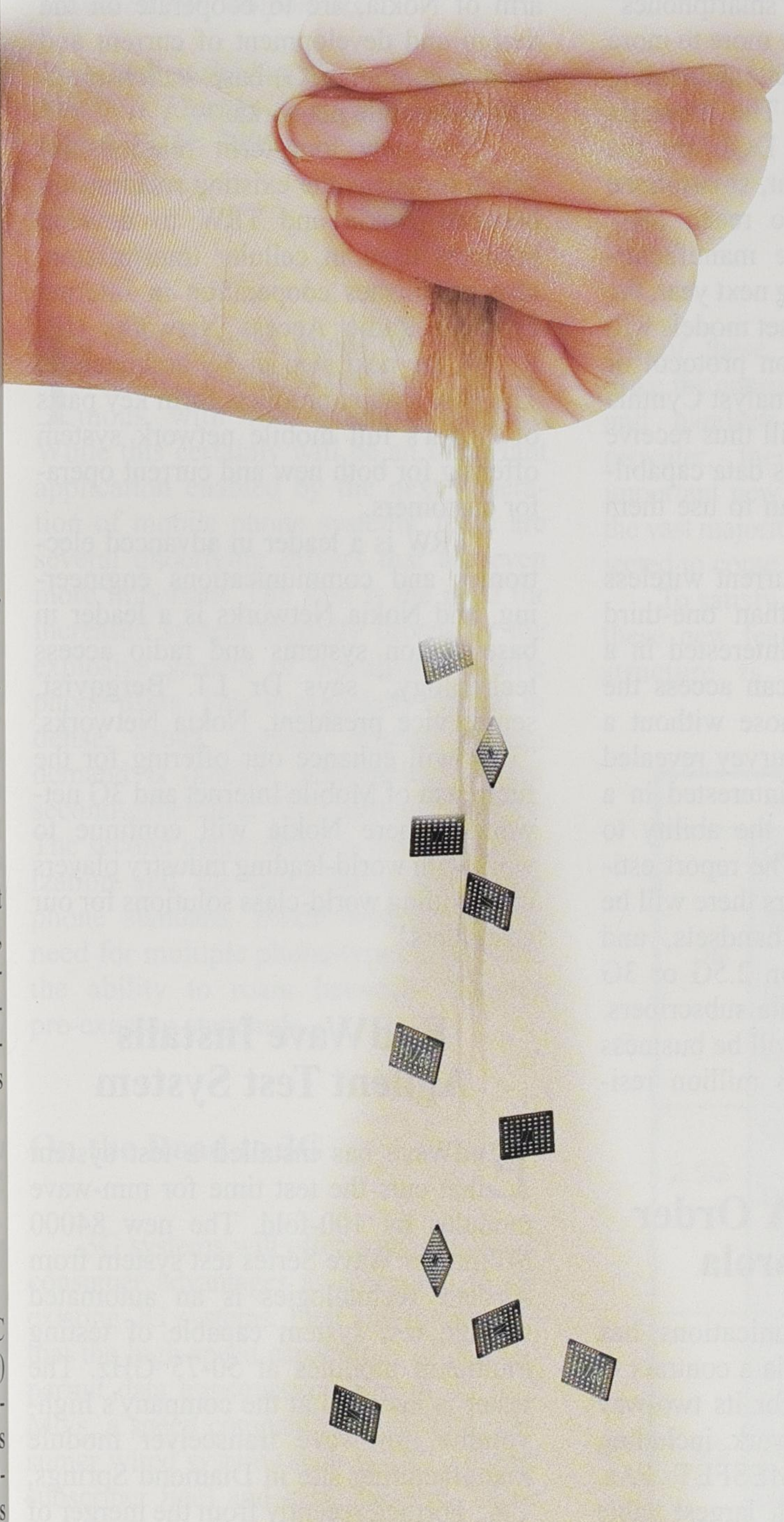
"Alpha's strategic decision to develop proprietary, enabling technology for broadband data access markets, including LMDS, is paying off," says Colin Sweeney, Alpha's Director of Application Specific Products. "We are now seeing orders and shipments for our GaAs ICs into a broad range of high-speed wireless and cable data access equipment."



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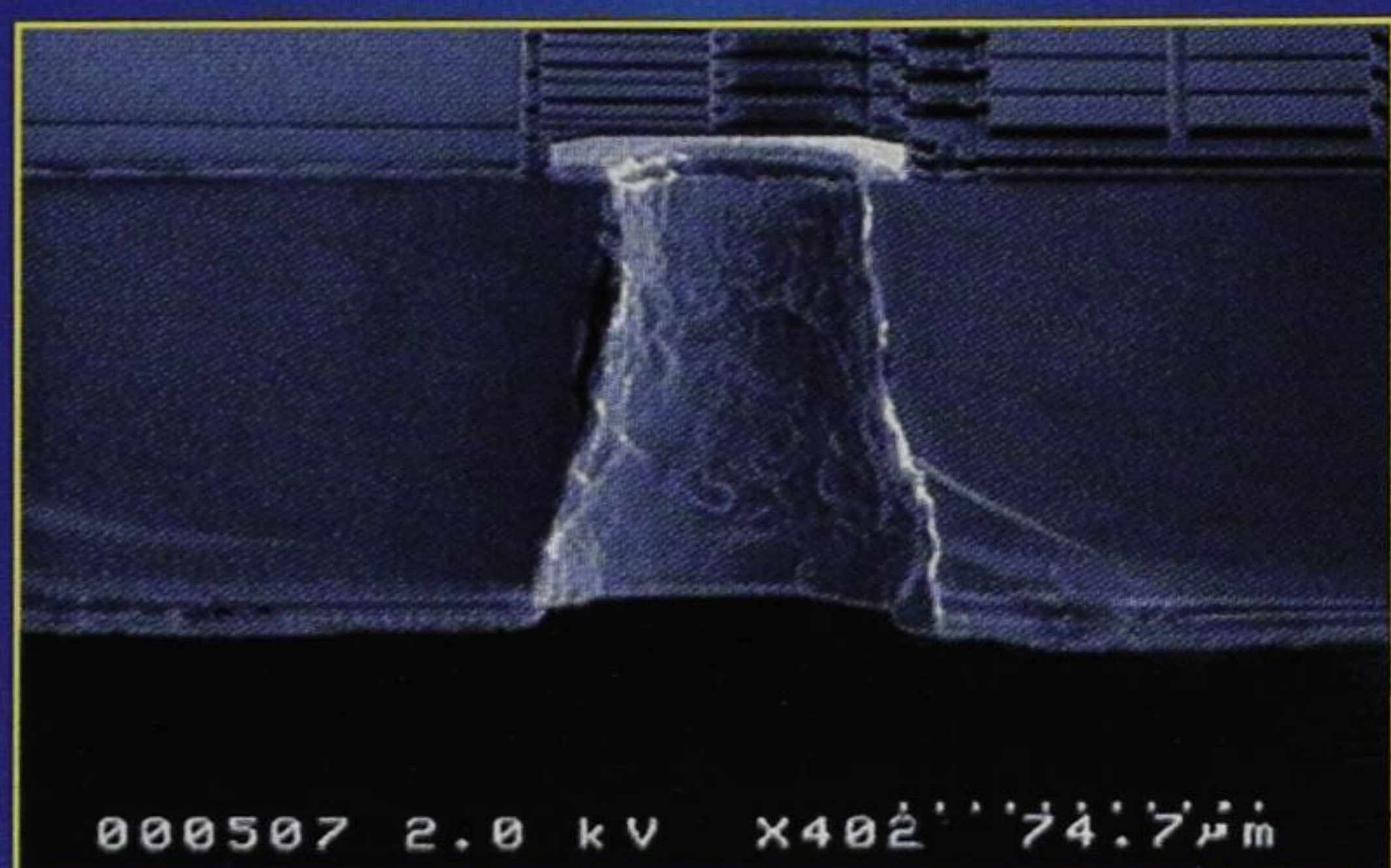
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\$8 Billion in Internet Phone Sales by 2005

Revenue from sales of mobile phones that can access the Internet – so-called “smartphones” – are projected to grow more to more nearly \$8 billion by 2005, according to a new report by The Strategis Group (Washington, DC). By the end of the current year, smartphone sales are expected to reach \$867 million. “Smartphone manufacturers says that beginning next year, the majority of new handset models will be wireless application protocol or WAP-enabled,” said analyst Cynthia Howe. “New users will thus receive handsets with wireless data capabilities whether they plan to use them or not.”

In a survey of current wireless phone users, more than one-third said they would be interested in a wireless phone that can access the Internet. Even for those without a wireless phone, the survey revealed that 20% would be interested in a wireless phone with the ability to access the Internet. The report estimates that in five years there will be around 60 million handsets, and more than 9.5 million 2.5G or 3G mobile high-speed data subscribers. 6.8 million of these will be business subscribers, with 2.8 million residential subscribers.

Cable TV PA Order for Motorola

Adelphia Communications has awarded Motorola a contract to supply components for its two-way broadband cable network, including 870 MHz GaAs MESFET PAs. Adelphia is the sixth largest cable television operator in the US, serving approximately 5.3 million subscribers, and is aggressively upgrading its plant capability to provide digital services, including high-speed data, video-on-demand and telephony.

Nokia and TRW to Develop 3G Base Stations

TRW's Space & Electronics Group and Nokia Networks, the infrastructure arm of Nokia, are to cooperate on the design and development of current and third generation (3G) base station products for mobile networks.

This new long-term relationship, which broadens the existing relationship between Nokia and TRW to develop products used in cellular transmission, also establishes cooperation in Internet Protocol Radio Access Networks (IP-RAN), the next step in 3G architecture. The base station products form key parts of Nokia's full mobile network system offering for both new and current operator customers.

“TRW is a leader in advanced electronics and communications engineering, and Nokia Networks is a leader in base station systems and radio access technology,” says Dr J.T. Bergqvist, senior vice president, Nokia Networks. “This will enhance our offering for the future era of Mobile Internet and 3G networks, where Nokia will continue to work with world-leading industry players in providing world-class solutions for our customers.”

EndWave Installs Agilent Test System

EndWave has installed a test system that cuts the test time for mm-wave modules by 100-fold. The new 84000 Millimeter Wave Series test system from Agilent Technologies is an automated module test system capable of testing multichip modules at 50-75 GHz. The tester is installed at the company's high-volume mm-wave transceiver module manufacturing site in Diamond Springs, CA. Formed recently from the merger of TRW Milliwave and Endgate [CS 6(2), p.80], EndWave has an exclusive agreement with TRW for the supply of GaAs ICs used in antennas, transceivers and outdoor units that transmit and receive radio signals.

RF Requirements for 3G Mobile Systems

SANJIV SHAH

Raytheon RF Components

Presented at the Key Conference on Compound Semiconductors

Key West, Florida

March 13-14, 2000

In many people's minds, third generation (3G) mobile systems are synonymous with the wireless Internet. While this certainly will be an important application enabled by the next generation of mobile phone systems, there are several underlying drivers that are even more important. The first is the need for increased system capacity driven by the explosive growth of worldwide mobile phone users. This is especially critical in dense urban centers where system demand is quickly outstripping current second-generation (2G) system capacity. The second major driver is that of globalization and the need for a worldwide phone standard, which will negate the need for multiple phone-types and create the ability to roam between different pre-existing standards.

On the Road to 3G

3G systems will offer a wide range of consumer advantages as compared to the existing 2G systems. First and foremost is that the high-speed capabilities of 3G will permit data transmission rates of up to 2 Mb/s, a speed comparable to current consumer wired systems such as DSL (digital subscriber line) and cable modem. These data rates will allow not only wireless Internet access, but also a whole host of applications including video mail, photo mail, E-mail, location services capabilities, and a wide range of E-money services. Higher system speeds and capacities should also lower the cost of service to the consumer.

All of these potential applications will drive the consumer's desire for 3G systems and handsets, while for the service provider, these applications represent important new revenue streams. However, the vast majority of 3G systems are not projected to come on line until 2002.

To satisfy the consumer's appetite for these new features before the 3G infrastructure is in place, most service

providers are attempting to implement what are often referred to as 2.5G services. In this scenario (Figure 1), GSM-based services typically migrate to the new GPRS standard, while TDMA moves toward the new EDGE standard, with both these new standards being backward compatible with the earlier standards (see Table). GPRS represents an evolutionary transition away from GSM, requiring

	Standard	Also known as...	Notes
2G	GSM	Global System for Mobile	World's most widely deployed 2G standard.
	TDMA	Time Division Multiple Access	
	CDMA	Code Division Multiple Access	Also known as IS-95
	PDC	Personal Digital Cellular	The most widely used 2G standard in Japan.
2.5G	GPRS	General Packet Radio Service	Based on GSM. Systems already up and running.
	EDGE	Enhanced Data rates for Global Evolution	Based on TDMA/GSM. Available by the end of 2000.
	HDR		Available in 2001. Introduced by Qualcomm.
3G	IMT-DS	WCDMA/UMTS	Compatible with GSM. Will be introduced in Japan in 2001 by NTT DoCoMo.
	IMT-MC	CDMA2000	Compatible with CDMA(IS-95)
	IMT-TC		Compatible with TDMA
	IMT-SC	UWC136	Compatible with TDMA
	IMT-FC		Compatible with DECT

Summary of second generation (2G), third generation (3G) and intermediate standards for mobile phone networks.

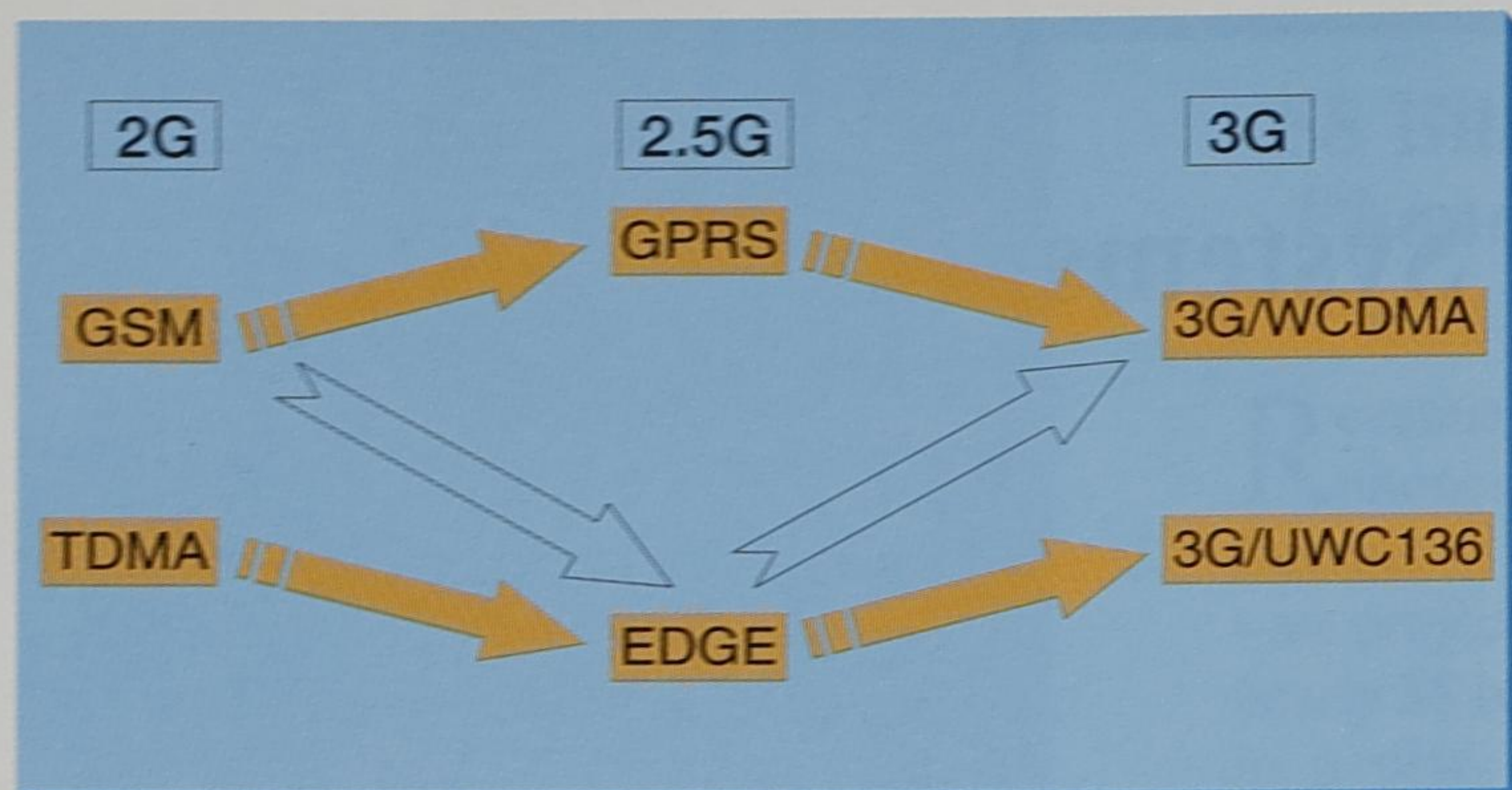


Figure 1. Migration path to 3G.

little additional investment in infrastructure, using the same modulation scheme as GSM, and will offer data rates up to 114 kb/s. Implementation of GPRS is currently underway with all major GSM operators. The EDGE standard represents a greater technical leap than does GPRS, in which major investments are required to upgrade networks, a new modulation scheme is used, and new handsets are required. The resulting data rate of the system is 384 kb/s, and TDMA operators—such as AT&T in the US—are now beginning to make this transition.

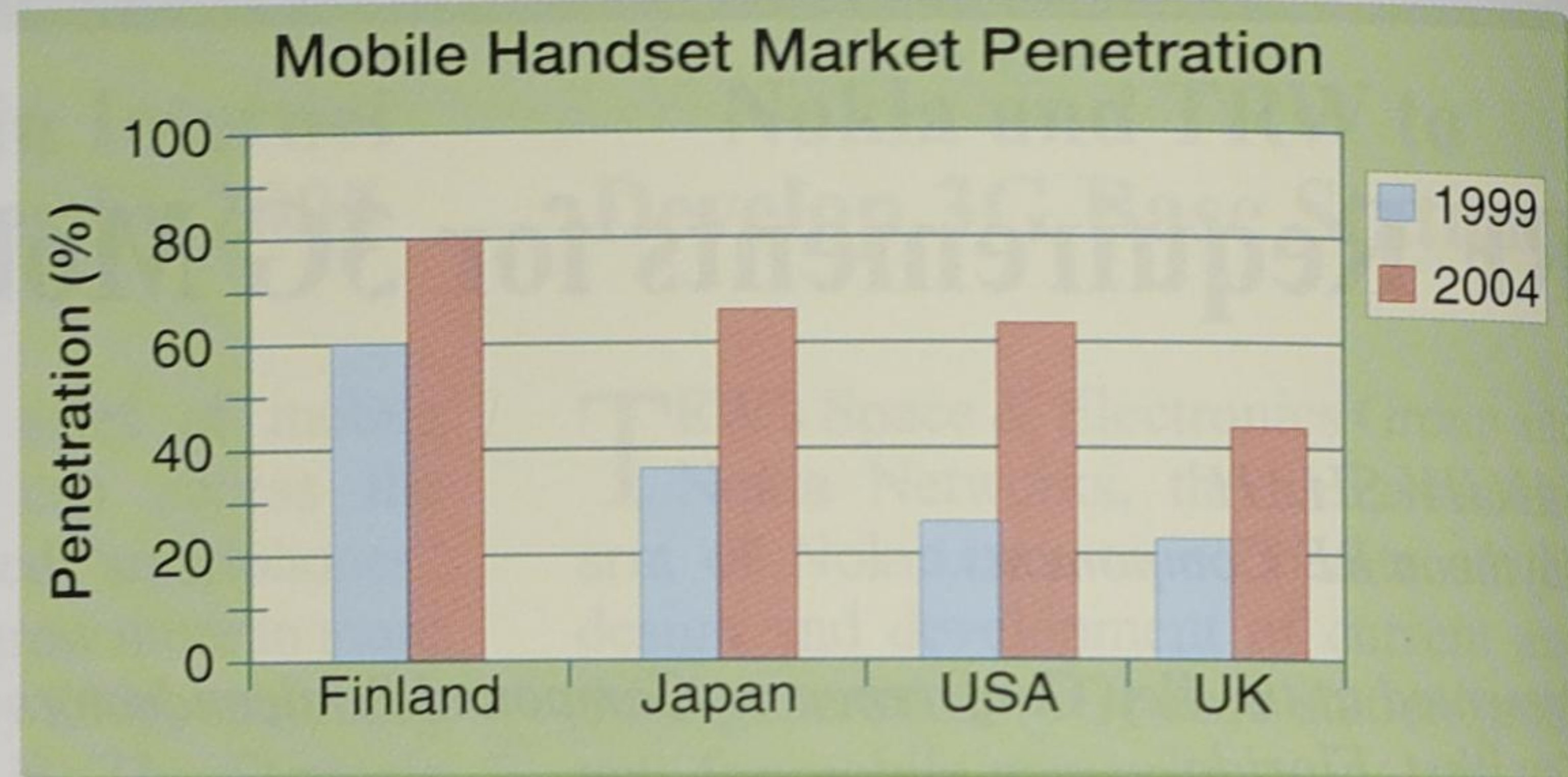


Figure 2. Market penetration of mobile handsets in certain countries, illustrating the continued rapid growth in the number of mobile phone users across the globe.

3G Demand

The introduction of 2.5G standards is only a temporary solution to the increasing demand for mobile communications capacity. Figure 2 illustrates the rapid growth of mobile phone users worldwide, which is responsible for generating system capacity constraints. A prime example of this is US growth, where the mar-



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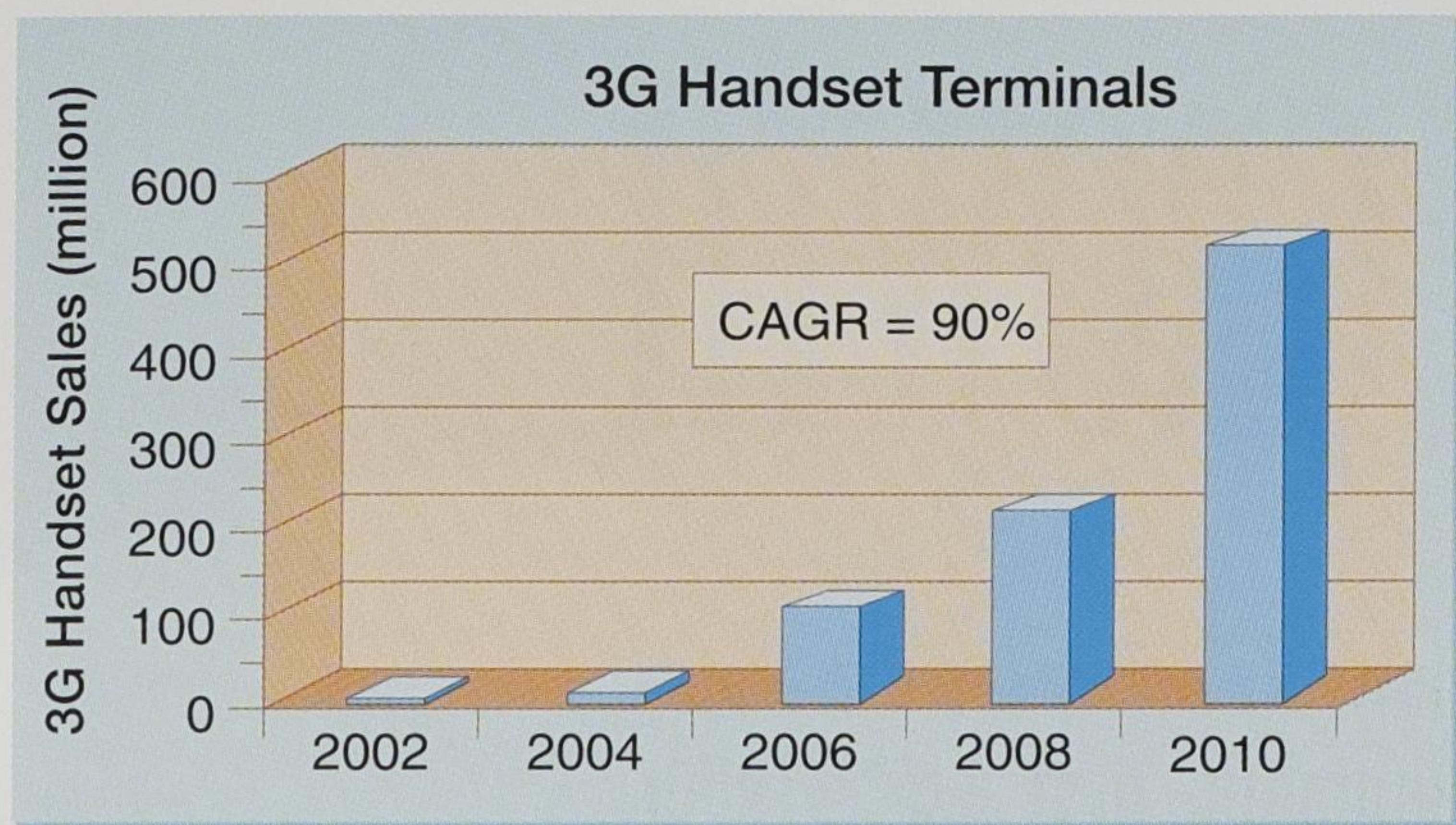


Figure 3. A number of very optimistic growth forecasts have been made for the 3G handset market, which could reach 500 million units by 2010.

ket penetration was 25% in 1999; this is expected to grow to 65% by 2004. And while these numbers indicate the need for increased system capacity, this is only half the story when phone manufacturers are considered. Market studies show that people currently upgrade their phones every 12 to 18 months, with 30% of current phone sales represented by those upgrading older phones.

Market forecasts for 3G handset sales indicate explosive growth during the next ten years (see Figure 3). With initial sales starting in 2001, growth is expected to ramp up at a CAGR of 90%, reaching an annual volume of 500 million handsets in 2010. 3G systems will first be implemented in pockets throughout dense urban centers, and then expand outward into existing 2G areas. Because of this, roaming requirements will demand that phones support multiple modes, i.e., both 2G and 3G capabilities. For example, Japanese providers will need to simultaneously support PDC and WCDMA standards, while in Europe phones will need to have GSM/GPRS and WCDMA capabilities. These requirements represent both challenges and opportunities to handset and infrastructure manufacturers.

The first commercial introduction of 3G systems is expected to take place in Japan during 2001 by service provider NTT DoCoMo. This early introduction is being driven by capacity saturation of the existing PDC system, the rapid penetration of wireless subscribers (estimated to reach 67% by 2004), and competition from existing wireless Internet services offered by Japan's I-Mode service. NTT DoCoMo must rapidly install 3G in order to avoid losing market share to other high feature wireless providers.

GaAs Power Amplifiers

The RF front-end for a typical mobile handset is shown in Figure 4. While a wide range of materials and devices are currently being used throughout the RF front-end, it is Raytheon's belief that power amplifiers (PAs) will be based on GaAs, with the remaining functions implemented in Si or SiGe technologies.

For 3G applications the PA faces several critical requirements. The PA should utilize devices that require only a single polarity power supply. This approach reduces design complexity

as well as component count, which in turn results in a smaller sized component. This aspect is extremely important in smaller phones, as well as in phones that incorporate additional circuitry to implement more functions. Another important consideration is that the PA should use a matched module approach—this reduces design time, allowing for quicker time to market. A matched module also reduces component count and reduces overall system cost.

Figure 5 shows some of the performance requirements of different mobile phone standards. WCDMA specifications require a PA that can accommodate 5 MHz channel bandwidths, OCQPSK modulation, peak to average gains that span 7 dB, and very high efficiencies. Initial systems insertions, such as in Japan, where the relatively low power consuming PDC phones will be replaced by higher power WCDMA phones operating at levels of 27 dBm, will require more efficiently performing devices in order to maintain adequate talk times. It is important from a consumer acceptance perspective that 3G phones not only offer added features as compared to previous generation phones, but that they also offer comparable or longer talk times than the phones they are replacing.

Consideration of these requirements allows one to narrow the range of devices that will be applicable for 3G PA applications. Si-based devices (MOSFET, LDMOS) as well as GaAs MESFETs will not have sufficient RF performance, while depletion-mode (D-) PHEMTs require an additional negative power supply. While SiGe HBTs show potential for this application, it is not yet clear if they will meet the desired RF performance requirements. As a consequence, this leaves GaAs HBTs and enhancement-mode (E-) PHEMTs as suitable devices for 3G PAs.

E-PHEMT v. HBT

An E-PHEMT requires only a single power supply, and promises greater power added efficiency (PAE) for a given lin-

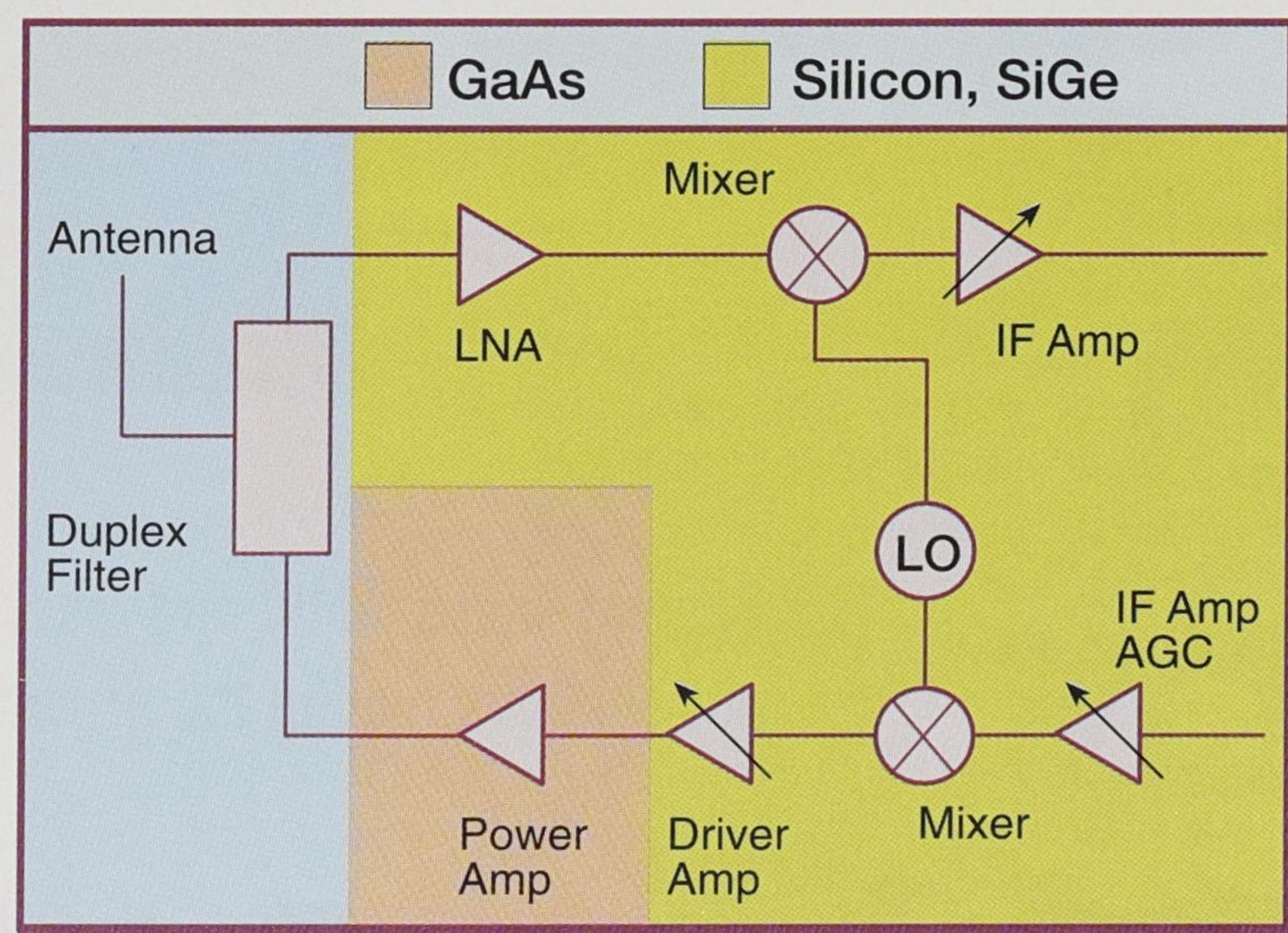


Figure 4. The RF front-end of a typical mobile handset. While the majority of components for 3G handsets will be silicon-based, the power amplifier will be GaAs—either HBT or enhancement-mode PHEMT.

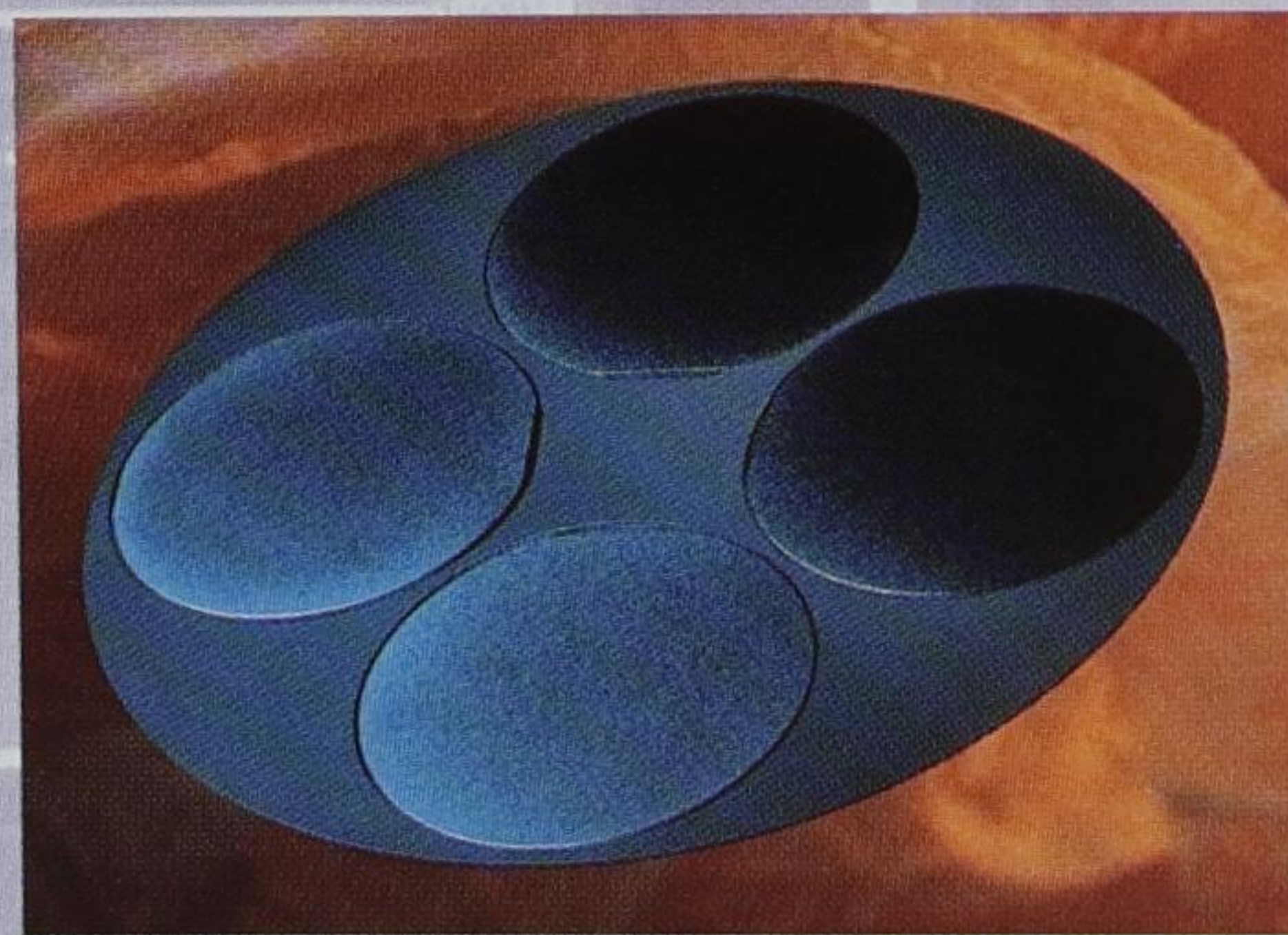
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Output Power	33 dBm	33 dBm	29 dBm	29 dBm	27 dBm
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Channel Bandwidth	200 kHz	200 kHz	200 kHz	1.25 MHz	5 MHz
Duty Cycle	12.5%	25%	50%	100%	100%
ACPR1	-	-	-30 dBc	-47 dBc	-38 dBc
Peak to Average	1.5 dB	1.5 dB		5 dB	7 dB
PA Technology	Silicon GaAs	Silicon GaAs	GaAs	GaAs	GaAs

Figure 5. Performance requirements for various mobile phone standards.

earity. Motorola has achieved 50% PAE for CDMA applications, while NEC has shown a 57% PAE for WCDMA. These values are typically better than those that can be obtained with HBTs. In addition, E-PHEMTs can be run at voltages as low as 1.5 V. GaAs HBTs also operate from a single power supply. In comparison to E-PHEMT technology, the HBT process is less complex, particularly in terms of lithographic requirements, and this results in higher yields and therefore lower costs. In addition, HBTs operate at higher power densities than E-PHEMTs, which allow for smaller die size for a given power requirement. This permits the fabrication of more die per wafer, and further reduces costs.

From a performance perspective, both HBTs and E-PHEMTs can satisfy 3G PA requirements. However, in addition to performance requirements, the other critical factors which drive RF front end development in the rapidly emerging 3G marketplace are time to market and cost. When considering those, HBTs appear to be the most logi-

cal device for this application at this time, although Raytheon is continuing to investigate and develop a next generation E-PHEMT for use in this application.

As a consequence, Raytheon's first implementation of a 3G PA module is based on a GaAs HBT with an InGaP emitter. The RMPA2050-78 (Figure 6) is a single band PA suitable for WCDMA/CDMA2000 applications. The device requires a single supply running at 3.5 V, comes in a 50 ohm matched module, and delivers 27 dBm of output power at 38% PAE while operating in the WCDMA mode.

While this device will satisfy the needs for early stage 3G PA applications, the drive for market share and enhanced handset performance will demand further improvements in device characteristics. To this end, Raytheon is not only transitioning into production a next generation HBT process as well as an advanced E-PHEMT process, but is also developing multimode PAs suitable for the multi-standard environment within which 3G handsets will need to operate.



Figure 6. Photo of the RMPA2050, Raytheon's first 3G PA module.

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Silicon Carbide and Gallium Nitride Circuits for Wireless Communications: Why, What and When

RAYMOND PENGELLY

Cree, Inc.

Presented at the Key Conference on Compound Semiconductors

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Sales of semiconductors for wireless applications are undergoing phenomenal growth. While the handset business attracts most of the attention, there is also a significant market for components for wireless infrastructure such as base stations and subscriber units. This market segment is currently valued at around \$48 billion worldwide and is growing at an estimated annual rate of 30%.

Why Silicon Carbide?

New core technologies for RF and microwave subsystems, which can reliably deliver higher power levels at competitive or lower costs, are key elements in the pursuit of this market. SiC possesses many fundamental characteristics that are superior to those of Si and GaAs, making it an ideal candidate for power applications. Because SiC is a wide bandgap material (3.0–3.3 eV) it can support very high breakdown fields of 3.0 MV/cm, typically six times higher than those of either Si or GaAs (0.5 MV/cm). As a consequence, SiC-based devices can support very high voltage operation and high RF voltage swings, making this technology well suited for high power operation.

Another critical parameter for power producing devices is thermal conductivity. The outstanding thermal conductivity of SiC—typically seven times better than GaAs and three times better than Si—allows SiC-based devices to more efficiently remove waste heat, and to operate at a lower transistor temperature which improves device lifetimes and reliability.

While the mobility of SiC is not as good as Si or GaAs, it is sufficient in the high electric field regimes where SiC devices typically operate. Under high field conditions the drift velocity is better than those found in either Si or GaAs, this being an extremely important characteristic when running at high current densities.

The traditional concern about SiC is the quality and availability of SiC substrates. However, it is now the case that SiC wafer size is no longer a limiting factor for manufacturing large

area MESFET-based power devices. Low defect density 3-inch diameter material is now routinely produced, and Cree is well advanced toward the commercial introduction of 4-inch material as well (see Figure 1).

All of these characteristics come together to enable SiC MESFETs to exhibit RF power densities four to five times greater than GaAs FETs. These larger power densities permit the use of smaller die size to achieve a desired total power level, which offsets the higher cost of SiC substrates as compared to GaAs or Si substrates. SiC MESFETs typically run at much higher voltages than their Si and GaAs counterparts, with drain voltages ranging from 24 to 48 volts and gate voltages from 5 to 10 volts. The resulting devices show much higher output impedance than a competing GaAs MESFET or Si LDMOS device. One consequence is that much simpler matching circuitry is needed, in contrast to the requirements of relatively low impedance GaAs MESFET and Si LDMOS devices.

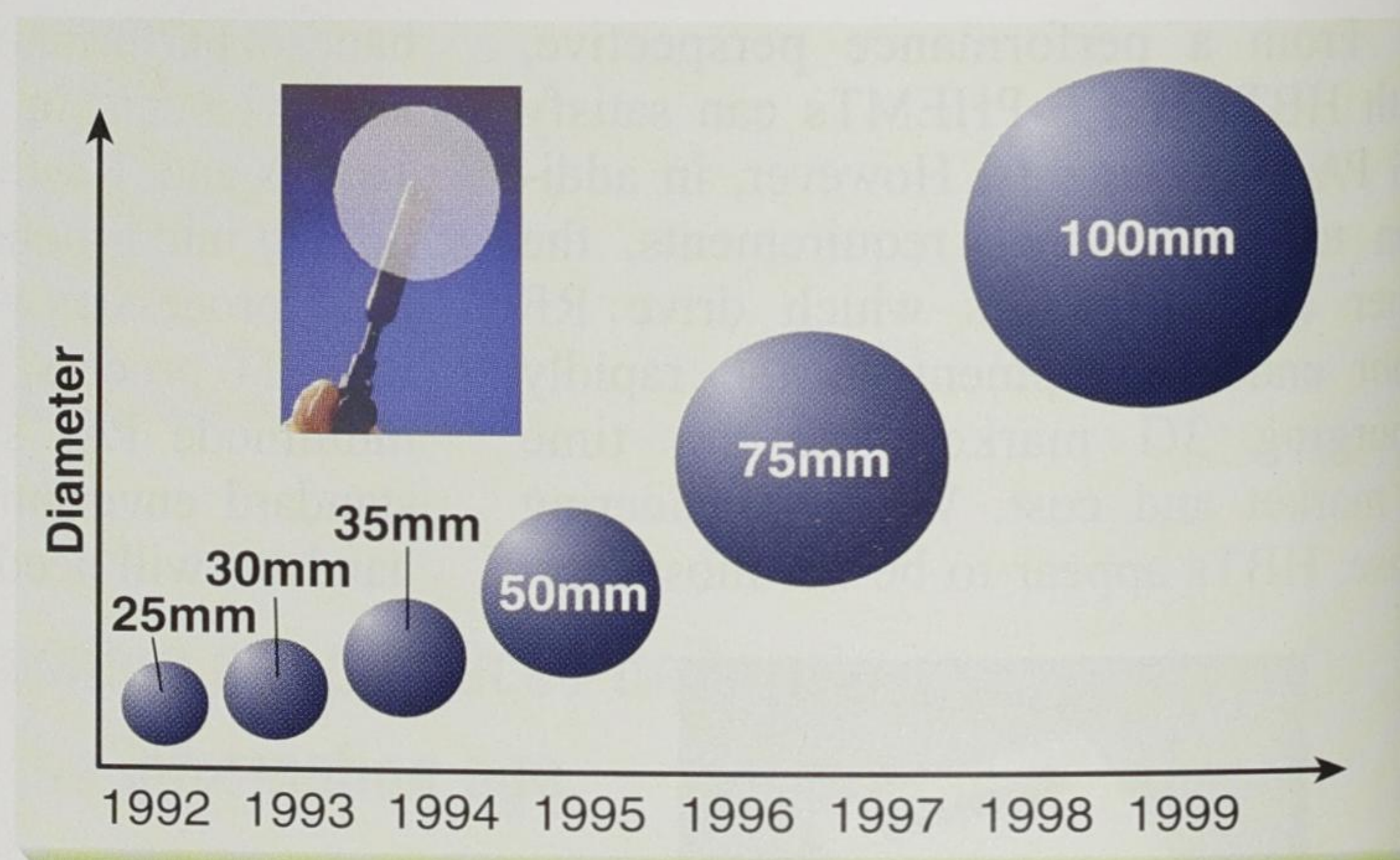


Figure 1. The diameter of silicon carbide substrates has increased steadily during the last decade and is now no longer a limiting factor in the production of commercial SiC MESFETs. 100-mm diameter wafers are currently at the R & D stage.

