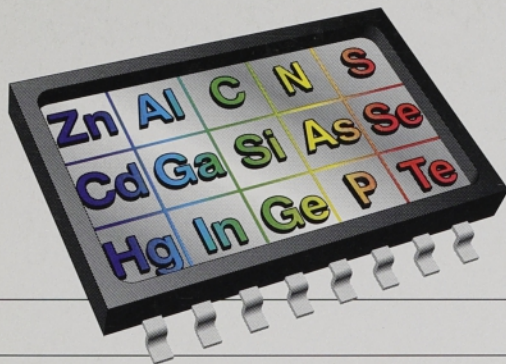




COMPOUND

SEMICONDUCTOR

August 2000

Volume 6 Number 6

- *CIBC World Markets on Analog GaAs Sales*
- *JDS Uniphase on 980 nm Pump Lasers*
- *Fraunhofer ISE on Solar and TPV Cells*
- *Altitudon on Tunable Lasers*



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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 September 15. The deadline for the subsequent issue is October 27. Interested parties should contact:

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Managing Editor
COMPOUND SEMICONDUCTOR Magazine
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Beverly, MA 01915
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R&D Engineer: Research next-generation products, develop processes and transfer processes to Engineering. The ability to interact with applications engineers and manage R&D projects is critical. A strong understanding of crystal growth, materials and devices, and a Ph.D. in E.E. or related field is desirable.

EpiWorks is located in Champaign, Illinois. Employees receive **significant** stock option compensation and a competitive salary/benefits. Fax resumes to EpiWorks, Inc at 217-373-1591.

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KEY ACCOUNTS MANAGER

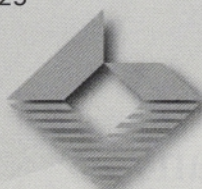
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SENIOR PROJECT MANAGER

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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Microfabrication Opportunities at Picometrix

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Advanced Device Development Scientist You will be responsible for developing high-speed optoelectronic devices, including InGaAs APDs and waveguide detectors. You will be a key player in our advanced device team, working with our microwave modeling, epitaxial and microfabrication scientists to develop innovative products. *Requires an M.S. or Ph.D. who is highly motivated and a team worker with five or more years experience in high-speed device processing and design.*

Microfabrication Production Manager You will be responsible for leading a team of process technicians in a high-growth, multi-product microfabrication production environment. Your strong organizational skills will enable us to control costs and maximize throughput in the fabrication of high-speed devices for telecommunications products. *Requires a B.S. or higher in a technical discipline or business/materials management and three or more years experience in semiconductor production.*

Microfabrication Process Engineer You will be working closely with our device scientists in developing next-generation, high-speed optoelectronic products. You will be involved with all aspects of III-V device process technology, including mask design, photolithography, metal and dielectric deposition, and wet/dry processing. *Requires a M.S. or higher with three or more years experience in III-V materials and device fabrication.*

Reliability and Quality Assurance Engineer You will be responsible for implementing and running our III-V device characterization and reliability facility, including device burn-in and screening and Bellcore quality assurance. You will work closely with our team of scientists to design test procedures and develop reliability and burn-in protocols. *Requires a B.S. or higher with three or more years experience in reliability and quality assurance.*

E-mail your resume to careers@picometrix.com or fax to (734) 998-3474. You can also mail to Picometrix, Inc., P.O. Box 130243 Ann Arbor, MI 48113-0243. Picometrix is an equal opportunity employer.



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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.

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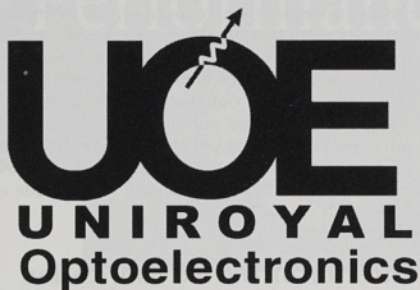
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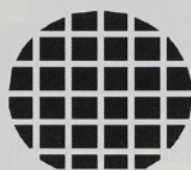
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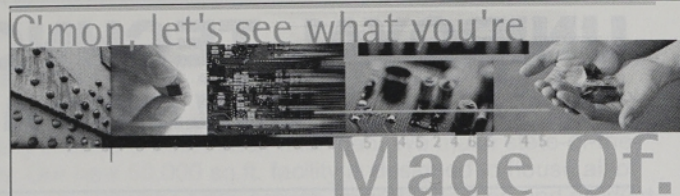
Applied Optoelectronics, Inc., a Houston, TX manufacturer of infrared and mid-infrared semiconductor lasers and photodetectors is seeking qualified applicants for the positions of **Engineer** and **Scientist**.