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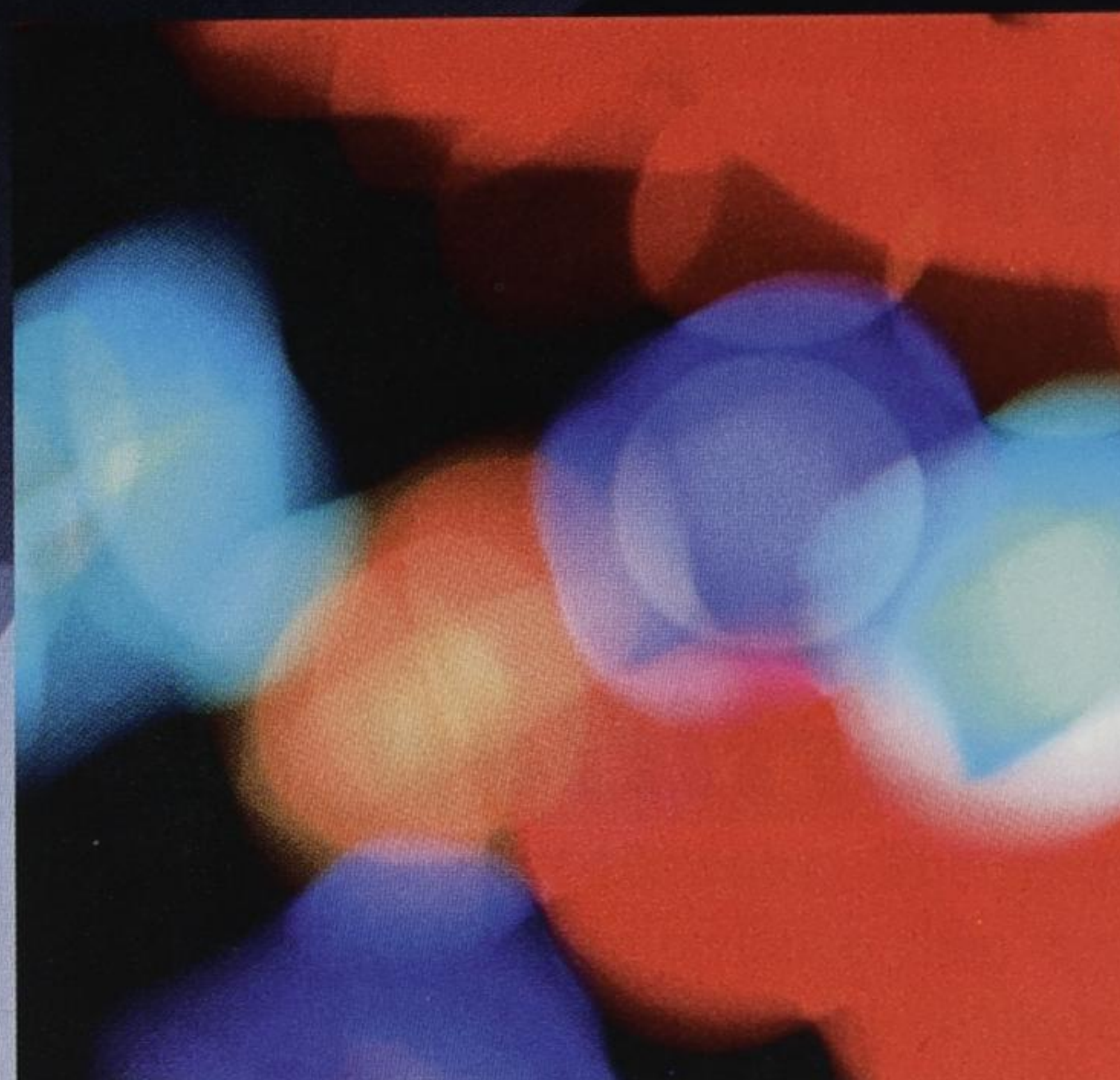
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	SiC MESFET	Si LDMOS	GaAs MESFET
Power Added Efficiency (%)	50	35	50
RF Power Density (Watts/mm)	2 (4)	0.4	1
Gain (dB)	10	10	12
Normalized Die Size	1 (0.6)	3.1	1.4
Package Size (mm ²)	200 (120)	320	300
Temperature Rise (°C)*	35 (76)	76	47
*For 50 watt transistors at case temperature of 85°C			

Figure 2. A comparison of alternative technologies for power transistors. SiC MESFETs offer important advantages in terms of RF power density and package size. Figures in parentheses represent future performance targets.

Figure 2 illustrates the comparison of SiC MESFETs to their Si and GaAs counterparts for 2 GHz operation. The SiC MESFET operating parameters show much higher power densities, allowing smaller die size, while the superior thermal conductivity minimizes device temperature rise.

SiC MESFET Performance and Reliability

For base station and subscriber unit applications, power level requirements can range anywhere from a few watts to several kilowatts. System designers want lower distortion, lower spectral overlap and higher efficiency from their RF power schemes. Whether linearization or predistortion are used most systems employ "backed-off" power amplifiers to provide compliant linearity at the expense of DC to RF conversion efficiency. In the infrastructure business, more efficient operation means there is less heat to be removed, which in turn means that fans or other cooling equipment can be eased or even eliminated from the base station. This space saving consideration is becoming increasingly important as base stations start to penetrate urban areas—in parts of Asia, micro-cell stations on lamp posts are becoming a more common sight. The small footprint of SiC devices is illustrated in Figure 3, which compares a packaged 30 W, 2 GHz SiC MESFET and its Si bipolar counterpart.

A typical operating result for a SiC MESFET running at 3.1 GHz under pulsed conditions is shown in Figure 4. A gain of 10 dB and 42% PAE is achieved for a peak output power of 120 W.

After price, reliability (and the reduction in maintenance associated with high reliability) is probably the most important factor that will influence the insertion of SiC MESFET technology. Balancing chip size, power density and temperature rise in the channel can enhance device reliability to achieve

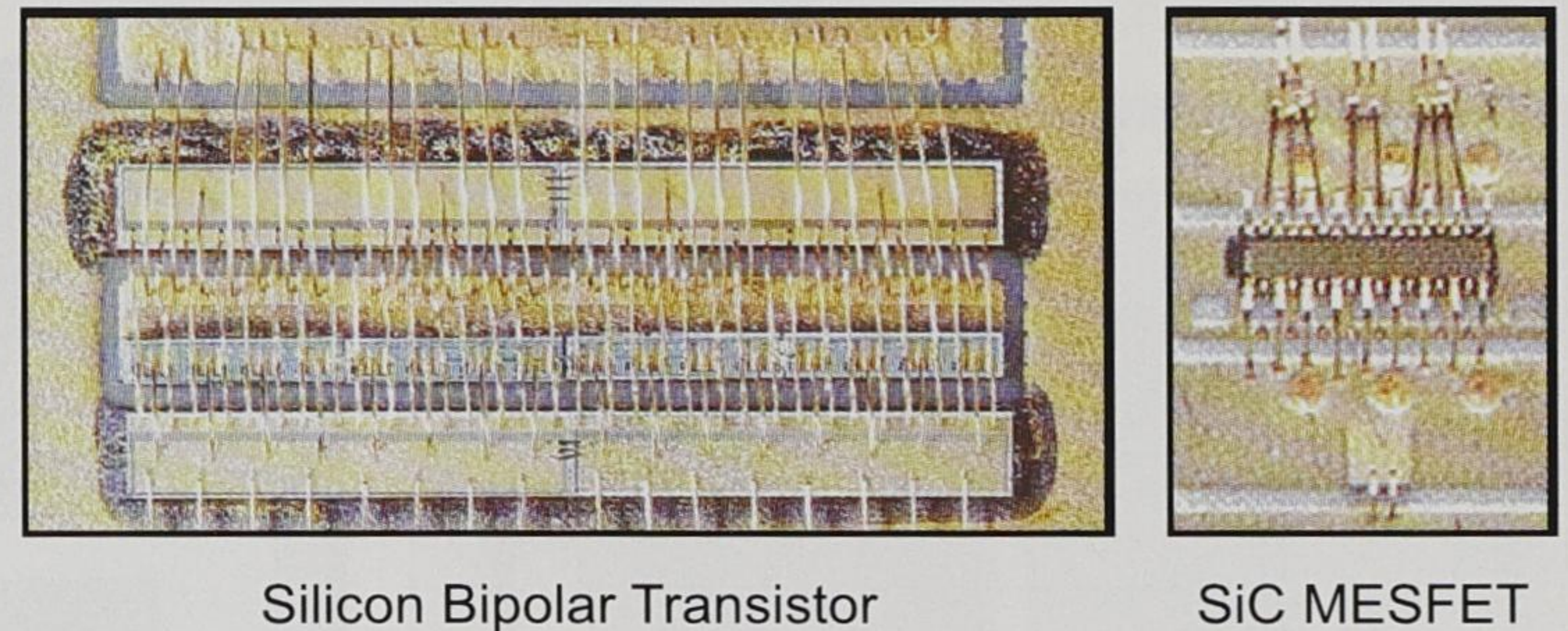


Figure 3. Comparison of SiC MESFET and Si bipolar transistors offering 30 W output power. The photographs are on the same scale, and show that the SiC device is considerably smaller and less complex.

figures of merit in excess of other technologies. The benchmark is that the gain or output power should not change by more than 10% over the lifetime of the device, and the change in gate threshold voltage (which affects the DC current) should not vary by more than $\pm 10\%$. One important difference is that the channel temperature of SiC MESFET devices can be 30 to 50°C higher than in Si LDMOS or GaAs MESFET devices, based on preliminary data. The median life of SiC MESFETs operating at 180°C is 2 million hours, with a 3-sigma time to failure of about 100,000 hours. These figures translate into a 99.9% probability that the device will be performing within specification after 11 years of operation.

SiC transistors are no longer laboratory curiosities. Cree recently introduced its first commercial SiC product, the CRF 20010, that meets the full IS95 CDMA requirement for linearity when backed-off from its 1dB compressed power of typically 12 watts to 3 watts (a back-off of 6 dB compared to 9 dB for LDMOS). The device is also suitable for TDMA, GSM, EDGE and W-CDMA applications. 30 W and 60 W transistors will be introduced later this year. These devices can be used in single-ended, quadrature combined and push-pull configurations

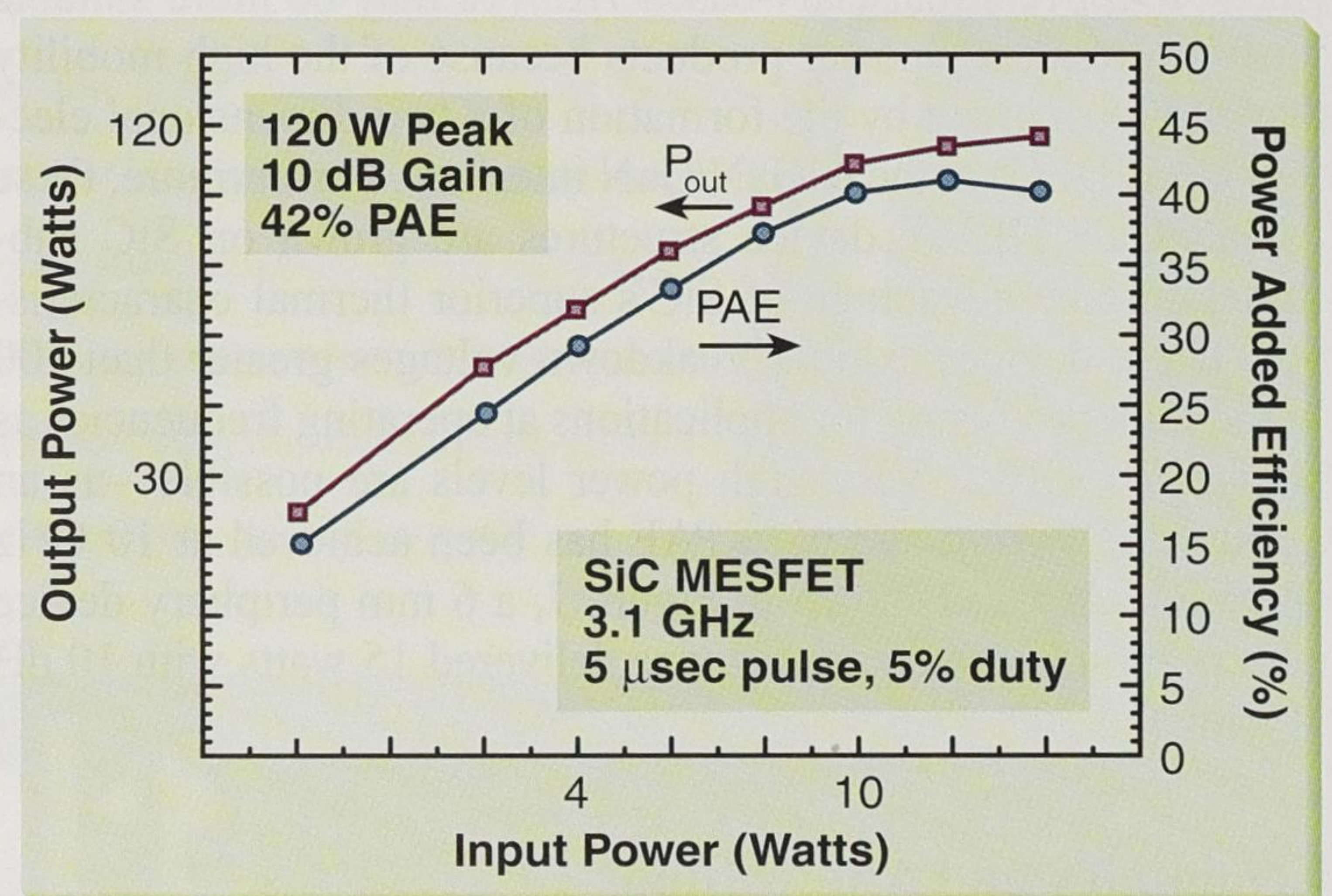


Figure 4. SiC MESFETs provide 120 watts peak power at 3.1 GHz.

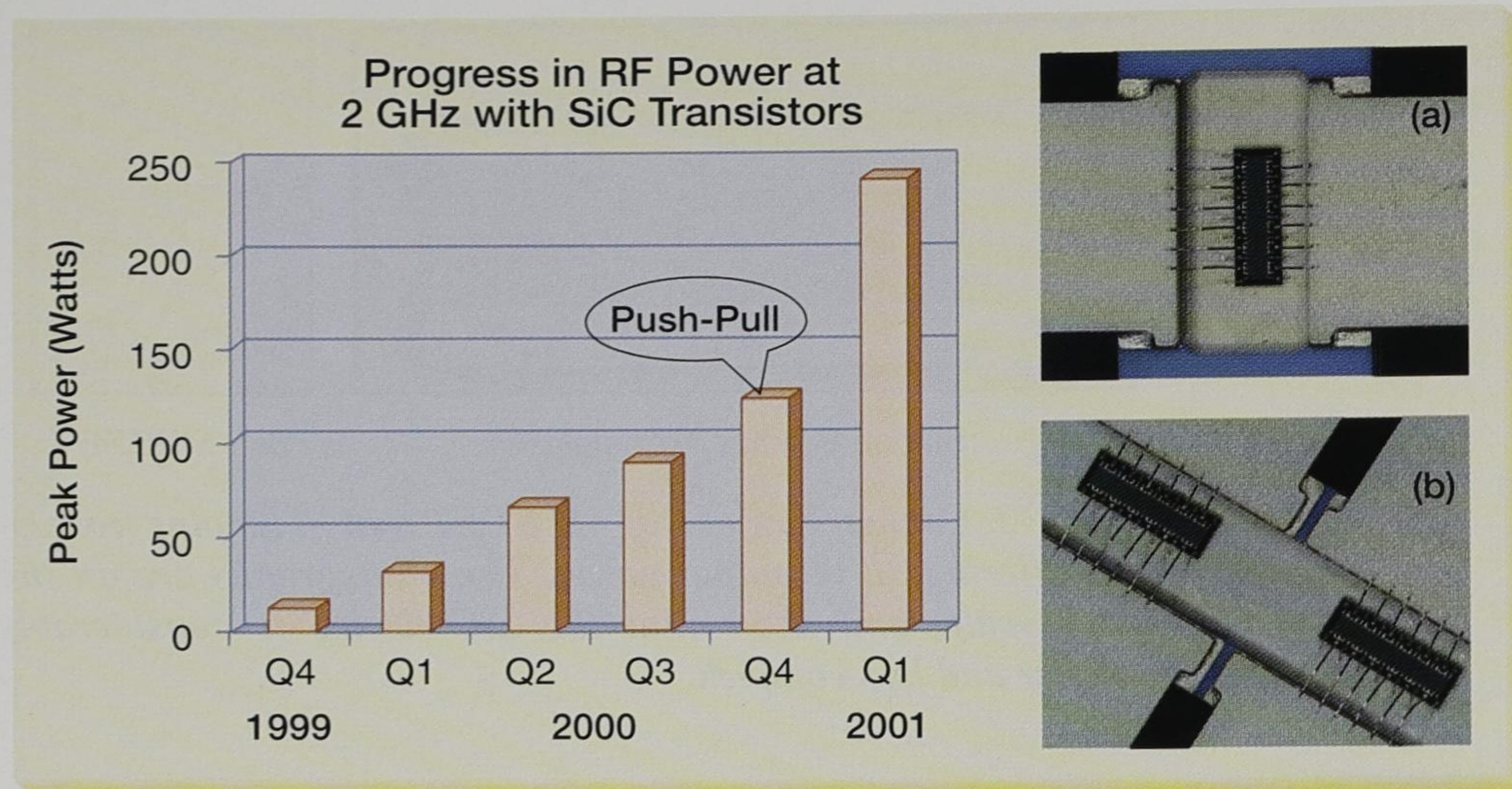


Figure 5. After launching commercial 10 W SiC MESFET transistors last year, Cree intends to introduce products with higher peak power, including (a) a 60 W device, and (b) a 120 W device in a push-pull configuration.

depending on application (see Figure 5). A push-pull configuration has the advantage of easing or removing filtering requirements following the power amplifier as it provides harmonic rejection.

The 10 W production device delivers a power density of approximately 2 W/mm, although much higher values are possible. The latest experimental SiC MESFET results are shown in Figure 6. Devices operating at 3.5 GHz exhibit an output power of 5.2 W/mm with 11.1 dB associated gain and 63% PAE; the power density figure is five times higher than typically found for GaAs MESFETs.

Gallium Nitride Devices

With f_t and f_{max} values typically in the 20 GHz regime, SiC MESFETs are best suited for applications at frequencies below 7 GHz. It appears that GaN-based HEMTs may be more suitable for high frequency power products because of the high mobility that can be attained by the formation of a two-dimensional electron gas (2DEG) at the AlGaIn/GaN interface. Furthermore, these AlGaIn/GaN HEMT device structures are grown on SiC substrates to take advantage of SiC's superior thermal characteristics. These devices exhibit breakdown voltages greater than 100 V and look promising for applications at operating frequencies as high as 35 GHz. Very high power levels are possible—as an example, 7 W/mm and 62% PAE has been achieved at 10 GHz operation. Also, as shown in Figure 7, a 6 mm periphery device incorporating on-chip source vias delivered 15 watts with 10 dB of gain and 30% PAE.

Economics and Applications

Cree's target for the pricing of SiC MESFETs is to be competitive with Si LDMOS at frequencies above 2 GHz, and to be

competitive with GaAs MESFETs at all frequencies. For applications above 2 GHz, a pricing figure of merit is approximately \$3–4 per watt. The price of 60 W SiC MESFET devices is somewhat above the market acceptable value at their introduction, but will fall rapidly through a combination of improved packaging and increased wafer size.

If these price points can be achieved, SiC RF transistors will gain access to a wide range of applications (see Figure 8). At the forefront are base station driver and power amplifiers for macrocells, microcells and picocells as well as base station transceiver systems. There is now also a great deal of emphasis on power amplifiers for wireless local loops and multi-channel, multi-point distribution systems (MMDS) and other systems for wireless Internet access at 2.4, 2.5 and 3.5

GHz. Other applications suitable for SiC MESFETs include cable TV amplifiers with very high dynamic ranges as well as other low frequency applications such as HDTV transmitters. There are also a host of applications in defense communications, and a variety of radars such as weather warning systems. GaN on SiC transistors appear promising for higher frequency applications such as local multipoint distribution systems (LMDS).

Summary

The technologies of SiC bulk crystal growth, epitaxy and device fabrication have matured to the point where commercially viable MESFETs can be manufactured for high

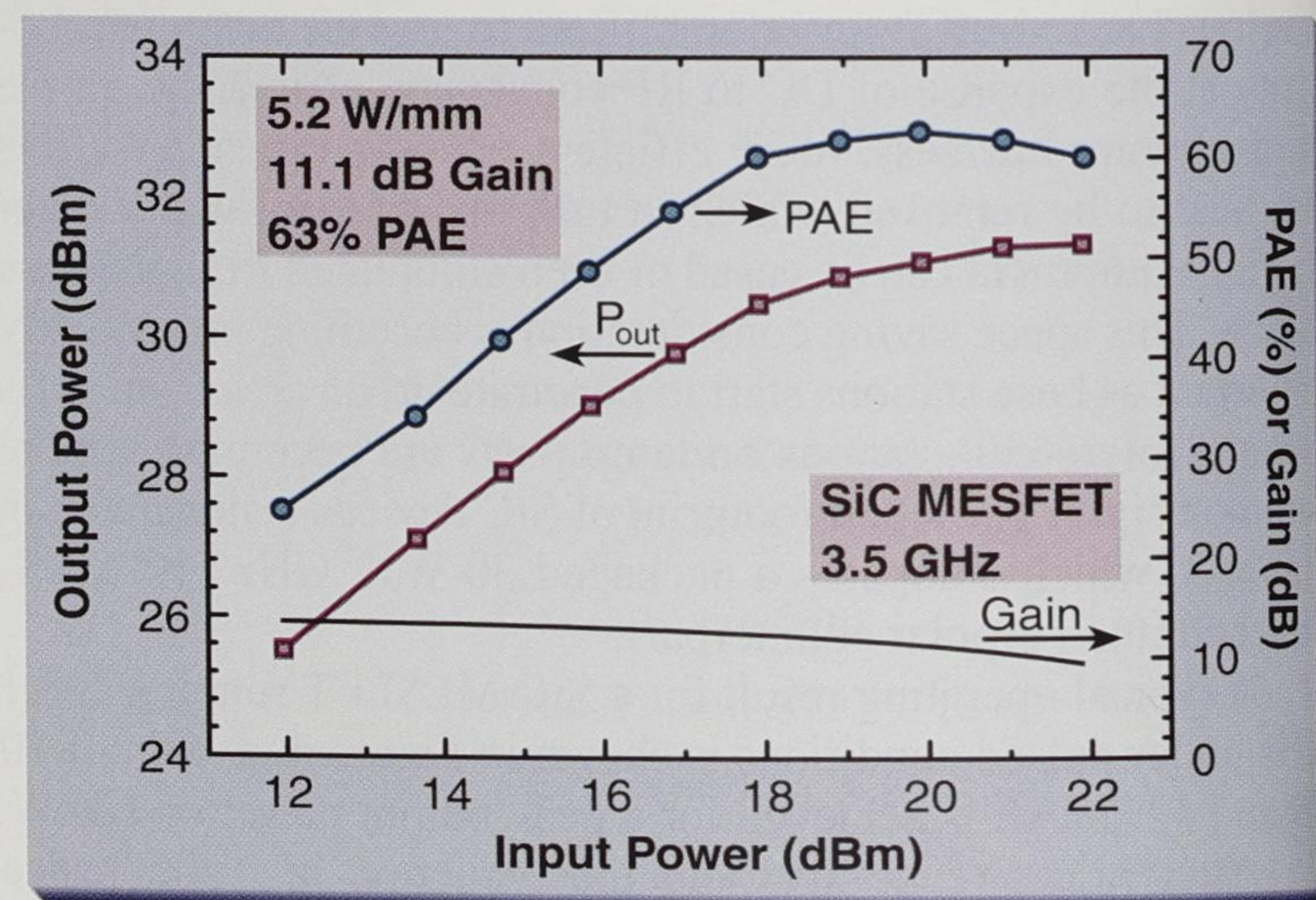


Figure 6. Cree's latest SiC MESFETs demonstrate 5.2 W/mm and 63% PAE at 3.5 GHz. The 0.25-mm devices operate with a drain-source voltage (V_{DS}) of 50 V and a gate-source voltage (V_{GS}) of -8 V.

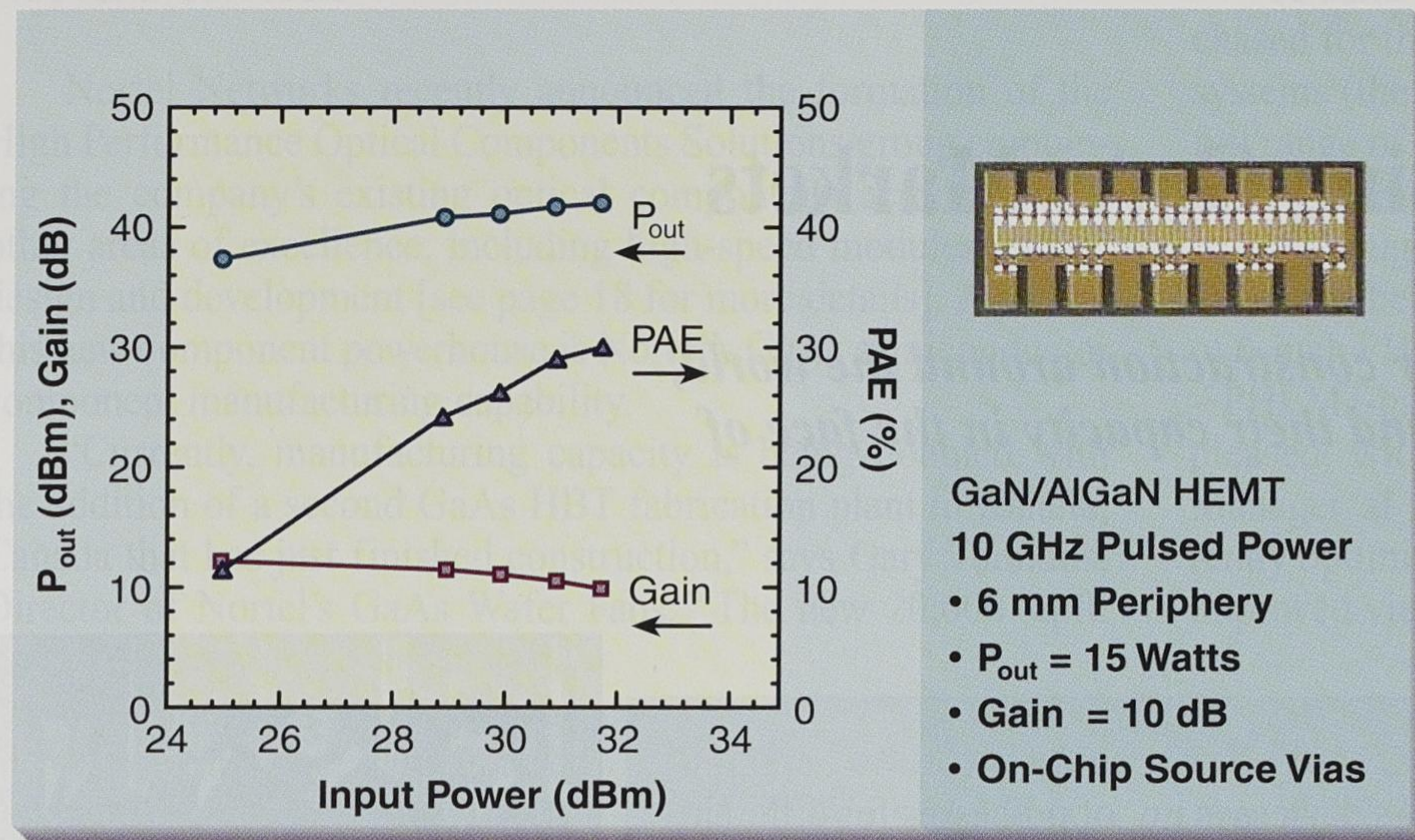


Figure 7. Characteristics of a 15 watt GaN/AlGaIn HEMT amplifier at 10 GHz.

power applications. During this year, devices that can deliver up to 60 watts on SiC substrates at frequencies up to 4 GHz will become available. The single biggest price driver is the ability to rapidly increase SiC wafer size without degrading the quality of the material. In addition, for higher frequency applications, GaN HEMTs on SiC should begin moving into production in the next few years.

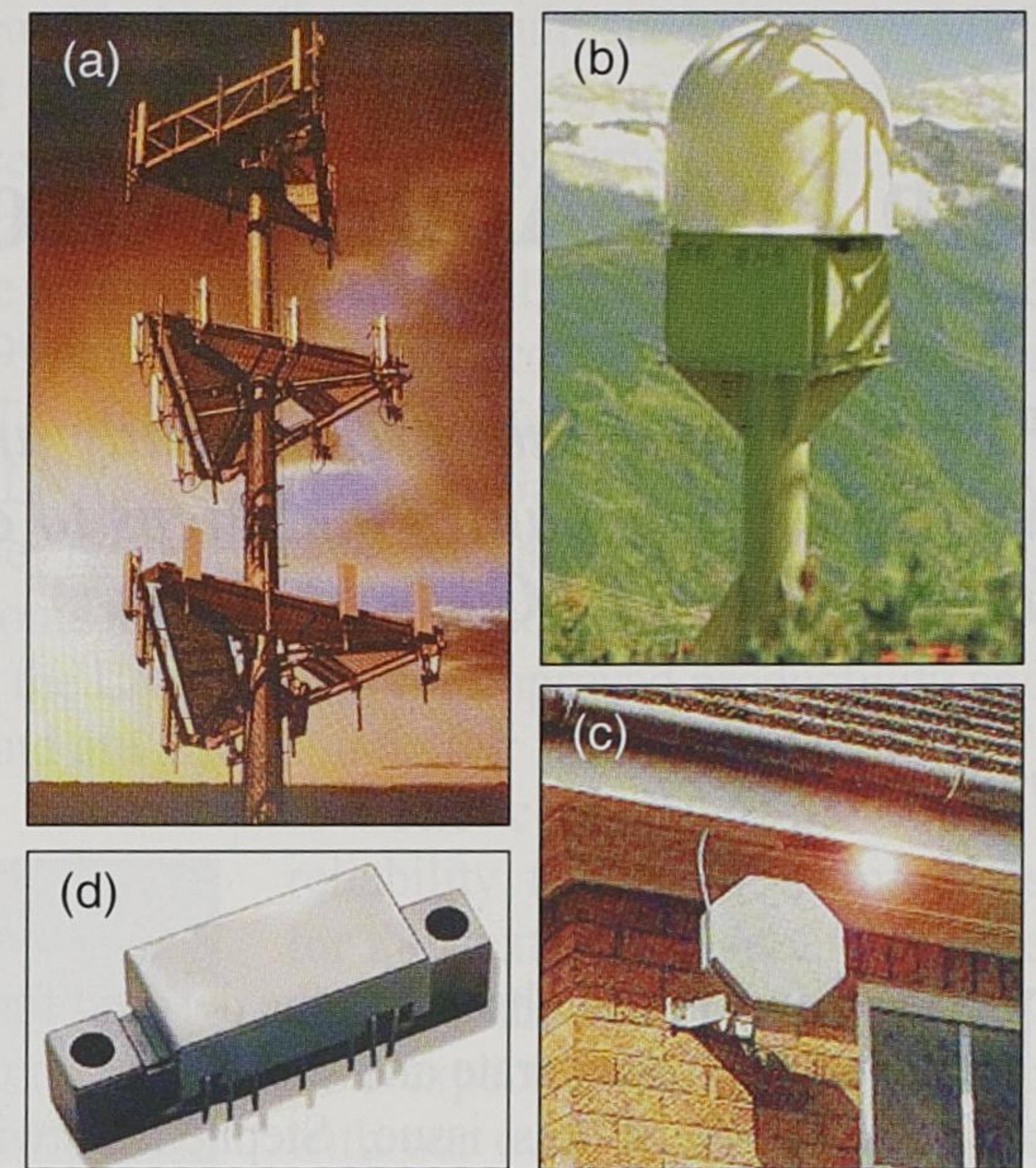


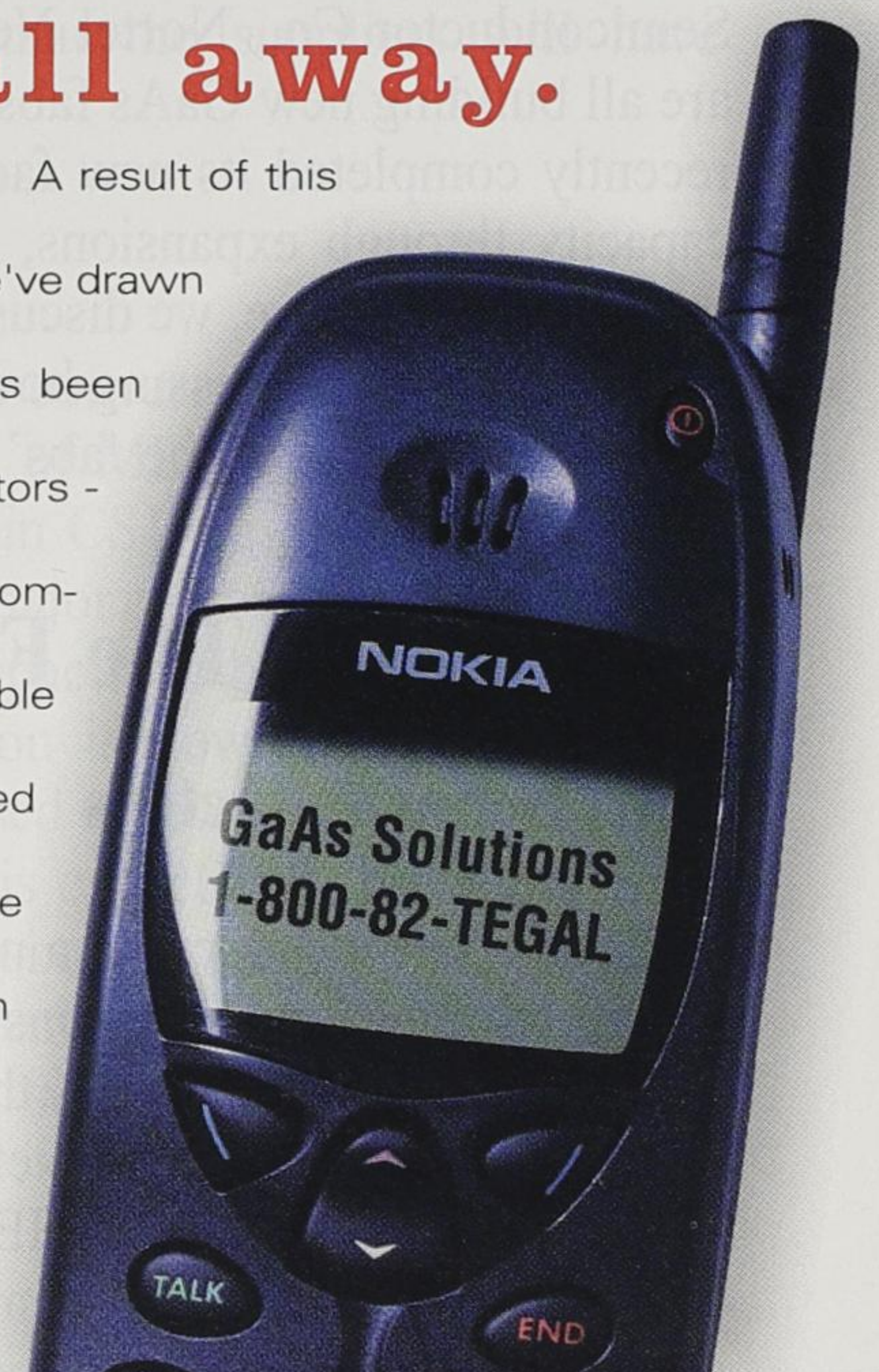
Figure 8. Potential applications for SiC MES-FETs include (a) cellular base stations, (b) MMDS – multi-channel, multi-point distribution systems, (c) WLL – wireless local loop, and (d) CATV amplifiers. MMDS photograph courtesy of Spike Technologies.

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Fab Four Address Growing GaAs Markets

Four new GaAs fabs are currently under construction around the world, while other companies take steps to extend their capacity in the face of huge demand for GaAs products.

TIM WHITAKER

In the view of most observers, the demand for GaAs devices is continuing to accelerate and shows no sign of slowing down. On page 49 of this issue, Stephen Entwistle of Strategy Analytics estimates that the GaAs market was worth around \$2.25 billion in 1999. Another well-known analyst, Earl Lum of CIBC World Markets, quotes an even higher figure – \$2.4 billion – just for the analog portion of the market. Lum also predicts that this sector will grow extremely rapidly over the next several years, reaching around \$11 billion in 2004. In comparison, the entire compound semiconductor industry was valued at around \$11 billion in 1999. Under these circumstances, the major problem faced by device manufacturers and companies further down the supply chain is how to increase capacity to meet this demand.

Four companies – WIN Semiconductors, Advanced Wireless Semiconductor Co., Nortel Networks and RF Micro Devices – are all building new GaAs fabs, while a fifth company, Filtronic, recently completed its new facility. Many others are increasing capacity through expansions, acquisitions, or conversion to 6-inch operation. Here, we discuss some of these activities in more detail as well as discussing how the industry supply chain is also gearing up to service the fabs' requirements.

The Fab Four

WIN Semiconductors

WIN Semiconductors, a newly formed Taiwanese company, is well advanced with the construction of a new 6-inch GaAs fab in Lin-Kou, Taiwan. WIN (the company name is abbreviated from Wireless Information Networking) intends to offer foundry services based on several HBT and PHEMT processes, using purchased epiwafers. WIN aims to process 10,000 wafers by the end of next year, and will ramp to a full capacity of 100,000 wafer starts per year by 2004.

The facility, which includes a 20,000 sq.ft. clean room, is expected to be finished by July 2000, and equipment outfitting will be complete by September. In addition to the OEM foundry service, WIN will also offer, through teaming agreements with design and packaging houses, circuit design and layout services as well as chip packaging. WIN's fab will accommodate a range

of processes for different products with operating frequencies up to 100 GHz. These include 2.0 mm, L-band, HBT devices for use in PCS/cellular (CDMA, GSM, TDMA, etc), GPS and cable television applications as well as 0.18 μm to 0.25 μm PHEMT devices for use in Ku-, Ka- and V-band applications such as LMDS, point-to-point radio links, and fiber optic communications.

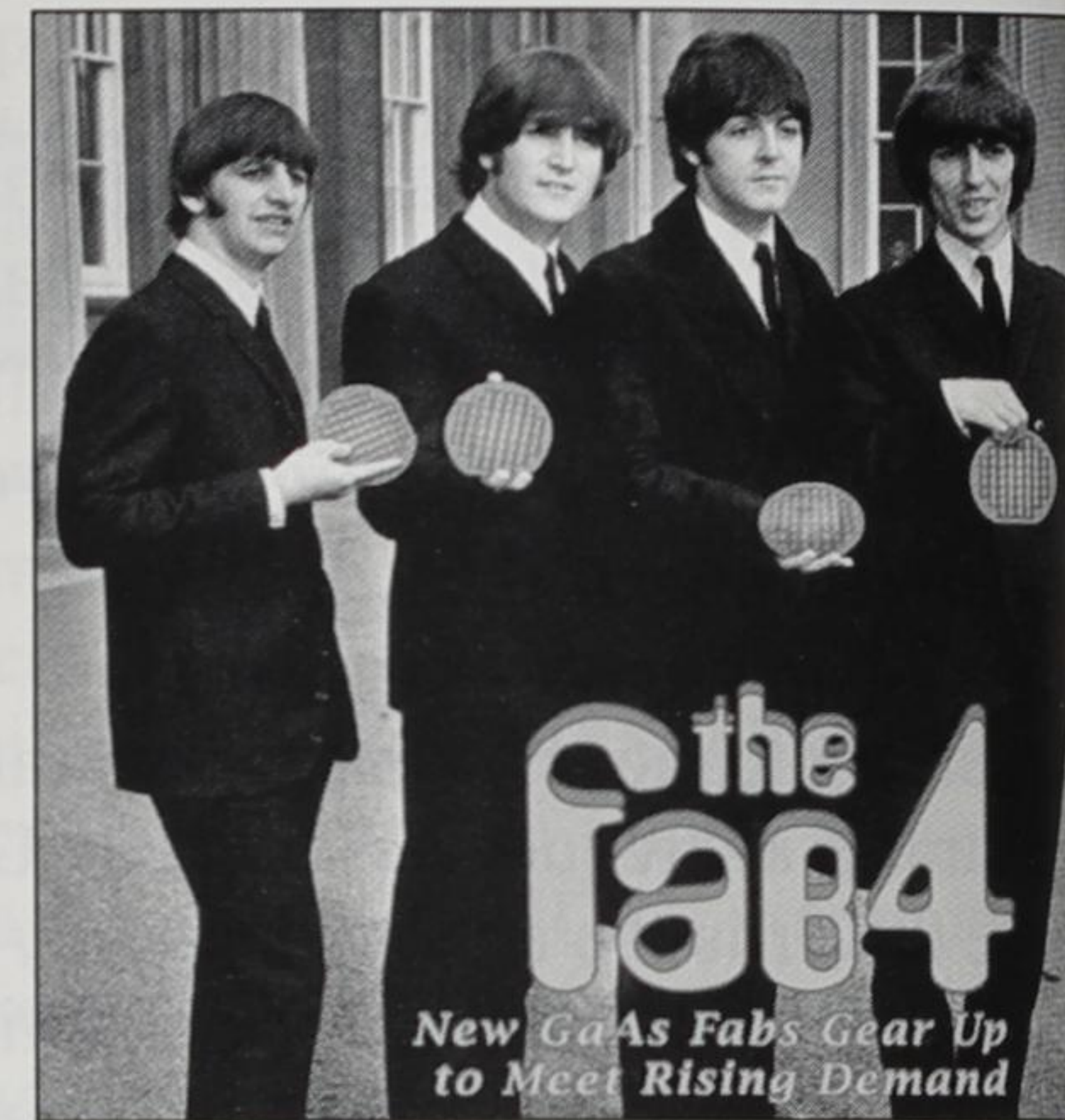
President and CEO, C. S. Wu, who spent time at the GaAs production lines of TRW and TI in Dallas, does not foresee a problem in obtaining sufficient 6-inch epiwafers to meet the company's production targets. "There is considerable confidence in the GaAs device market in the next few years and we are confident of our technology," he comments.

The company states that Mitsubishi is one of the investors in WIN Semiconductors; funding has also come from ACER Computers, the China Development Industrial Bank and private sector investors.

Advanced Wireless Semiconductor Company

Located in the Tainan Science-Based Industrial Park in South Taiwan, Advanced Wireless Semiconductor Company (AWSC) is a GaAs HBT foundry. The company states that its goal is "to provide the highest-quality, lowest-cost GaAs HBT foundry services available for wireless module manufacturers and fabless design houses."

AWSC currently operates a 4-inch GaAs HBT facility with a capacity of 600 wafers per week. In June, the company will commence construction of a second fab to process GaAs HBTs on 6-inch wafers. This facility will also have a capacity of 600 wafers/week, providing AWSC with a total capacity of 4-inch equivalent wafers of approximately 1,950 per week – or over 100,000 per year. AWSC recently signed a foundry agreement with Conexant, which is described below.



Nortel Networks

Nortel Networks recently announced the formation of the High Performance Optical Components Solutions group combining the company's existing optical components activities with other areas of excellence, including high-speed modules and IC design and development [see page 18 for more details]. A part of this new component powerhouse is Nortel's GaAs semiconductor component manufacturing capability.

"Currently, manufacturing capacity is being doubled with the addition of a second GaAs HBT fabrication plant in Kanata, Canada that has just finished construction," says Gary Tomkins, Director of Nortel's GaAs Wafer Fabs. "The new 20,000 sq.ft. class 100 cleanroom is located 3 km from the present HBT Fab, and will be fully operational fabricating advanced GaAs HBT wafers by the second quarter of 2001." This facility is part of a US\$400 million investment that Nortel Networks announced in November for its booming optical networking and components business.

"We've manufactured our first devices – PHEMT-based LNAs – on the 6-inch GaAs line and we're very pleased with the results."

RF Micro Devices

According to plans announced last year [see CS 5(7), p. 52], RF Micro Devices is building a second GaAs HBT fab in Greensboro, NC. RFMD's existing fab has a capacity of 50,000 4-inch wafers per year. The first phase of construction of the new fab will provide a capacity of 60,000 4-inch wafers by late 2000 – a spokesperson stated that the building is already complete and equipment installation is expected to begin shortly. The second fab will eventually provide an additional 210,000 wafers per year by the end of 2001.

Work in Progress

Filtronic

Filtronic is well advanced in establishing not one but two 6-inch GaAs processing facilities. The company is converting the former Litton Solid State fab in Santa Clara, CA to 6-inch operation – the 45,000 sq.ft. facility has 12,000 sq.ft. of class 100 clean room and will focus on process development and fast MMIC prototyping.

Meanwhile, another subsidiary, Filtronic Compound Semiconductor, has established a 6-inch GaAs fab in Newton Aycliffe, UK for high volume PHEMT production, targeting wireless handset applications. The UK facility is housed in a former DRAM fab acquired from Fujitsu that has 100,000 sq.ft. of clean room space, over 54,000 sq.ft. of which is capable of achieving class 10 standard. The phase one facilitization of this plant is intended to provide a throughput of 30,000 six-inch wafers per year. This phase one stage utilizes about one third of the available area, and Filtronic says that market demand will determine the future growth.

Around 200 individual pieces of equipment have been purchased for the new fab, including two multi six-inch wafer MBE systems (the first being due for delivery in August), as well as a full range of processing equipment and systems for materials and device characterization.

Although the acquisition of the facility was only completed in September 1999, the fab is already producing pilot quantities of 6-inch PHEMT wafers. "We've manufactured our first devices – PHEMT-based LNAs – on the 6-inch GaAs line and we're very pleased with the results," says Richard Kerrigan, General Manager at Filtronic Compound Semiconductor. "We are currently optimizing the LNA process for improved productivity and improved yield, and are also running our first power amplifiers."

The company will conduct reliability testing of its products for the next several months before entering the commercial market. "We expect to go into production with our own devices towards the end of 2000," says Kerrigan,

"although we do have the capability for foundry work in accordance with external designs. We've achieved a great deal in a short space of time, due largely to the hard work of our staff and sub-contractors."

Kerrigan says that Filtronic was originally cautious about committing the UK facility to 6-inch operation because of fears that substrate manufacturers might not be able to provide enough 6-inch wafers. However, these fears were allayed. "All the suppliers that we contacted said they were installing extra capacity for 6-inch wafers," he says. "By the time we have ramped up our production volume, we expect that the suppliers will have ramped up as well."

Motorola

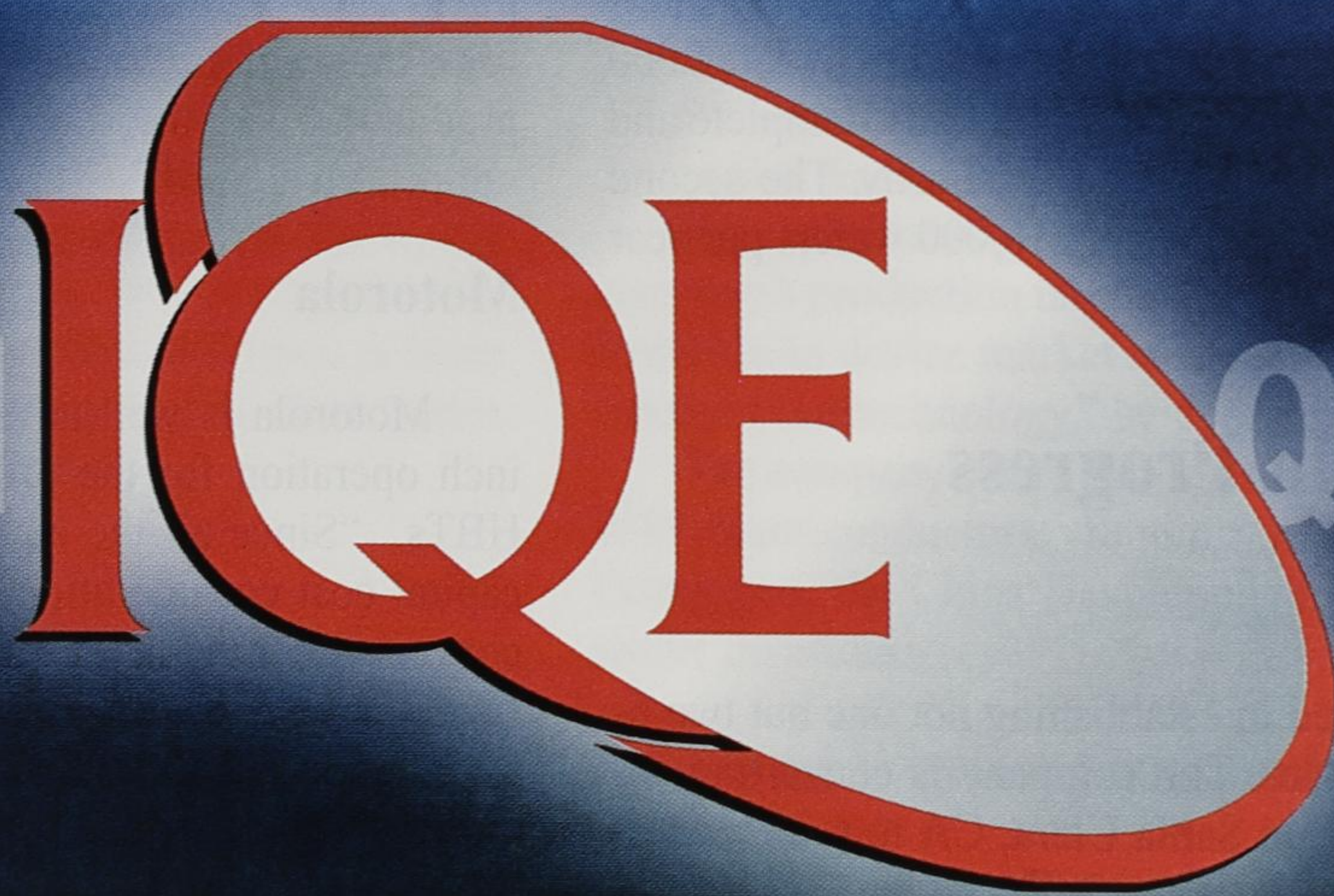
Motorola is well advanced in converting its CS1 fab to 6-inch operation for the production of MESFETs, PHEMTs and HBTs. "Since all the equipment in CS1 was 150-mm capable, capital cost consideration was a major factor in the decision to convert rather than add 100-mm capacity or build a new facility," says Mark Wilson. The conversion is now in the production ramp-up phase, which has progressed to several hundred six-inch wafers per week, and completion is expected by the summer of 2000. The ultimate capacity of the six-inch facility is expected to be 2200 wafers per week, representing a 3.5-fold increase in overall capacity. For more details, see Mark Wilson's article in our July issue.

Alpha Industries

Alpha is close to completing the second phase of a major expansion program at its facility in Woburn, MA. The company has accelerated its expansion efforts in the face of growing market demand, and has also significantly increased its capacity with the recent acquisition of Network Device Inc (NDI). A spokesperson stated that Alpha will soon have excess capacity that will allow the company to begin its conversion to 6-inch



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GaAs. By transferring processes to the NDI facility (Sunnyvale, CA), Alpha will be able to convert one of its lines in Woburn to 6-inch operation without suspending production.

Anadigics

Anadigics' 6-inch fab was completed during 1999 and is now fully operational. However, due to increased demand for its products, Anadigics is already expanding the new facility. An additional 10,000 sq.ft. clean room will double the size of the fab, and work is scheduled to be completed sometime in the second half of 2000.

Tyco M/A-COM

M/A-COM, Inc., a unit of Tyco Electronics, has increased its production capacity on two fronts. The company's facilities in Lowell, MA and Colorado Springs, CO were both recently expanded. A spokesperson stated that M/A-COM is adding 6-inch capacity that will be on line late this year. Also, M/A-COM recently acquired the GaAsTEK unit of ITT Industries [see CS 6(2), p. 76].

Recently Completed

Conexant Systems

Conexant Systems recently completed a major expansion of its GaAs manufacturing facilities in Newbury Park, Calif. and has also signed a foundry agreement with AWSC. These moves will provide Conexant with a total capacity of 125,000 four-inch GaAs HBT wafers starts per year by the end of 2000.

The expansion has increased capacity to a record 75,000 four-inch wafer starts per year, as compared with 15,000 annual wafer starts just one year ago. Conexant invested approximately \$80 million in capital equipment to achieve this five-fold increase, and is planning a further increase to 95,000 four-inch equivalent wafer starts annually by the end of 2000. All the new manufacturing equipment that Conexant has installed in its expanded facilities can be upgraded to

process six-inch wafers - this conversion would increase available capacity to approximately 210,000 four-inch equivalent wafer starts annually.

The multi-year agreement with AWSC guarantees Conexant capacity for an additional 30,000 GaAs HBT wafer starts annually, and production will commence in the fourth calendar quarter of this year.

TriQuint

TriQuint Semiconductor has completed the expansion of its wafer fabrication facility in Hillsboro, OR. The clean room floor space within the existing manufacturing complex has been increased by 35%. The additional space is being used to increase production of 4-inch wafers and for future conversion to 6-inch manufacturing.

"This additional space gives us the flexibility to continue our production ramp, qualify the 150-mm process, and install the capacity to produce 150-mm wafers," says David Pye, TriQuint's VP of Operations. New equipment has been installed in the additional space, and it is expected that this equipment will be qualified and in production by the end of May.

Future Plans

Global Communication Semiconductors

According to company officials, the strong growth in demand experienced by Global Communication Semiconductors (GCS) in 1999 created the need to expand the company's fab facility in Torrance, CA from its current 7,000 sq.ft. to the planned 15,000 sq.ft. by the end of 2000. Fortunately, expansion plans were taken into consideration during the acquisition of the 40,000 sq.ft. warehouse facility that is the current home of GCS. The expansion program, already in progress, allows for an increase in the number of 4-inch wafer starts per week to increase from 250 to 500 by the end of 2000. By the first quarter of 2001, the capacity is due to increase to 2,000 4-inch equivalents.



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Suppliers Respond

However, the company states that this alone will not meet the needs of its expanding business. To address the market demand and the trend towards 6-inch wafers, GCS has plans to establish a 6-inch fab in Hsinchu, Taiwan. Wafer production from this new facility is scheduled for the second quarter of 2001, and will increase GCS's total capacity to 5,000 4-inch equivalent wafers per week. The Hsinchu facility also has reserved floor space for increased capacity.

Incorporated in August 1997, GCS has now been delivering HBT PA and digital ICs, PHEMT, epitaxial wafers, SAW and optoelectronic devices for over one year. GCS's business goal is to supply low cost, high quality, specialty semiconductor materials, devices, ICs and solutions to the wireless and telecommunications markets.

To address the market demand and the trend towards 6-inch wafers, GCS has plans to establish a 6-inch fab in Hsinchu, Taiwan.

Agilent Technologies

Agilent Technologies Semiconductor Products Group is currently experiencing very high demand for our GaAs RF products, driven by the explosive growth in wireless communications applications. "GaAs production has increased 200 percent over the last nine months alone," says an Agilent representative. "To meet this tremendous demand and ensure that we do not become limited by our wafer fab capacity we are expanding our wafer production facility. These expansion plans not only increase our current wafer capacity, but include the introduction of a six-inch GaAs fab in 2001."

Microsemi

Microsemi recently acquired the HBT group of Infinesse and announced plans to convert some of their existing silicon fab facilities over to production of GaAs HBTs.

Of course, all this activity is placing heavy demands on the industry's supply chain. With many manufacturers opting for 6-inch GaAs, the availability of 6-inch substrates and epiwafers is a particular concern at the moment. While there is likely to be a shortfall this year, it appears that most vendors are gearing up their own production capacities to meet the projected demand for the years to come:

- **IQE** says that it is growing rapidly to service the growing customer demand for 6-inch PHEMT and HBT epiwafers. "IQE believes that the major compound semiconductor device manufacturers are constantly looking for a competitive advantage," says Jim McKeown, IQE's Director of Marketing.

"By upgrading to a 6-inch process line, customers can achieve greater economies of scale with increased production throughput. IQE is committed to support its customers by undertaking an aggressive 6-inch epiwafer capacity expansion plan which will provide IQE with 3 times the 6-inch epiwafer throughput of its nearest competitor."

By year-end 2000, McKeown says that IQE Bethlehem will take delivery of ten more multi-wafer 6-inch MBE reactors in addition to the one it has at present. The company will eventually have five VG Semicon V150 machines, four Riber 6000 systems and two EPI Gen2000 reactors. IQE Bethlehem has recently completed a facility expansion, and is planning for an additional expansion to be completed by the 4th quarter 2000. Furthermore, IQE Cardiff will take delivery of an additional four Aixtron 2600 multi-wafer 6-inch MOVPE reactors by year-end 2000, making a total of six such machines.

- **Emcore** recently doubled its capacity to supply MOVPE-grown HBT and PHEMT epiwafers, and has launched a second phase of expansion that will result in a

further 2-fold capacity increase [see CS 6(3), p. 20].

- **AXT** recently announced plans to triple its GaAs substrate production capacity by the end of the third quarter of 2001, citing strong growth in the wireless handset market and the increasing popularity of 6-inch substrates [see page 23].

- **Freiberger Compound Materials** is constructing a second facility that will more than double the company's output of 6-inch GaAs wafers. Full production from the new facility is expected by the end of March 2001, and the company has also allocated a site for a third facility.

- Late last year, **Hitachi Cable** completed its mass production line for large GaAs wafers, which has a capacity of up to 30,000 wafers per month. The company also increased its output of MOVPE-grown epiwafers to around 12,000 per month, including an increase in the supply of 5- and 6-inch diameter epiwafers [see CS 5(9), p. 24].

- **United Epitaxy Company (UEC)** has just ordered a large number of MOVPE systems, some of which will be used to manufacture HBT epiwafers [see page 23].

- **Kopin** is building a second factory to house a large number of MOVPE systems for the growth of HBT epiwafers: the company has just installed six new machines and will add 8 more by the end of the year [see page 23].

Summary

In the face of huge demand from wireless and fiber optic applications, the GaAs manufacturers are taking steps to increase capacity through construction, acquisition, expansion or conversion to 6-inch operation. The industry's supply chain is also gearing up to meet the challenge. Even though the "fab four" and the other manufacturers are working eight days a week, they should be able to get by with a little help from their friends.

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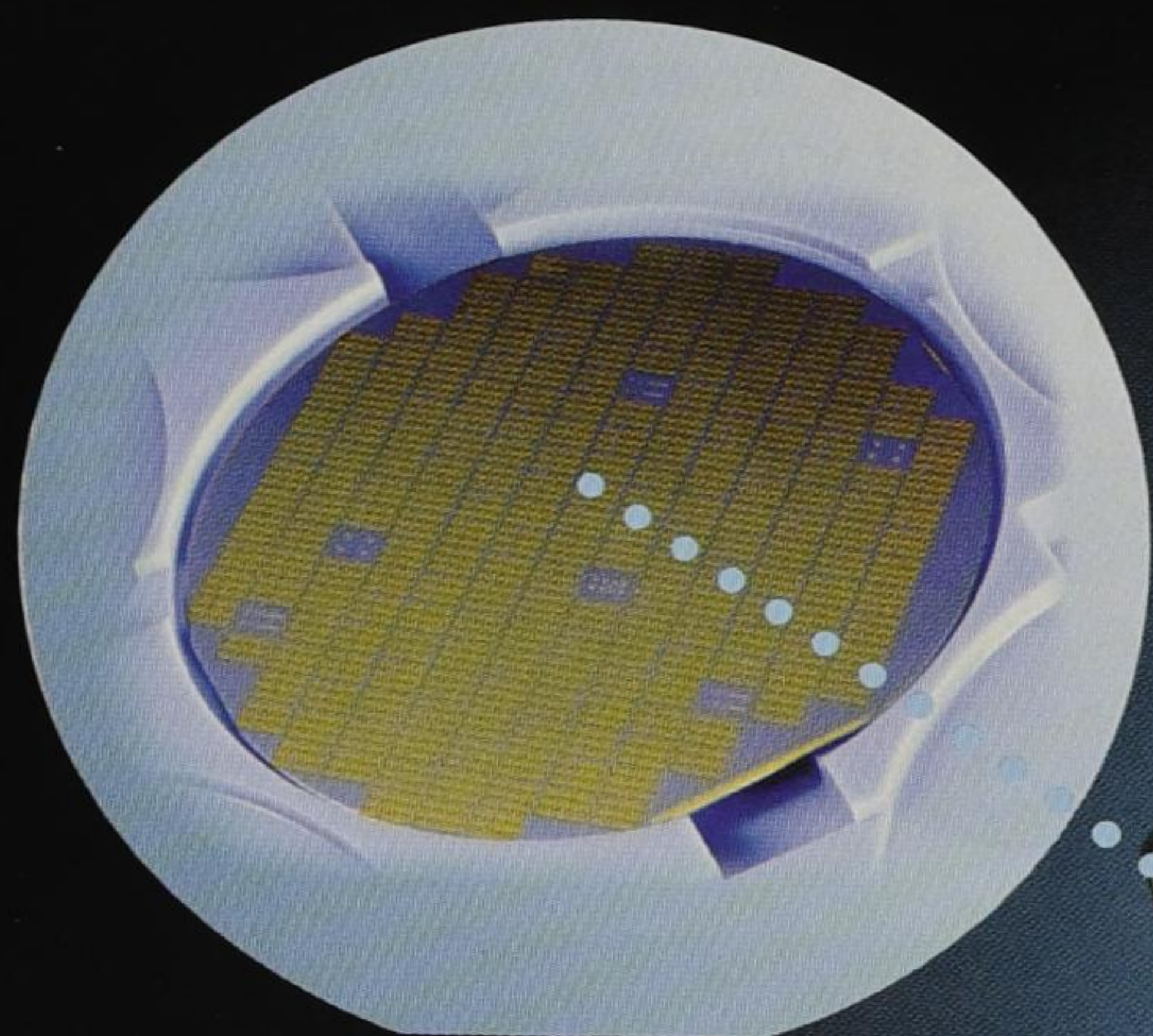
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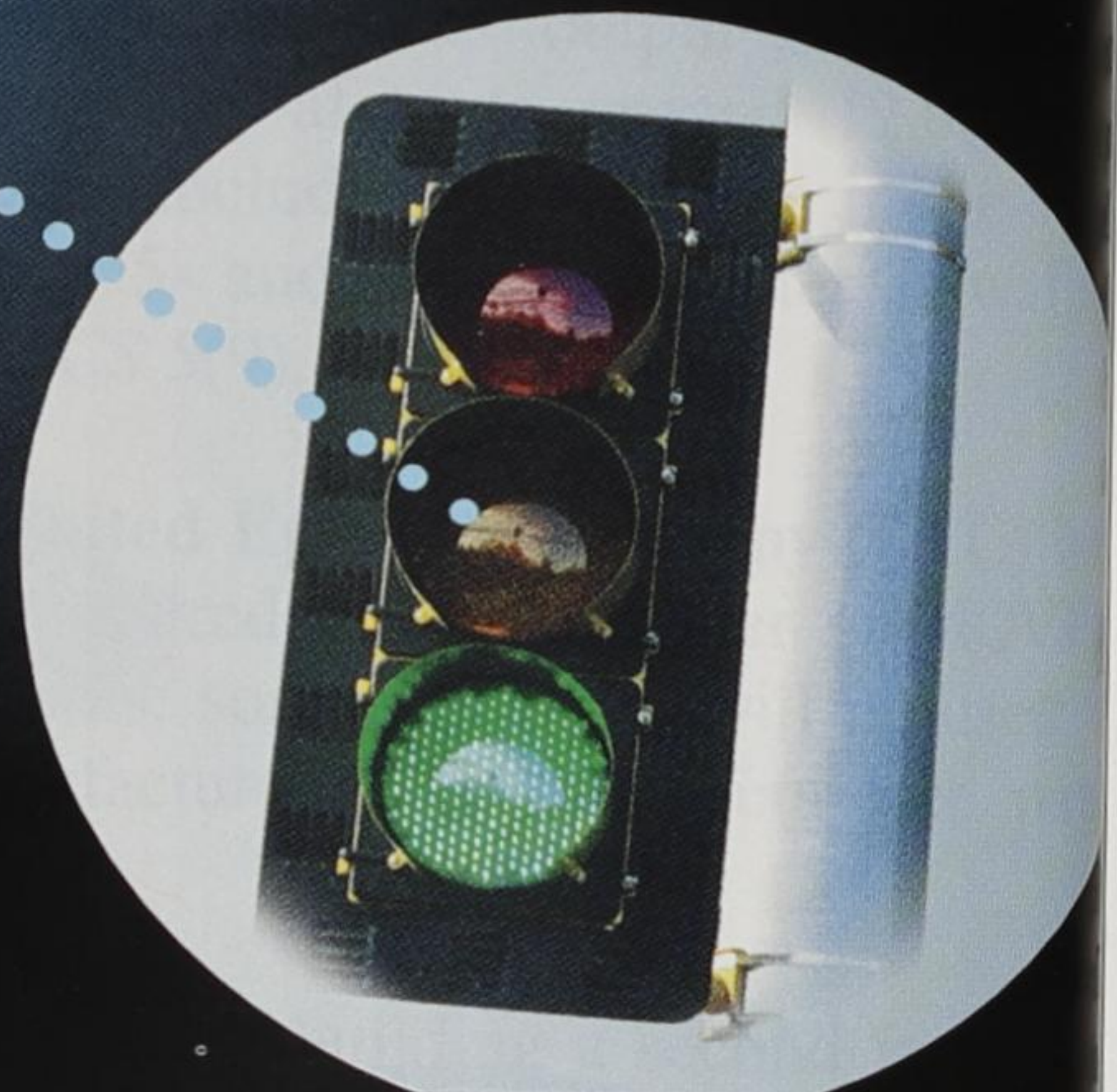
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Trends in the Market for GaAs Devices

STEPHEN ENTWISTLE
Strategy Analytics*

*Presented at the Key Conference on Compound Semiconductors
Key West, Florida
March 13-14, 2000*

The GaAs IC industry is currently undergoing very rapid change. This is largely being driven by the booming cellular business and fast-growing fiber optic network markets. In cell phones, the analog transmit/receive portion requires high power, highly-linear power amplifiers (PAs) and switches operating at RF frequencies. The fixed-line telecommunications industry requires high-speed analog transmit and receive devices and digital framing and switching components.

Many companies are working hard to position themselves in these burgeoning wireless/data communications industries, leading to recent successes for US companies such as RF Micro Devices (RFMD), Conexant and Anadigics, and in Japan, Matsushita, Sony and Fujitsu (see below). For the fast-growing fiber optic markets, digital ICs are being supplied by companies such as Vitesse and analog ICs by Anadigics and TriQuint.

Markets for GaAs ICs

The GaAs device market can be sub-divided into discretely (FETs), MMICs (including all analog RFICs) and digital devices. The market for these devices can also be divided into merchant sales, where manufacturers sell all the devices, and captive sales, where devices are consumed internally. The total market including captive and merchant sales was almost \$2.25 billion in 1999, up 31% from the year before (see Table). Of this, the MMIC market comprises by far the biggest proportion, and is one of the fastest growing sectors. In 1999, total sales of MMICs added up to more than \$1.4 billion, an increase of almost 40% compared to the 1998 figure. This trend should continue, leading to a total market value for GaAs MMICs of \$1.8 billion by the end of 2000 (Figure 1). By 2003, sales of MMICs will exceed the \$3 billion mark. In all categories of devices, merchant sales are set to increase much more rapidly than captive sales.

In 1999, FETs made up \$439 million of the market for GaAs devices. However, with single digit growth rates, this busi-

ness is evolving modestly in comparison to MMICs, and is generally dominated by Japanese suppliers. The digital IC market was also worth around \$400 million last year, and is dominated by players such as Vitesse. In contrast to FETs, this is a fast-growing sector: digital ICs have increased merchant sales by 54% compared to 1998.

So where are these devices going? Analyzing the major consumers by region, North America was the biggest consumer in 1999, using 42% of all merchant GaAs ICs produced (Figure 2). Europe used 27%, mainly for its cellular business. (To date, nearly all handsets that use the GSM standard are still manufactured in Europe.) Japan follows closely with 25% of all GaAs devices consumed.

In terms of applications, wireless communications companies are by far the biggest users of GaAs devices, with a 62% share of the market (see Figure 3). Two other significant sectors exist for fiber optic communications (both for digital and analog devices) and consumer electronics, which consume 10%, predominantly in set-top boxes and cable applications. While it was once the main driver for GaAs, the military market now represents only 4% of current requirements.

Data Drives Cellular Markets

One of the main reasons for the growth in cellular markets is the move to wireless data. The WAP or Wireless Application Protocol is a new standard that allows handset manufacturers to offer Internet services on mobile phones. This factor will drive the market for replacement phones, and generally increase the

	1999 Revenues (\$ million)		1998 Revenues (\$ million)		% Change 1998-99	
	Merchant	Captive	Merchant	Captive	Merchant	Captive
MMIC	1212	220	863	181	40	22
FET	321	118	303	113	6	4
Digital IC	330	47	214	42	54	12
Total	1863	385	1380	336	35	15

1999 revenues derived from FETs, Digital ICs and MMICs (including all analog RFICs). The total device market, which is dominated by MMICs, is up 35% on 1999 to \$1863 million.

* Strategy Analytics is a business planning consultancy based in Luton, UK with offices in the United States, Japan, Australia and mainland Europe.

market penetration for new data-enabled handsets. The so-called third generation or 3G technology, a family of standards that will ensure backward compatibility with other standards for data rates up to 2 Mbps, is now under development for the transmission of voice, data and also video.

In Japan, this is expected to happen early in 2001 [see CS (6)1, p. 69]. This is primarily a result of the lack of capacity on the country's existing phone systems. However, in Europe and North America, the phone operators are not expected to follow this trend as quickly as some observers might expect. Significant subscriber conversions are likely to occur in the next four to five years, largely because cellular operators first need to recoup their investments in existing wireless infrastructure.

Other questions surround 3G. It is not clear at present if customers would be willing to pay extra for 3G if their data rate requirements could be met using 2.5 G. As the name implies, 2.5 G partially bridges the current second generation (2G) digital cellular standards such as GSM and CDMA (which allow some low-speed data communication) and the new data-enabled 3G standard. 3G also places strict performance requirements on the RF portion of the phone, particularly the PA. And this will also favor GaAs as the technology of choice.

It is likely then that European and North American operators will first employ the 2.5 G technology. The advent of systems such as GPRS (General Packet Radio Service) and EDGE (Enhanced Data rates for Global Evolution) means that the cellular operators can modify existing systems to provide faster data rates and use 2.5 G as a proving ground for new value-added services.

Other Contenders for RF – Silicon

Strong competition exists between GaAs and silicon for digital cellular applications. But GaAs, and in particular GaAs MMICs, will continue to play a strong role in cellular applica-

tions in next five years. It is expected that in excess of 50% of handsets will contain GaAs MMIC power amplifiers and switches. Currently, the demand for GaAs components suited to the RF portion of digital cellular phones was reflected in a market value of around \$750 million in 1999 (Figure 4). This market is estimated to grow to \$1.5 billion by 2003, and will be driven mainly by the move to higher frequencies (1.8/1.9 GHz) for dual-band phones, and the need for amplifiers with high performance at both of the dual frequencies. There is also a trend towards lower operating voltages in cellular phones.

The addition of data capabilities, either dedicated or using modifications to existing systems, means that the demands on the power amplifiers are higher, particularly in terms of linearity and power-added efficiency (PAE). This is good news for GaAs power amplifiers, which exhibit excellent linearity and high PAE compared to their silicon counterparts. In addition, CDMA phones are becoming more popular, and are now the fastest growing cell phone standard. CDMA uses direct sequence spread spectrum technology to provide more conversations per bandwidth, and requires very linear transmission to avoid spectral interference and also high DC to RF conversion efficiency. These stringent performance requirements are currently best met by GaAs MMICs – especially for the power amplifiers and a number of other receiver components, including LNAs.

Silicon is very strong in the small-signal portion of the radio, which has led to speculation about single-chip radios. However, this is unlikely to occur on one IC. In the longer term, it is rather envisaged that Si and SiGe could be integrated into most parts of the radio, with the exception of the power amplifier and switch. Indeed, SiGe is now offered as a higher performance version of silicon that can be employed in certain portions of the phone, e.g. as an LNA in the receiver.

Epitaxial Devices - HBTs and PHEMTs

For a long time the GaAs industry had to “push” the technology forward. However, having accepted the performance

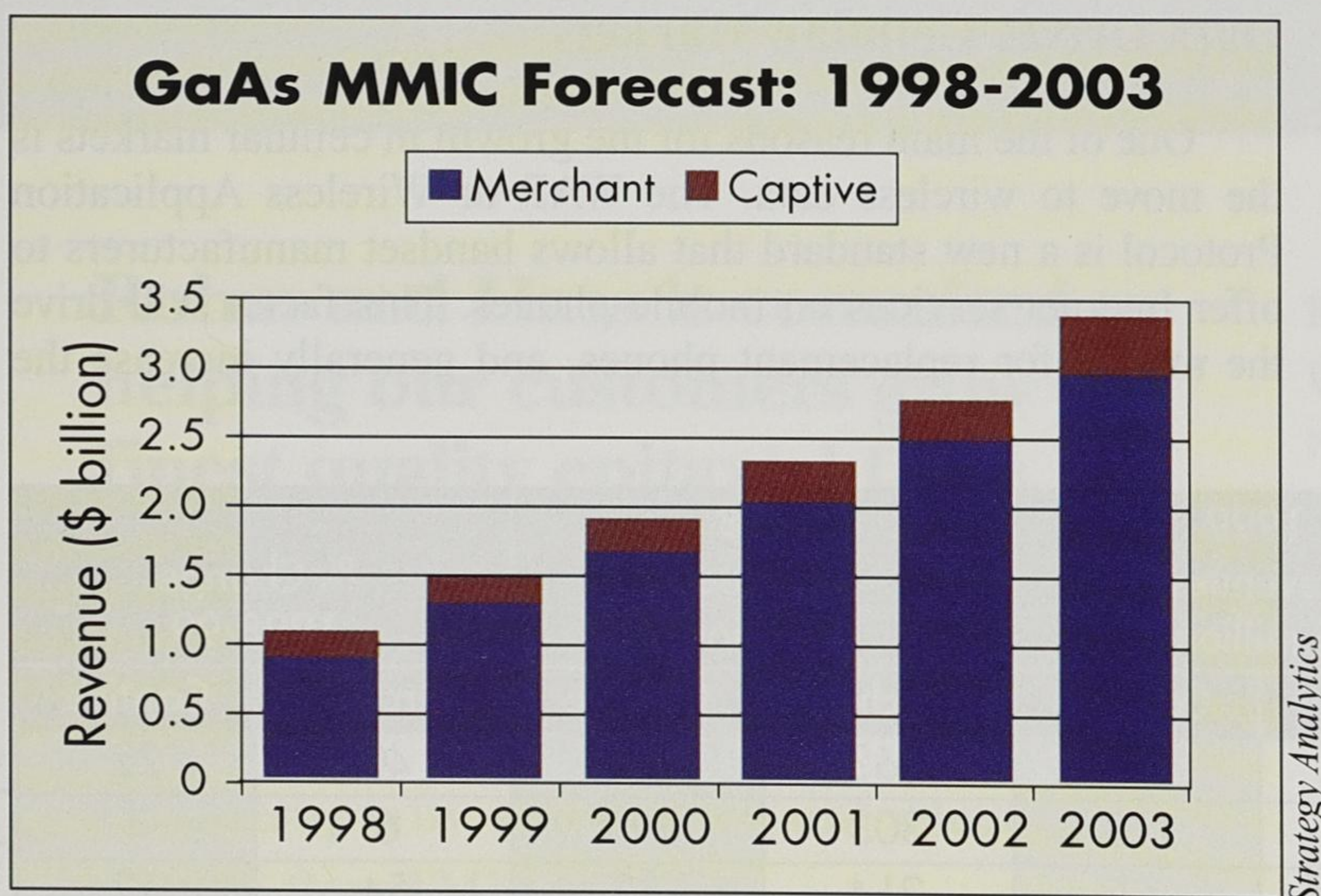


Figure 1. Sales of GaAs MMICs reached \$1.4 billion in 1999 and should reach \$1.8 billion by the end of 2000. MMIC merchant sales will approach the \$3 billion mark by 2003. In all categories (MMICs, FETs and Digital ICs), merchant sales are growing much faster than captive sales.

Regional Consumption of GaAs Devices

(1999 Merchant Market: Total \$1863 million)

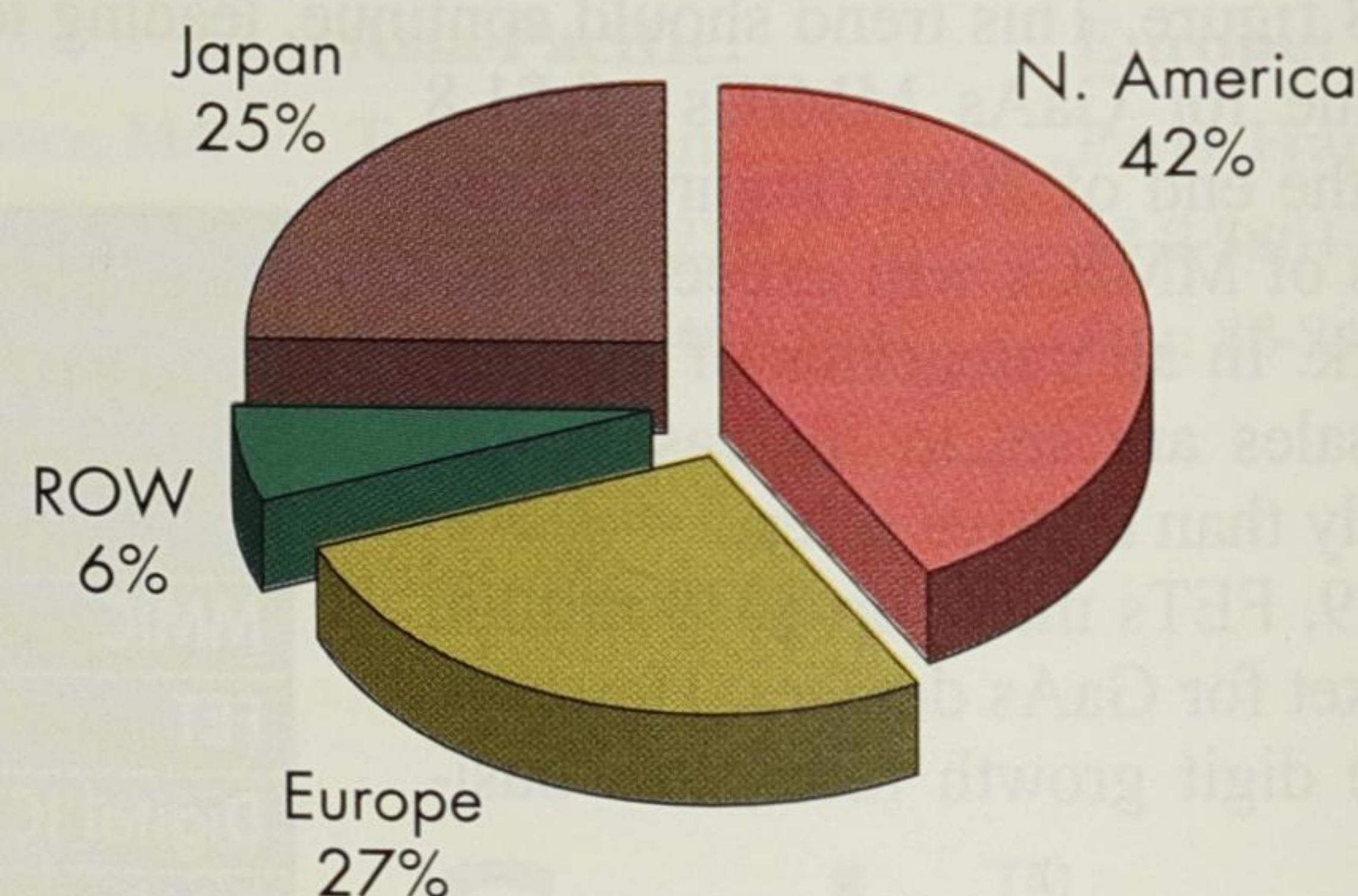


Figure 2. The merchant market for GaAs ICs in 1999. Device consumption is dominated by North America, followed by Europe and Japan.

advantages of this new material, device designers are now attempting to "pull" the technology to use better devices. In particular, epitaxy is being used to fabricate devices such as HBTs and HEMTs. The HBT was the first epitaxial technology to be widely commercialized by companies such as TRW, RFMD and Conexant for cellular applications, other personal wireless communications, and also fiber optics.

This "push" trend is now coming to fruition, and, as a conservative estimate, around 50% of the GaAs MMIC market will consist of HBTs and PHEMTs by 2003. Many companies are now entering this area, among them Alpha Industries, Anadigics, TriQuint and Infineon. Another factor has been the performance gains made by SiGe, which has forced GaAs companies to examine the device advantages offered by GaAs HBTs and HEMTs. Of course, for some applications such as millimeter wave systems, the PHEMT is considered a technology enabler.

However, the HEMT is not as well developed commercially as the HBT, and device volumes are presently quite low. Vendors expected to lead the push for large-scale PHEMT production include Celeritek and Raytheon, in addition to Anadigics, a company that has recently developed PHEMT MMICs for fiber optic applications. Other applications could include cellular markets, both for handsets and base stations, millimeter wave technologies, up/down links for satellites, and automotive radar markets.

Despite these projections, it is still envisaged that devices based on MESFET technology will continue to play an important role. This will in part depend on the pressure that can be brought to bear on prices; it will also depend on leveraging the benefits that companies such as Vitesse and Anadigics will gain now that they have moved to 6-inch diameter GaAs wafer production. And for a lot of applications, the performance of MESFETs is good enough, which makes price the deciding factor.

Supplier Vital Statistics

The major suppliers of GaAs MMIC devices in 1999 are broken down in Figure 5. This illustrates the merchant MMIC demand (not including captive sales and the discrete market).

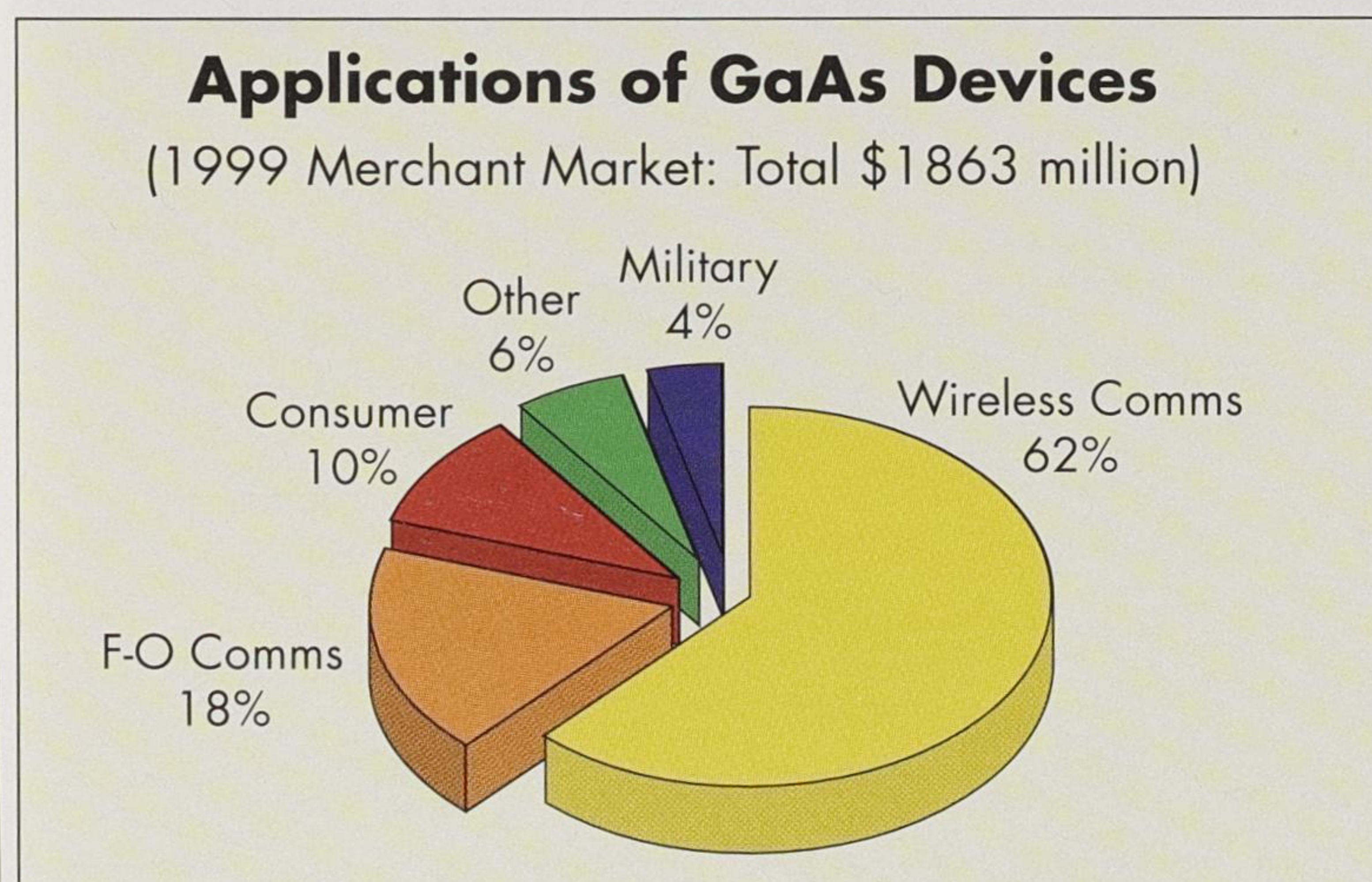


Figure 3. Wireless communications (PAs, LNAs) is by far the biggest application for GaAs ICs, with two other significant sectors existing for fiber optic communications (both for digital and analog devices) and consumer electronics.