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Responsible for the transfer and development of GaAs wafer fabrication process technology related to photolithography and dry etch in support of a 150mm wafer size conversion start-up activity. Key activities include process tooling specification, acceptance and qualification, and existing process transfer and development. Will interface with quality, facilities, EH&S, process engineering and development groups to insure all process yield and throughput goals are met. Must have an in-depth understanding of yield/process improvement techniques including SPC, DOE and statistical analysis. Good communication, interpersonal and team working skills are essential. Ideal candidate will have a BS/MS in Chemical Engineering, Electrical Engineering, Microelectronics, Material Science or Physics and 5+ years' GaAs wafer fabrication process experience including supervisory responsibility.

Fab Process Engineering Positions

We are currently looking for shift sustaining engineers for B, C and D shift for our GaAs fab. Individual will be responsible for general sustaining of photo, etch, and metals, as well as be responsible for addressing any electrical issues that occur on their shift.

We are also looking for a Wet Etch and Metals engineer. The Wet Etch engineer should come from a GaAs background and be intimately familiar with both the tool set (Semitool, SSEC, Automated Wet benches, etc.) and the process (recess etch, liftoff, resist strip, etc.). The Metals engineer can come from either a GaAs or Silicon background and should be very knowledgeable in the area of evaporation and sputtering. This individual will be responsible for metals in both our GaAs and Silicon fabs. Both candidates should have a minimum of a B.S. in a technical field and 3+ years experience.

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Equipment Engineer Photolithography Dry Etch

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GaAs Fab Yield Engineer

This individual will be responsible for driving the yield improvement activities in the GaAs Fab. Responsibilities include base lining current on wafer yield; developing a yield model for power amp developing a "Maverick Lot" program; establishing correlations between processes, tools and environment; and generating weekly Cusum and/or other yield analysis tools. Should have experience in GaS MESFET and/or PHEMT, experience working on yield improvement, and a thorough understanding of what needs to be done to improve yields. Minimum of a BS in Material Science, Electrical Engineering. A minimum of 4 years' experience working on yield improvement and strong project leadership skills are necessary.

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PROCESS TECHNICIAN

Responsible for supporting Engineers in the development and fabrication of next generation microwave and millimeter-wave compound semiconductor devices and circuits. Duties include the operation of photolithography and/or wet/dry etching equipment and/or deposition equipment. Requires an AS, strong attention to detail with keen observation and meticulous record keeping skills, and hands-on laboratory experience. Previous wafer fabrication experience desired.

PROCESS ENGINEER

Responsible for development and fabrication of next generation microwave and millimeter-wave semiconductor devices and processes. Duties include support of the design of process development experiments, as well as performing and sustaining routine process steps such as photolithography and wet/dry etching. Requires a BS, 2 years of hands-on laboratory experience, and strong attention to detail with keen observation and meticulous record keeping skills. Previous experience with basic semiconductor device physics and wafer fabrication techniques is desirable.

TEST TECHNICIAN

Responsible for the testing and modeling of state-of-the-art microwave circuits and devices. Requires an AS and 2 years of directly related experience. Previous experience with Libra and a strong understanding of device physics and modeling are highly desired.

TEST ENGINEER

Responsible for circuit/device measurements and characterization of state-of-the-art microwave circuits and devices. Requires an AS and 4 years of experience in microwave test and measurement of devices and circuits; BS preferred. Programming skills (Labview, Visual Basic, C) are also desirable.

MATERIALS ENGINEER

Responsible for the design and conduct of epitaxial MBE growth experiments for metamorphic HEMT and wideband semiconductor devices. Duties include the operation of an MBE machine, planning of growth experiments and interpretation of material characterization results. Requires a minimum of a MSEE with 3 years of directly related experience.

SENIOR DESIGN ENGINEER

Responsible for design of next generation high-efficiency microwave and millimeter-wave MMIC power amplifiers, LNAs, phase shifters and switches using various device technologies including pHEMT, metamorphic HEMT and wideband gap semiconductors. Requires a BS and 6 years of directly related experience; MSEE preferred. Previous experience with MMIC design tools (Libra, Momentum, Cadence layout) is also required.

DEVICE DESIGN ENGINEER

Responsible for the design and fabrication of next generation microwave and millimeter-wave compound semiconductor devices. Duties include the design and implementation of material, process and device development, and characterization experiments. Requires a BS and 3-7 years of directly related experience. Experience with III-V compound semiconductors is desirable.

SYSTEMS ENGINEER

Responsible for the development of OFDM radio architectures and designs within a multi-disciplinary team. Provide system design expertise in the area of Wireless Networking technology and lead evaluation of algorithms and timing trade-offs for OFDM radios. A BS in a technical discipline and 7+ years of directly related experience are required. Knowledge of OFDM, 16/64 QAM modulation, DSPs, forward error correction schemes, Viterbi decoders and digital and analog conversion schemes is necessary. Familiarity with Matlab, PCI, Cardbus interfaces and ASIC development is a plus.