RFMD is revealed as the top player in a \$1.2 billion market, with 19% (around \$220 million). Other MMIC players include Anadigics, Conexant and TriQuint in the US, and Matsushita, Fujitsu and Infineon in Japan and Europe. A large number of smaller companies make up the remaining one third.

Underpinning this device manufacturing effort are the suppliers of substrates and epiwafers. Increasing business for cellular applications is filtering down, and the market for bulk semi-insulating GaAs substrates, a mature business currently worth about \$125 million, is also very dynamic.

Some of these substrate vendors are also benefiting from the increasing use of epiwafers. At present, the rapidly-growing epiwafer market is worth somewhere between \$150 and \$200 million. Around 11% of this material (0.116 million inch²/year or around 760 x 4-inch wafers/month) is consumed internally, and the remaining 89% (0.974 million inch²/year or 6,430 x 4-inch wafers/month) of the merchant epiwafers originate in the facilities of manufacturers such as Kopin and QED.

These commercial epiwafer houses are finding the supply-demand equation challenging at present, and this situation has led the GaAs industry to call for the establishment of new wafer sources. An increased volume of epiwafers and sources for these materials should supply the environment required to promote lower epiwafer prices.

In terms of the growth techniques employed, the MOCVD market (Figure 6) is set to expand from over 2 million inch²/year (13,200 x 4-inch wafers/month) in 1999 to around 5.5 million inch²/year (~36,300 x 4-inch wafers/month) in 2003, largely for merchant markets. Captive markets will remain static at approximately 0.5 million inch²/year (~3,300 x 4-inch wafers/month). MBE epiwafers are projected to grow with a CAGR of 38% from around 1.7 million inch²/year (11,200 x 4-inch wafers/month) to 5 million inch²/year (~33,000 x 4-inch wafers/month) over the same period. Captive production for devices such as HEMTs will increase to almost 50% of this total.

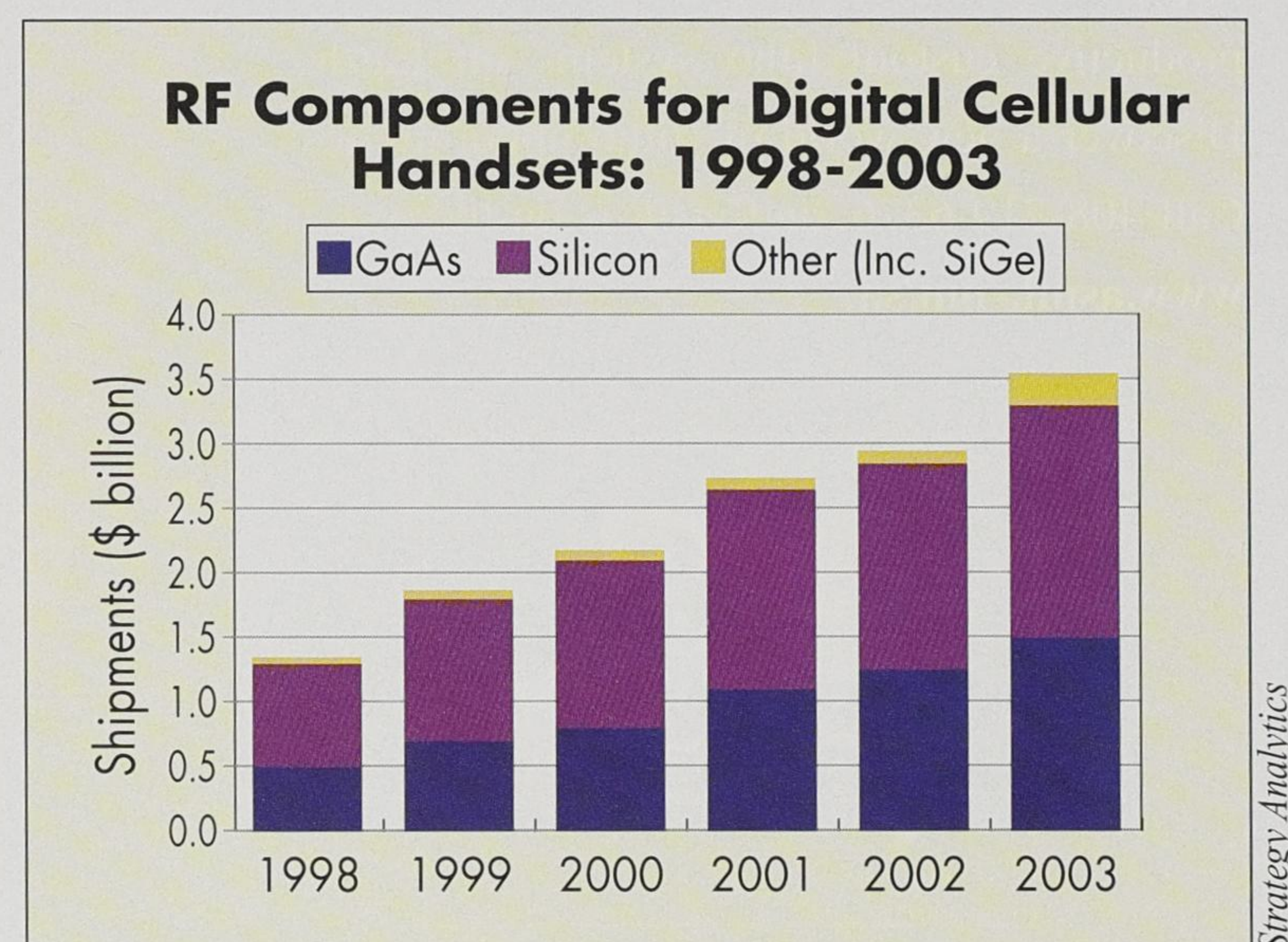


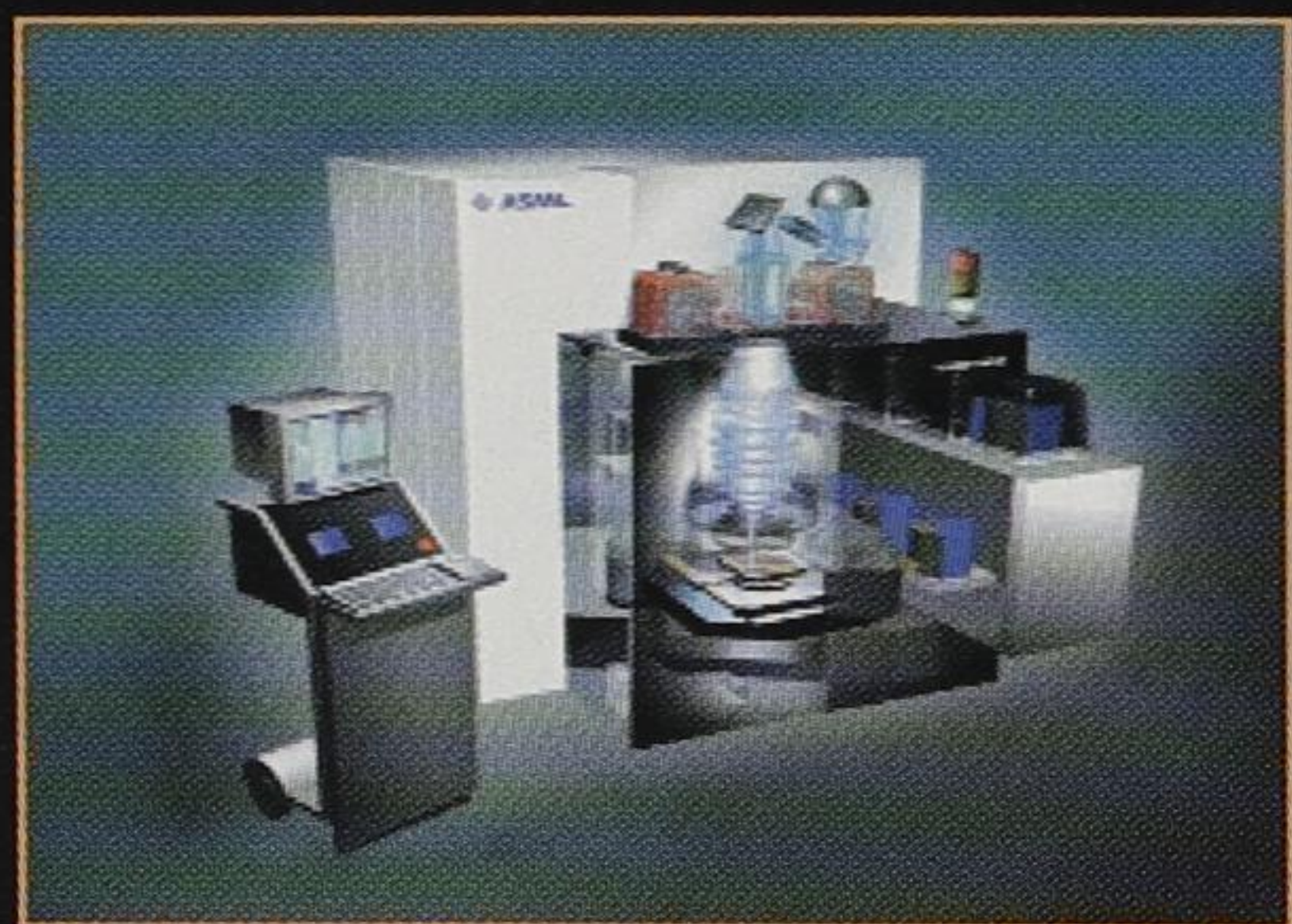
Figure 4. In the next five years, more than 50% of handsets will contain GaAs MMIC PAs and switches. Last year, the market for these devices was around \$750 million, and this value will double by 2003.

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Emerging Opportunities for GaAs

New opportunities are also expected to emerge for GaAs ICs. High performance devices operating at RF and microwave frequencies will experience demand from cellular base station manufacturers. And while laterally-diffused MOS (LDMOS), a higher performance Si-based amplifier, has won many of the high-power applications from GaAs, some opportunities exist in this area.

In the consumer arena, CATV (cable TV) applications, both in the infrastructure with line amplifiers and in cable modems and set-top boxes, are becoming increasingly important. The set-top box industry should provide a good outlet for GaAs devices, both for the cable and satellite applications. Indeed, satellite communication is one of applications for which GaAs devices were originally developed, and remains a strong market for a number of dedicated companies such as Fujitsu and Anadigics.

There is also a great deal of interest in the Bluetooth standard, which operates at 2.4 GHz. Applications at this frequency should explode onto the market very soon, and while this may not represent big business for GaAs companies, it will have a positive affect on the use of GaAs for wireless local area networks (WLANs). These systems have been around for a number of years, but as yet haven't been widely adopted. In addition, some of the bigger computer companies are beginning to offer personal computers with WLAN technology.

At millimeter wave frequencies, a number of companies are successfully supplying point-to-point links used in the cellular infrastructure industry. These include PHEMT devices, and represent a dynamic growth area for this kind of device. For the local multipoint distribution service (LMDS) or point-to-multi point applications, a window of opportunity exists for GaAs-based wireless technology to deliver data to businesses. But strong competition comes from asynchronous digital subscriber loop technology (ADSL), cable modem, satellite and some other wireless systems. It is likely that companies will offer a mixture of

technologies, enabling them to accommodate a range of data rates requested by their customers.

The automotive industry has also seen the beginnings of radar or intelligent cruise control. The Mercedes Benz S-class model is now being offered with a system that employs 77 GHz radar [see CS (5)1, p. 28] to automatically regulate the distance from the vehicle in front. But this technology still needs a number of years before it will be widely available on non-luxury cars, and currently only translates into low production volumes of MMICs. However, the potential for high volumes of components inherent in the automotive industry holds considerable promise for millimeter wave devices, and will probably emerge around 2002-2003. But for millimeter wave devices, it is difficult to ignore the associated packaging and manufacturing issues. This is an area that needs to be addressed, and one that could lead to opportunities for companies that can innovate.

The GaAs MMIC marketplace is clearly very dynamic, giving rise to some important changes in the industry. And whenever there is rapid change in the structure of a market, there are opportunities for companies to enhance their market share. This will make it a very exciting time for everyone in the GaAs industry.

GaAs MMIC Vendor Merchant Market Share: 1999

Total \$1200 million

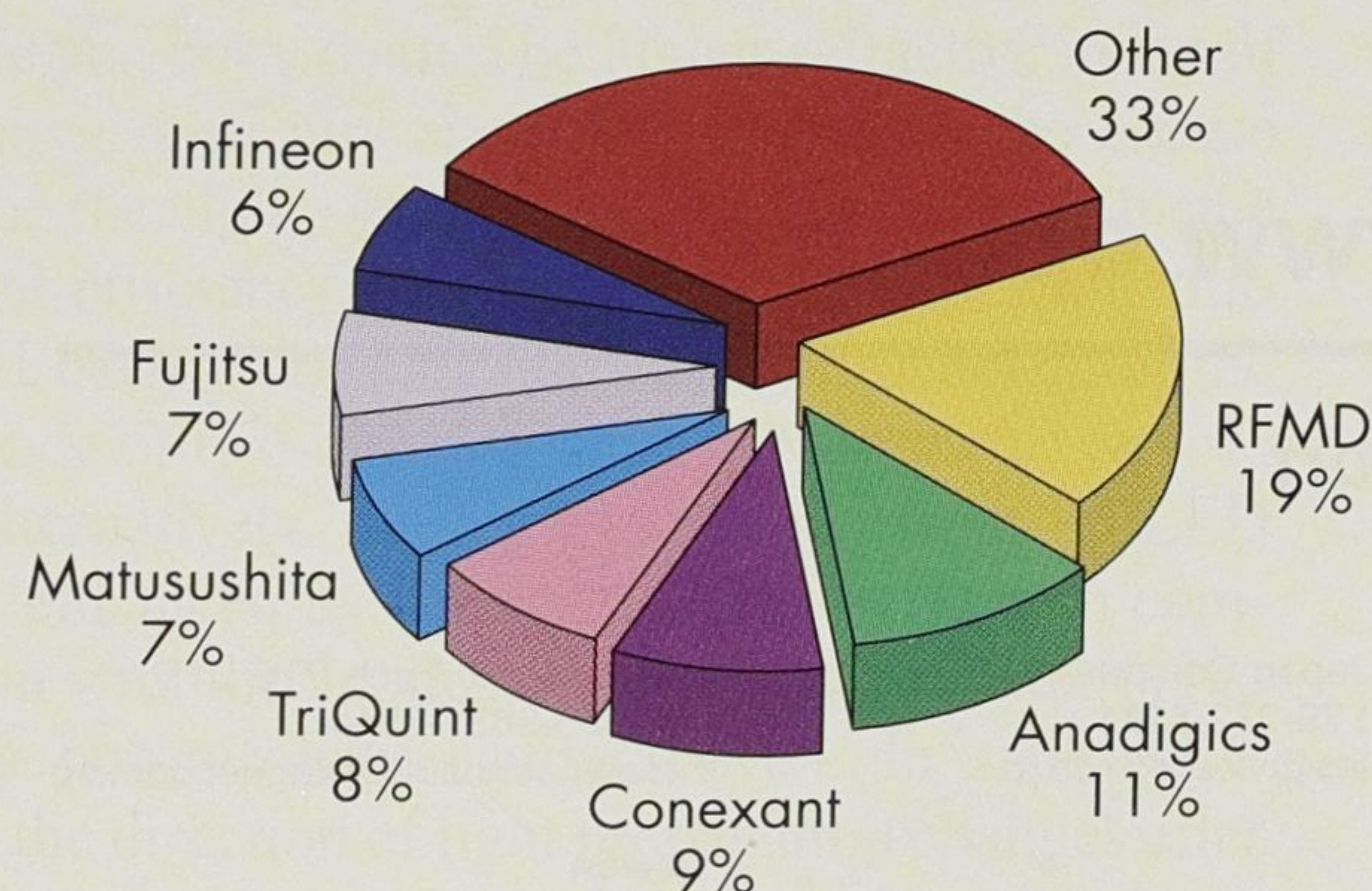


Figure 5. Major suppliers of GaAs ICs in 1999. With captive sales and the discrete market excluded, the total sales of merchant devices amounted to \$1.2 billion.

MOCVD/MBE Markets: 1998-2003

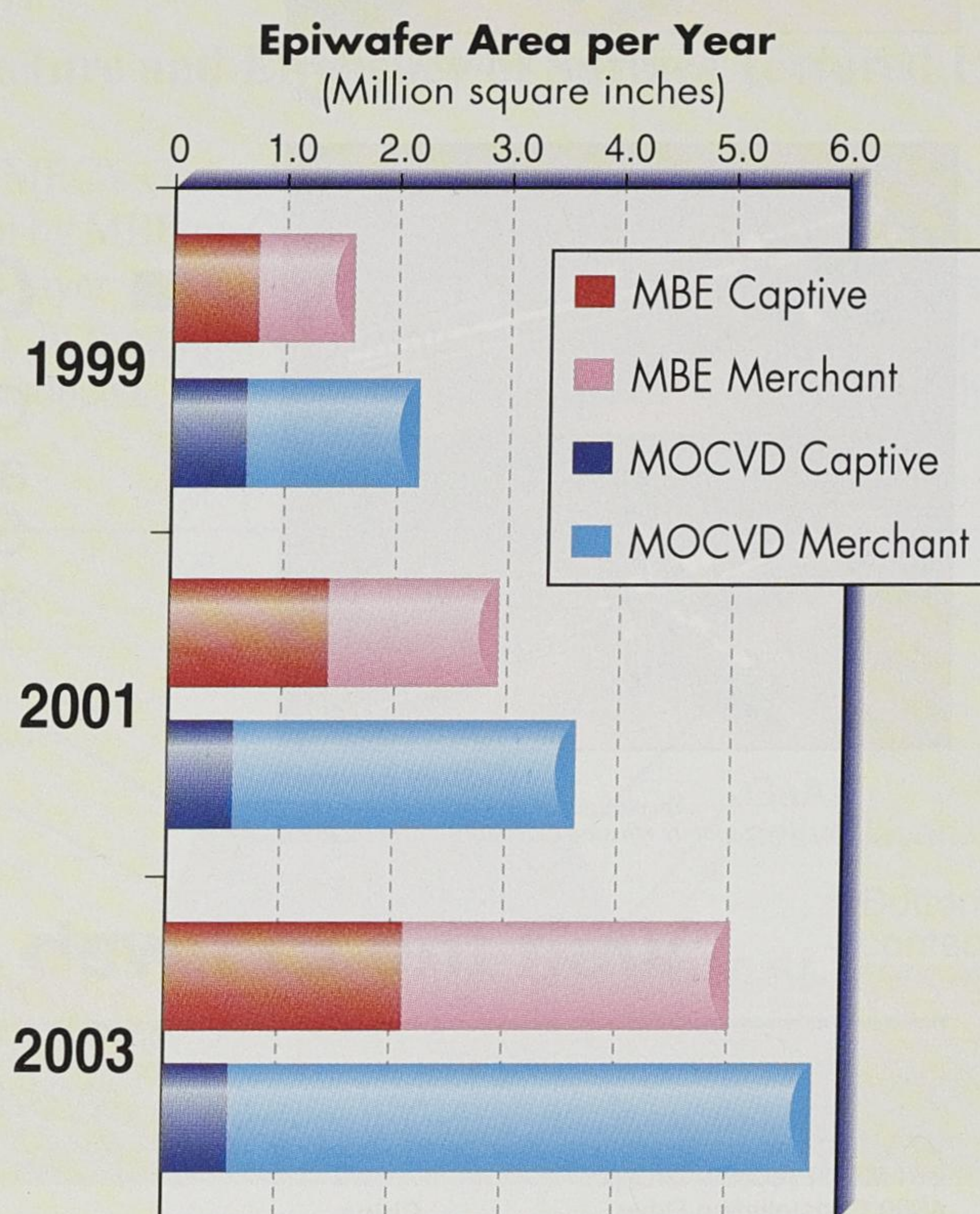


Figure 6. The MOCVD market will expand from over around 2 million inch²/year (13,200 x 4-inch wafers/month) in 1999 to around 5.5 million inch²/year (~36,300 x 4-inch wafers/month) in 2003, mainly for merchant markets. MBE epiwafer supply will grow at a similar rate but will consist of a higher proportion of captive production for devices such as HEMTs.

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High-Efficiency Surface-Textured LEDs

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IMEC, Leuven, Belgium

* Vrije Universiteit Brussel, Brussels, Belgium

† Universität Erlangen-Nürnberg, Erlangen, Germany

LEDs are attracting increasing interest for use as highly-efficient and reliable light sources. The recent development in green and blue InGaN LEDs and efficiency improvements in red AlInGaP devices has led to their increasing use in display and lighting applications as a replacement for conventional incandescent light sources. In addition, LEDs now represent a low-cost alternative to lasers in local/system area network applications, which are commonly used where the systems do not require lasers. However, despite the recent performance gains, for all types of LEDs the problem of how to efficiently extract the light from the device structure still remains.

Getting the Light Out

The large difference between the refractive index of a semiconductor and that of air causes most of the light generated to suffer from total internal reflection, which occurs at the semiconductor-air interface. This limits the external quantum efficiency of conventional LEDs, i.e. devices with a single, flat out-coupling surface, to values of around 2%. The rest of the light is either trapped in an internal wave-guide structure, or absorbed in the substrate.

In most commercial LEDs, this problem is partially solved by packaging, i.e. by encapsulating the LED in an epoxy resin. The higher refractive index of the epoxy (typically about 1.6) increases the escape cone of the light, leading to an improvement in the external efficiency. As this method is only applied to single LEDs, it does not allow an improvement of the efficiency of two-dimensional LED arrays.

Alternatively, the light extraction from an LED can be enhanced by texturing its top surface in combination with the application of a rear reflector [1] to form a non-resonant cavity (NRC). In such NRC LEDs, the direction of light propagation changes after

every internal reflection at the top surface due to scattering at the textured surface. Hence, as the light oscillates between the top surface and the rear reflector, the angle of reflection at the top surface is different for successive reflections (Figure 1).

As soon as the photon hits the surface at an angle smaller than the critical angle for total internal reflection, it has a high chance of being extracted from the semiconductor. In this way, surface scattering in combination with a rear reflector significantly enhances the light extraction efficiency of waveguides formed within the LED structure [2].

Structure and Efficiency of Surface Textured LEDs

IMEC's GaAs/AlGaAs surface-textured or NRC structure is grown by MBE on GaAs substrates. It consists of a 120 nm active GaAs layer embedded in AlGaAs current-confining layers (Figure 1). In the upper confining layer, an AlGaAs current aperture is introduced. As this oxide is formed by selective wet thermal

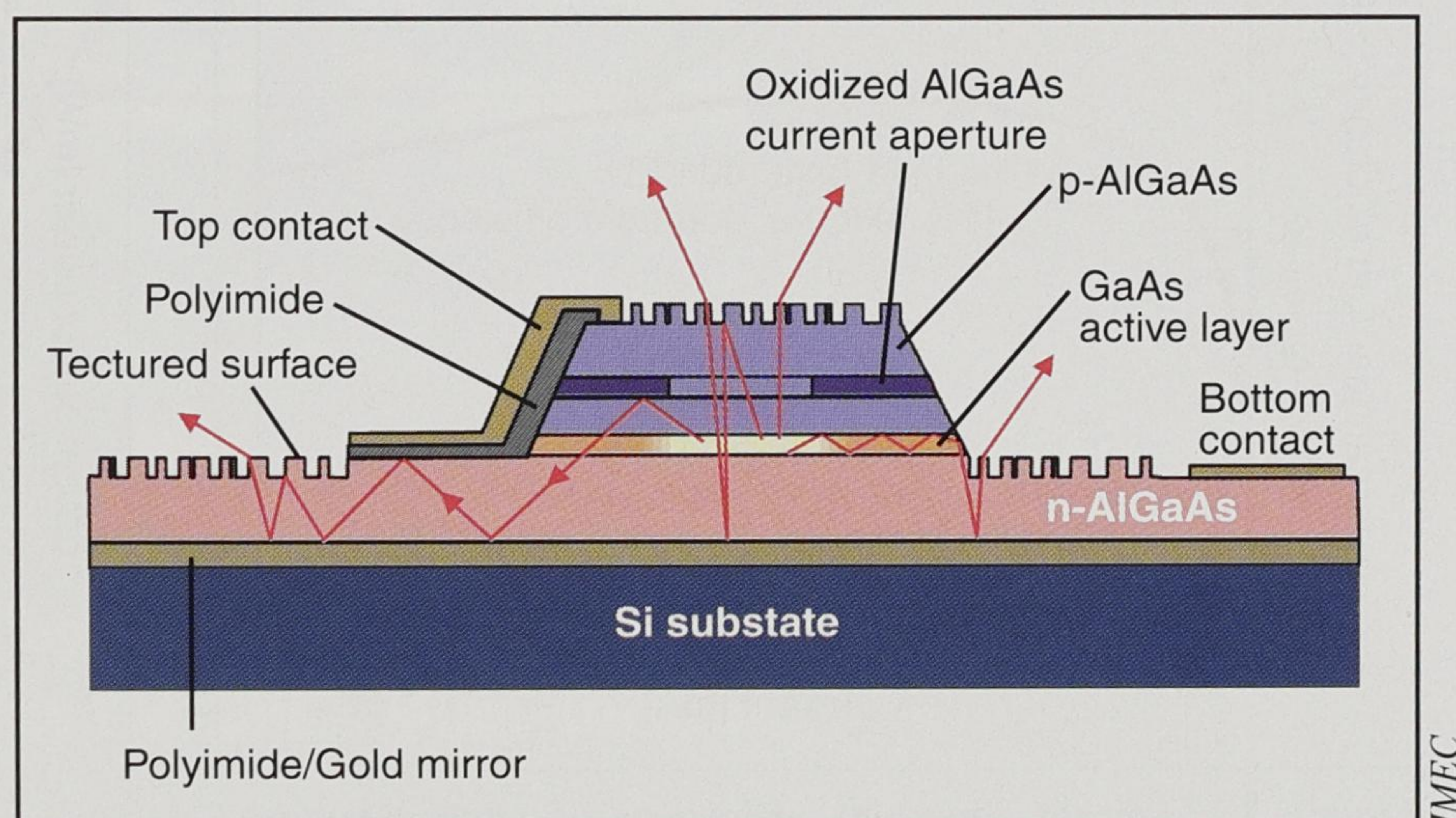


Figure 1. Schematic illustration of the surface-textured, thin-film NRC LED structure. The injection current is confined by the electrically-insulating, oxidized AlGaAs current aperture, thereby avoiding the generation of light underneath the top contact.

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oxidation and is electrically insulating, this avoids light generation occurring beneath the top p -contact.

The surface texturing is performed with a technique called natural lithography. A monolayer of randomly-positioned polystyrene spheres is used as a mask for dry etching. This produces randomly-positioned cylindrical pillars on the surface with an optimum diameter and height of about 300 nm and 180 nm, respectively [3]. The original GaAs substrate is removed by epitaxial lift-off. The LED structure is subsequently Van der Waals bonded to a polyimide/gold mirror (the latter deposited onto a silicon substrate).

Figure 2 compares the external quantum efficiencies of such surface-textured LEDs to those of non-textured devices still attached to the original substrate. We obtain external quantum efficiencies as high as 40% for NRC LEDs—a factor of 20 improvement compared to conventional LEDs [3, 4]. This is the highest external quantum efficiency reported for unencapsulated devices to date.

For LEDs with an oxidized current aperture diameter of 45 μm , the maximum efficiency is reached at currents between 3 and 4 mA, as is shown in Figure 2. As the series resistance of the LEDs is not yet fully optimized, we obtain a wall plug (power conversion) efficiency of 30% at currents of around 1 mA.

The total light output power of the NRC LED is compared to that of a conventional LED in Figure 3. The 40% external quantum efficiency of the surface textured device corresponds to an efficiency of 0.57 mW of light per mA. This value is 20 times higher than that of the conventional LED device structure.

External quantum efficiencies as high as 40% are measured for surface textured LEDs—a factor of 20 improvement compared to conventional devices.

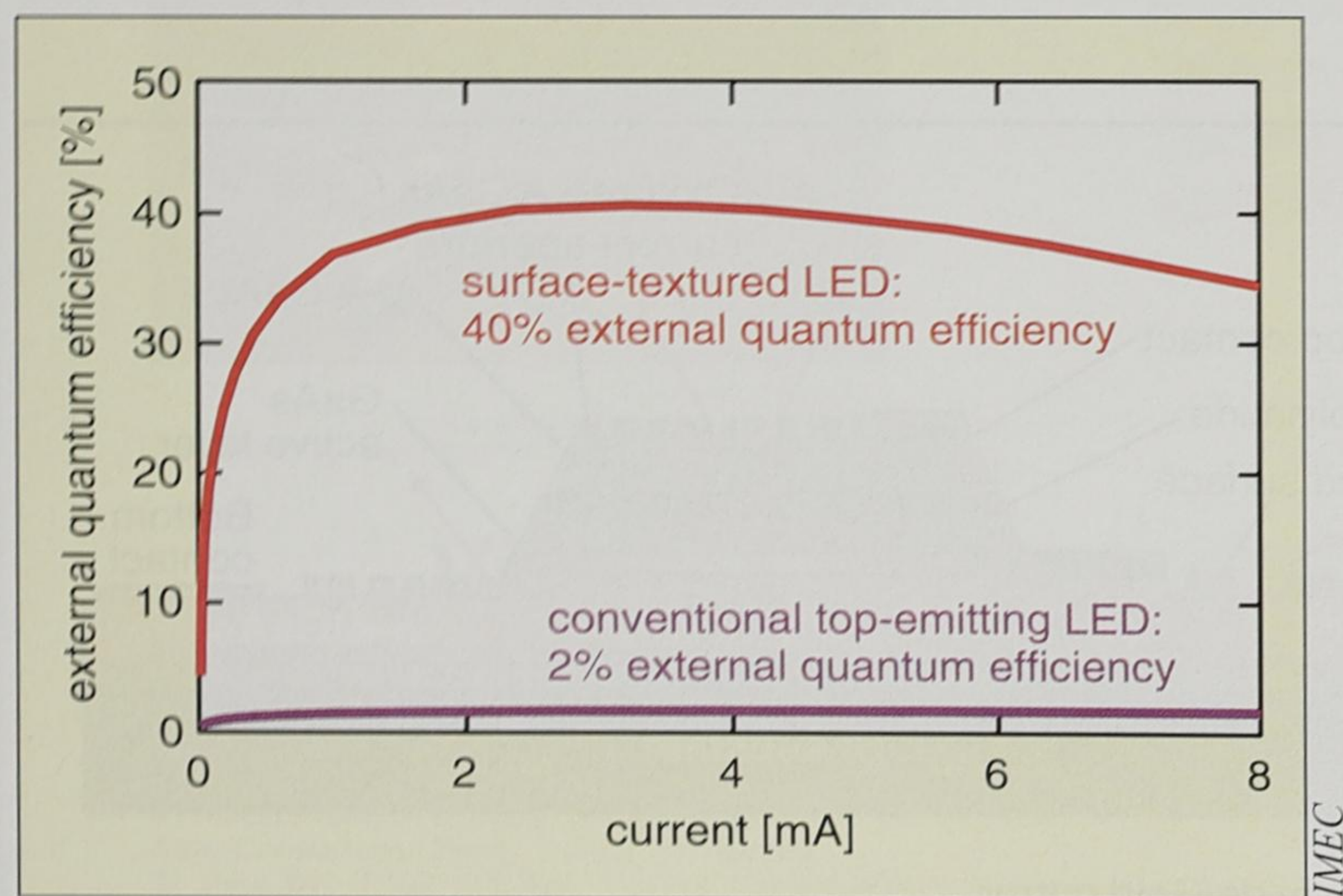


Figure 2. External quantum efficiency of surface-textured device (120 nm GaAs active region) and conventional LEDs versus injection current. The decrease in efficiency at low currents is due to non-radiative recombination, while the decrease in efficiency at high currents is due to carrier spill-over.

LEDs for Optical Communications

As these high efficiencies are obtained from unpackaged devices, the fabrication of planar two-dimensional arrays of highly-efficient LEDs is now feasible. Arrays are required for parallel optical interconnect applications, and these surface textured LEDs represent a low-cost alternative to VCSELs. The high-efficiency at low currents make these devices particularly interesting for short-distance, low-power interconnects, such as board-to-board or chip-to-chip connections for use in future computers. In this case, the small temperature dependence of the diode light output is an especially important advantage compared to VCSELs. However, VCSELs remain important because of the nature of the highly directional light output.

In order, then, to improve the directionality of the light output from the IMEC device, we have successfully integrated a ball lens, made from 100 μm diameter glass spheres, on top of the surface textured LED [5]. An SEM photograph of a micro-lensed diode is shown in Figure 4.

This lens geometry is close to that of an ideal lens for the production of a parallel beam. It enhances the light output in normal direction by a factor of 3.5 compared to the Lambertian light output of a conventional LED. As a result, we have calculated that a factor of two improvement is achieved in the efficiency of coupling to an optical fiber with a numerical aperture of 0.5. The corresponding calculated coupling efficiency is 50%.

However, this lens geometry limits the external efficiency because it does not ensure normal incidence of the light onto the glass-air interface: hence, it does not exclude total internal reflection.

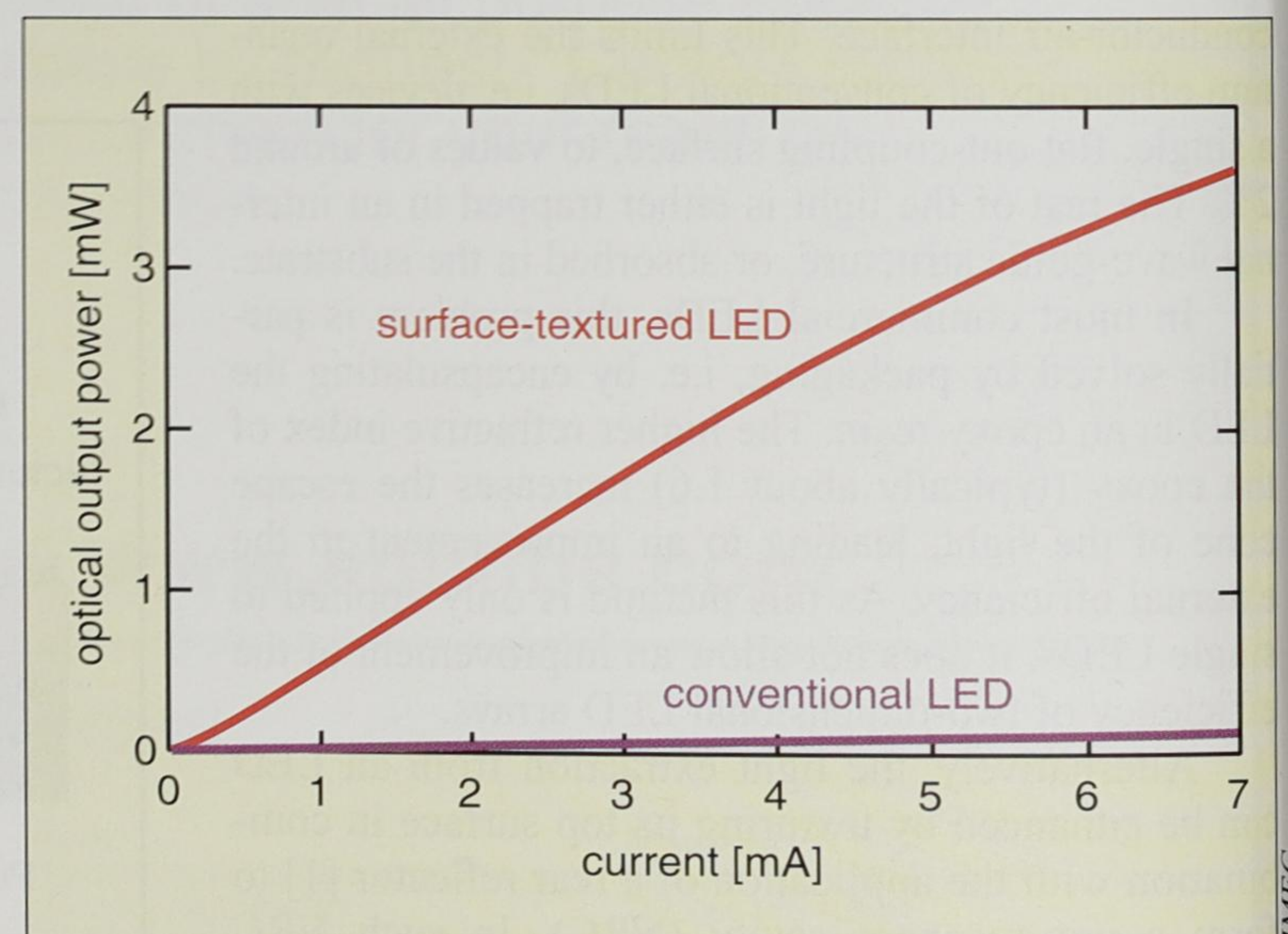


Figure 3. Total light output power of IMEC's surface-textured device and conventional LEDs as a function of injection current. The 40% QE of the modified LED corresponds to an output power of 0.57 mW/mA.

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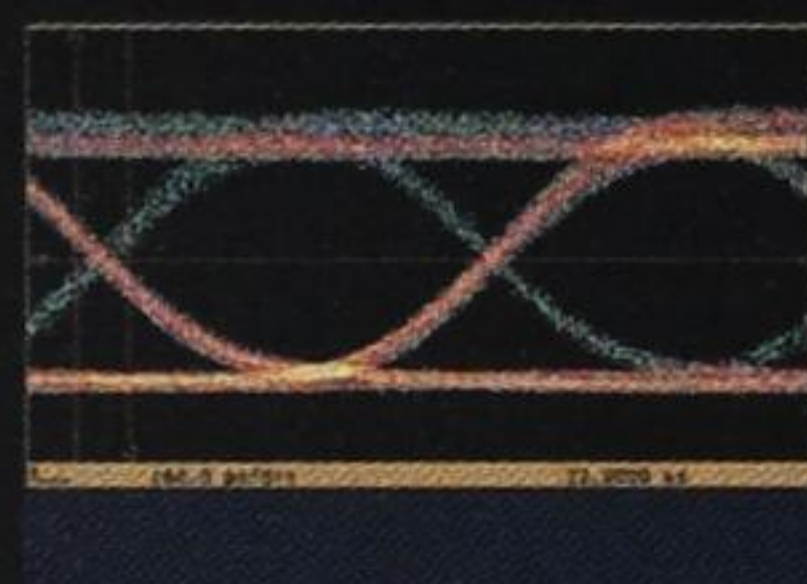


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tions at this interface. Thus, while beam directionality can be improved, the addition of the lens only results in a slight improvement in the external efficiency.

Frequency Response

For optical communications, the frequency response of an LED is an important quantity. This depends on the design parameters and operating conditions. The time constants are similar to the radiative recombination lifetime, which decreases with increasing carrier concentration in the active region layer. Thus, the frequency response can be improved by using thin active layers and high injection-current densities.

We have fabricated NRC LEDs with GaAs active layer thicknesses of 10, 20 and 30 nm, employing the structure shown in Figure 1. The use of the wet thermally-oxidized current aperture reduces the effective device size compared to that of the open aperture. This allows the injection of high current densities at low total values of current, resulting in a fast response and lower power consumption.

Figure 5 shows the external quantum efficiencies and the bit rates obtained using NRC LEDs with thin active layers. The thinner the active layer, the higher the injected-carrier concentration, and the higher the achievable bit rate. However, a high injected-carrier concentration also gives rise to carrier spill-over from the active layer into the current-confining layers, reducing the external quantum efficiency. This explains the reduction of the efficiency for the fastest LEDs.

In addition, high injection currents improve the achievable bit rate. However, the efficiency decrease due to carrier spill-over

at high currents is more pronounced for thin active layers (i.e. those with a 10 nm active layer) than for the 120 nm active layer LED shown in Figure 2. Therefore, surface textured LEDs can be used either at moderate currents with high quantum efficiency and moderate bit rate, or, at higher currents, which results in a lower efficiency and a higher bit rate. This behavior is represented by the curves for each of the three different active layer thicknesses shown in Figure 5.

The achievable bit rate has been defined as the bit rate at which eye diagrams still appear at least half as open as those measured at low frequencies. An example of an open eye diagram measured for a device containing a 20 nm active layer operating at 1 Gbps is given in the inset in Figure 5. At the operating current where this eye diagram is obtained, the LED has a quasi-static external quantum efficiency of 29%.

The high efficiency-bit rate product makes NRC LEDs with thin active layers attractive for the use in highly-parallel short-range optical communication systems. In particular, their small temperature dependence is a big advantage for on-chip integration compared to surface-emitting lasers and microcavity LEDs.