PRINCIPAL EE DESIGN ENGINEER

Responsible for GaAs IC or RF component designs used in commercial applications such as cellular telephones and base stations. Work closely with an integrated team of professionals from layout wafer processing, packaging and testing to take designs from concept through pre-production phases in an environment where time-to-market is of critical importance. A BSEE and 5+ years of experience in MMIC or RF hybrid circuit design using linear and non-linear simulators are required. Demonstrated experience with HP Libra or similar design tools, pHEMT, or HBT based power amplifiers is highly desirable.

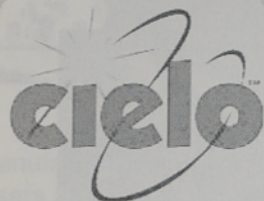
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Lead VCSEL device design activities at Cielo! You'll assist in device characterization, providing support for process development, test development, reliability development, and module performance characterization. Good opportunity for management role! Requirements include a Ph.D. in EE, Physics or related field; 4+ years' experience in optoelectronics, and a solid understanding of VCSEL dynamics, operation and impact on module performance. Preferred candidate will have fabrication and characterization of optoelectronic compound or semiconductor devices experience.

VCSEL Development Engineer

Develop Vertical Cavity Surface Emitting Laser materials for future Cielo products! Responsibilities include materials growth, device characterization, and data analysis; programming and computer modeling; and assisting with operation and maintenance of an MBE system. Requirements include a B.S. in EE, Mat'ls Sci, Physics, or equivalent experience; knowledge of semiconductors and optoelectronic devices; 2+ years' laboratory and instrumentation experience; experience in UHV systems and repair of electronic equipment. Experience in semiconductor materials characterization and optoelectronic device fabrication and characterization preferred.

VCSEL Device Engineer

Participate in VCSEL device design activities including device characterization, process development, reliability characterization, and generating reports of the results. We require a Ph.D. in EE, Physics, Materials Science, or a related field, as well as experience in the development of VCSEL devices and materials. The preferred candidate will additionally have fabrication and characterization of optoelectronic compound or semiconductor devices experience.

Process Development Engineer

Develop new processes and improve on our existing proprietary Vertical Cavity Surface Emitting Laser (VCSEL) manufacturing technology. The Process Engineering group is responsible for the process development and transition to production of exciting new optoelectronic devices that enable the company's high-speed telecom and datacom products. We require a Bachelor's degree in Electrical or Chemical Engineering or Materials Science and 5+ years of semiconductor processing experience in a manufacturing or development environment. Preferred candidates will additionally have direct experience with GaAs processing technology.

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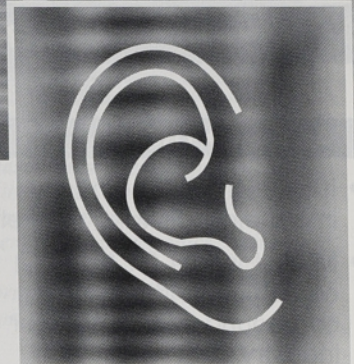
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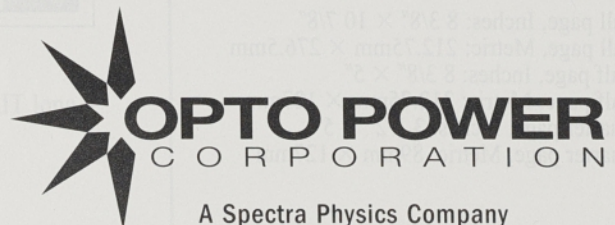
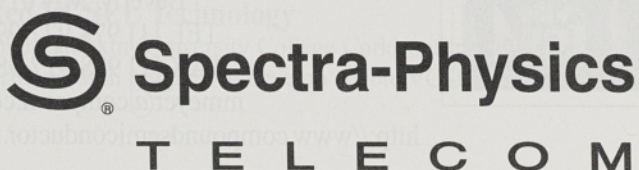
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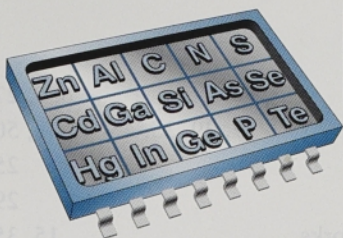
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COVER STORY—FIBER-OPTIC COMPONENTS

6 Consolidation and Investment in Fiber-Optic Components Reaches New Heights

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Consolidation and Investment in Fiber Optic Components Reaches New Heights

The major manufacturers of fiber optic components have been announcing new acquisitions and investments at a torrid pace this summer (see box), spurred on by demand that is growing at double and, in a few cases, even triple digit rates. On the whole, the worldwide market for fiber optic components is growing at >40% per year, and according to market-research firm RHK, it will reach \$23 billion in the next three years—see chart, below. Compound semiconductors currently make up somewhere between a third and half of that market, with the rest comprised of passive components and active components made out of other materials, such as Si photodetectors and LiNbO₃ modulators.

There are now four major suppliers—see chart, next page. JDS Uniphase is generally considered the biggest, and its position will only be improved if its pending mega-merger with SDL is approved. However, Nortel recently revealed that its components operation is much larger than previously believed. The issue turns on the prices assigned to Nortel's components, given that 80% of their component production is consumed internally. If third party prices are used, Nortel says their fiber optic components business will have \$2.5 billion in revenue in 2000, and grow by 200% from 1999 levels. Which means that Nortel's component operation is already as large as JDSU and SDL combined, and is growing faster.

After Nortel and JDSU, the next largest suppliers are Lucent and Corning. Like Nortel, Lucent has a large networking equipment business and a lot of captive component production.

However, that situation will change over the next 12 months, as Lucent has announced that it is spinning off its semiconductor operation—see below. Corning, like JDSU, is a merchant supplier. There are also 10–12 medium-sized suppliers, with projected component sales in the \$50–\$500 million range for 2000.

This is an industry where size matters, to gain buying power on the supply side and leverage on the customer size. Size also implies greater access to investment capital, an important factor when customers are screaming for more production capacity and accelerated R&D. But this is also an industry that has seen more than its share of merger and acquisition activity in recent years. As a result, there are not a lot of eligible partners left.

JDS Uniphase & SDL

It is only in this context that one can make sense of JDS Uniphase's decision, announced on July 10, to pay \$41 billion for SDL. The price is 142 times SDL's sales for the last twelve months, and the deal is the biggest ever in the network equipment industry.¹

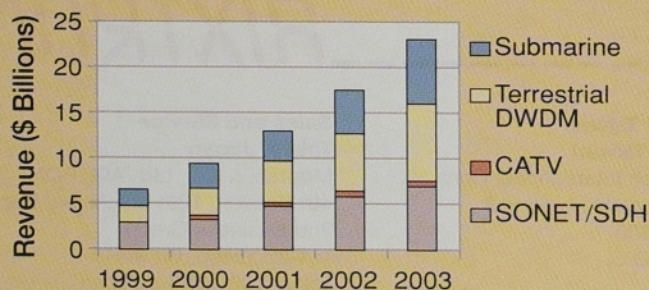
The transaction still faces review from the U.S. Department of Justice. While the response from the industry thus far has been mostly positive, executives at Nortel have not ruled out trying to block the deal. "We are concerned at the level of consolidation in the vendor community that's going on," said Nortel CEO John Roth on a conference call. Nortel is JDSU's second largest customer.

The one area where JDSU and SDL directly overlap each other is in the production of 980nm pump laser chips. Until recently, these two companies were virtually the only players in this field. However, analysts at Merrill Lynch believe that there are now more than 10 suppliers, including ADC, Corning, and Mitsubishi. But the JDSU/SDL combination would still have what Merrill Lynch describes as "a strong majority share" of this critical component.

Headlines from July & August

- JDS Uniphase is acquiring SDL for \$41B
- Lucent will spin-off its Microelectronics Group, valuation likely to reach \$100B
- Nortel to invest \$1.2B to triple opto capacity; considering spin off
- Corning to invest \$270M to increase laser output 6×
- Alcatel to create a "tracking stock" for its Optronics subsidiary

Worldwide Fiber Optic Component Market



¹ It is more than double the previous record holder—Lucent's \$20 billion acquisition of Ascend Communications, a manufacturer of routers, in 1999. Interestingly enough, the third-largest deal was JDSU's \$18 billion acquisition of passive component manufacturer E-TEK Dynamics, which received final regulatory approval in July.

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If the deal goes through, SDL will operate as a wholly owned subsidiary of JDSU. The principals are hoping to close the deal in December. Both companies have been growing at >40%, and their combined sales for 2000 would top \$2.5 billion. SDL would add 1,700 employees to JDSU's existing base of 17,000 and the combined entity would have 4.4 million square feet of manufacturing capacity in 39 locations around the world.

Inside of Lucent's modestly successful networking business is a potentially very successful semiconductor business waiting to get out.

What's Next for Nortel?