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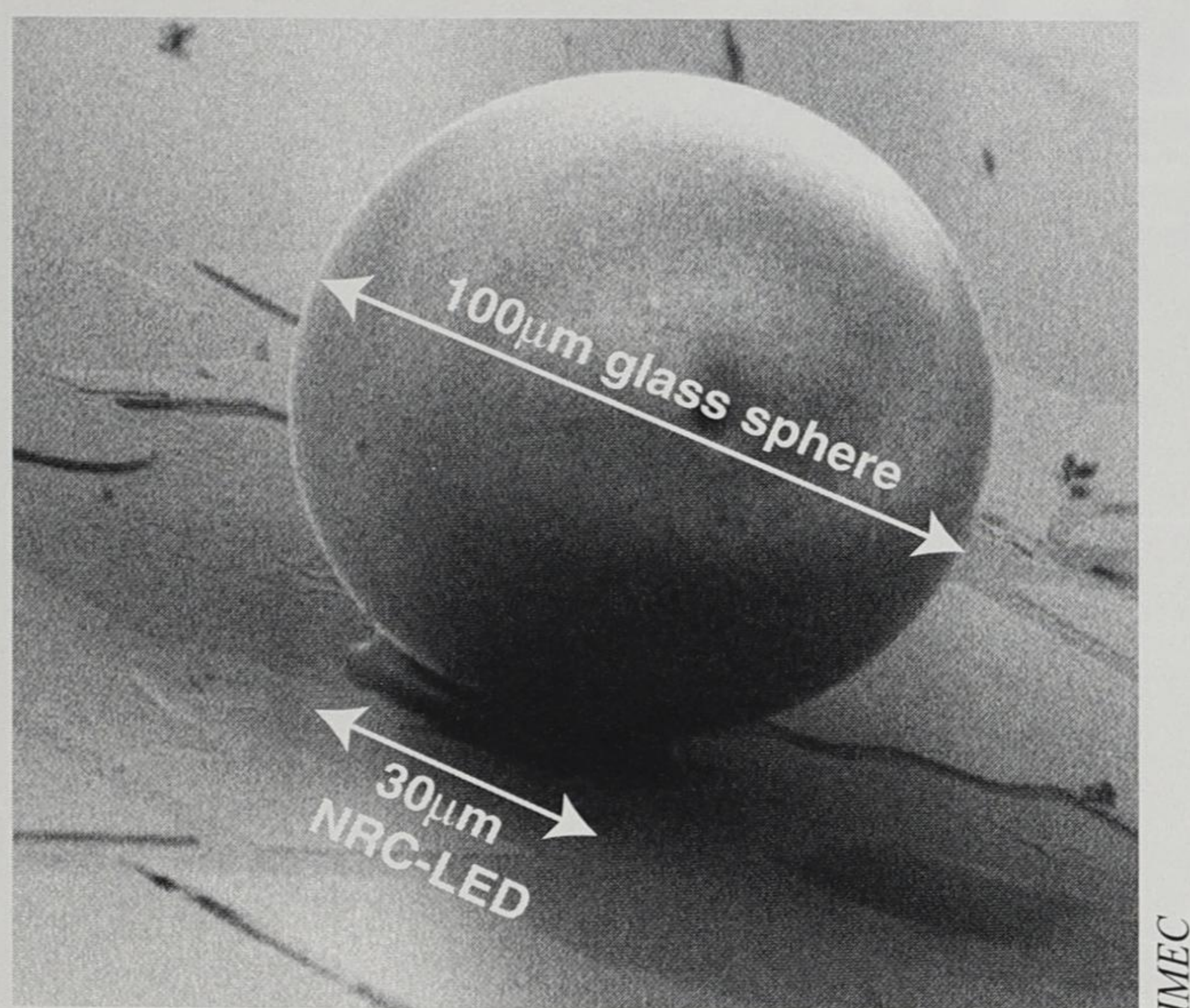


Figure 4. SEM image of a 100 μm diameter glass lens integrated on top of a 30 μm diameter NRC LED. The lens leads to a 3.5-fold enhancement of the light emission in the vertical direction. This arrangement still leads to total internal reflection at the glass-air interface and limits the QE.

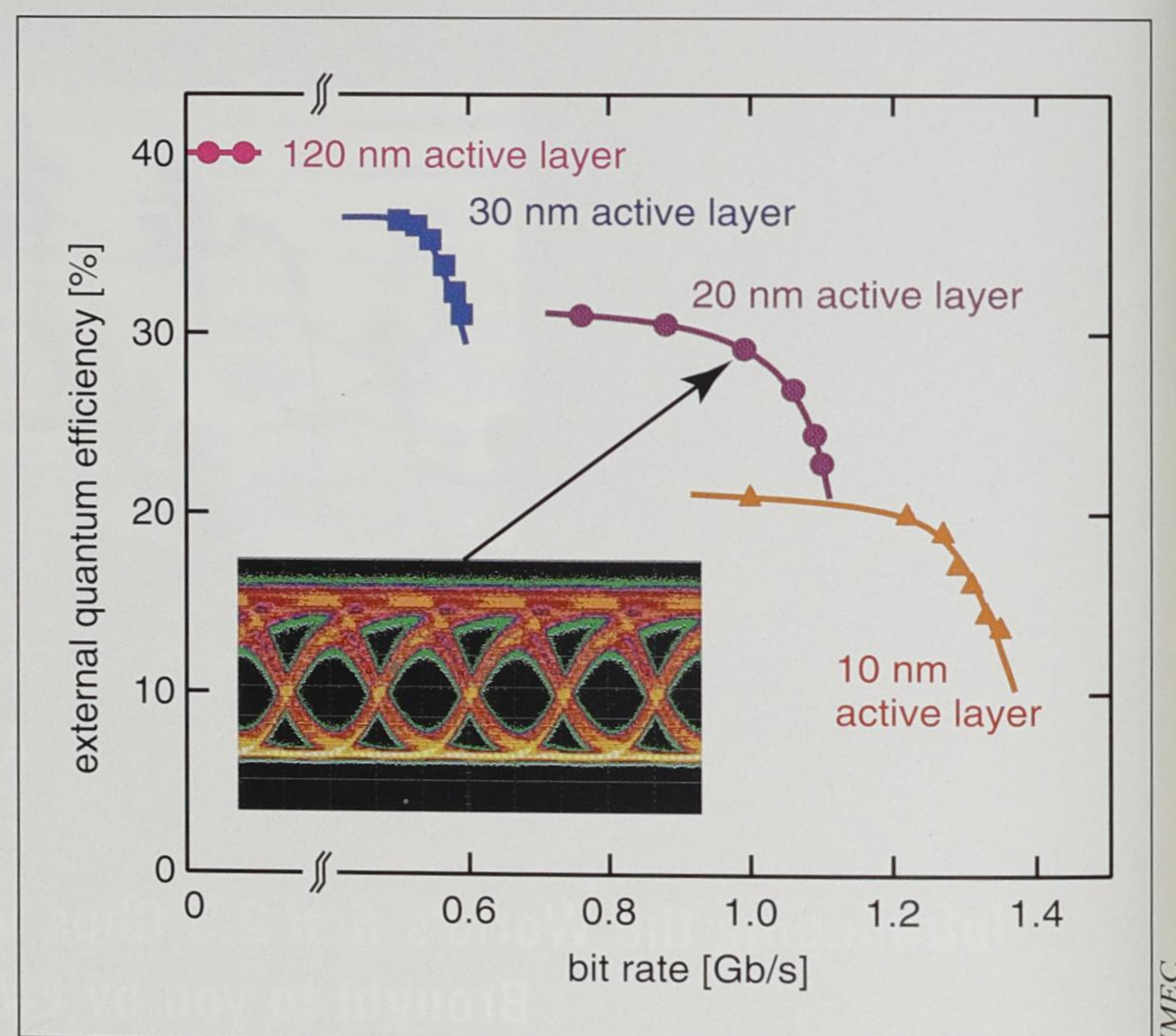


Figure 5. External quantum efficiency and achievable bit rate for various NRC LEDs. The inset shows an eye diagram measured at 1 Gbps with an on-state injection current efficiency of 29%.



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Application of GaAs ICs to Communications

J. AIDEN HIGGINS*

Rockwell Science Center

Presented at the Key Conference on
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GaAs-based integrated circuits lend themselves to a wide range of applications that can be broadly categorized into three market segments: analog ICs, mixed mode ICs, and digital and low power ICs. For many of these applications, in particular analog power amplifiers and mixed mode analog to digital converters, GaAs PHEMTs and HBTs offer distinct advantages over competing Si-based devices. The performance of circuits is tightly coupled to device performance, and, in the case of GaAs devices, and HBTs in particular, significant improvement in RF performance can be achieved through new processing approaches. In turn such improvements translate directly into both enhanced circuit performance and the opportunity for continued growth in existing markets as well as penetration into new markets.

Analog ICs

The analog IC market consists of microwave and millimeter-wave ICs for functions such as power amplifiers, sources and low noise amplifiers. The three GaAs-based technologies—MESFETs, HEMTs and HBTs—compete in this market segment, which currently generates \$1.2 billion in revenues. The predicted compound annual growth rate (CAGR) for this market is around 35%, which should result in a market valued at \$3.9 billion by 2003 [1].

The potential for any device to produce RF power and gain at a given frequency is dictated by material properties such as breakdown electric field, electron saturated velocity and resistance (which is normally determined by the material's mobility). When viewed from this perspective, it appears that for applications up to 20 GHz the best solution for RF power is to use GaAs HBTs, while GaAs PHEMTs are best suited for the 40–77 GHz range.

Rockwell Science Center (RSC) has been involved with GaAs technology for over thirty years, and offers low volume custom designs and initial production runs in GaAs HBT and PHEMT technology. The GaAs HBT process for microwave and mixed signal ICs is transferable to the production facility of Conexant Systems; this company was spun-off from Rockwell in early 1999 and is one of the leading producers of HBT-based ICs for mobile phone handsets and fiber-optic networks. Former employees of Rockwell have also established several other leading companies—Vitesse Semiconductor, Network Device Inc. (NDI—recently bought by Alpha), EiC and Global Communication Semiconductors (GCS).

For applications between these frequency regimes, either HBTs or PHEMTs may be the solution of choice depending on the specific system requirements. For higher frequency applications in excess of 77 GHz, GaAs PHEMTs are currently the best choice, but InP-based HEMTs and HBTs are likely to challenge in these and other areas in the near future [see CS 6(3), p. 28].

The major analog power amplifier market continues to be for handsets operating over the 1–2 GHz range, and a wide range of technologies consisting of both Si- and GaAs-based are battling in this competitive arena. However, there exists a higher frequency market ideally suited to GaAs—point to multipoint radio systems (also known as local multipoint distribution systems, or LMDS), a “last mile connection” application which requires devices with high bandwidth performance. An example of this need

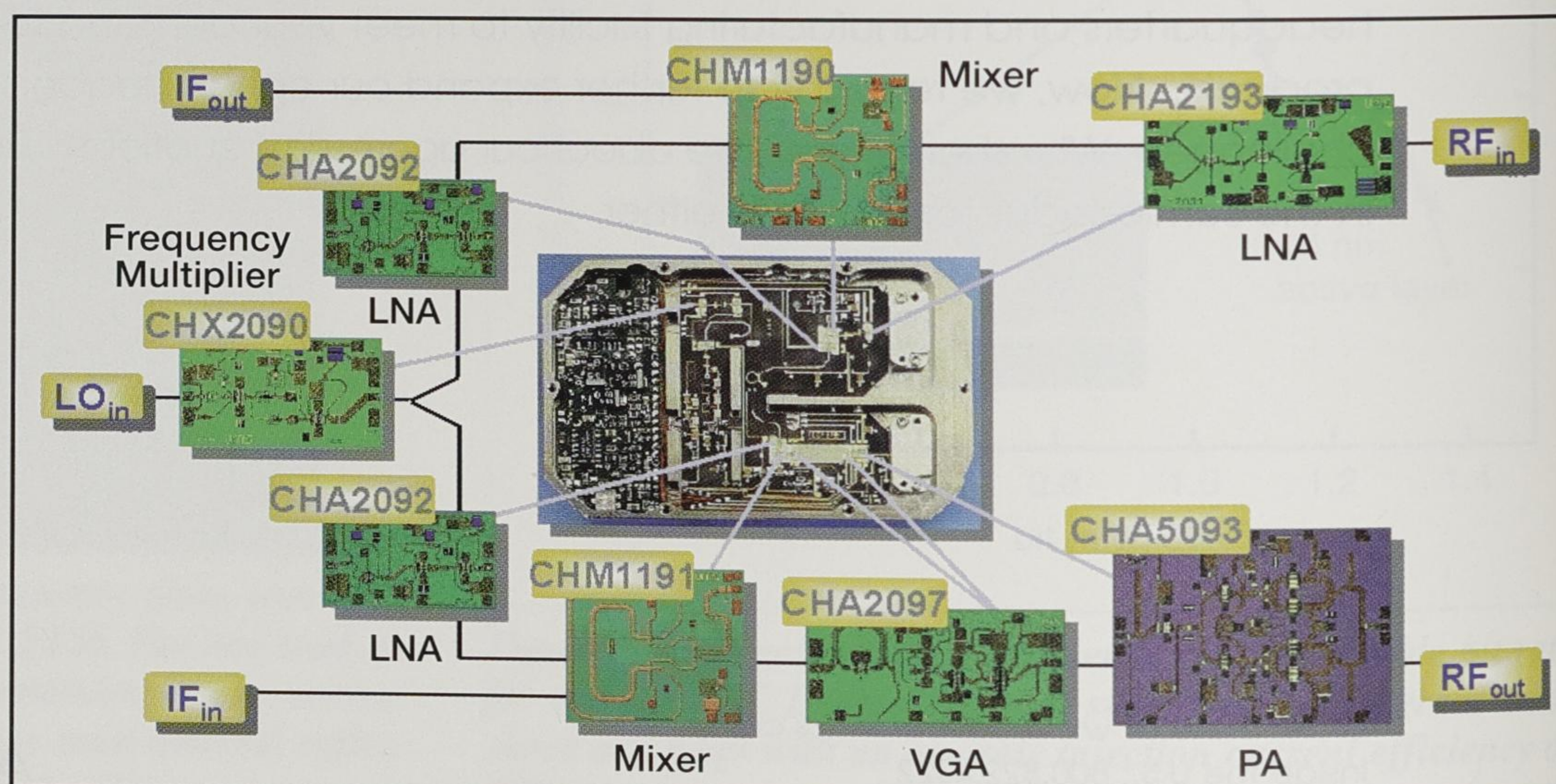


Figure 1. MMIC chipset fabricated by United Monolithic Semiconductors (UMS) for 24–26 GHz millimeter-wave transceiver modules used in point-to-multipoint radios.

*Co-authors: Dominique Pons, United Monolithic Semiconductors (UMS), and Ken Weller, Conexant Systems

is reflected in the fact that 97% of the commercial buildings in the US with over 100,000 square feet of floor space are currently not being served by internal fiber systems[1]. For these environments, broadband data delivery by millimeter wave radio is an ideal solution. LMDS can provide data for these environments at 155 Mb/s per 50 MHz channels. The current market for such point-to-multipoint systems is below \$300 million, but is expected to grow to \$3 billion by 2004 [2].

GaAs PHEMTs are well suited for LMDS applications, and are becoming commercially available from several vendors including United Monolithic Semiconductors (UMS), TriQuint, Alpha and M/A-COM. UMS currently offers a complete transceiver chip set for K/Ka Band systems as shown in Figure 1. This Ka-band transceiver, based on GaAs PHEMTs, contains MMICs that use auto-biasing for the gate electrodes and therefore require only a single bias supply. RSC has developed PHEMT-based custom ICs for LMDS and other millimeter-wave applications. One example is a MMIC based on a double heterojunction PHEMT with 0.18 μm gate length, which provides 1 Watt of output power at 40 GHz.

Another potential future GaAs market is in communications systems requiring high power levels, at frequencies between 20 and 60 GHz, currently being served by travelling-wave-tube (TWT) solutions. These high power applications are satellite communication systems, terrestrial communication systems and radar. An example of the first type is the power amplifier for the transmitter of the MILSTAR uplink that requires over 15 Watts of power at 44 GHz. A commercial terrestrial version would be a 38–42 GHz “hub amplifier” for point-to-multipoint systems for which the saturated output power must be 20 Watts with ultra-linear amplification available at the 5 Watt level. GaAs PHEMTs using quasi-optical (a.k.a. “spatial”) power combining techniques will soon be an attractive alternative, providing higher reliability and smaller size solutions. Figure 2

shows an example of a Ka-band high power amplifier that consists of 112 two-stage PHEMT 70 mW amplifiers that amplifies a power beam that passes “through” the amplifier chip. The normally incident beam is received through slot antennas that feed the signal to the amplifiers. The amplified signals are then fed to orthogonal transmit slot antennas. Two versions of this amplifier have been demonstrated; the microstrip based driver amplifier, shown in the figure, and the grid amplifier for higher power. The latter type, with a greater density of amplifier cells, has demonstrated peak power of 7 W at 38 GHz and 17% PAE, making this a strong competitor for TWT replacement.

While PHEMTs deliver impressive high frequency power results, the RF performance of HBTs is continually being improved. Conexant is shipping GaAs HBT-based power amplifier ICs for mobile phone handsets at a rate of 4–5 million units per month. The technology is constantly in transition—AlGaAs emitter designs are being replaced by InGaP emitters for improved temperature stability and reliability. Packaging systems are

also being improved through the introduction of $6 \times 6 \text{ mm}^2$ MCMs and $4 \times 4 \text{ mm}^2$ leadless plastic MMIC packaging. Conexant also recently announced programmable PA products in which the output power is set by CMOS control logic, providing improved efficiency over the full dynamic range [see CS 6(2), p. 77].

HBTs are particularly well suited where phase noise is a critical parameter. Figure 3 shows a low phase noise GaAs HBT cascode power amplifier that provides 5 W output power at 4 GHz, with 33% PAE. The cascode design provides improved thermal stability, ruggedness and reliability. Power amplifiers using cascode and common emitter configuration for 2 GHz through 12 GHz are capable of providing excellent phase and amplitude noise double-sideband levels exhibiting a phase noise better than -145 dBc/Hz at 1–11 kHz from the carrier frequency. SiGe HBT technology can also deliver excellent phase noise characteristics, and is often viewed as a contender for these applications. However, SiGe’s overall RF performance and breakdown limitations will probably limit it to applications below the 6 GHz regime, with

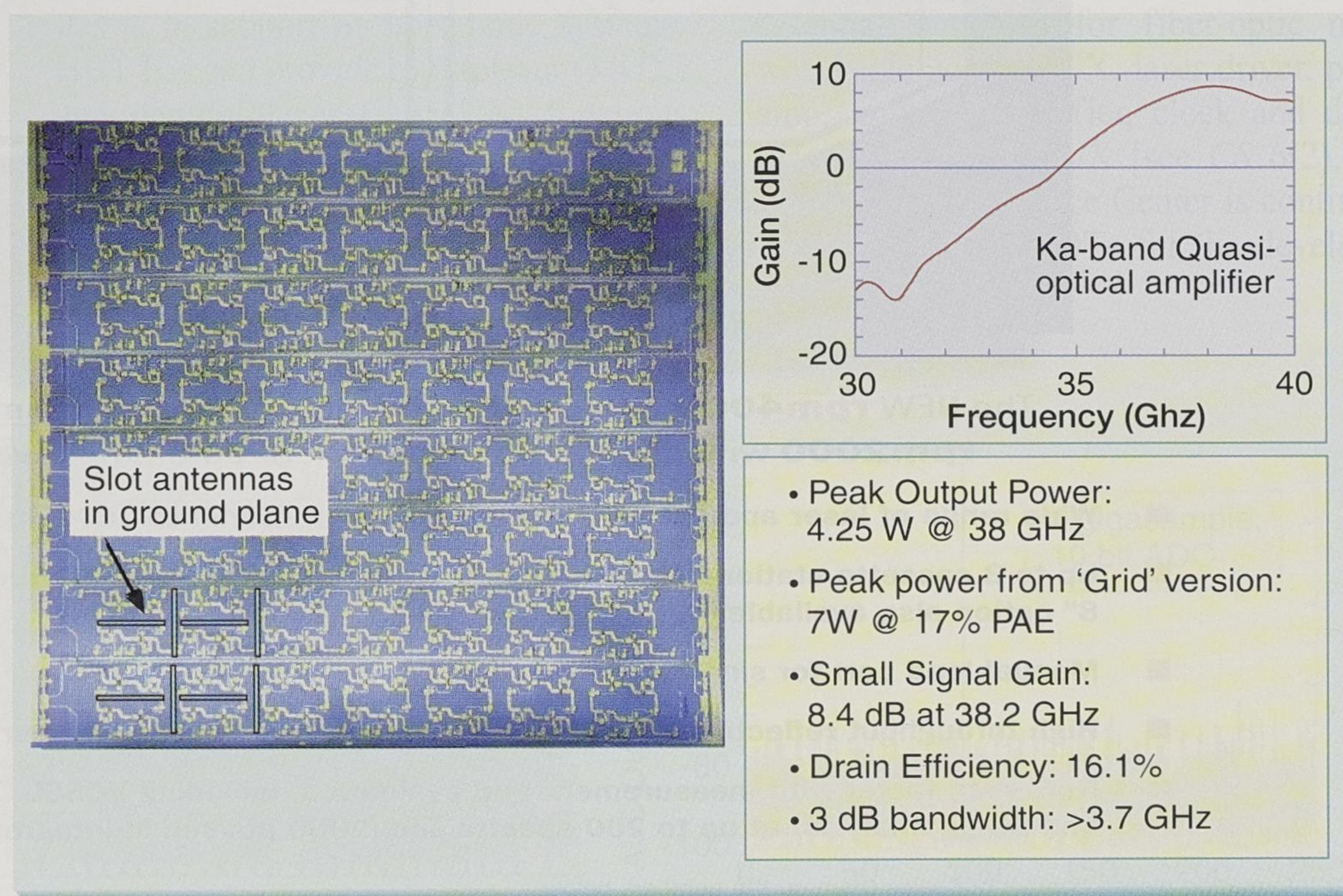


Figure 2. A Ka-band quasi-optical amplifier, designed as a replacement for a travelling wave tube (TWT) amplifier, that delivers 4.25 W at 38 GHz. The chip has 112 two-stage amplifiers, each coupled to a slot antenna on the back side. The signal enters the back of the array, is amplified and sent to the octagonal slot in the ground plane (visible in the photograph) from where it is re-radiated normal to the front surface.

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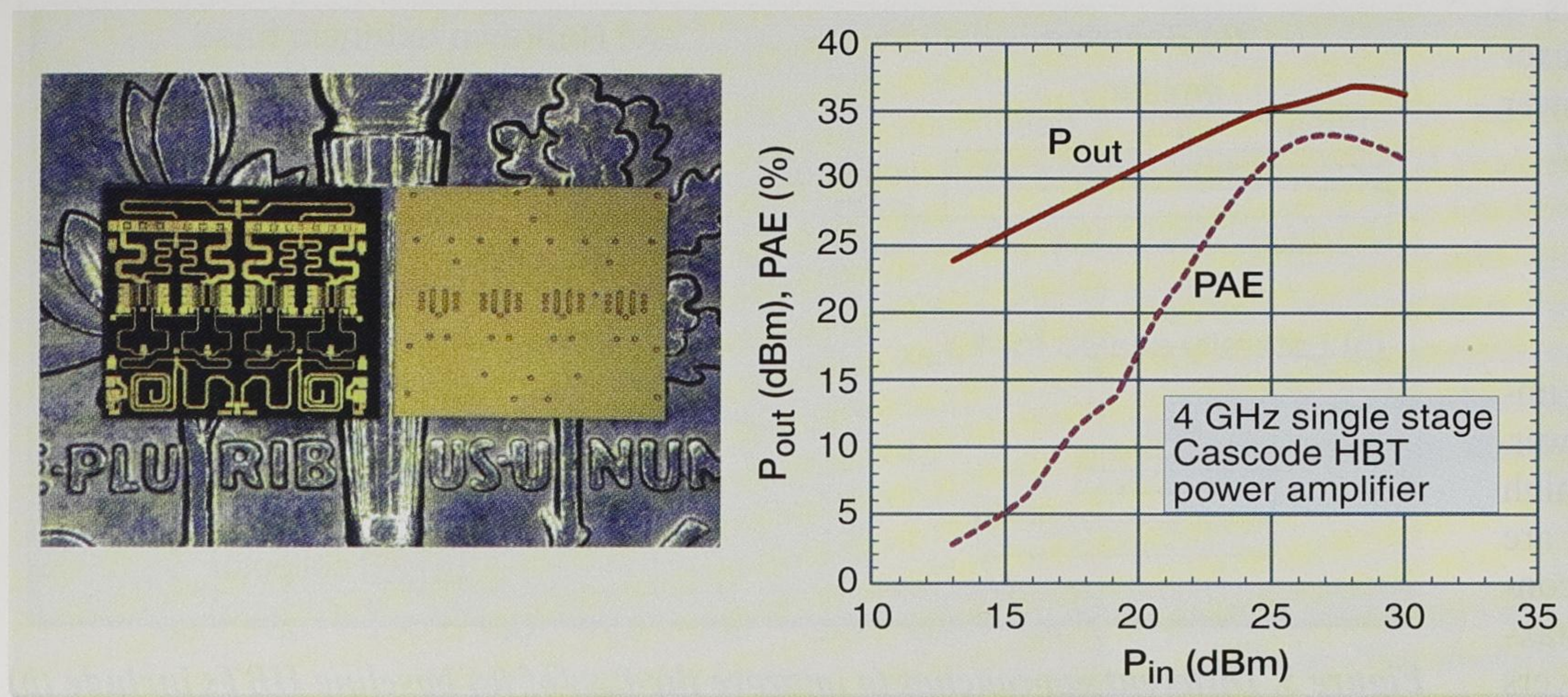


Figure 3. A 4–8 GHz cascode HBT power amplifier with an output power of 5 watts at 33% PAE. This technology can provide amplifiers and sources up to 44 GHz with low amplitude (or phase) noise sideband power.

higher frequencies best served by GaAs HBTs. The GaAs HBT technology is capable of operating up to 44 GHz—a $210 \mu\text{m}^2$ (emitter area) device has delivered greater than 250 mW of power at 6 dB gain and 20 % power added efficiency in the research laboratory [3].

Mixed Mode Integrated Circuits

GaAs HBTs are particularly well suited to this market segment, which includes such applications as analog to digital converters (ADCs), digital to analog converters (DACs) and direct digital synthesis (DDS). These applications typically require a high transistor count, coupled with transistors that exhibit high breakdown voltages (at least 5 V), large current densities, and low $1/f$ noise in order to minimize jitter. Furthermore, the higher the speed (as characterized by f_T), the greater the available number of bits (resolution) for a given sampling speed.

Figure 4 shows a 10 bit, 1 giga-sample ADC comprised of 9000 devices, implemented in Conexant's HBT process. DDS circuits with 10,000 transistors have also been implemented in the same mature GaAs HBT process with a yield of 70–80%. These devices

were designed specifically for Rockwell Collins and have been used by that company in secure communications systems that employ wideband frequency and phase modulation.

Digital and Low Power ICs

The primary application for digital ICs is in support of fiber optic systems. HBT ICs can provide multiplexer (MUX) and demultiplexer (DEMUX) functions and clock recovery circuits [4]. This market is currently valued at around \$400 million and is expected to grow at a

CAGR of 35%, reaching a total market of \$1.3 billion by 2003.

At the moment, these fiber optic systems mainly operate according to the OC-12 (622 Mb/s) and OC-48 (2.5 Gb/s) standards. The circuitry used to implement these systems is fabricated using a wide range of technologies, including GaAs MESFET and HBT, SiGe HBT, silicon BJT and CMOS. As systems migrate upward to the OC-192 (10 Gb/s) standard, a battleground is being established that will determine if the best approach is that of GaAs MESFET, SiGe HBT or GaAs HBTs. Next generation systems operating at the OC-768 (40 Gb/s) standard require extremely high speed (f_T) devices, which at the moment can only be

implemented by indium phosphide HEMTs or HBTs exhibiting f_T values in the 150 GHz regime. However, as the speed performance of GaAs HBTs continues to improve, these devices should, in the near future, also be able to satisfy OC-768 system requirements.

Conexant Systems has already released a large number of 2.5 Gb/s and 10 Gb/s GaAs HBT-based ICs covering all essential functions for fiber-optic networks, including MUX, laser driver, pre-amp, limiting amplifier, clock and data recovery and DEMUX [see CS 6(2), p. 72]. Rockwell Science Center is continuing to use GaAs HBTs for the develop-

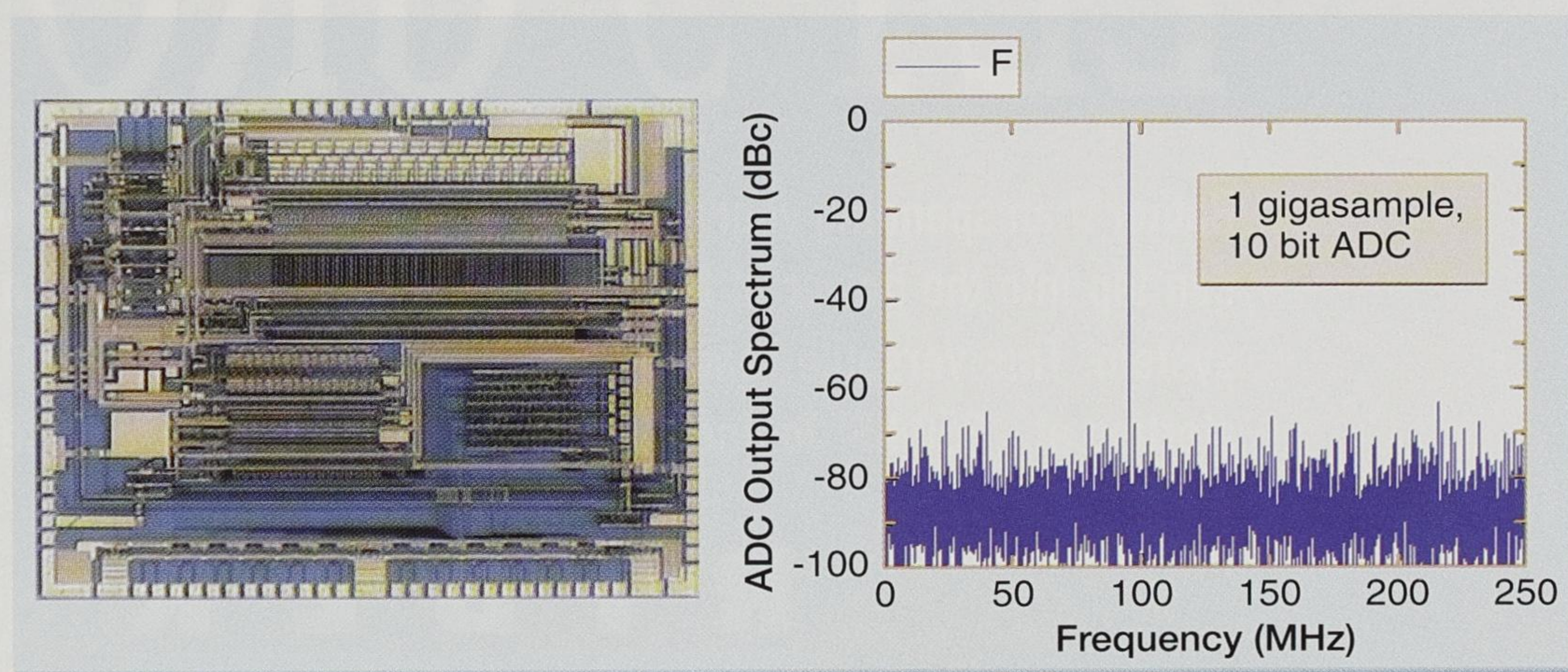


Figure 4. A 10 bit, one giga-sample analog-to-digital converter (ADC) designed at Rockwell Science Center and implemented in Conexant's GaAs HBT process. The IC contains 5,500 transistors and 9,000 devices in total, and dissipates 7 W of power.

ment of next generation high-speed ICs—one example is a 30 Gb/s 1:4 demultiplexer IC operating from a single -7.7 V power supply with a power dissipation of 2.5 W.

GaAs HBT Enhancements

All applications would benefit from improved efficiency and less dissipated power. High performance too often means high power consumption. Several approaches are being implemented to reduce the power consumption of HBT devices. Enhanced epitaxial designs incorporating thinner base layers and emitter epilayers with lowered doping levels have resulted in higher f_T values, while lateral scaling results in moderate improvements in f_{max} (see Figure 5). Straight-forward scaling down of the emitter can significantly reduce power requirements.

GaAs HBTs with $2 \times 2 \mu\text{m}^2$ emitters and an f_T of 40 GHz were scaled down to produce $0.8 \times 1 \mu\text{m}^2$ emitter devices with the same f_T value. The required current for constant f_T was reduced from 0.9 mA to 0.6 mA. The replacement of the AlGaAs emitter in the GaAs HBT with an InGaP emitter provides a more constant DC current gain, β , as the device temperature varies.

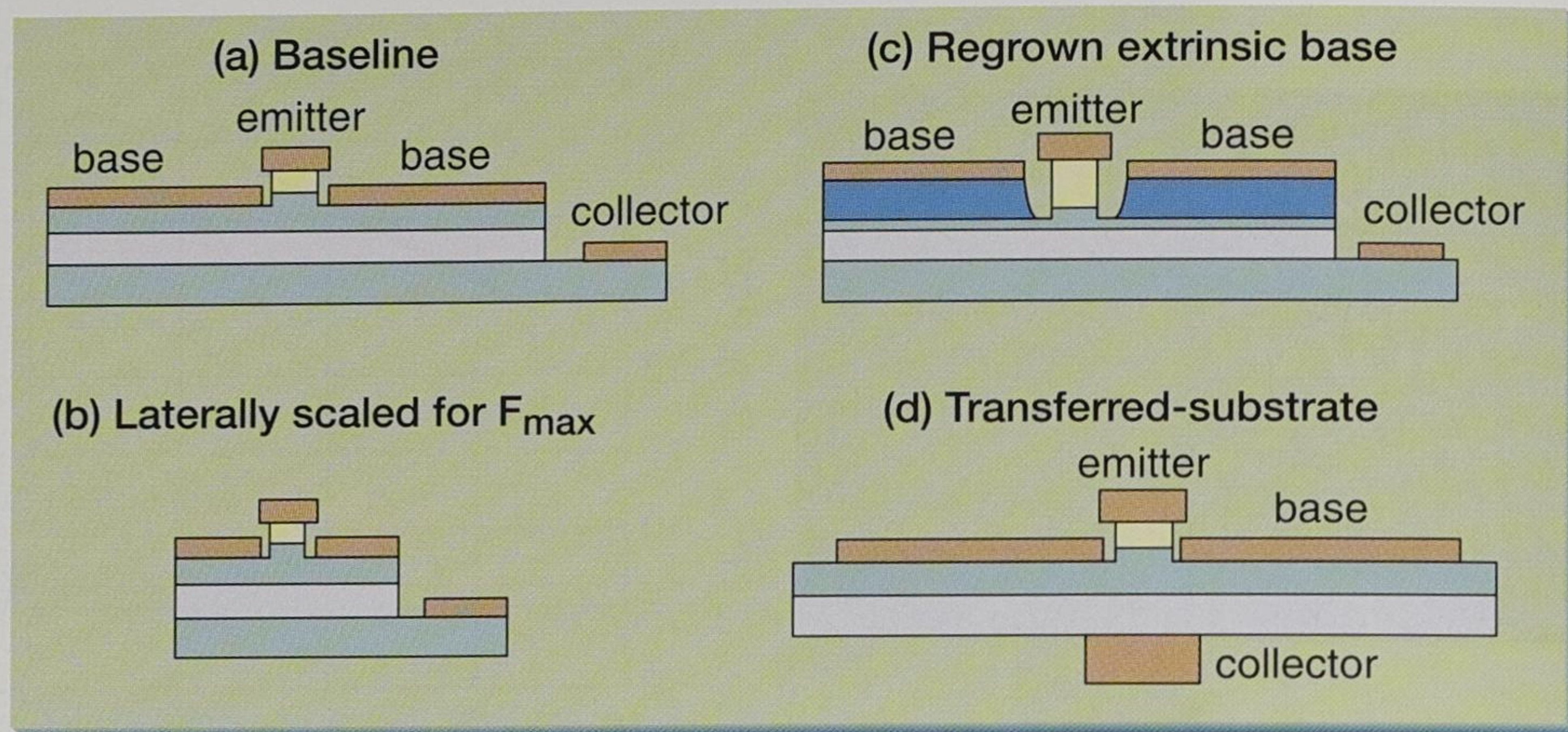


Figure 5. Different approaches to improve the f_{max} of (a) baseline HBTs include (b) lateral scaling, (c) regrowth of the extrinsic base, and (d) the transferred-substrate technique developed by UCSB. This latter approach has resulted in f_{max} values of 1000 GHz and f_T values of 200 GHz. (Figure courtesy of Rodwell, UCSB)

A more radical approach to improved GaAs HBT performance involves processing techniques intended to greatly reduce the parasitic capacitance of the device—in particular the base-collector parasitic capacitance. The University of California at Santa Barbara [5] has demonstrated a two-sided processing technique in which an InP/InGaAs/InAlAs HBT is removed from the original InP substrate and transferred to a second substrate. This

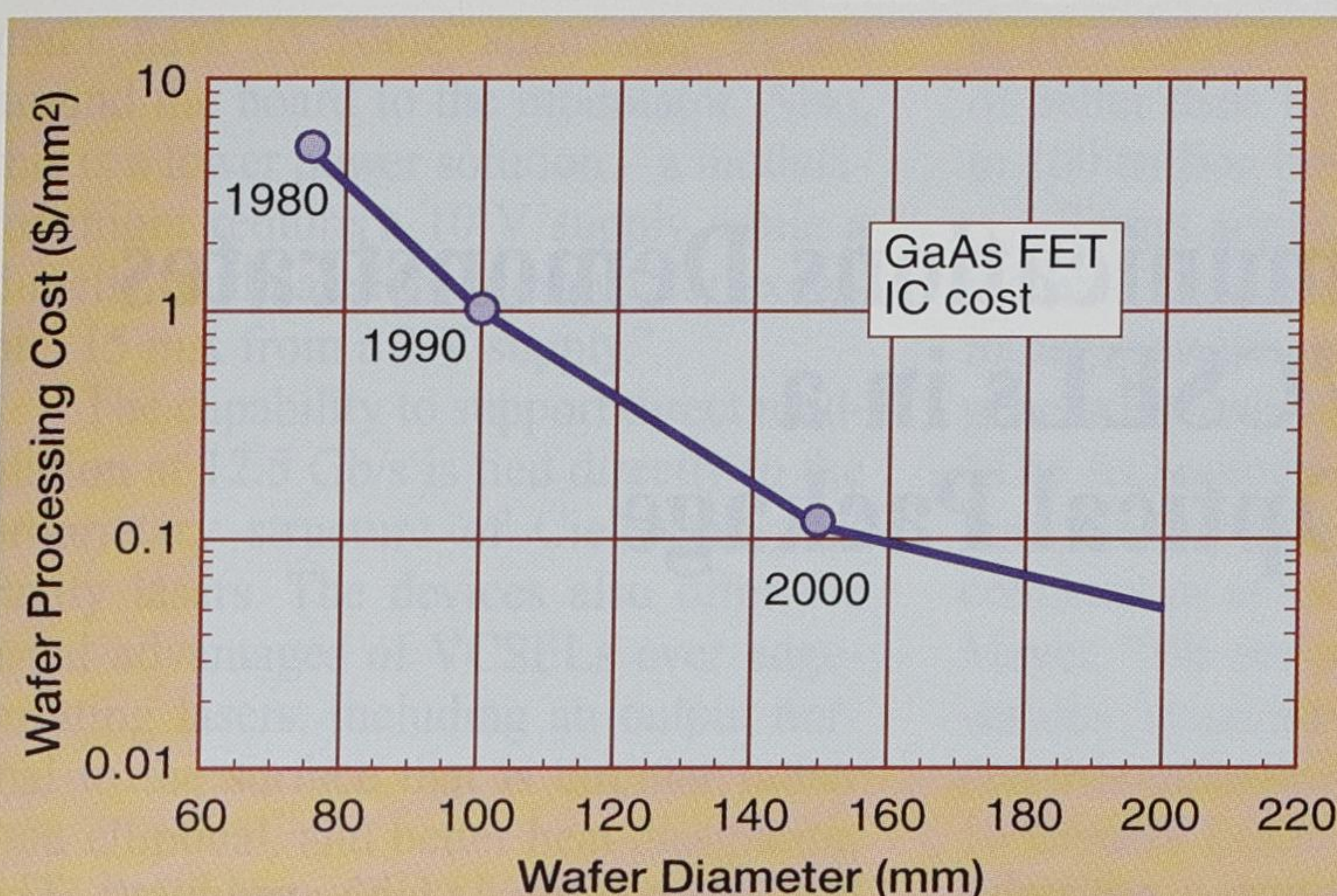
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	GaAs HBT		SiGe BiCMOS	
Feature size (μm^2)	2		<0.5	
Wafer cost (\$)	600		200	
No. mask levels	14		32	
Photolithography cost (\$)	1400		3200	
Wafer & Fab. Cost/wafer (\$)	2000		3400	
Wafer diameter (mm)	150		200	
Yield (%)	70	100	95	100
Die cost (\$/mm ²)	0.16	0.11	0.11	0.1

Figure 6. Comparison of wafer processing costs for GaAs HBT and SiGe BiCMOS parts. The cost advantage of silicon is not significant except for very large numbers of devices.

allows additional processing, which greatly reduces the base-collector junction capacitance (see Figure 5d). This technique has been utilized to produce InP HBTs with $f_{\text{max}} > 1000$ GHz and $f_T > 200$ GHz. Using such high performance devices, implemented in GaAs HBT technology, in any of the applications discussed will radically improve circuit performance and make it possible to create new applications.

Cost Issues

While performance improvements are of critical importance to further the penetration of GaAs-based devices into the marketplace, it is equally important that these devices remain cost competitive with other potential solutions. It is often perceived that GaAs-based devices are intrinsically more expensive than Si-based devices due to the fact that while a 6-inch GaAs substrate typically costs \$600, an 8-inch Si substrate costs only \$200. However, there are many more costs associated with producing a high performance device than simply substrate costs. This is illustrated in Figure 6, which compares a GaAs HBT process to a SiGe BiCMOS process. The major driver for processing costs are the number of mask layers which must be executed [6]. An HBT process requires, typically, only 14 mask levels of one micron minimum geometry, while the more sophisticated processing needed to combine Si CMOS with SiGe HBTs requires 32 mask

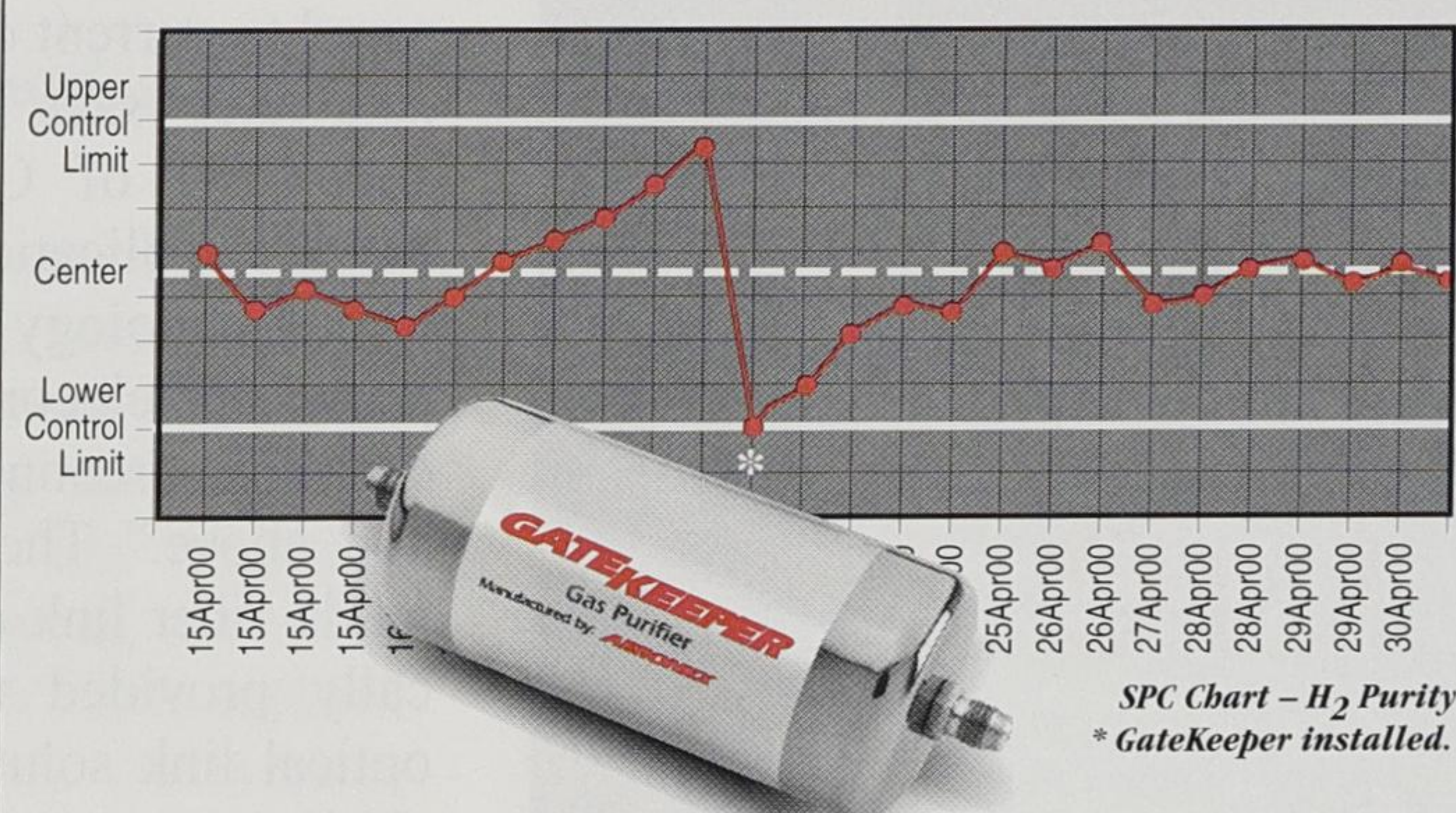
layers, several of sub quarter micron resolution. Although more die can be obtained from an 8-inch silicon wafer than from a 6-inch GaAs wafer, and the GaAs wafer is more expensive, the reduced mask and processing costs for GaAs result in comparable costs per die for GaAs or SiGe BiCMOS parts.

This illustrates quite clearly that superior GaAs-based device performance can be obtained at near Si-based device costs. This powerful combination of improvement in performance and reduction in costs will result in an ever-expanding number of applications for GaAs-based communication devices.

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Cielo Communications Demonstrates 12.5 Gb/s VCSELs in a Low Cost Optical Package

TIM WHITAKER

Cielo Communications, a privately-held manufacturer of gigabit-per-second components for optical communications, recently demonstrated an 850 nm VCSEL operating at 12.5 Gb/s along a 300 meter span of Lucent LazrSPEED™ multi-mode fiber. The laser supports direct modulation and was packaged in a low-cost optical subassembly (OSA) designed to couple light efficiently into the new fiber. In combination, these innovations offer the promise of simplified system design and lower optical interconnect costs for applications requiring bandwidths in excess of 10 Gb/s.

"A 12.5 Gb/s shortwave VCSEL represents a significant cost reduction compared to current device technology at this data rate," says Mike Cowley, president and CEO of Cielo Communications. "Target applications for this next-generation technology include optical backplanes in telecom equipment as well as optical interconnect standards at 10 Gb/s and above." The 850nm VCSEL/multi-mode fiber link combination has historically provided the most cost-effective optical link solution for high bandwidth applications, and this demonstration extends the low-cost serial link to applications at 10 Gb/s and above.

"The combination of a VCSEL operating at 12.5 Gb/s in a low cost package has been a challenge for the industry," says Bob Mayer, Cielo's VP of Marketing. "Other demonstrations of high speed VCSELs have used fairly elaborate laboratory test set-ups." Packaging generally introduces parasitics – more capacitance and more inductance – that slow down the available data rate. Cielo has developed an optical subassembly that is very simi-

lar to existing 1 Gb/s products. The VCSEL is placed onto a high-speed header and aligned through a ball lens into the fiber (see Figure 1).

Devices Designed for Direct Modulation

An important feature of Cielo's VCSELs is that they support direct modulation at up to 12.5 Gb/s. An external optical modulator is traditionally required to achieve such high data rates in optical transmission systems. "Direct modulation simplifies the optical interface design and reduces cost and complexity," says Bob Mayer. "By driving the laser directly you

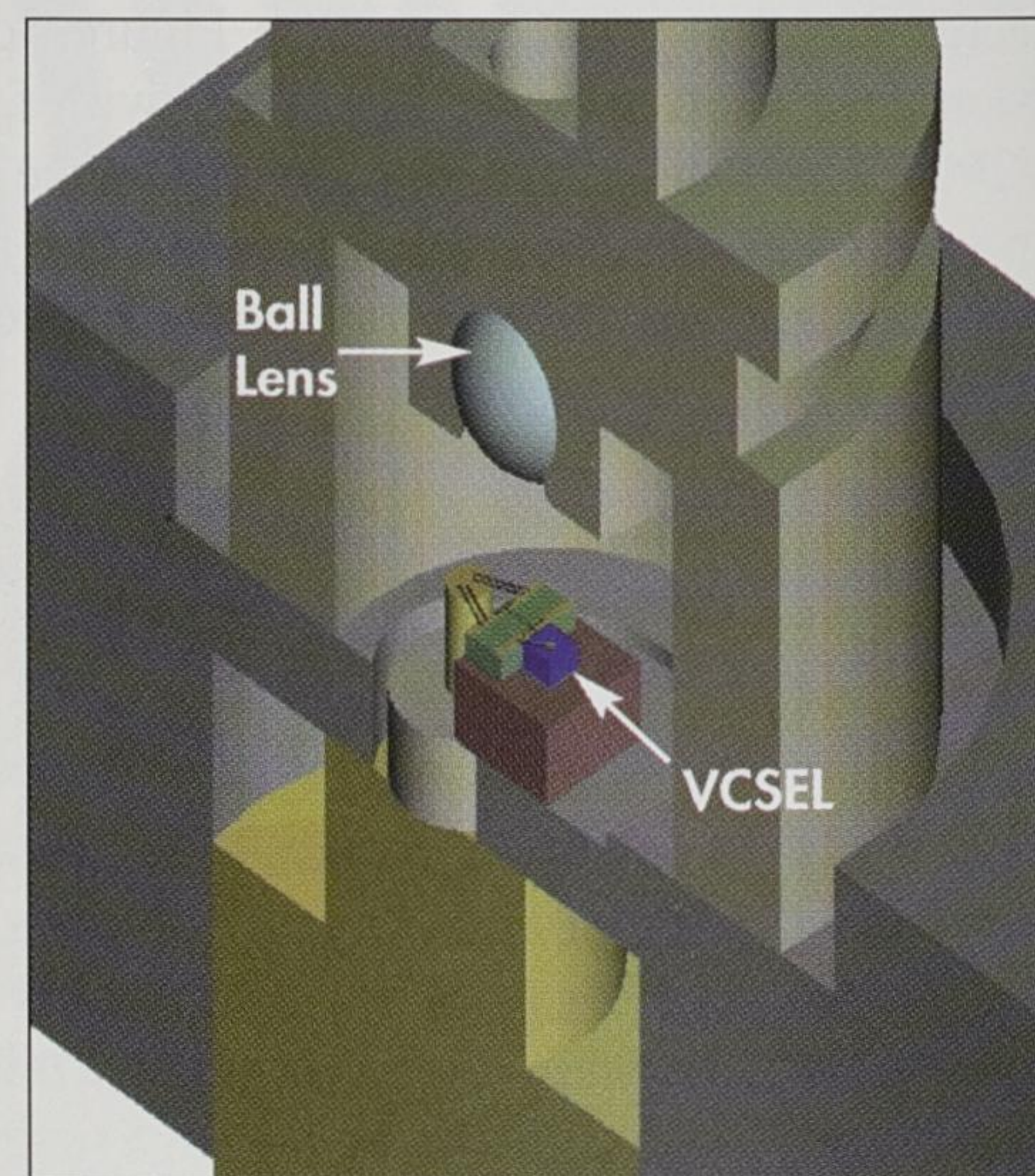


Figure 1. Cross-section of the optical subassembly (OSA). The VCSEL chip (blue) is mounted on an optical header and its output is aligned through the ball lens into multi-mode fiber (not shown). Electrical signals to drive the VCSEL are provided by the SMA connector shown at bottom (yellow).

don't have to route additional signals around the board to the modulator. Also, this is a lower power solution – a modulator might require a 10 V supply while a directly modulated laser draws, for example, 15 mA from a 2 V supply."

The capability to support direct modulation at 12.5 Gb/s is tied directly to the proprietary structure of Cielo's vertical cavity lasers. The devices also offer the usual advantages of VCSELs over edge-emitting lasers, including an output normal to the surface that is circular rather than elliptical, and better heat dissipation from the mirror facets buried within the structure. VCSELs also allow on-wafer testing, and support similar optical packaging to LEDs. In some quarters it is felt that oxide-confined apertures are necessary in order to achieve high-speed operation, but Cielo disagrees. "As we were able to readily achieve 12.5 Gb/s operation using proton implanted devices, we used this more mature technology rather than oxide confinement," says Bob Mayer.

Demo Results and Applications

The optical subassembly containing the VCSEL chip was tested using the configuration shown in Figure 2, which allowed a data signal to be transmitted through a 300 meter span of Lucent's new LazrSPEED multi-mode fiber. At a data rate of 12.5 Gb/s, an open eye diagram was observed as shown in Figure 3.

One of the main motivations in moving to higher data rates is to increase system bandwidth. However, fiber optic cable has a fixed bandwidth that determines the maximum link length for a given data rate – as the data rate increases, the available transmission distance decreases. For a Gigabit Ethernet system operating over 220 m, a 10X increase in data rate (from 1.25 Gb/s to 12.5 Gb/s) would result in a link length of only 22 meters. Hence the demonstration of 12.5 Gb/s over 300 m represents a huge improvement in system performance.

Furthermore, the OSA package was stable enough to allow investigation of the long term bit error rate (BER) of these VCSEL-based links. In initial performance tests, the 850 nm VCSEL operated

at 10.3 Gb/s over 300 meters with a BER of better than 10^{-14} (i.e. less than 1 error in 100 trillion bits).

Target applications for this technology are high-speed board-to-board and intrasystem interconnects, as well as next-generation optical interconnect standards. "The technology is suitable for any systems that need to support high bandwidth connections at less than 300 m," says Bob Mayer. "We are presenting our results to various standards committees to show that this technology is now available." The 10 Gigabit Ethernet standard is currently being developed, and is expected to be finalized in March 2002. One variant is likely to specify a data rate of 10.3 Gb/s over a 300 m link, corresponding to Cielo's demonstration.

Data transmission using VCSELs operating above 10 Gb/s is one of the proposed solutions at the Optical Internetworking Forum (OIF), which is also reviewing the use of parallel VCSEL-based links [see CS 6(3), p. 52]. Although parallel links do not require data to be multiplexed up to 10 Gb/s, the cabling cost is higher, and there may be skew effects if the propagation delay of one of the channels is significantly different from the others.

About Cielo Communications

Cielo Communications, Inc., based in Broomfield, Colorado, was created in February 1998 as a spin-off from Vixel Corporation, a leading developer of VCSEL-based devices. The company, which now has 81 employees, was established to commercialize VCSEL technology for high-speed optical communication applications. Three rounds of financing, the most recent in December 1999, have raised a total of \$72 million.

Epitaxial growth and chip fabrication is carried out at the Broomfield site. Cielo uses MBE, which according to Bob Mayer allows greater control over the growth process than MOCVD. "Also, this market does not currently require the higher volumes that MOCVD can provide," he says. Cielo also performs system-level design to create cost-effective optical transceiver modules, the assembly of which is sub-contracted.

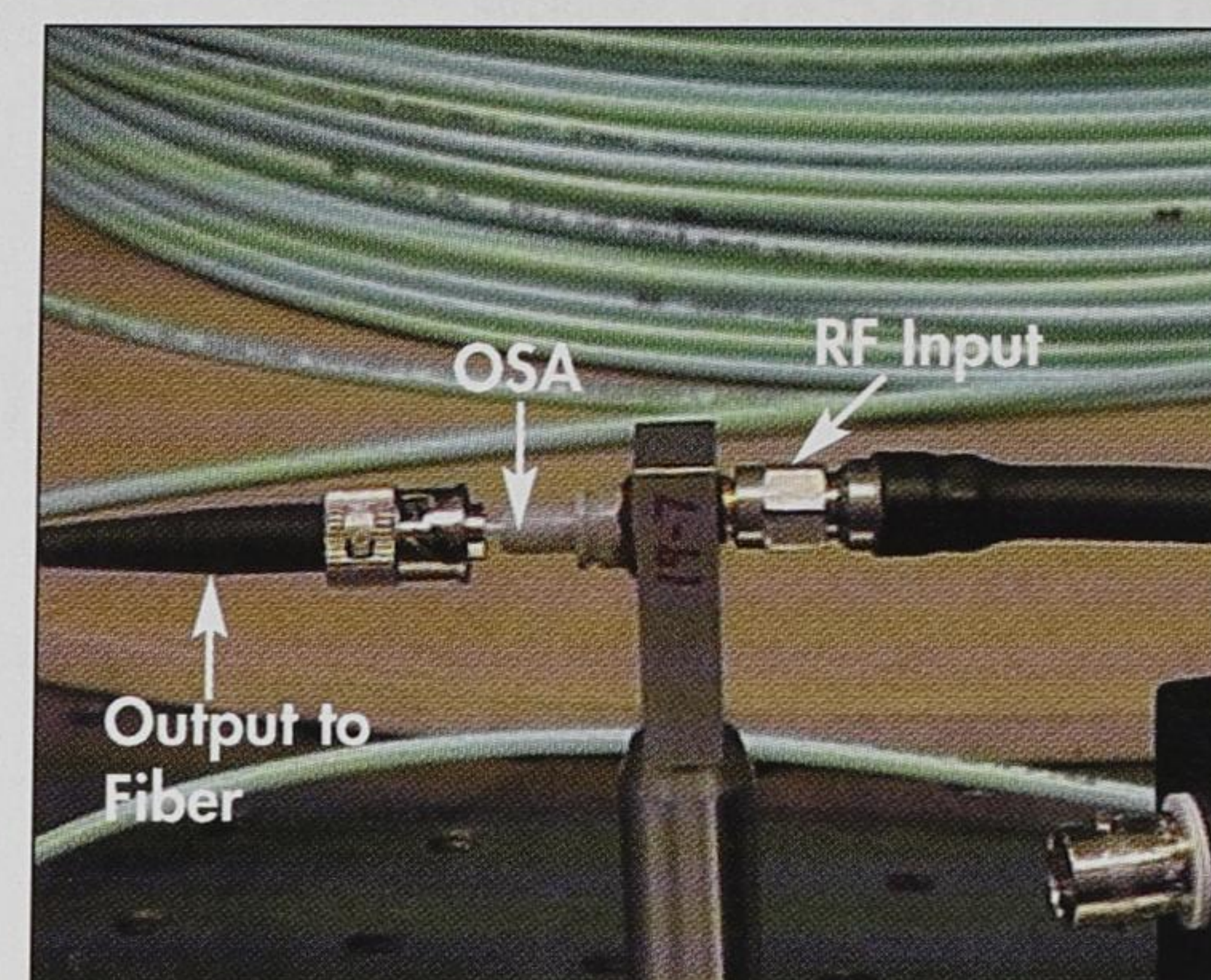


Figure 2. Experimental set-up used to evaluate the performance of the VCSEL packaged in an optical subassembly (OSA). The fiber bundle is visible in the background.

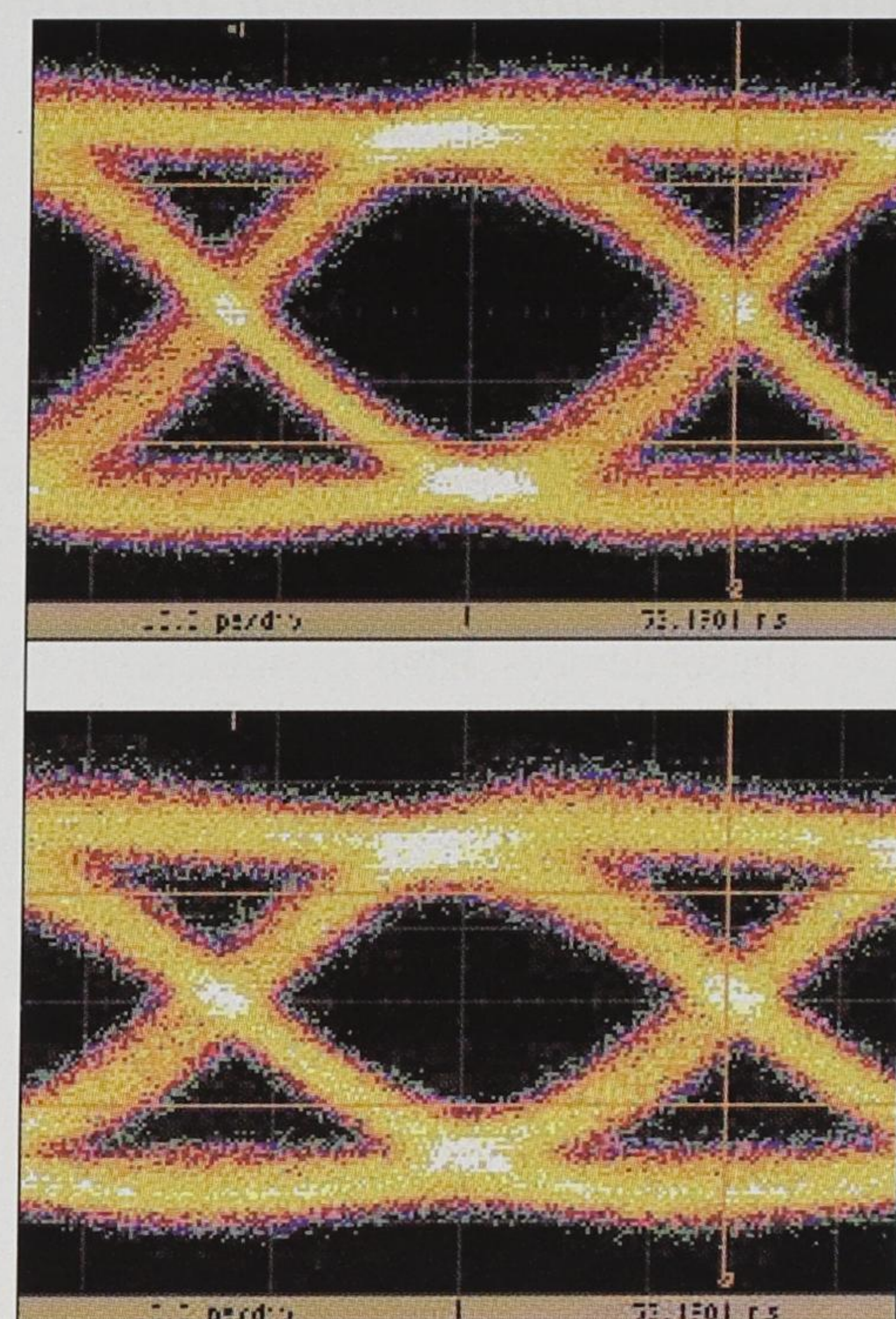


Figure 3. Eye diagrams showing (top) the output of an 850 nm VCSEL at a data rate of 12.5 Gb/s, and (bottom) the same device after transmission through 300 m of Lucent's new LazrSPEED multi-mode fiber. The open eye diagram demonstrates that this technology is a viable solution for high-speed optical interconnect schemes.

"Cielo sells at the integrated module level," says Bob Mayer. "Although we have offered 1 Gb/s products over the last couple of years, these have now been discontinued to allow us to focus all of our engineering expertise onto the new high speed technology up to and beyond 10 Gb/s. We expect to have product to market within the next 12 months."

Photon-Recycling for High Brightness LEDs

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A novel LED “recycles” the photons emitted by a short wavelength active region to produce a second, longer wavelength emission, which can be combined to generate white light without the use of phosphors. The addition of a third active-region makes a white emitter with good color rendering properties. With theoretical efficiencies in excess of 300 lm/W, photon-recycling LEDs are contenders for signs and future general illumination applications.

LEDs have long since become ubiquitous in their role as humble status indicators for domestic and industrial appliances. However, in the last ten years, the emergence of blue and violet emitters from the development of GaN, AlGaIn, and InGaIn materials [1] and improvements in efficiencies have led to high brightness LEDs suitable for a range of indoor and outdoor applications [2].

These devices have a significant advantage compared to conventional light sources: ideal LEDs can have internal quantum efficiencies approaching 100 %, where nearly every injected electron generates a photon. However, this is a figure of merit mainly of interest to device engineers. The efficiency or lumi-

nous performance, on the other hand, is a measure of the brightness of white light sources as it is perceived by the human eye. It is measured in lumens per Watt (lm/W).

In terms of their luminous performance, LEDs can achieve theoretical efficiencies exceeding 300 lm/W. This is not the case for incandescent light sources such as conventional light bulbs, which have typical efficiencies of only 15-20 lm/W. This is due to the fact that incandescent lamps emit mostly in the infrared where the eye is insensitive.

Fluorescent light sources exhibit a higher efficiency - around 60 lm/W. This is, however, limited by the fact that the gas discharge inside the lamp occurs in the UV, and considerable energy is lost during down-conversion to the visible region by the phosphor coating on the inside of the fluorescent tube. In comparison, the LED's ability to emit very efficiently makes it the light source of the future. And the race is now on to develop semiconductor-based light sources suitable for general purpose lighting applications, including white and colored light.

The high efficiency of LEDs means that the potential exists for enormous energy savings. It is estimated that about 30 % of all electrical power generated is used for lighting. If the energy savings promised by LEDs could be realized, calculations predict that no new power plants would need to be built during the next 20 years. Since much of the electrical power is generated using oil-consuming power plants, it is clear that the dependence on this finite resource could be substantially reduced if efficient LEDs could replace power-hungry incandescent light sources.

The Approach to General Illumination

A conventional LED emits close to monochromatic light, and the number of possible colors is limited. Many approaches

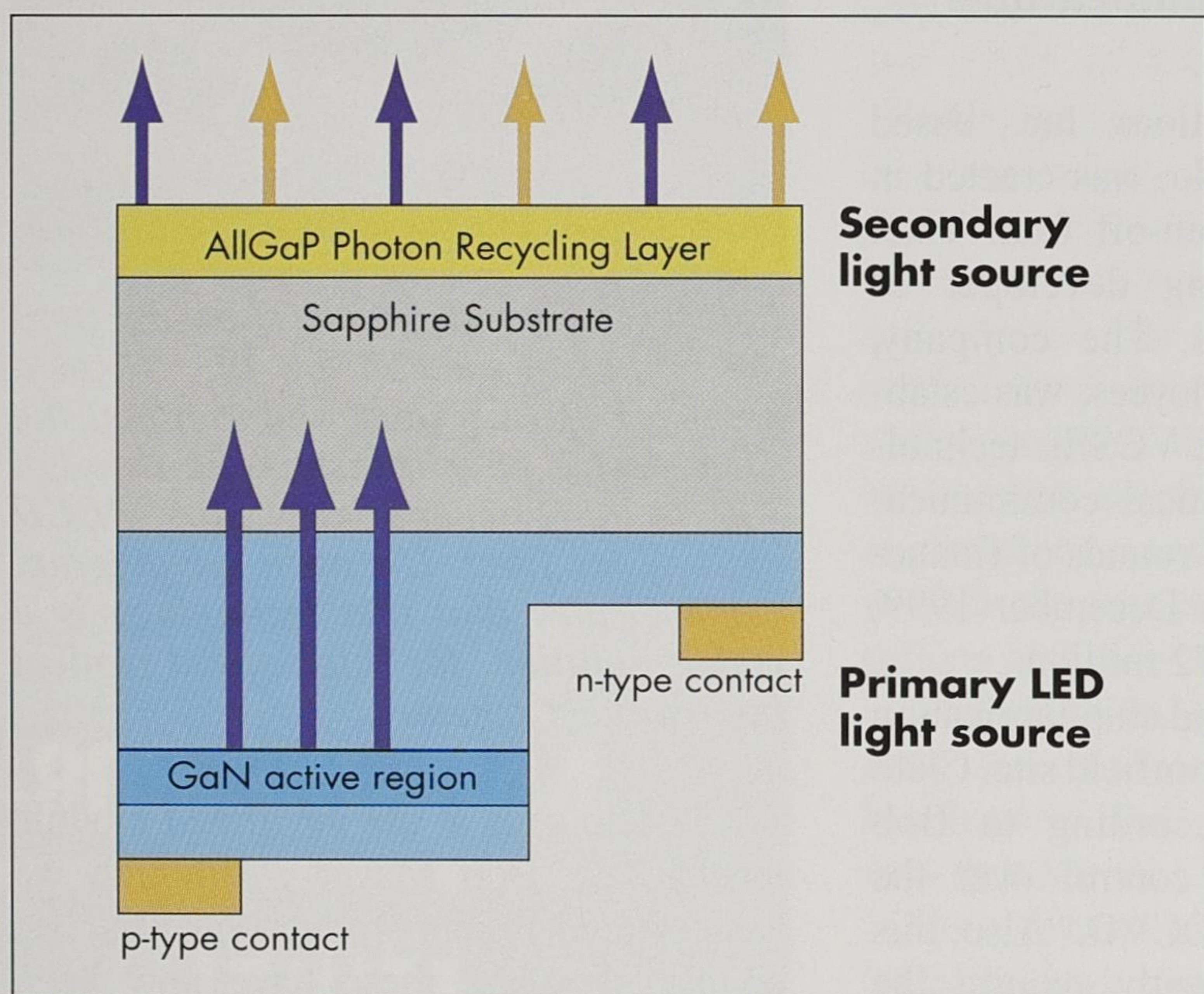
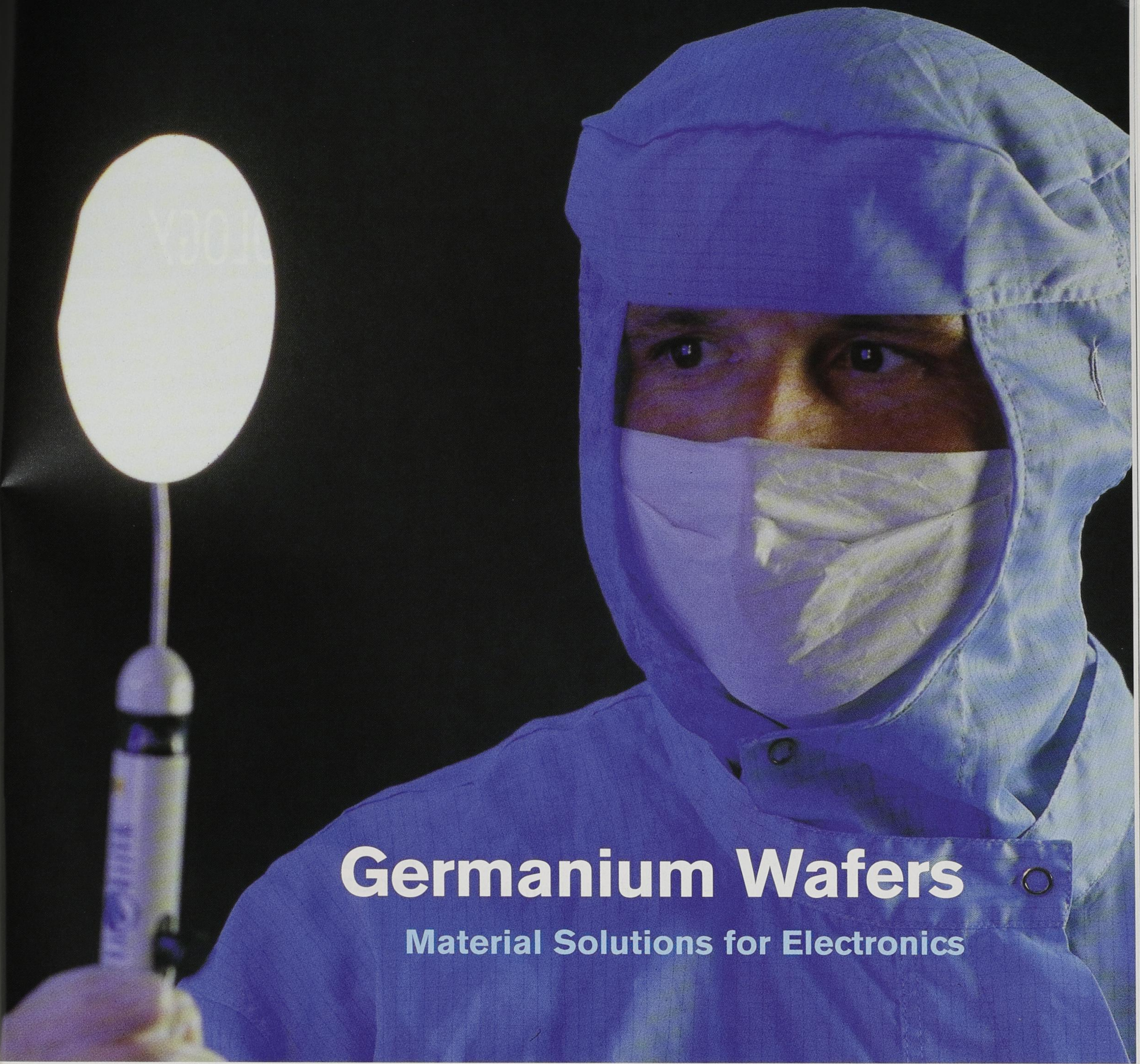


Figure 1. Structure of the photon-recycling semiconductor (PRS) LED. The device consists of the primary active region emitting in the blue wavelength range and an electrically-inactive photon recycling wafer re-emitting a complementary color such as yellow/orange.

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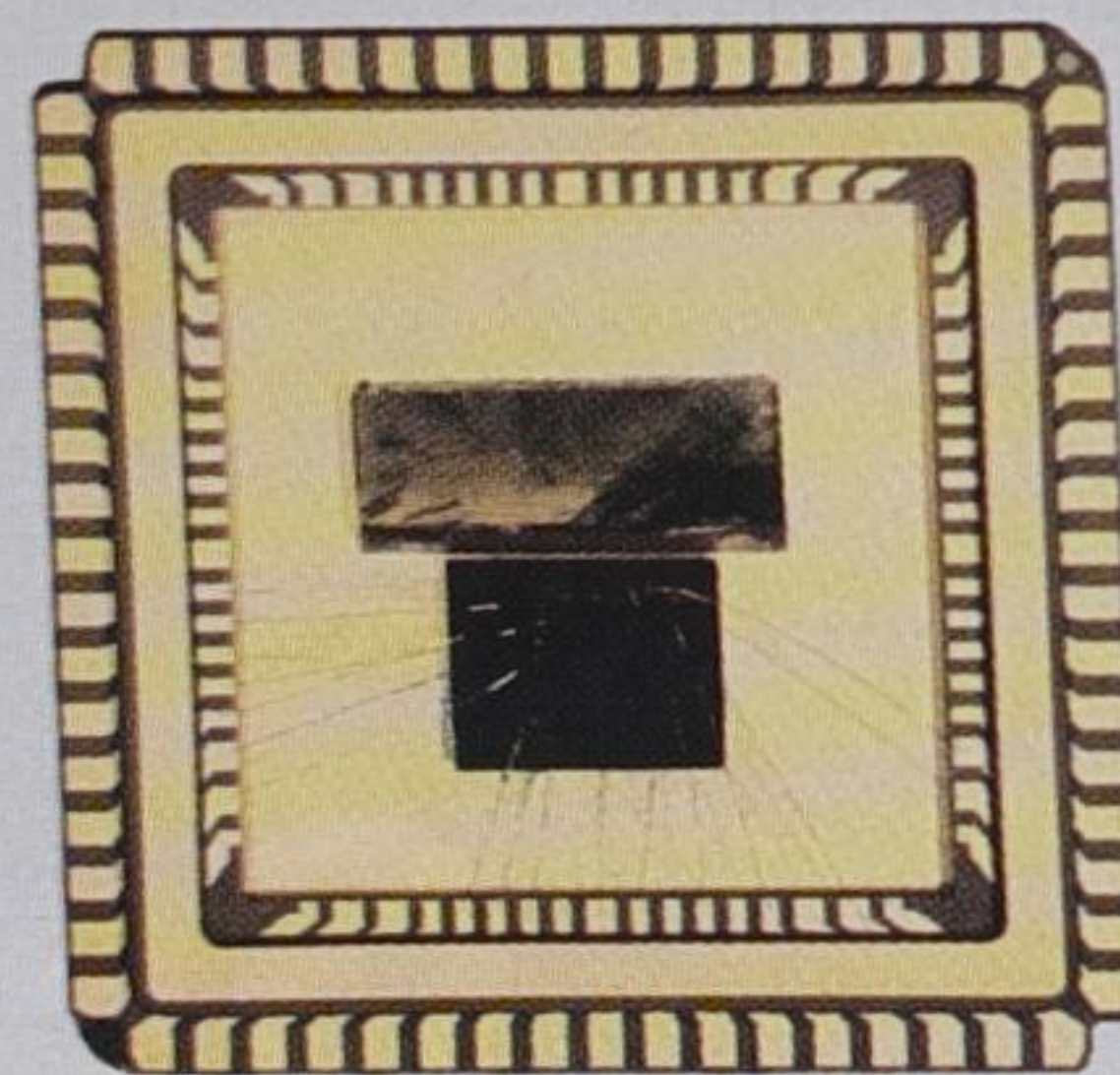


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exist that transform this narrow spectrum into one recognizable as white light. White can be generated in LEDs through the use of a phosphor film, either by coating the device or the plastic encapsulant [1]. The phosphor, which is optically excited by a semiconductor LED, emits over a broad range of wavelengths, resulting in the appearance of white light. However, the deposition of the phosphor increases the manufacturing cost of white emitters compared to conventional monochromatic LEDs.

White light emission can also be achieved by mixing the outputs of three discrete LEDs emitting in the red, green, and blue range of the visible spectrum, such as frequently used for full-color displays. Again, the fabrication of a white-light source using three LEDs is more expensive compared to the single-chip approach, making this solution inappropriate for low-cost general illumination applications.

Yet another approach uses organic dye molecules to convert the short-wavelength light to a longer wavelength. However, under long-term optical irradiation, the efficiency of organic dye molecules, which lack the long-term stability provided by semiconductors, degrades. White light LEDs can also be made from polymers. These exhibit much lower electrical conductivity than either metals or semiconductors, and as a result, cannot be subjected to high electrical current densities. This limits their use to lower-brightness applications such as displays rather than high intensity light sources.

Therefore, device designs that are capable of fully exploiting the potential of high brightness LEDs are currently being sought to devise energy-efficient sources for general illumination and other applications. Here we discuss a novel concept for an LED based on a ‘photon-recycling semiconductor’ LED, or PRS-LED. This device represents an all-semiconductor approach to white light emission, and can produce either white light or a range of colors with theoretical efficiencies in excess of 300 lm/W.

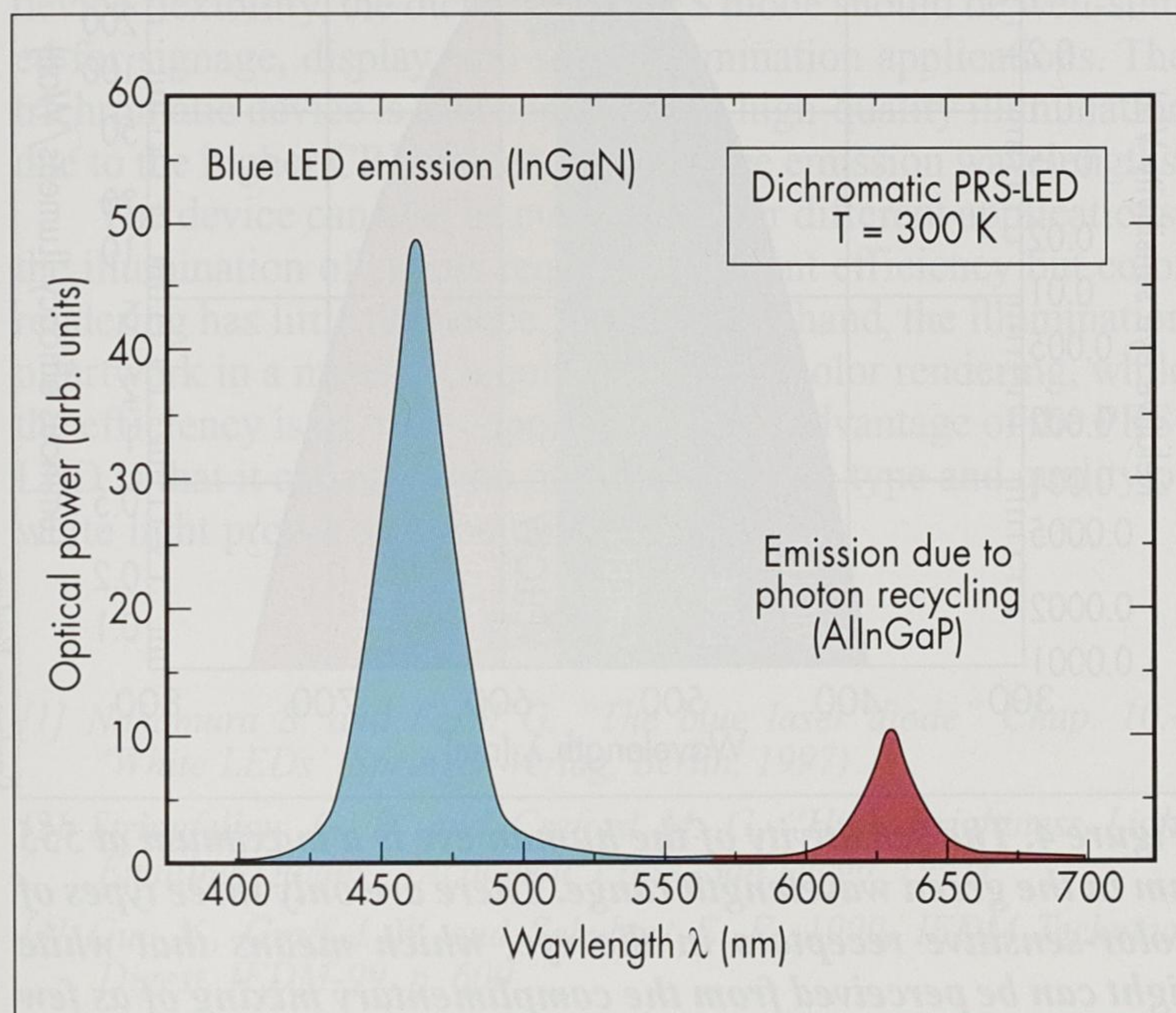


Figure 2. The emission spectrum of a PRS-LED consists of a primary peak from GaN/InGaN at 470 nm and a secondary emission peak from AlInGaP at 625 nm.

The Photon Recycling LED

The first PRS-LED was demonstrated as a hybrid device by Guo and colleagues in 1999 [3]. This device consisted of an epitaxially-grown InGaN-based blue LED bonded to a second wafer containing an AlGaInP active region. The device thus emits two or more discrete wavelengths, and the combined output is perceived as white light. The PRS-LED can also be designed to emit a multitude of other colors, which is not possible with conventional LEDs. In addition, more recycling layers are possible, giving rise to bi- and trichromatic PRS-LEDs.

We first discuss the ‘dichromatic’ PRS-LED, which emits two discrete wavelengths. The device structure is shown in Figure 1. It consists of a primary and a secondary light source. The primary light source is an GaN/InGaN LED grown on a transparent sapphire substrate, designed to emit in the blue spectral range. The InGaN/GaN LED measures 600 x 600 μm and employs 50 nm-thick Al and Ni for the *n*- and *p*-type contacts, respectively. Electroluminescence is generated in the active region by current injection. The primary wavelength is centered around 470 nm.

For the secondary source, the PRS-LED employs an AlGaInP active region wafer-bonded to the sapphire substrate of the primary emitter. The GaAs substrate of the AlInGaP is removed by chemically-assisted polishing and selective wet etching to reduce further losses in efficiency due to absorption. In

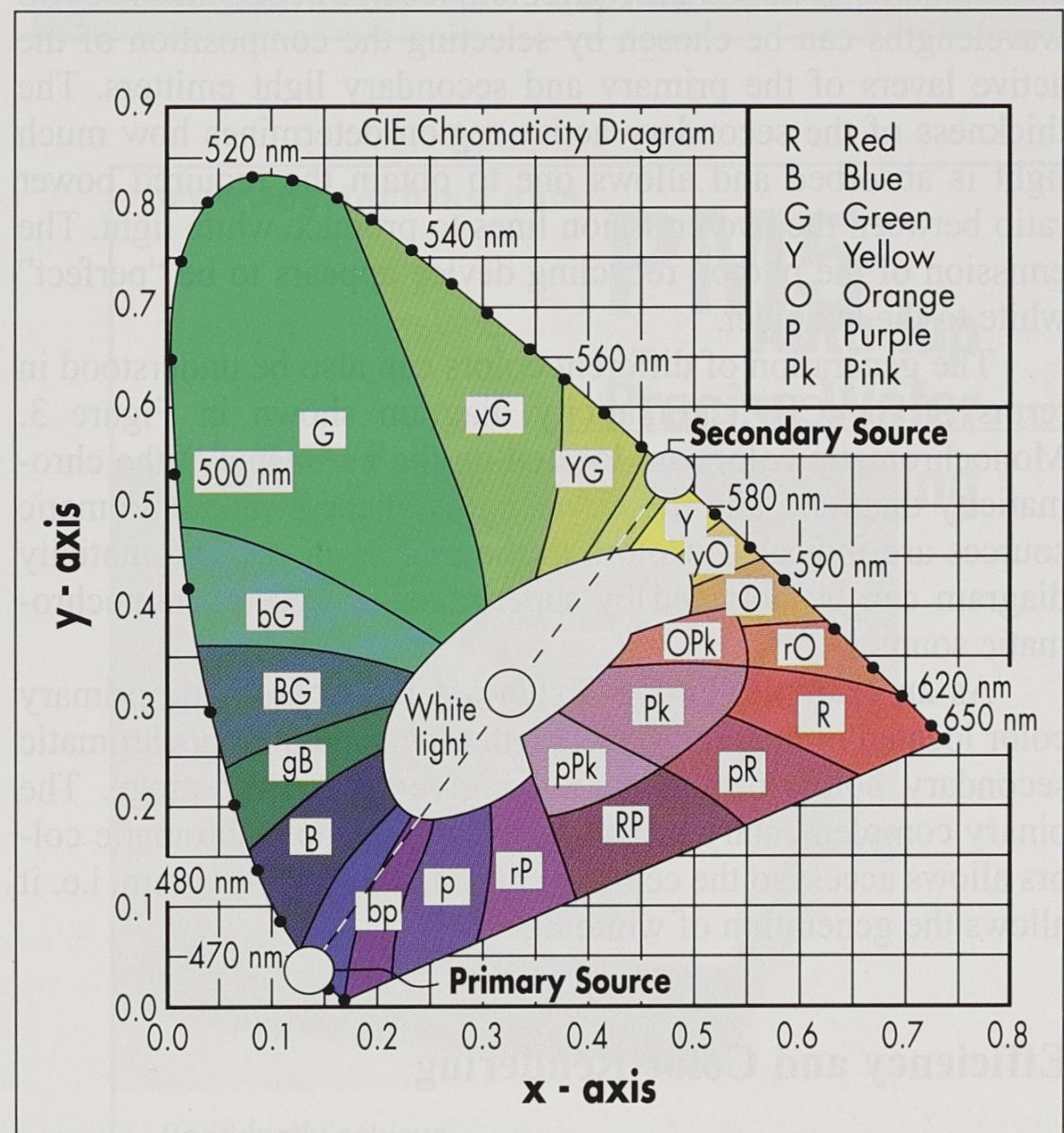


Figure 3. Illustration of different colors on the chromaticity diagram. White light is located in the center. The PRS-LED generates white light using two monochromatic colors - the primary and secondary light source – shown here located on the perimeter of the chromaticity diagram (after: Commission Internationale de l’Eclairage, CIE).

operation, some of the photons emitted by the primary light source are absorbed by the AlInGaP region and re-emitted (or recycled) as light at a longer wavelength. If these are complementary wavelengths and the two light sources have the correct power ratio, then the light appears white to the observer. Hundreds of other colors can be generated if the two light-emitting regions emit two non-complementary colors. In theory, it is possible to generate any color with the PRS-LED [3, 4].