Hard on the heels of the JDSU/SDL merger came the news that Nortel and Corning were discussing merging their fiber optic component operations. The resulting company would have been a stunner, with the equivalent of \$3.5 billion in fiber optic component sales in 2000. However, talks were broken off shortly after they began, reportedly over disagreement over which company would control the new entity.

So what is next for Nortel? As noted above, they are taking steps to gain more recognition for the size and scope of the fiber optic components operation. This could be preparation for spinning the business off as a separate company, following Lucent's lead.

Nortel's systems business is growing rapidly, but it could possibly do even better if it wasn't held back by supplier shortages. Part of the solution lies internally. The company announced on July 24 that it is investing \$1.2 billion to more than triple its own production of fiber optic components. Nortel CFO Frank Dunn said that the company is confident in its supply of components for this year, but that expansion is necessary to meet demand 15–18 months from now. 80% of Nortel's current component production is captive. The company hopes to raise merchant sales to about 40% of total component revenue when the expansion is complete.

If Nortel were to spin-off its components business, the resulting company could raise more funds for acquisitions and expansion, while its parent company would have more cash avail-

able for its own aggressive acquisition strategies. Roth told the Canadian *Globe and Mail* newspaper that Nortel would still want to maintain majority control of the new company, if it came about, but that there would be no barriers to the spin-off

selling products to Nortel competitors. Roth also said that the highly profitable and fast-growing division would generate a much higher market valuation on its own than if it remained within Nortel. That would allow the new company to

use its valuable stock as a "powerful weapon" to make acquisitions more cheaply than if Nortel did the deals itself. The new company would then be able to supply Nortel with more components for the network operation.

Analysts agree that if the spin-off occurs, it will be valued in excess of \$100 billion.

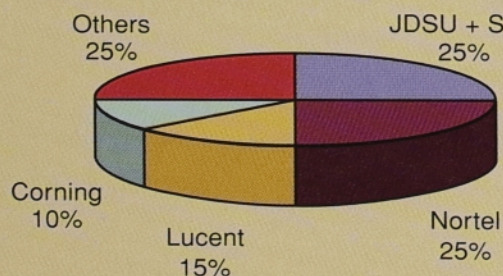
Lucent Microelectronics

While Nortel mulls over a spin-off, Lucent has already committed to doing one. On July 20, 2000, Lucent announced that it would float its microelectronics division as a separate company. Around 20% of the company will be offered in an IPO in the first quarter of next year. This deal also carries a potential valuation of more than \$100 billion.

Lucent reported \$1.8 billion in sales for the microelectronics group in the June quarter, up 38.5% over the previous year. Analysts estimate that Lucent's fiber optic component sales are up 80% over 1999, and will reach \$1.5 billion in 2000. The new company will be unique among the major fiber optic component suppliers because it is also a top supplier of silicon ICs for a variety of communications applications. "It will be the only stand-alone component company with the ability to marry the worlds of silicon and optical on its own," said Richard McGinn, Lucent Technologies CEO. Lucent reports that the new company will be the worldwide leader in communications semiconductors, ranking No. 1 in digital signal processors (DSPs) for wireless networks, ICs for SONET and SDH optical networking systems, wired communications ICs, modem ICs for laptop computers and system-on-a-chip solutions. Lucent says the company will also lead the optoelectronics industry in manufacturing automation, modulators for 10 and 40 gigabit-per-second optical networking systems, submarine optoelectronics, and a variety of communications lasers.

So why does Lucent want to spin off this unit? According to McGinn, "this move will unleash the shareholder value of our microelectronics business, whose success will now be more fully recognized outside of Lucent's larger communications networking systems business." In other words, inside of Lucent's modestly successful networking business is a potentially very successful semiconductor business waiting to get out. This move also removes conflicts of interest that may be putting a damper on component sales. More than 75% of the division's current rev-

**Fiber Optic Components
Market Shares of Leading Manufacturers**



venues come from merchant sales, which means that it often sells to Lucent's competitors, setting up conflicts of interest. "If you're selling to Ericsson, Nortel, Cisco or others, they're unlikely to give you the business they want to give you if you're part of a company that has a Lucent logo on it," McGinn said at a press conference. "When it has full independence, you'll see continued growth in the business."

The new company will be headquartered in Allentown, PA, and will employ more than 16,000 people in 105 locations worldwide. John Dickson, who currently heads the Microelectronics

group, will continue on as the new company's CEO. Over the last 18 months, Lucent has invested \$1 billion in expanding its microelectronics manufacturing capability. [For more, see page 13.]

Corning

Corning may have been left at the altar by Nortel, but they don't need any sympathy. Company-wide revenues are up 80% and income is up 100% over last year. "Corning has truly emerged

Selected Fiber Optic Component Manufacturers

Company*	Market Cap	Last Q Sales	2000 FOC Sales**	FOC Product Line Includes:	Notes
Alcatel	\$65B	\$7B	\$400M	Mainly active components, including 980nm & 1480nm pumps, tunable lasers, photodetectors and optical amplifier subsystems.	Creating a "tracking stock" for its optical components subsidiary, Alcatel Optronics, with a tentative valuation of \$40B—almost 1/5 th the total value of Alcatel. FOC sales projected to grow >60% in 2001.
ADC	\$27B	\$709M	\$400M	Mostly passives (splitters, couplers, isolators, etc.).	Acquisitions of Spectracom in 1999 (pump lasers) & Altitun in 2000 (tunable lasers) brings ADC into the active component market. Recently began shipping 980nm pumps, expected to begin shipments of tunable lasers in near future.
Corning	\$74B	\$1.78B	\$1B	Pump and transmit lasers, PINs and APDs. EDFA modules, wavelength add/drop multiplexers, couplers for submarine cables.	FOC sales up 100% over last year. Investing \$270 million for a 6× capacity increase at Lasertron. Pitted against JDS Uniphase as the #2 merchant supplier.
Furukawa Electric	\$18.5B	NA***	\$460M (FY 2000)	>80% of opto sales come from 1480nm lasers; also makes Raman lasers and passive components such as gain equalizers and FBG modules.	Supplies 70% of the world's 1480nm pump lasers; spending \$90 million to double production capacity to 100,000 units per month. Owns 16% of JDSU. Often overlooked, as FOCs are mixed in with 55 other Furukawa subsidiaries. FOC sales target for FY 2001 = \$920 M.
JDS Uniphase	\$90B	\$525M	\$2.5B	Virtually every type of active and passive component.	Growth by acquisition in active components—IBM Laser Enterprise, Philips Optoelectronics, Epitaxx, plus the pending mega-merger with SDL. Recent E-TEK acquisition brings passives to the party. Currently increasing capacity company-wide by 4× in 18 months.
Lucent	\$141.7B	\$8.7B	\$1.5B	Mostly active components: lasers, PIN and APD photodetectors, integrated transmitters and receivers, and EDFAs. Also CATV lasers, via Ortel acquisition.	Investing \$40 million in the former Ortel to increase capacity 16×; recently quadrupled output of its laser fab in PA. Microelectronics Group will be spun out as a separate company, roughly 20% of Group sales are FOCs. Spin-off may be valued at >\$100 B.
Nortel	\$216B	\$7.8B	\$2.5B	Mostly active components—source lasers and pumps, detectors, transmit and receive modules. Some passives, such as mux/demuxes.	FOC production is >75% captive. Top supplier of fiber optic systems, with 2000 sales >\$10 billion. FOC sales up 200% from 1999, investing nearly \$1.9 B in expanding production capacity.
SDL	\$30.6B	\$110M	\$500M	Highest power 980nm pump laser chips, the leader in Raman amplifier laser technology.	FOCs account for >85% of sales; revenues expected to increase nearly 2× in 2001. Ramping capacity by 5× over the next 12–18 months. Pending merger with JDSU.

*There are several other important suppliers who do not release sales figures for their fiber optic components businesses. The list includes Ericsson, Pirelli and Infineon in Europe, and Fujitsu, Mitsubishi, NTT and Sumitomo in Japan.

**FOC = Fiber Optic Components. Unless otherwise noted, estimate is for calendar year 2000.

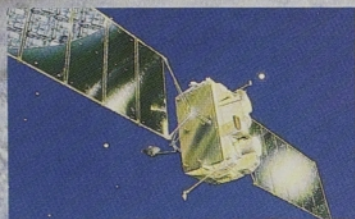
***Last quarter sales not available. Sales for FY1999 = \$4.75 B.

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as a world-leading provider of technologies and products in the optical layer, where fiber joins with photonic devices to power today's optical networks," said Roger G. Ackerman, Corning's CEO. Sales in the Photonic Technologies Division—Corning's fiber optics components group—are twice what they were last year, led by demand for the company's optical amplifiers. They will be one of just four companies to record \$1 billion in fiber optic components this year. Corning is also likely to benefit from the JDSU/SDL deal, as they will become the logical alternative for customers looking for a second source of pump lasers.

In July Corning announced that it would invest \$225 million to build a new fab for its Lasertron division to increase output of pump lasers, transmission lasers and receivers. The company says this move underscores Corning's plan to build its position as an industry-leading optical layer company. The expansion will impact Lasertron's entire operation, from wafer fabrication through packaging.

The new funds are in addition to the \$45 million investment announced in April to expand Lasertron's existing facility in Bedford, MA. The combined effect of these two expansions will be to increase capacity by six times over the next two years and will create more than a thousand new jobs. The site for the new fab has not been announced yet.