The PRS-LED can also be monolithically integrated by employing InGaN with two different indium mole fractions for both the primary and secondary active regions, and growing the two active regions during the same growth run. InGaN has been shown to be suitable for emission up to the yellow range of the optical spectrum, and a white, a light blue, a whitish green and a light blue-green should all be feasible. No additional light-emitting materials - phosphors, dyes or semiconductor layers - are required to generate white light. The monolithic approach could allow lower manufacturing costs compared to other semiconductor-based white-light emitters.

Chromaticity Considerations

The emission spectrum of a prototype PRS-LED is shown in Figure 2. The emission of the primary LED occurs in the blue region of the visible spectrum (noted above), and a secondary emission line occurs in the red region, located at 625 nm. The two wavelengths can be chosen by selecting the composition of the active layers of the primary and secondary light emitters. The thickness of the secondary active region determines how much light is absorbed and allows one to obtain the required power ratio between the two emission lines to produce white light. The emission of the photon recycling device appears to be “perfect” white to the beholder.

The generation of different colors can also be understood in terms of the CIE chromaticity diagram shown in Figure 3. Monochromatic colors are located on the perimeter of the chromaticity diagram, and the wavelengths of these monochromatic sources are indicated. Colors in the middle of the chromaticity diagram can be obtained by superimposing several monochromatic sources.

As an example, Figure 3 shows a monochromatic primary color located in the blue wavelength range and a monochromatic secondary color located near the greenish-yellow range. The binary complementary mixing of these two monochromatic colors allows access to the center of the chromaticity diagram, i.e. it allows the generation of white light [4].

Efficiency and Color Rendering

The sensitivity spectrum of the human eye, which has a maximum in the green wavelength range at 555 nm, is shown in Figure 4. The eye's sensitivity strongly decreases in the red and the violet and has essentially zero sensitivity for wavelengths <390 nm and >750 nm. Thus, light sources operating near this maximum in the green wavelength region have the highest lumi-

nous performance. The PRS-LED takes advantage of this: allowing for the energy loss occurring during the recycling process, a very high luminous performance of 330 lm/W is theoretically obtained. The ability to exactly design the two (or even three) wavelengths of the device allows one to attain the maximum performance from a white light emitter.

Color rendering is another important property of white light sources. This quantity describes how objects illuminated by a light source are perceived. Most white and off-white illuminants for typical reflecting surfaces feature a relatively high color rendering index (CRI) i.e. > 50. On the other hand, mercury vapor lamps and high pressure sodium lamps have CRIs around 20, causing some surfaces to appear odd in certain circumstances – this is often tolerated to take advantage of high luminous efficiency. In the case of the dichromatic PRS-LED, the CRI is much lower than that of typical lamps such as incandescent and fluorescent light sources. This makes it well-suited for indicator light applications but less amenable to illumination applications.

However, by adding a second photon-recycling active region, a ‘trichromatic’ LED can be fabricated. The CRI of the trichromatic device, at around 60, is comparable to conventional light sources. At 290 lm/W, the theoretical luminous performance of the trichromatic PRS-LED is still very high, preserving the efficiency advantage of this device compared to other light sources. Thus, the color rendering properties of the PRS-LED can be optimized for different applications.

Another important advantage of the modified LED relates to design of broad-spectrum white light sources that simulate sunlight. White sunlight is distributed over the entire visible spectrum, i.e. a high light intensity is emitted by the sun even at the edges of the visible spectrum, where the eye is insensitive. In

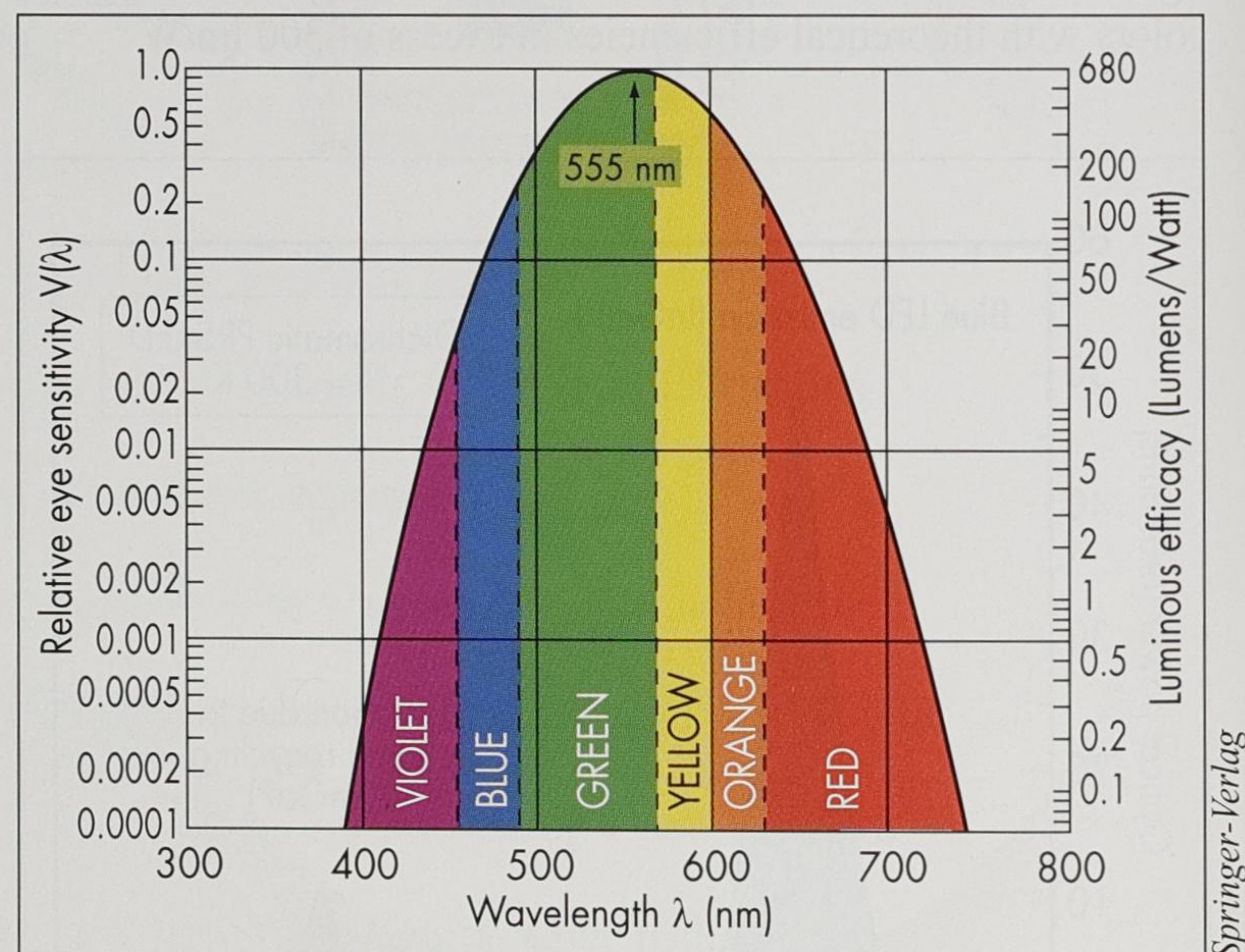


Figure 4. The sensitivity of the human eye is a maximum at 555 nm in the green wavelength range. There are only three types of color-sensitive receptors in the eye, which means that white light can be perceived from the complimentary mixing of as few as two separate wavelengths. With its use of just two complementary wavelengths positioned well inside the eye's spectral envelope, the PRS-LED produces white light very efficiently.

designing white light generators, the close reproduction of the sun's spectrum is not an efficient way to produce white light. The PRS-LED takes a fundamentally different approach. In this device, several monochromatic light emitters are positioned at wavelengths chosen such that the emission results in the highest possible luminous performance.

How the PRS-LED Efficiency Compares

Tungsten filament and halogen incandescent light sources have a luminous efficiency of 15-25 lm/W. Fluorescent tubes and the newer compact fluorescent light bulbs have a luminous performance of about 60 lm/W. In comparison, the calculated theoretical efficiency of the dichromatic PRS-LED is around 330 lm/W, which is much higher than that of conventional light sources. Even if only 50 % of the PRS-LED's efficiency, i.e. about 160 lm/W, can be demonstrated within the next 5 years, this LED would significantly outperform conventional light sources. At the present time, the PRS-LED has a luminous performance of less than 10 lm/W.

As mentioned above, other technical approaches to making white LEDs exist, including diodes based on phosphor (similar to fluorescent light) and also light-emitting polymers. However, the maximum theoretical luminous efficiency of phosphor-based white LEDs is 280 lm/W, lower than the efficiency of the dichromatic PRS-LED. Polymer LEDs are not expected to be suitable for high-brightness light emission due to their inherently high electrical resistivity.

Potential Applications

The PRS-LED has many possible applications. In terms of device flexibility, the dichromatic PRS diode should be well-suited for signage, display, and some illumination applications. The trichromatic device is also applicable to high-quality illumination due to the higher CRI afforded by its three emission wavelengths.

The device can also be customized for different applications: the illumination of streets requires excellent efficiency but color rendering has little relevance. On the other hand, the illumination of artwork in a museum requires excellent color rendering, while the efficiency is of little importance. A big advantage of the PRS-LED is that it can allow the properties for the type and quality of white light produced to be tailored.

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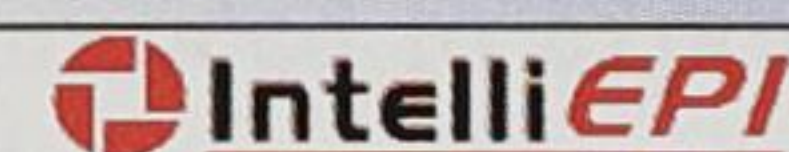
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A Roadmap for Optoelectronic Interconnects for Integrated Circuits

The future role of III-V optoelectronics as interconnects for CMOS devices is discussed in a white paper¹ published by the Advanced Research Initiative in Microelectronics, a program funded by the European Union. The editors of that work are Alfred Forchel and Pierpaolo Malinverni. Extracts are reproduced here by permission, with an introduction by the editors of this magazine.

The second part of this article will appear in our next issue.

Introduction

High performance integrated circuits are not islands. To be of any use, they must communicate with other chips. Communication within different parts of a sophisticated chip is also necessary. But as CMOS dimensions decrease the current technology for electrical interconnects is becoming increasingly unsatisfactory, especially for circuits operating above 1GHz. Within the next decade interconnects will likely become the dominating factor in IC performance and manufacturing cost. The silicon industry has already implemented new technologies to address this problem, and, for the time being, the replacement of Al interconnects by higher conductivity Cu interconnects and the use of low k dielectrics will be sufficient. But qualitatively new approaches are sought for the generations of ICs to be introduced after 2005.

At the present time, the two best candidate technologies appear to be 3D integration and/or the use of optoelectronic interconnects. Indeed, the current SIA roadmap calls for these two to both make their debut as production technologies in 2005.

All of the components needed for optoelectronic interconnects (emitters, light guiding systems, detectors and receivers) have been demonstrated. But what is required are 2D arrays with up to a few thousand channels. The requirements for yield, uniformity and reliability are extremely challenging. Power dissipation and interconnect size are further major issues. Additional open questions concern the connection to the ICs. These include the issue of hybrid or monolithic integration as well as, for example, the choice of wavelength and thereby material for the optoelectronic devices.

This article, which will appear in two parts, discusses many facets of this challenging issue. It should be noted at the outset that the success of optoelectronic interconnect technology is not guaranteed. Resistance from "the silicon industry" is to be expected, until current technology fails completely. Electronic interconnects will remain entrenched for short distance connections where time constraints are not critical. Therefore, this technology will certainly be used in IC fabrication beyond the time frame of the currently available roadmaps. For example, extensions using 3D electronic inter-

connects and packaging structures are foreseeable. Therefore, initial applications of optoelectronic interconnects should be identified in the area of high-performance systems, where cost is not a dominant factor. Examples include medium and long distance interconnects between PCs or workstations and in distributed memory or multiprocessor based computers.

1) Materials

For optoelectronic interconnects materials have to be chosen which allow the efficient generation and detection of light and for which suitable waveguides are provided. As massively parallel, high performance systems with typically 1000 channels are the target, the material technology has to be very mature to provide the required reproducibility, homogeneity, and lifetime specifications in addition to performance.

The most promising emitters for inter- and intra-chip optoelectronic interconnects are vertical cavity surface emitting lasers (VCSEL) and high-efficiency light-emitting diodes. VCSELs based on high precision epitaxial InGaAs/AlGaAs layer stacks show low threshold and high efficiency, and the technology for fabrication of individual devices is mature. High-efficiency LEDs like non-resonant



¹ Technology Roadmap – Optoelectronic Interconnects for Integrated Circuits was produced by the Advanced Research Initiative in Microelectronics (MEL-ARI OPTO), which is part of the European Commission's IST Programme for Future and Emerging Technologies.

cavity LEDs operate with very low or no threshold, with high efficiency and appreciable modulation speed. An alternative to using emitters as output devices is the use of modulators based on the quantum confined Stark effect in GaAlAs/GaAs or InGaAs/GaAs quantum wells. Very large arrays of modulators (several thousands) have already been integrated with CMOS chips and operated in experimental optically connected systems.

Short wavelength emitters ($\leq 0.6 \mu\text{m}$) are attractive, because they are well matched to the attenuation spectrum of low cost PMMA-based plastic optical fibres. The use of longer wavelengths has a number of attractive features. By using an operation wavelength of $1.5 \mu\text{m}$, high bit rate data streams coming from long-distance fibers could be directly fed into ICs. Furthermore, the Si substrate of the ICs is transparent at this wavelength and can be used for waveguide fabrication.

The choice of the detector and waveguide material will be governed by the operating wavelength of the emitters. InGaAs/AlGaAs, InGaAsP on InP as well as Si can be used. Si-based detectors, naturally, have the highest potential for monolithic integration. However, it is not yet clear whether processes required for fabricating high-speed, high efficiency detectors are fully consistent with the IC technologies.

Waveguides based on polymeric materials with losses of less than 0.1 dB/cm may offer a viable alternative for optical interconnects due to their ability to be processed at temperatures compatible with CMOS processes i.e. below 250°C .

Table 1 shows, in addition to the current workhorse systems GaAs/AlGaAs and InGaAs/AlGaAs, a number of material systems which are under investigation for the use in optoelectronic interconnects. The different grey levels in Figure 1 indicate the expected research and development efforts for the various material systems and wavelength ranges. VCSELs in the $0.8 \mu\text{m}$ and $1.0 \mu\text{m}$ wavelength range are available as high performance single devices as well as in small arrays. Here the main development targets address the fabrication of large 2D arrays. All other material systems are at a much earlier stage of development. In conjunction with plastic optical fibres

AlGaP based VCSELs or even shorter wavelength emitters based on GaN are particularly interesting. For AlGaP, AlGaSb and GaInNAs the development and optimisation of electrically pumped single VCSELs will be the main target in the coming years.

Emitters at 1.5 and $1.3 \mu\text{m}$ are usually realised in the InGaAsP material system on InP substrates. Using this wavelength in optoelectronic interconnects would have the advantage that long-distance communication would be directly compatible with the short-range interconnects. Furthermore, the turn on voltage of these devices would be compatible with reduced operation voltages of future IC generations. Although high quality edge emitters are available, due to the small refractive index change between InGaAs and InP there are severe problems regarding the monolithic fabrication of VCSELs. Currently available VCSELs with InGaAsP active layers are therefore predominantly realised by employing wafer fusion of high quality AlGaAs Bragg reflectors or by using metal/dielectric mirror layers, which are sandwiched around the active material. This restricts the device yield and the lifetime to unacceptably small numbers. Here, GaInNAs/GaAs based lasers are very promising because they permit the shift of the wavelength into the $1.3 \mu\text{m}$ range while essentially maintaining a GaAs device. Due to the large refractive index difference GaSb/AlGaSb VCSELs at $1.5 \mu\text{m}$ are an alternative with considerable potential. InAs-based quantum dots may

allow the operation wavelength of GaAs-based lasers to be shifted to $1.3 \mu\text{m}$ and eventually to $1.5 \mu\text{m}$. Furthermore, quantum dot VCSELs at $0.98 \mu\text{m}$ may be used to develop very low threshold devices.

2) Hybrid versus monolithic integration

Optoelectronic interconnects will be most likely based on III-V materials on the output side (e.g. InGaAs VCSELs, InGaAs modulators). The combination with the Si IC will involve technologies like wafer fusion or bonding, epitaxial liftoff or flip-chip bonding. This has the advantage that the IC processing may be completely finished before the interconnect subsystem is placed onto it. In particular, there is no need to expose the Si wafers to critical temperatures in excess of about 400°C . Here the main technological problems concern the yield of flip-chip VCSEL arrays involving a very large number of devices. A known good die selective and/or collective transfer technology would have important consequences for improved yield. High yields have been achieved in experiments in which modulator arrays, containing thousands of devices, have been flip-chip bonded to CMOS.

For monolithic integration technologies the above temperature limitation is very challenging because the epitaxy on Si usually involves temperatures in excess of 800°C . Here, low temperature deposition processes for III-Vs on Si have to be developed.

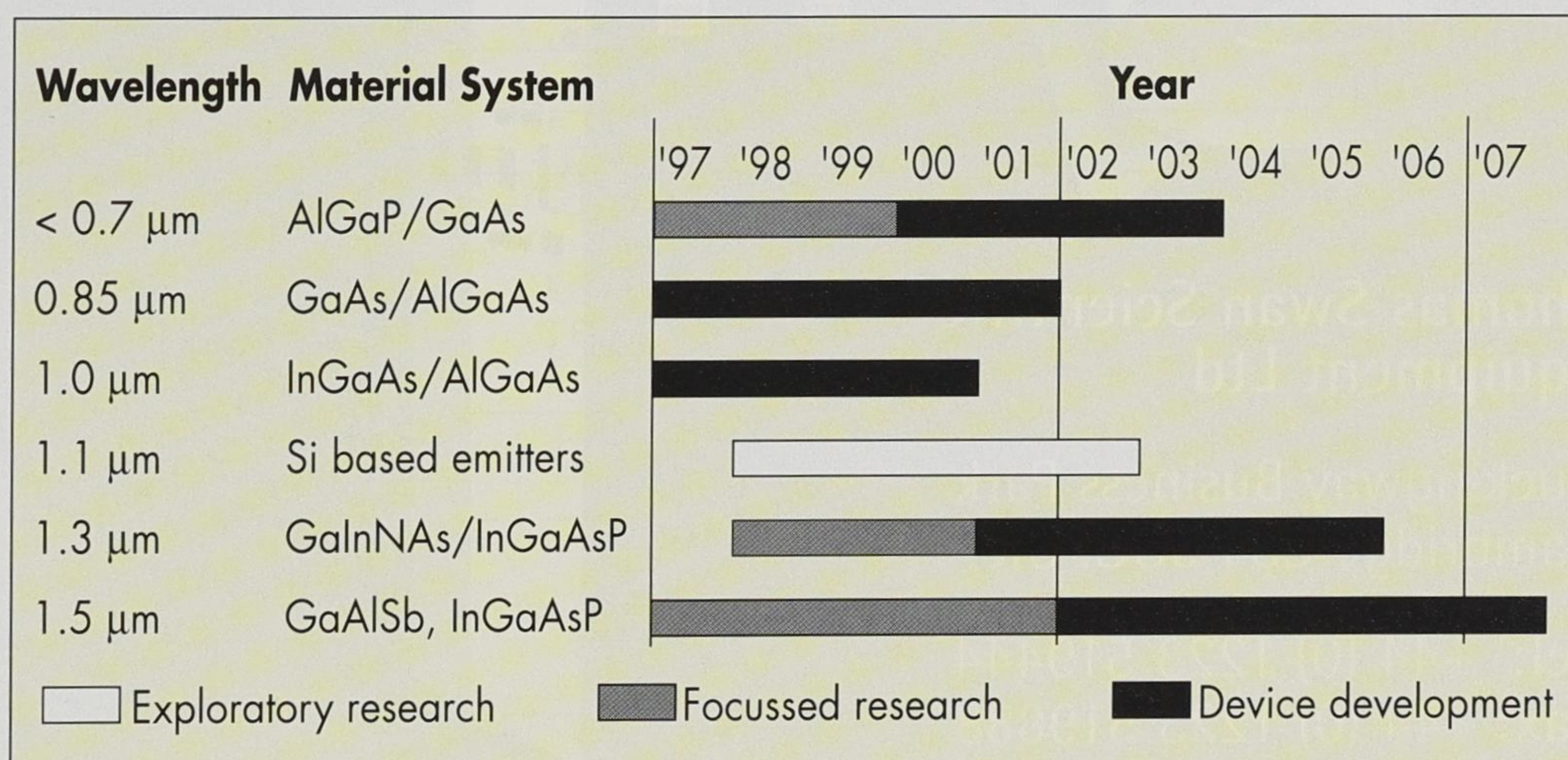
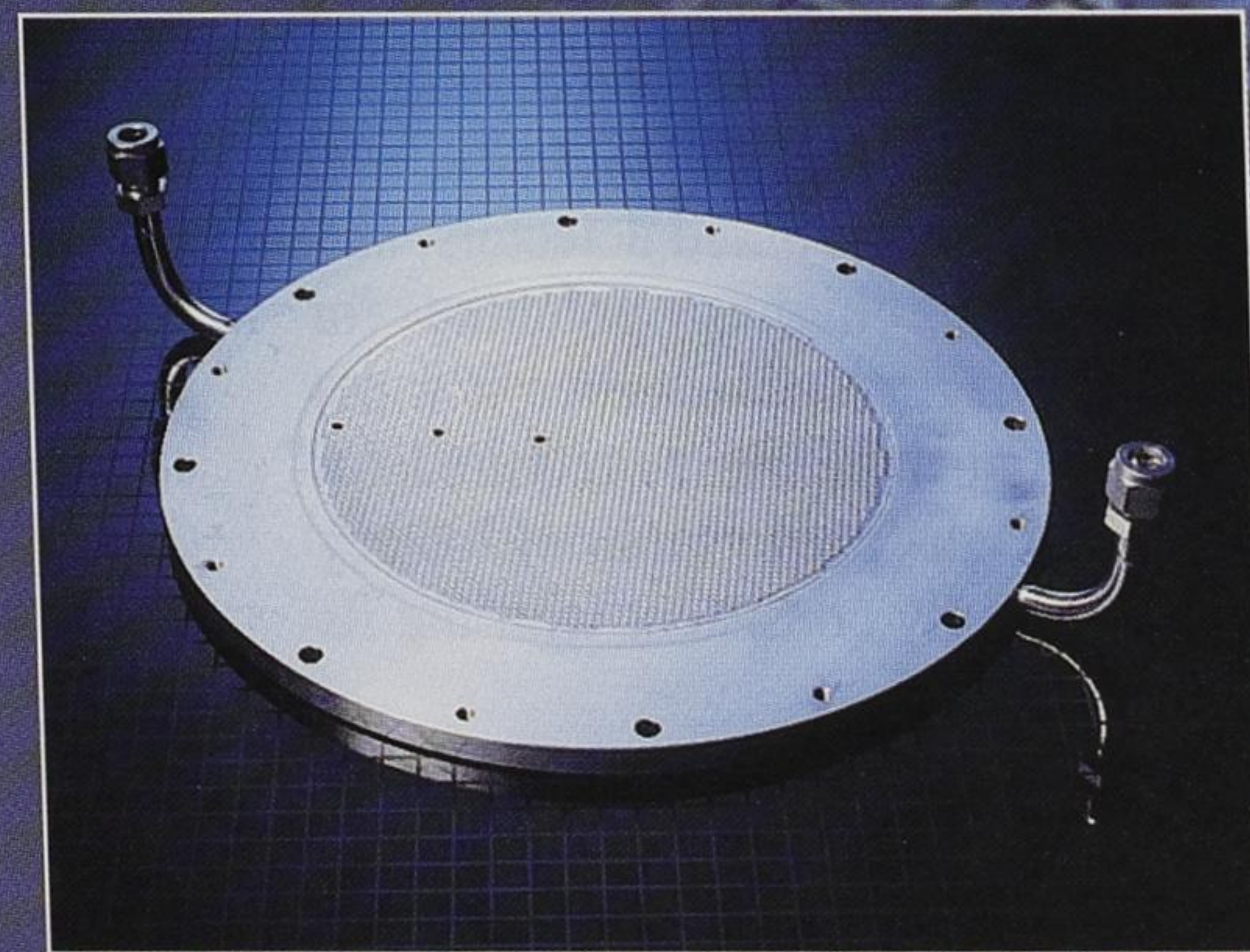


Table 1 - Projection of main R&D effort on different material systems and wavelength ranges for optoelectronic interconnects

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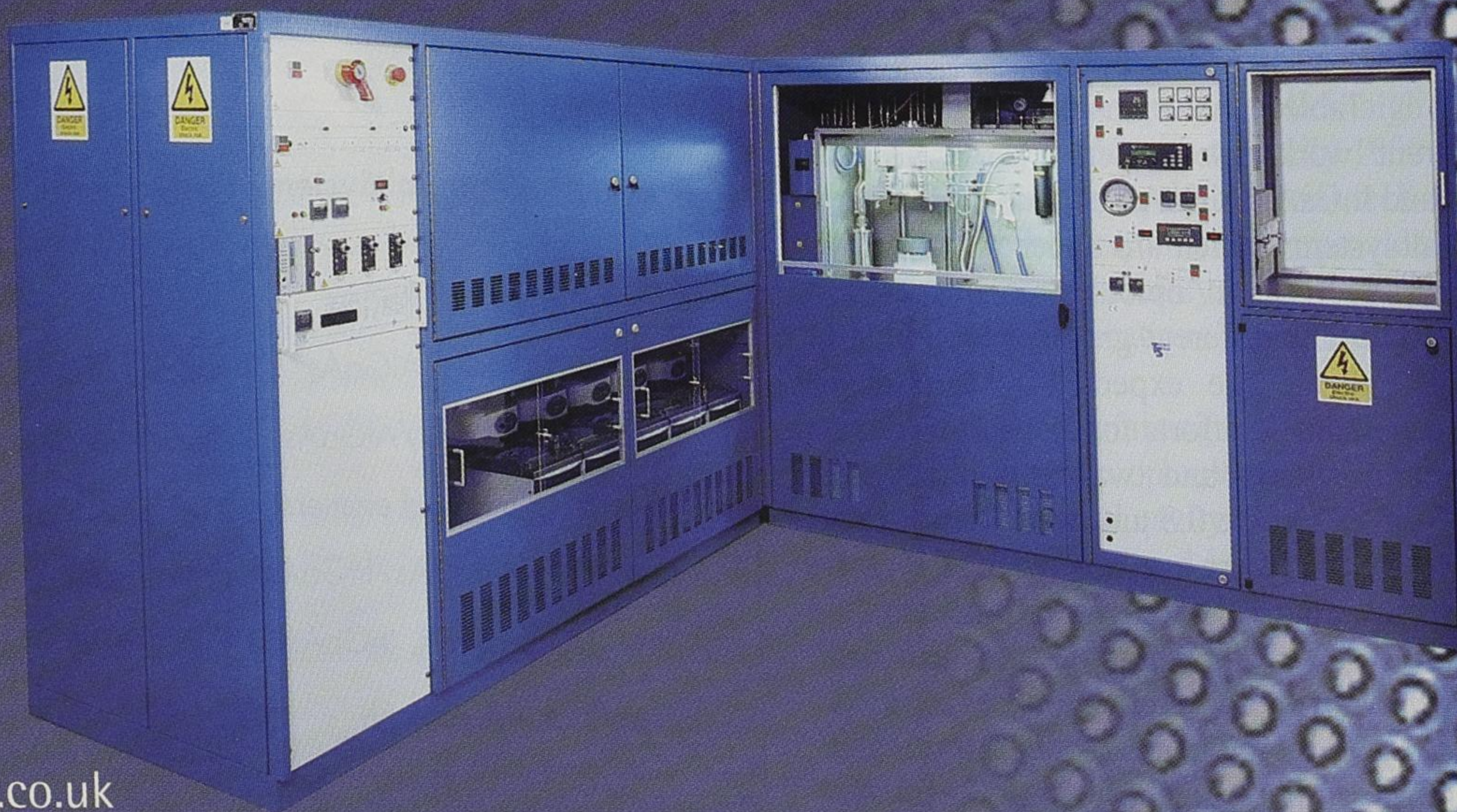
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Optoelectronic interconnects based on Si are from the materials side naturally compatible with the IC. However, difficulties in a monolithic approach may result from additional process steps to which the ICs would have to be submitted for the fabrication of e.g. the emitters. Therefore, even for Si-based optoelectronics hybrid approaches may be more important than monolithic ones.

3) Components for inter- and intra-chip optoelectronic interconnects

3.1) General aspects

The interconnection schemes in which inter- and intra-chip optoelectronic interconnects have to be integrated are strongly application dependent.

The underlying target specifications of optoelectronic interconnects can be summarized as follows:

- single I/O channel band width = > 1 Gbit/s
- number of parallel channels = > 1000
- power consumption per channel = < 1 mW

Massively parallel interconnects for dedicated processors should be based on 2D arrays with a power consumption considerably below 10 W. In addition to the main specifications, the development criteria of optoelectronic interconnects have to take into account the continuing trend in IC development to smaller dimensions. Optoelectronic intra-chip interconnects which are comparable in size or larger than the Si chips they connect can hardly be expected to be acceptable in a product due to space and cost considerations.

3.2) Emitters, modulators and drivers

Two concepts are followed on the emitter side. One relies on fast directly modulated light sources, the other uses specific modulators. In the first case, due to their high efficiency, low threshold current and the possibility of 2D array fabrication as well as the intrinsic compatibility with fibre and free space optics, VCSELs and microcavity LEDs are currently the most promising emitter devices. However, the use of VCSELs restricts the

available wavelength range to about 0.8 μm to 1 μm . Prototype 1.5 μm devices have been fabricated with fused mirrors. These are, however, not yet stable enough for applications.

Modulators, based on electro-absorption effects, are designed to work at specific wavelengths (e.g. 850 nm, 980 nm, 1047 nm, 1300 nm, 1500 nm). These wavelengths are chosen to match available lasers (e.g. edge emitting laser diodes or diode-pumped lasers), the outputs of which are fanned out. Modulator based concepts are compatible with fibre and free space optics.

Single VCSELs with sub mA threshold and wall plug efficiency of more than 50% have been demonstrated. These few μm diameter devices deliver output powers of up to more than 10 mW. In order to realize low threshold currents for a given device size, current confinement by controlled thermal oxidation of an AlAs aperture has been shown to be a significant improvement over current confinement by ion implantation.

Table 2 summarises current estimates for the development of VCSEL arrays including drivers for a period of 10 years. Table 3 provides projections on LED bi-dimensional arrays for use in massively parallel optoelectronic interconnects.

For optoelectronic interconnects VCSEL arrays, including up to several thousands of lasers, have to be developed within the next decade. Low power consumption (<1 mW) per device is very important in these dense arrays. Even if these values are achieved, the power dissipation in a 64 x 64 channel emitter and driver array may reach values close to 10 W. Further, very stringent criteria concern the single device yield (>>99 %) and the performance uniformity in the arrays. A high uniformity is required, for example, for threshold currents, differential quantum efficiency, and switching times. The target value for the data rate is 8 Gbit/s per channel. Simultaneously, the signal delay between the driver and the optical output will have to be reduced to less than 100 ps.

Year	1997 (A)	1999 (A)	2002 (E)	2007 (E)
Optical channels	256 (16 x 16)	256 (16 x 16)	1024 (32 x 32)	4096 (64 x 64)
Chip size (mm ²)	2.5 x 2.5	2.5 x 2.5	3.2 x 3.2	4.0 x 4.0
Pitch (VCSEL + driver) (μm)	125 (250)	125 (250)	100	System dependent, envisage 62.5
VCSEL active diameter (μm)	15	10	4	2
Bit rate per channel (Gbit/s)	0.6	1.2	4	8
Aggregate bit rate (Gbit/s)	10 154	80 320	4000	33000
Modal properties	multi-mode	multi-mode	single mode	single mode
Operating voltage (V)	2.5	2.5	2.0	1.8
Threshold current (mA)	3	1	0.5	0.1
Operating current (mA)	6	6	1.5	0.5
Optical output power (mW)	1	2	0.5	0.3
Power dissipation - individual VCSEL (mW) - VCSEL array (W) - VCSEL driver array (W) (@ 50 % duty cycle)	14 1.8 + 0.7 3.8 + 1.4	11 1.4 + 0.2 1.5	2.5 1.3 + 0.4 5	0.6 1.2 + 0.3 7
Signal delay (ns) Driver to optical output	0.8	0.5	0.15	0.08
Uniformity Threshold current $\pm$ (%) output power $\pm$ (%) delay $\pm$ (ns)	10 20 0.4	10 20 0.4	5 10 0.1	5 10 < 0.06
Yield within array (%)	99%	99%	99.9%	99.9%

Table 2. Performance of 2D InGaAs VCSEL and driver arrays (980 nm). The data for 1997 and 1999 is actual, where as the data for 2002 and 2007 is projected/estimated.

The emission of the devices of the second and third generation VCSELs will be single mode mainly due to space constraints. An output power of 1 mW or more is essential for systems with large fan-out as required, for example for clock distribution. Otherwise, output powers of 0.5 mW will be sufficient, which may be obtained with highest efficiency from small single mode devices.

3.3) LEDs

High performance vertical-to-surface emitting LEDs are candidates particularly suited for massively parallel optical interconnects. The main advantages of LEDs include the wide temperature window of operation and low power consumption. LEDs have no threshold current, and can operate at voltages smaller than the bandgap equivalent. Notorious problems of LEDs include the limited external quantum efficiency and the limited modulation bandwidth. Impressive progress has recently been made on these two fronts.

High-efficiency LEDs have been demonstrated with more than 20% external quantum efficiency (1997). State-of-the-art LEDs in 1999 operate at 600 Mbit/s at 860 nm and have an external quantum efficiency of 36%. This wavelength range is particularly attractive due to its compatibility with Si-based detectors. Because of the stringent requirements of low power consumption in optoelectronic interconnects, LED light sources with a high wall plug efficiency at low currents are very interesting candidates. As LEDs with more than 1 GHz cut-off frequency have also been demonstrated, it is expected that Gbit/s data transfer will be achievable with acceptable bit-error rates using LEDs.

The light output of LEDs is less directional than in the case of VCSELs, which is a drawback in certain optical systems, particularly if optics with low NA are involved. The most promising LED types include microcavity (or resonant cavity) LEDs, non-resonant cavity LEDs and photonic bandgap LEDs. In

microcavity LEDs, the emission profile can be tuned to a certain extent to meet criteria of numerical aperture. Small LEDs, with 20 μm diameter, have been reported to have an efficiency of 9% combined with a bit rate of 600 Mb/s ($\text{BER} < 10^{-12}$). The efficiency of small non-resonant cavity LEDs has been reported to be above 20%. However, to date, no information about the modulation bandwidth is available. Large technological challenges have to be solved before LEDs using photonic bandgap structures can be made. Theoretically though, the potential of such devices is formidable: multi-GHz modulation can be combined with 50% or more quantum efficiency and well controlled directional emission.

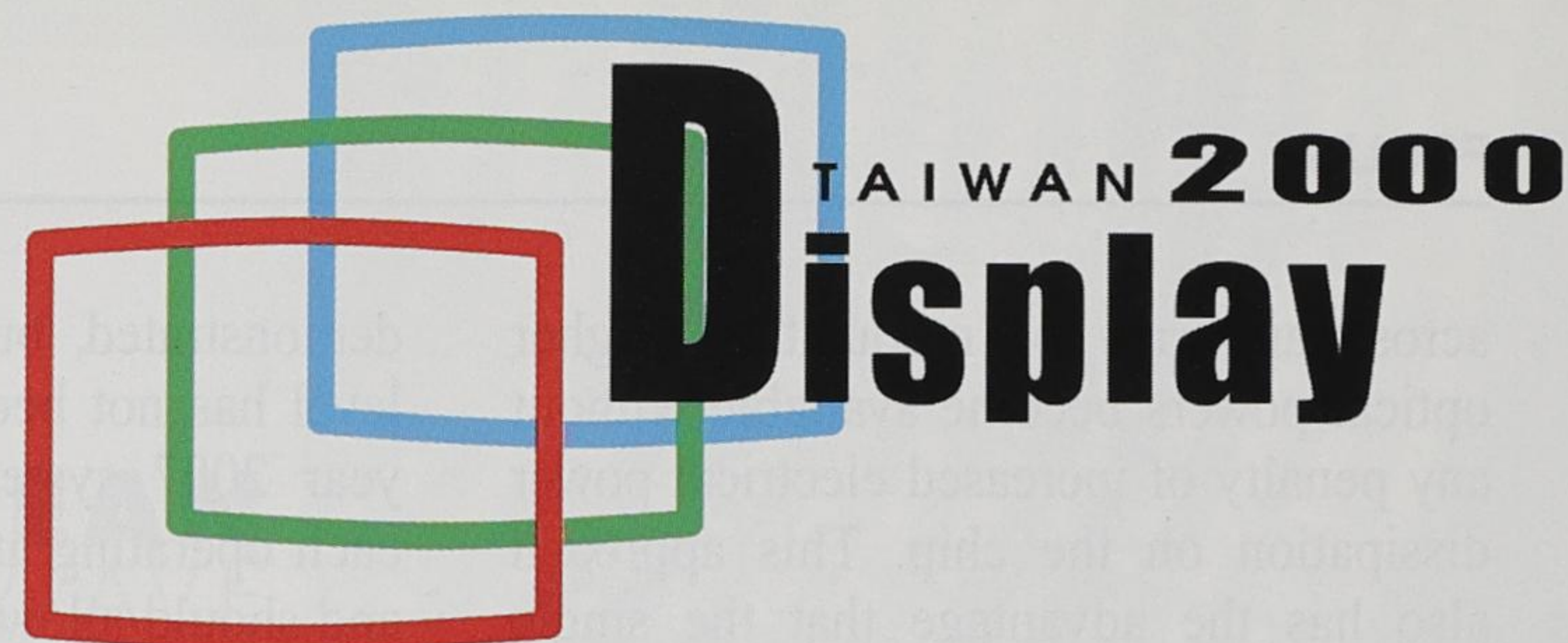
Independently of the particular emitter type, the individual channel footprint of emitter and driver as well as of detector and receiver should be minimised and finally approach the 100 μm^2 range. The mode field diameter should be comparable to the mode field of the light conductor (not applicable if free space is used) to optimize coupling into the light conductor and minimize alignment requirements. The pitch between channels should be of the same order.

An important issue concerns the operating wavelength of the interconnect systems. The emitter wavelength determines which materials are suitable for passive waveguides and which can be used as detectors. Using GaAs based devices interconnects at 850 nm and 980 nm can be realised. This excludes the use of Si as a waveguide material. However, these wavelengths are compatible with Si or GaAs based-detectors, which are available at comparatively low cost.

Instead of directly modulated emitters, separate modulators that are capable of switching independently generated light beams are promising output devices for massively parallel high speed optoelectronic interconnects. The modulators are based on the quantum confined Stark effect, by which the absorption of a semiconductor is shifted into the wavelength range of the laser light in order to attenuate it. The use of a separate modulator allows individual optimisation of light source and output device. By using a single, independent source, in conjunction with diffractive optics to fan the beam out

Year	1997	1999	2002	2007
Wavelength (nm)	850 nm 980 nm	< 860 nm	< 860 nm	< 860 nm
Optical channels	1024 (32x32)	1024 (32x32)	4096 (64x64)	16K (128x128)
Chip size (mm ²)	25	9	20	26
Pitch (μm)	150	100	70	40
LED active diameter (μm)	30	25	10	7
Max. channel density (ch/mm ²)	44	100	200	625
Bit rate per channel (Gbit/s)	0.250	0.500	1	1.5
Aggregate bit rate (Gbit/s)	250	500	4000	24000
Operating voltage (V)	2.5	2	2	1.5
Operating current (mA)	2	2	1	0.4
Optical output power (μW)	300	400	300	150
Optical output power into e.g. POF (NA=0.5) (@ operating current)	30 % of P _{tot}	30 % of P _{tot}	40 % of P _{tot}	50 % of P _{tot}
Temp. Dependence (%/°C) $1/P \cdot dP/dT$	-0.8	-0.3	-0.3	-0.3
Power dissipation - individual LED (mW) - individual driver (mW) - per unit area (W/mm ²) @50% duty cycle	2.5 1 0.3	2 1 0.3	1 0.5 0.3	0.3 0.15 0.3
Signal delay (ns)	2.4	1.2	0.6	0.4
Yield (%)	99.9	99.95	99.99	99.99

Table 3. Projected performance of 2D LED and driver arrays The specification for operating temperature range is -20 to 120 (°C) and the specification for output power uniformity is 10%.



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across an array of modulators, higher optical powers become available without any penalty of increased electrical power dissipation on the chip. This approach also has the advantage that the single laser providing the array of read beams can be switched so as to give precisely clocked read-out of the modulators. Compared with directly modulated VCSELs, modulator based interconnects require close control of the laser wavelength as the modulation contrast is large only within a few nanometers below the band gap of the modulators. The absorption in the modulators is bleached at high laser intensities. The corresponding saturation power is an important criterion for the modulators, because it limits the total optical power in the signal path. As shown in Table 3, the saturation power is expected to decrease to about 0.5 mW within the next ten years (as devices get smaller), which should still allow realization of systems with a large fan-out using modulators.

In 1997 the first chips with 1000 channels each operating at 600 Mbit/s were realised in research laboratories (see Table 4). The potential for modulator-based output data-rates from a single chip at an aggregate speed of 1 Tbit/s has been

demonstrated, but full operation at this level has not been achieved yet. For the year 2007 systems with 16K channels each operating at 2.5 Gbit/s are foreseen and should allow aggregate bandwidth of 41 Tbit/s. The operating voltage of the modulators, which currently is around 5 V, is expected to decrease to about 1 V in 2007 approximately parallel to the change of the CMOS operating voltage. A decrease in the operating voltage of the modulators implies a reduction of the number of absorbing quantum wells. In order to maintain a sufficient contrast, stacked or resonator structures may be required. Unlike VCSELs, modulators have no intrinsic turn-on delay, being limited only by their (small) capacitance charge times. The signal delays indicated in Table 4 refer to latency in the drive electronics.