Commenting on these developments, Gerald Fine, V.P. and general manager for Corning Photonic Technologies, said "currently, Corning Lasertron manufactures semiconductor chips for state-of-the-art pump lasers with powers as high as 225 milliwatts. We have demonstrated powers nearly twice as high and expect to commercialize these products as part of this expansion plan." Corning acquired Lasertron from Oak Industries in November, 1999.

Alcatel Optronics to be Tracked

Alcatel has plans to boost its profile by creating a tracking stock for its fiber optics components subsidiary, Alcatel Optronics. Alcatel's sales of fiber optic components in 2000 are expected to top \$400 million, and are projected to grow by more than 60% next year. Analysts have given the Optronics division a tentative valuation of \$40 billion, based in part by looking at the high share prices for companies like JDSU. If this is accurate, then the Optronics division represents almost 20% of Alcatel's total value—despite the fact that it generates just 5% of the company's revenues.

A tracking stock tracks the performance of a part of a larger company, and is often used to separate a high-flying subsidiary from its more dowdy parent. However, this device stops far short of spinning-off an independent company. The tracked company can still lean on its parent for support, and in turn, the

parent can still control the subsidiary. Tracking stocks give shareholders fewer rights and much less control than conventional stocks.

The tracking stock can be issued to existing shareholders, or the company may opt to sell a portion of the shares to the public through an IPO. Alcatel is reportedly planning to offer 20% of the shares to the public.

Commentary

Much of the recent activity seems to prove the old theory that the people who really make money in a gold rush are not the prospectors who brave the wild frontier, but the people who make the picks and shovels. Demand for fiber optics is largely driven by the Internet boom. While the dot-com companies are struggling, the telecom equipment companies are soaring. Amazon, the top dot-com, has amassed a loss of \$500 million on sales of \$2 billion over the last twelve months. Its value has dropped to a

"mere" \$12 billion. On the other hand, Nortel, the top network equipment maker, has earned \$2.4 billion on sales of \$26.5 billion, and has a market cap of \$216 billion.

Analysts expect to see even more consolidation in the telecom industry in the near future. "Even with the steady pace of mergers and acquisitions in the communi-

cations equipment industry in recent years, the competitive landscape remains fragmented as explosive demand and new technology have enabled smaller vendors to break in on the larger, more established players' turf," says Greg Geiling, an equity analyst at J.P. Morgan Securities. Case in point: it could be argued that fiber optic networks were practically invented in the research labs at Corning and Lucent's Bell Labs. Yet upstart JDS Uniphase, who didn't even enter the telecom market until 1995, sells as many fiber optic components as both of the more senior companies combined.

But major telecom companies can't be expected to assemble their networks piece-by-piece, using a hundred small suppliers. "Carriers prefer more complete solutions from a handful of suppliers," says Geiling. "Therefore, we expect vendors to respond with an acceleration of merger and acquisition activity in the next 6-12 months, focused on expanding and rounding out product portfolios in order to build the end-to-end solutions customers desire."

It remains to be seen how many more fabulous marriages and mega-deals the components industry can support. The sums are already very high. The total value of the recent deals (JDSU/SDL, Lucent Microelectronics, Alcatel Optronics) is nearly \$200 billion. If Nortel proceeds with the mooted spin-off, it will add another \$100 billion. All the match-making will likely continue, until there are no more partners left to woo.

Much of the recent activity seems to prove the old theory that the people who really make money in a gold rush are not the prospectors who brave the wild frontier, but the people who make the picks and shovels. Demand for fiber optics is largely driven by the Internet boom. While the dot-com companies are struggling, the telecom equipment companies are soaring.

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FIBER OPTICS NEWS

Nova Crystals Demonstrates 1.3 μ m VCSEL with 1 mW Output Power

Nova Crystals Inc., a developer of laser and LED components for fiber-optic applications based in San Jose, CA, has demonstrated an electrically pumped, 1.3 μ m VCSEL with an output power of 1 mW. The company describes this as "the world's first practical 1.3 μ m VCSEL" since it delivers all of the operating characteristics necessary to enable telecom/datacom transmission. As well as a CW output of 1 mW without active cooling, these features include a bandwidth of 2.5 Gbps and an operating voltage of less than 2 V. Most important, says Nova, this source is inherently reliable (up to 100°C) and robust enough for commercial use, and lends itself to low-cost, high-volume manufacture.