In addition to the strong requirements on the emitter performance in the arrays there are stringent limitations to the fabrication cost. According to the 1996 OIDA roadmap, the cost for a laser in an array for parallel optoelectronic interconnects is expected to decrease from USD 200 per device in 1995 to USD 1 in 2010.

Furthermore, the reliability of the

emitters is a key issue. The output characteristics of lasers and other components should withstand temperature variations between 10 and 80 °C. As such constraints apply to a large number of individual array elements, a 10,000 hours lifetime requirement with <10% variation in output characteristics may be unrealistic, even for a highly advanced technology. Therefore, error correcting schemes involving a sufficient fraction of redundant channels should be developed. Cost effective standardized tests for arrays with a large number of elements have to be developed.

In addition to III-V based emitters, the potential of Si based light sources is also evaluated in a number of research laboratories. Here it has to be pointed out that Si based emitters will have to fulfil the same criteria as III-V based sources, because these features are a set of minimum requirements to make even a partial change from electronic to optoelectronic interconnects attractive for IC designers. For both III-V and Si based devices the main competition is from advanced electronic interconnects. An introduction of optoelectronic interconnects will therefore require similar values of output power, external quantum efficiency, yield, uniformity, reliability and speed etc., from Si based emitters as for III-V devices. Currently there are no Si light sources available which seem capable of fulfilling these requirements. Emitters based on Er-doped Si, Si/Ge dots or silicides show some promise, but still need dramatic improvements in order to come close to applications.

The second half of this article, covering receivers and detectors, as well as potential obstacles to realizing optoelectronic interconnects, will appear in our next issue.

Downloadable copies of the complete white paper are available from the MEL-ARI OPTO Web Site at <http://www.cordis.lu/esprit/src/melop-rm.htm>.

Printed copies are available from the the Office for Official Publications of the European Communities - reference catalog number ISBN 92-828-7762-0. The editors of Compound Semiconductor would like to thank Pierpaolo Malinverni for his help with this article.

Year	1997	1999	2002	2007
Material	GaAs	GaAs	GaAs	GaAs
wavelength (nm)	850	850	850	850
Optical channels	1024 (32 x 32)	1024 (32 x 32)	4096 (64 x 64)	16k (128 x 128)
Modulator size (µm)				
- optical window	11 x 11	15 x 15	10 x 10	7 x 7
- modulator + driver + bonds	15 x 45	15 x 45	10 x 30	7 x 20
Cell pitch (µm)	160	160	System dependent, envisage 125	System dependent, envisage 62.5
(incl. Detector/receiver, logic & mod/driver)				
Channel bit rate (Gbit/s)	0.600	0.600	1.2	2.5
Aggregate bit rate (Tbit/s)	1.2	1.2	5	41
Operating voltage (V)	5.0	3.5	2.0	1.0
Power dissipation per modulator driver (mW)	~ 0.6	~ 0.6	0.3	0.15
Signal delay (electrical input to driver to modulator output) (ns)	~ 2	~ 2	1.4	1
Uniformity:				
mod. contrast ± (%)	~ 20	~ 20	10	10
output power ± (%)	~ 10	~ 10	5	10
mod. delay ±	negligible	negligible	negligible	negligible
Yield (%)	99.9	99.9	99.98	99.995k

Table 4. Projected performance of 2D modulator and (CMOS) driver arrays.



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Ka-Band LMDS MMICs from Infineon

Munich, Germany. Infineon Technologies has announced two complete chipsets manufactured using its 0.13 μm gate (HEMT110) and 0.18 μm gate (HEMT60) GaAs PHEMT technology for Local Multipoint Distribution Service (LMDS) systems. Designed for the 24–27 GHz and 27–31 GHz frequency ranges, both chipsets comprise: a two-stage high-power amplifier offering 27 dBm output power at 1 dB compression (small signal gain of 11 dB); a two-stage medium power amplifier with $P_{1\text{dB}} = 22$ dBm (17 dB small signal gain); a three-stage LNA with a noise figure below 3 dB in conjunction with 20 dB gain; finally, a single balanced mixer with 9 dB conversion loss and frequency multipliers (doubler for 24–27 GHz and tripler for 27–31 GHz).

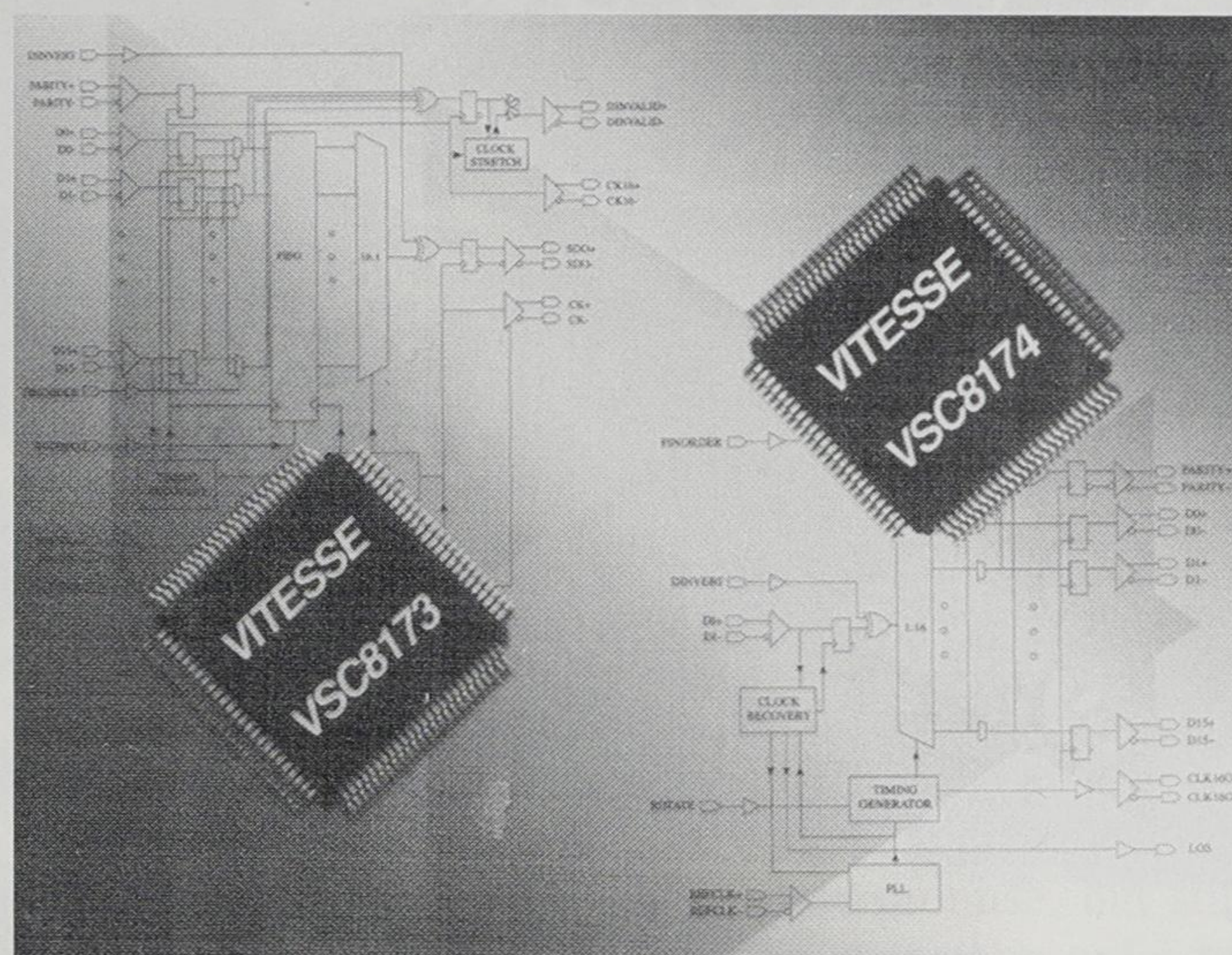
A third complete chipset for 38–42 GHz broadband wireless access systems will be available by beginning of 2001. Infineon says its GaAs PHEMT processing line is currently in transfer from 4- to 6-inch and will be fully operational on 6-inch GaAs wafers by mid-2001.

RFMD 3 V PCS Down-Converter

Greensboro, NC. RF Micro Devices (RFMD) now offers the RF2458, a GaAs HBT-based downconverter for PCS, PHS and WLAN applications that contains a double-balanced Gilbert cell mixer and a balanced IF output. The RF2458's high gain (+14 dBm) makes the device suitable for front-end applications. With a frequency range of 1500–2500 MHz and a power supply range of 2.7–3.6 V, the RF2458 is targeted at CDMA/TDMA/DCS 1900 PCS, PHS 1500/WLAN 2400 systems and microcell PCS base stations.

Vitesse Lowers Cost and Power of 10 Gbps Transmitters/Receivers

Camarillo, CA. The first parts to be manufactured using Vitesse's Colorado Springs 6-inch H-GaAs-V process have been introduced. The company's new 3.3 volt VSC8173 16:1 multiplexer and VSC8174 1:16 demultiplexer 10 Gbps chipset is designed to lower component costs and power requirements for OC-192 and STM-64 applications such as DWDM, undersea and transmission and test equipment. The VSC8173 is a 16:1 multiplexer with clock multiplication unit (CMU) that integrates a high-speed clock output to re-clock data at the laser driver. The VSC8174 companion chip is the demultiplexer that incorporates the clock and data recovery functions. A low value of 50mV for the input sensitivity reduces the overall system cost by improving the low-input signal response.

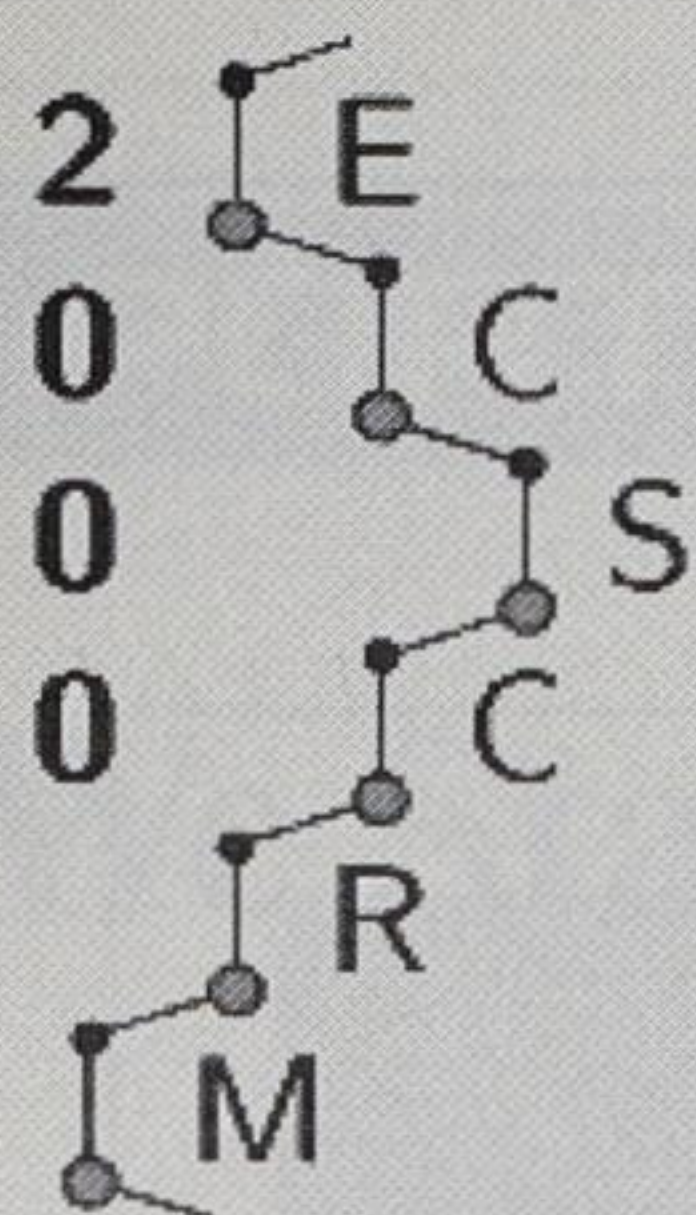


Anadigics Dual-Technology Reverse Amplifier for Digital Cable

Warren, NJ. The ARA2000S12 reverse amplifier from Anadigics uses a combination of GaAs and Si CMOS technology to deliver data to interactive digital cable, cable modems and IP-telephony systems. Featuring a three-wire serial to parallel bus architecture, this device is designed to be compatible with Broadcom, Conexant, and Texas Instruments' upstream modulator solutions. Featuring a +5 V DC supply, the ARA2000 delivers 17 dB of gain. The integrated step attenuator ranges from 0 to 56 dB in 1 dB steps, enabling the device to meet MCNS/DOCSIS requirements.

Boston Laser Telecommunications Diode Module

Boston, MA. Boston Laser Inc. has introduced a compact ($64 \times 27 \times 62$ mm) module for telecommunication applications. Six diodes are coupled to a standard female SMA-905 fiber optic connector for coupling into a 200 μm core, 0.11 NA fiber. The module was designed specifically to optically pump commercially available double-clad EDFA cavities or double-clad Raman fiber-optic amplifier cavities. Operating at 915 and 975 nm, these modules couple up to 10 W of optical power, and contain an integrated laser driver and thermoelectric cooler to maintain pump wavelength, and power feedback control to track pump power.



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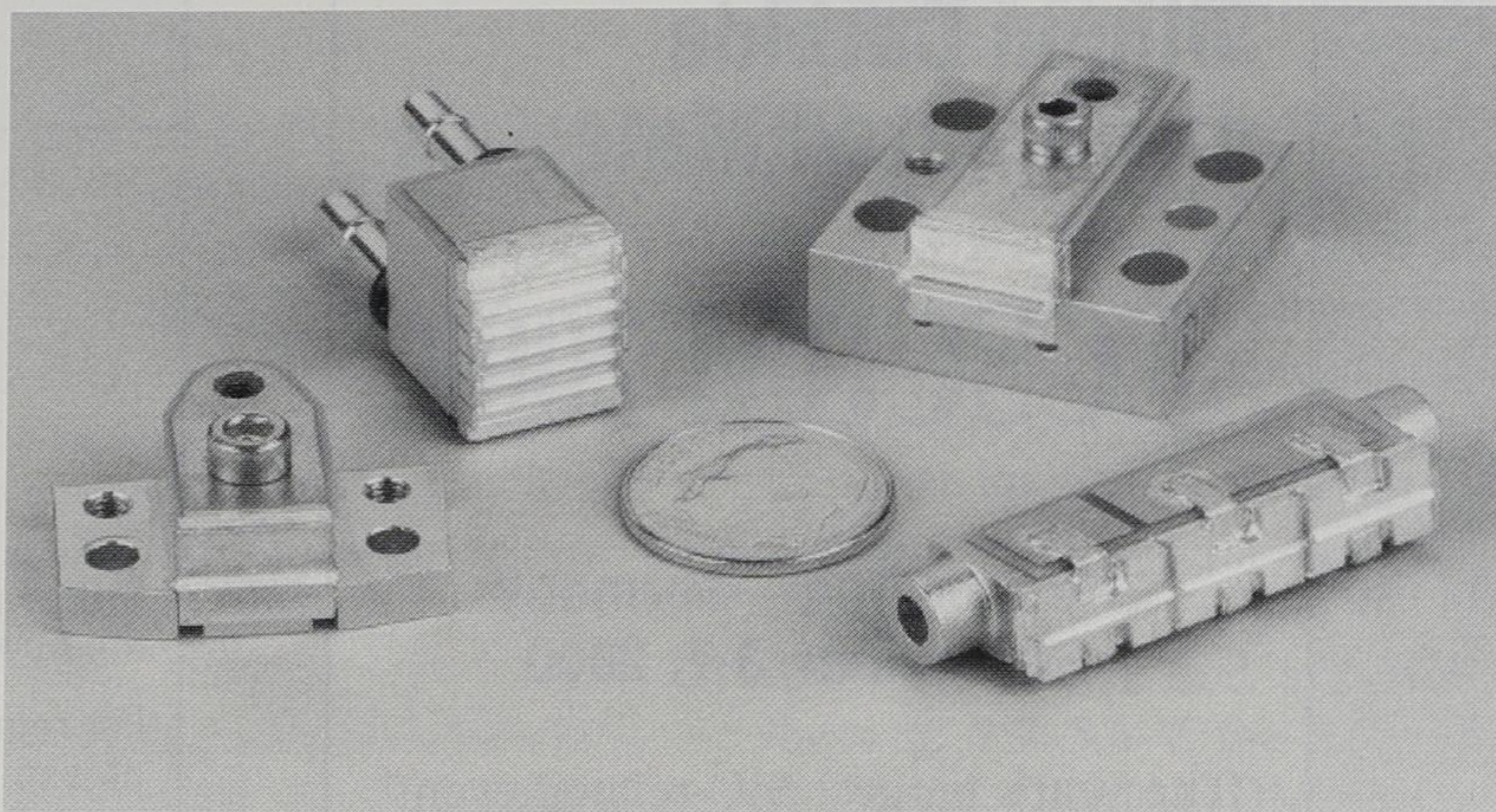
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IMC High-Power Laser Diode Arrays

St. Charles, MO. Industrial Microphotonics Company (IMC) has unveiled a family of $10^\circ \times 1^\circ$ FWHM laser diode arrays consisting of stacks of 2 to 15 bars mounted on a water-cooled heat exchanger. These arrays are capable of CW powers from 32–320 W and QCW powers from 80–600 W. The company's high-power laser diodes cover the 780–1000 nm wavelength range, and are available in packaged and unmounted CW and pulsed formats. Laser diode bars, lensed bars and arrays, fiber coupled modules, and laser diode drivers are also available.



Lucent Announces Optical Transceiver Suite

Allentown, PA. A suite of optical transceivers has been launched by Lucent Technologies Microelectronics Group for use in fiber-optic data communications systems. The NetLight 2417 consists of four transceivers, each 0.5-inch wide and hence 50% smaller than previous generation products, meeting the small-form-factor multi-source agreement previously established by six optoelectronic component manufacturers. NetLight transceivers can be used in communications equipment such as hubs, network interface cards (NICs), routers and switches. The devices support Gigabit Ethernet, Fiber Channel, asynchronous transfer mode (ATM), and synchronous optical network (SONET) applications (from OC-3/STM-1 to OC-48/STM-16 data rates) and use a Fabry Perot (FP) laser and photo-intrinsic negative (PIN) photodetector.

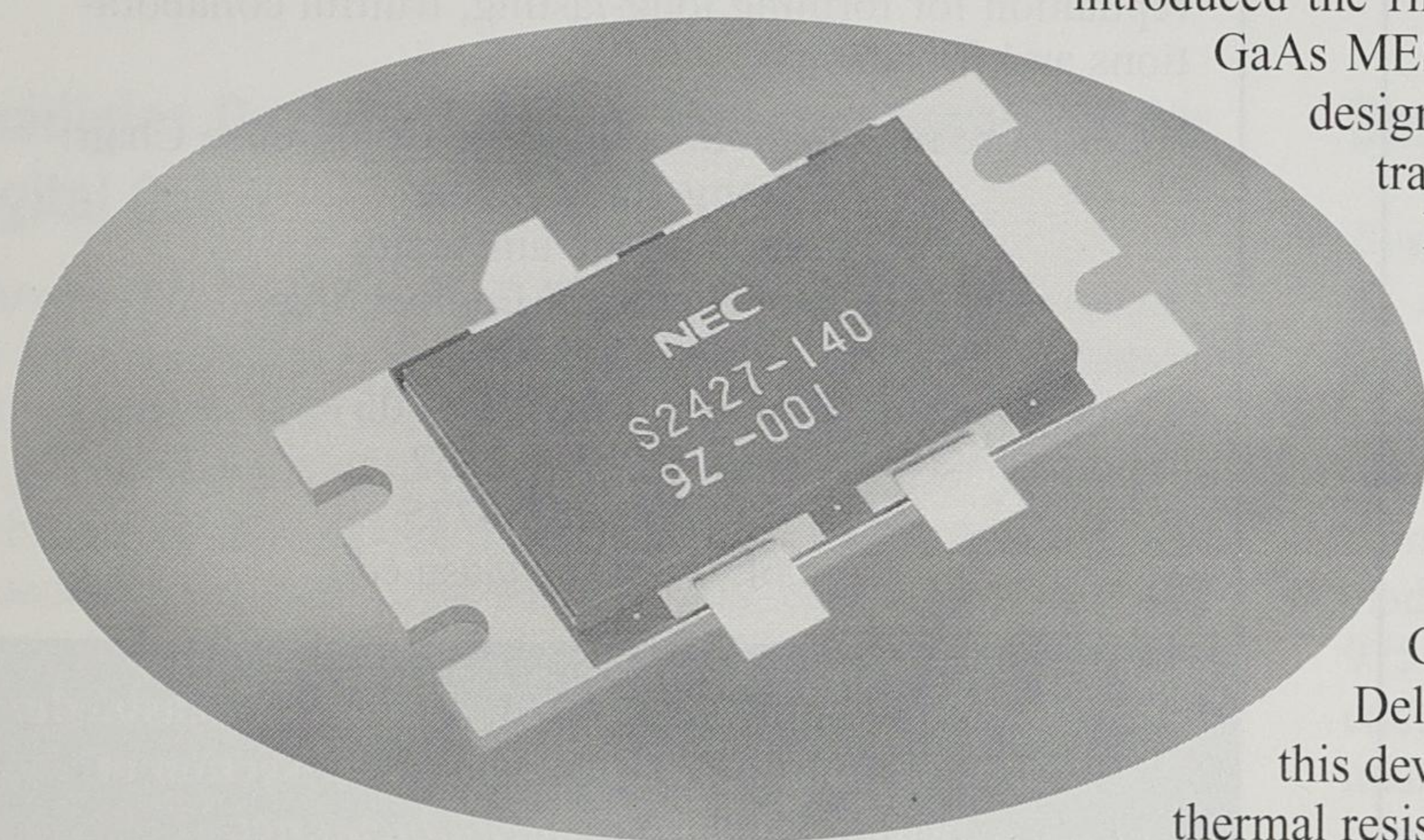
20 GHz Photodetector from Discovery Semiconductors

Princeton, NJ. With the new DSC-R401ER, Discovery Semiconductors has introduced a fiber-coupled photodetector targeting telecommunication system designers working with OC-192 (10 Gbps) systems that use Return to Zero (RZ) format with Forward Error Correction (FEC). Featuring a typical bandwidth of ranging from 100 kHz to 20 GHz, this InGaN PIN and preamplifier provides the low jitter and clean eye diagrams required for front-end bandwidth performance that exceeds 12.3 Gbps by 50%. In addition, this device offers 100 V/W and 2 V_{p-p} linear output.

60 and 140 W MESFETs from NEC/CEL

Santa Clara, CA. CEL, NEC's North American Source for RF products, has introduced the first devices in a planned series of high-power L and S Band GaAs MESFETs. The new NES2427P-60 is a four-chip 60 W version designed to serve as an output stage in high power S-Band transmitter applications such as MMDS/Wireless Internet and Point-to-Multipoint/WLL. The device's primary band lies at 2.5–2.7 GHz, but with modified external matching it can deliver more than 200 MHz of instantaneous bandwidth from 2.1–2.8 GHz. The NES2427P-60 features a P_{1dB} power output (typical) of 48.0 dBm and linear gain of 12 dB.

The NES2427P-140 partially matched, twin-transistor GaAs MESFET is designed to serve as an output stage in PAs. Delivering 140 W of output power and 200 MHz of bandwidth, this device features a typical PAE of 41%, linear gain of 9.5 dB and thermal resistance 0.4 °C/W.



We Stand Corrected

MARIE MEYER

It is hard to say where the dividing line between a "correction" and an out-and-out rout lies. But somewhere in that gray area is where the U.S. stock markets now sit. And while the stocks in our Portfolio did no worse or better than the market as a whole, the last eight weeks will not be remembered fondly by anyone in the industry.

All of the Portfolio companies are now trading below their historic highs. The amount of the drop varies widely, and with no apparent pattern. For example, shares in JDS Uniphase are down 44%, but SDL and Ortel shares are down less than 15%. Conexant has been hit the hardest - as this issue went to press they were trading at \$44, which is down 66% from their 52 week high. The other Portfolio companies that are now trading at less than half their former value are Tegal, Anadigics, Vitesse, Agilent and Emcore. Buried in all this bad news is the fact that many of the Portfolio companies continue to report record earnings. But this somehow seems oddly appropriate, given that the wild run-up in share prices last year often seem divorced from real-world considerations.

Here is a brief round-up of the results for the first quarter of 2000.

GaAs Companies

Alpha Industries reported net sales of \$56.9 million, up 66% compared with the same period last year. Income was \$9.7 million, up 74% over the year ago quarter.

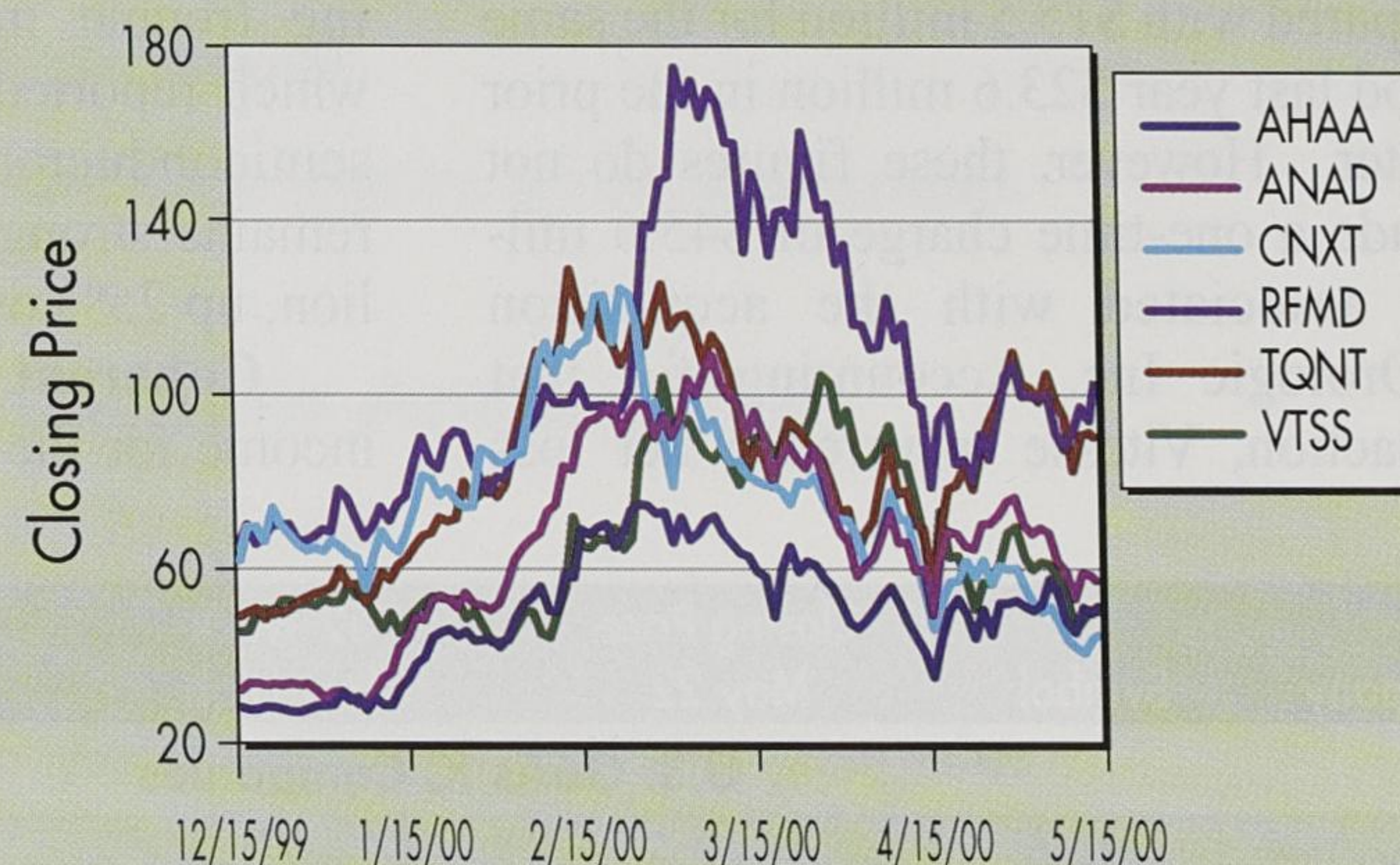
Sales for **Anadigics** in the first quarter reached \$43.0 million, a 72% increase over the first quarter of 1999. Net income was \$5.7 million, compared with \$1.2 million in the year-ago quarter.

For the quarter ended March 31 **Celeritek** reported revenues of \$15.5 million, compared with revenues of \$10.1 million for the same quarter in 1999, an increase of 53%. The company reported net income of \$92,000, compared with a net loss of \$1.9 million for the same period a year ago.

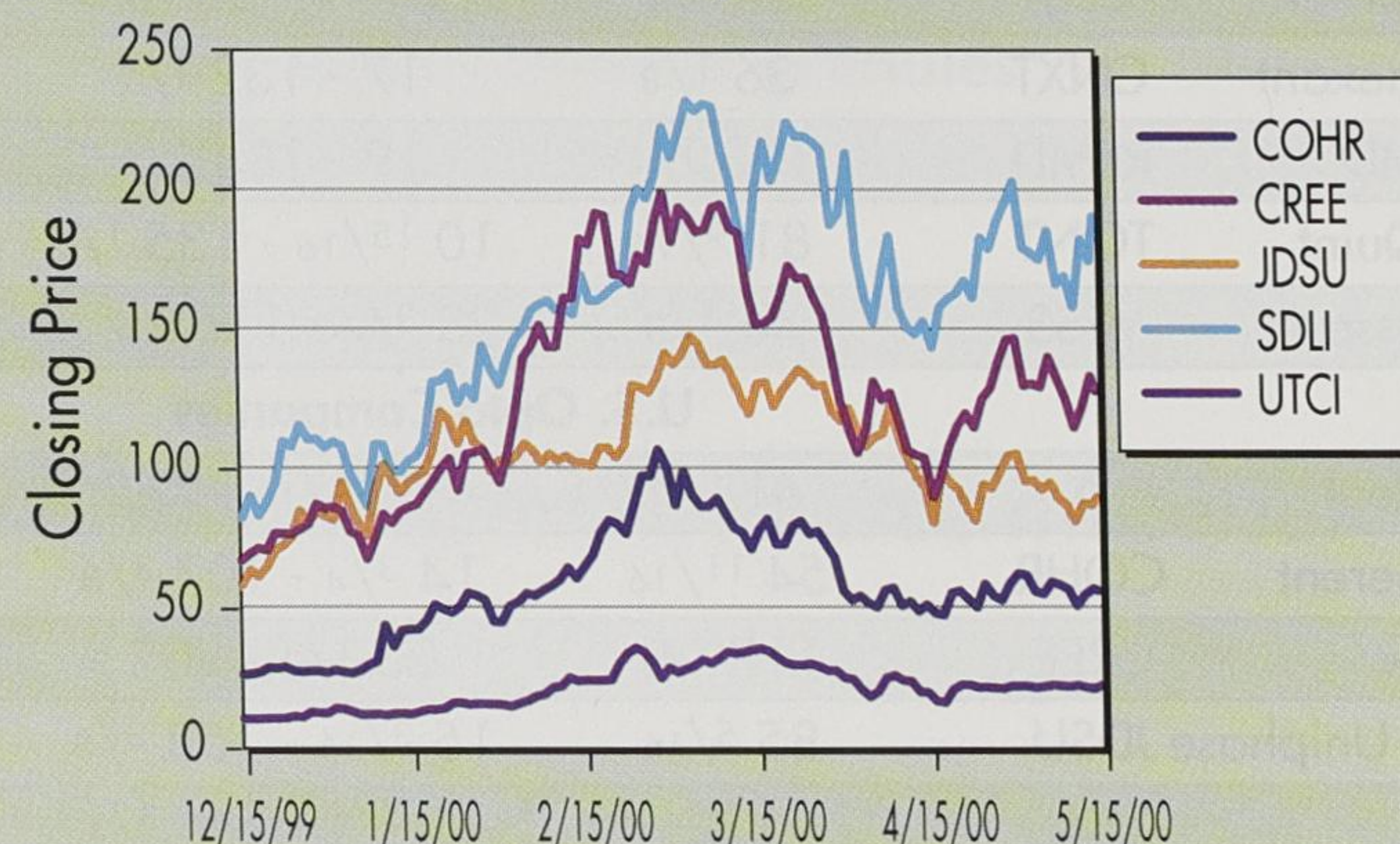
Conexant reported revenues of \$501.7 million, up 58 % over the same period in 1999, but down slightly from the previous quarter. Net income for the quarter was \$47.1 million, compared with \$8.9 million in the year-ago period and \$53.3 million in the previous quarter.

RFMD's revenues for the quarter were \$84.8 million, an increase of 50% over the corresponding quarter of 1999 and an increase of 15.9% over the previous quarter. The increase was attributed to continued strong demand for RFICs from the handset industry. Gross profit rose 96.6% to \$42.0 million, and increased 18% over the December quarter. This was attributed to increased production from the company's GaAs HBT wafer fab.

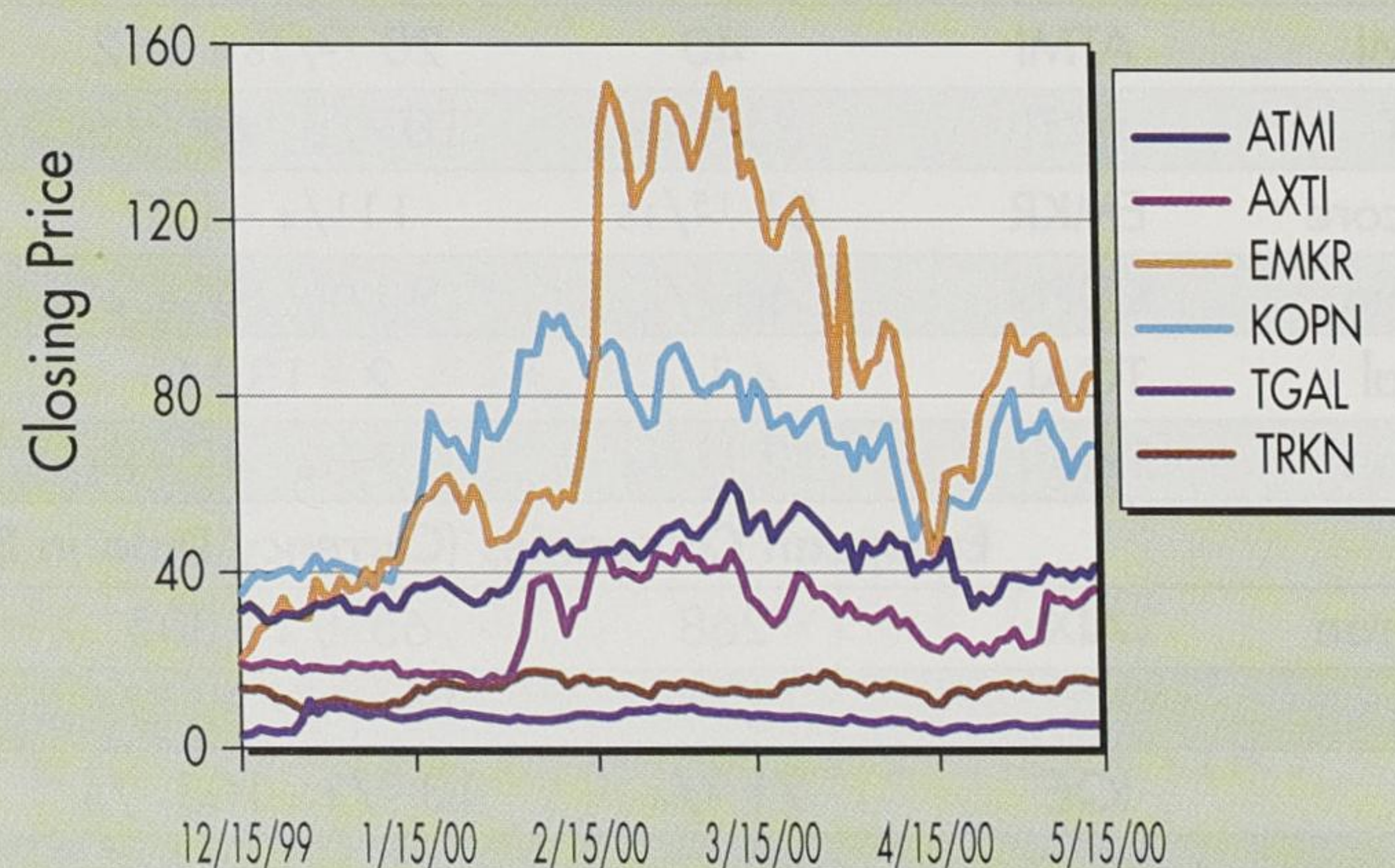
GaAs Companies



Opto Companies



Materials and Equipment Companies



Net income was \$14.6 million, compared to \$9.9 million for the year-ago quarter and \$12.6 million for the previous quarter.

Revenues at **TriQuint** increased 76% to \$59.3 million from \$33.7 million in the comparable period of 1999. Net income rose 237% to \$10.8 million.

Vitesse reported revenues of \$100.2 million, an increase of 50% over the year-ago quarter and up 12% over the previous quarter. Net income was \$27.0 million, compared with \$15.5 million for the same period last year \$23.6 million in the prior quarter. However, these figures do not include a one-time charge of \$45.6 million associated with the acquisition of Orologic Inc. Accounting for that transaction, Vitesse incurred a net loss

of \$18.6 million for the quarter ended March 31, 2000.

Opto Companies

Agilent Technologies reported that revenue rose to \$2.5 billion, up 24 percent. Earnings, however, declined 11% as the company incurred extra costs relating to the spin-off from its parent, Hewlett-Packard. Agilent's earnings were \$214 million. The company is also experiencing trouble in its healthcare business, which reported a drop in revenues. The semiconductor operation, however, remains strong, with sales of \$497 million, up 25% over the year-ago period.

Coherent reported sales and net income for the quarter of \$136.7 million

and \$8.4 million respectively. Sales increased by \$20.1 million (17%) and net income increased \$3.0 million (56%), compared to the year-ago period.

Cree's revenue for the quarter was a record \$28.3 million, a 19% increase over the previous quarter and a 77% increase over the same period last year. Net income increased 171% to \$9.1 million compared to \$3.4 million in the year ago period. The company reports that their new high brightness LEDs now account for over 80% of Cree's LED shipments. High brightness LED shipments nearly doubled from the December to March quarters.

JDS Uniphase reported sales for the quarter of \$394.6 million, and net income of \$85.8 million. The sales figure represents a 40% increase over the previous quarter and 155% more than the year-ago results (consisting of the pre-merger results for JDS Fitel and Uniphase Corporation). But, as always, JDSU had substantial acquisition-related charges that needed to be accounted for in the quarter. So once all the one-time charges related to their purchase of OCLI are factored in, the company showed a loss \$240.9 million for the quarter.

Revenues at **SDL** were a record \$72.2 million, and net income of \$17.0 million was reported. The revenue figure represents an increase of 92% over the year-ago quarter. Revenue from fiber optic communications was up 163%.

Uniroyal Technology reported operating income in the first quarter of \$3.1 million. Sales for the company's Optoelectronics Division were \$902,000, compared to \$85,000 in the prior year period. The segment began shipments of LEDs from its Tampa, Florida facility during the quarter. The Optoelectronics Division reported a loss of \$3.1 million which reflects the continued start-up costs related to the ramp-up of production of high brightness LEDs.

A Change to the Table

There is one change to the table of companies in this issue. Ortel, which was recently acquired by Lucent, is no longer a separately listed company and therefore has been dropped.

Company	Symbol	Closing Price May 22	52 Week Low-High	Market Cap*	P/E Ratio**
U.S. GaAs IC Companies					
Alpha Ind.	AHAA	41 5/16	16 - 78 1/4	1.643B	70
Anadigics	ANAD	37 3/4	15 1/4 - 112 1/8	1.123B	147
Celeritek	CLTK	54 5/8	4 3/4 - 85 1/4	511.3M	N/A
Conexant	CNXT	36 1/8	17 - 132 1/2	7.851B	N/A
RFMD	RFMD	103 1/4	19 - 184 1/2	8.240B	176
TriQuint	TQNT	81 9/16	10 15/16 - 135 1/2	3.131B	110
Vitesse	VTSS	46 1/8	23 3/4 - 115 11/16	7.589B	177
U.S. Opto Companies					
Agilent	A	61 3/4	39 13/16 - 162	27.911B	47
Coherent	COHR	54 11/16	14 3/4 - 107 3/8	1.374B	88
Cree	CREE	117 1/2	23 1/2 - 202	3.894B	165
JDS Uniphase	JDSU	85 5/16	15 3/16 - 153 3/8	66.719B	N/A
SDL	SDLI	192	21 5/8 - 244 3/4	14.698B	376
Uniroyal Tech.	UTCI	20 5/8	4 5/16 - 36 7/16	510.3M	70
U.S. Semiconductor Materials & Equipment Companies					
ATMI	ATMI	40	20 13/16 - 162	1.184B	51
AXT	AXTI	35 1/16	10 7/8 - 49 9/16	654.2M	203
Emcore	EMKR	81 15/16	11 1/4 - 173	1.358B	N/A
Kopin	KOPN	66 3/4	9 1/8 - 99 3/4	2.099B	705
Tegal	TGAL	4 3/4	2 - 13 1/2	52.8M	N/A
Trikon	TRKN	13 13/16	1 13/16 - 17 1/4	146.9M	N/A
European Companies (Currency Data in Euros)					
Aixtron	AIX	268	65 3/4 - 305	4.2B	250
Filtronic	FTC	16 3/4	16 3/4 - 37 7/8	1.2B	42
IQE	IQE	71 3/4	13 3/4 - 108 1/8	975M	100
Picogiga	PICO	99 1/2	10 5/8 - 134	157M	100

*Market Capitalization = # shares x current share price

** Price/Earnings Ratio = (income for last 4 quarters ÷ # shares) ÷ current share price



The Wafer Technology Product Range

✓ *Gallium Arsenide*

Semi-insulating : Undoped

n-type : Si or Te doped

p-type : Zn doped

Polycrystalline ingots, slices or granules

✓ *Indium Antimonide*

n-type : Te or undoped

p-type : Ge doped

Polycrystalline ingots, slices or granules

✓ *Indium Arsenide*

n-type : S or undoped

p-type : Zn doped

Polycrystalline ingots, slices or granules

✓ *Zinc Germanium Diphosphide*

Polycrystalline ingots for non-linear
optical applications

✓ *High purity indium metal*

✓ *Indium Phosphide*

Semi-insulating : Fe doped

n-type : S, Sn or undoped

p-type: Zn doped

Polycrystalline ingots, slices or granules

✓ *Gallium Antimonide*

n-type : Te doped

p-type : Zn or undoped

Polycrystalline ingots, slices or granules

✓ *Gallium Phosphide*

Polycrystalline ingots, slices or granules

✓ *High purity MBE source material*

✓ *High purity gallium metal*

✓ *SiC wafers*

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For more information on any of the products visit the
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