Gore has previously demonstrated an output power of about 1 mW from its 1.3 μ m VCSEL, which is optically pumped and is fabricated using wafer bonding [see CS 6(5), p. 57]. Meanwhile, Cielo and Sandia recently announced an electrically pumped 1.3 μ m VCSEL grown using GaAs-based materials in a single epitaxial step [see CS 6(5), p. 67]. However, the output power of this device was only 60 μ W, making it unsuitable for practical applications [see correction, below]. Nova's device is fabricated using InP-based materials and does not require the use of wafer bonding, although the company declined to release further details.

"Several other research groups have demonstrated 1.3-micron VCSELs in the lab, but none of these have combined all the performance, high-reliability and cost factors necessary for a commercially viable device," noted Felix Ejeckam, CEO of Nova Crystals. "We plan on making units available for sampling and testing in October 2000."

VCSELs have a number of inherent advantages over edge-emitters, and are the technology of choice in short-range data links using multi-mode fiber. The advantageous properties of VCSELs include the ability to process and test the devices at the wafer level. VCSELs also have symmetrical, low divergence output beams—in this case with a FWHM of 18°—which results in improved fiber coupling. The development of single-mode 1.3- and 1.55- μ m VCSELs is likely to extend these advantages into longer reach applications. These include Gigabit Ethernet/Fiber-Channel modules for LAN/WAN systems, fiber-to-the-home (FTTH) networks, low-cost WDM systems and other SONET/SDH applications.

Correction

In our last issue we mistakenly reported that the output power of the Cielo/Sandia 1.3 μ m VCSEL was 60 mW [see CS 6(5), p. 67]. This should have read 60 μ W, and we apologize for this error.

Lucent Champions Automated Optoelectronics Manufacturing

Over the last 18 months, Lucent's microelectronics business has invested about \$1 billion in expanding manufacturing capability and has made almost \$4 billion in acquisitions, most notably the \$2.95 billion purchase of Ortel earlier this year. According to John Dickson, CEO of the microelectronics business, the optoelectronics segment earned more than \$1 billion in revenues in the last four quarters. "This is a business that's going through truly explosive growth," says Dickson. "Optoelectronics grew 80% last year, and we expect that it will continue to grow at that level or higher."

Compound Semiconductor recently had the opportunity to visit Lucent's automated optoelectronics manufacturing facilities in Breinigsville, PA. A \$24 million expansion has been recently completed that will quadruple capacity by year-end. The expansion includes a new 143,000 sq.ft. building which houses the company's Manufacturing Realization Center (MRC) for the assembly and test of laser components. The facility uses purpose-built equipment to automatically build optical sub-assemblies (OSAs), which consist of lasers, monitoring photodiodes and spherical lenses mounted on silicon optical benches. After wire or ribbon bonding, the OSAs undergo packaging, testing and fiber alignment [see CS 5(7), p. 17].

The new manufacturing space is about 50% occupied, with additional machines being added at a rate of about one per week. At the same time, improved technologies such as new vision systems and faster aligners are being introduced to all the equipment.

One of the features of the MRC is that it does not contain a conventional clean room: instead, each piece of equipment has an individual clean room environment. Among the advantages of this approach is that operators do not need to wear clean room clothing. Another feature is that the MRC is designed to allow product flexibility. All the machines are capable of manufacturing all the different OSA variants without re-tooling—this allows the product mix to be modified in accordance with demand

fluctuations. A powerful computer system tracks each laser chip from its precise position on the wafer through to the final product.

The main products of the MRC are cooled DFB lasers and electroabsorption modulated lasers (EMLs), along with transponders and sub-assemblies for incorporation into uncooled laser products. The transponders demonstrate the increasing levels of integration being employed by Lucent: the multi-chip modules contain several ICs and OSAs mounted on a printed circuit board.

The trend towards module-based integration is clearly part of Lucent's strategy to meet customer demands for bandwidth. Devices need to become smaller and cheaper, to operate with lower power, and to be programmable and flexible—all these point to integration using common platforms. "We are building products based on a common automation platform of wafer/chip fabrication and OSA assembly," says Dan DiLeo, president of Lucent's optoelectronics business. "These are platforms on which we can include the 'next big thing'—the next breakthrough technology such as tunable lasers."

The fiber-optic component industry now demands that products are brought to market rapidly, in high volume. In this respect, the level of automation at the MRC facility provides a strong competitive advantage.

New Facilities for CyOptics

CyOptics, a manufacturer of InP-based components for 40 Gb/s systems and ultra-long-haul optical transmission, has opened a new development and manufacturing facility in Yokneam, in Northern Israel. "Our new Yokneam facility includes state-of-the-art cleanrooms and equipment for optoelectronic device packaging, test, burn-in and qualification, as well as development labs and expanded office space," says Dror Motovilov, CyOptics' VP of operations. "The new facility enables us to continue on our aggressive development, hiring and manufacturing ramp up."

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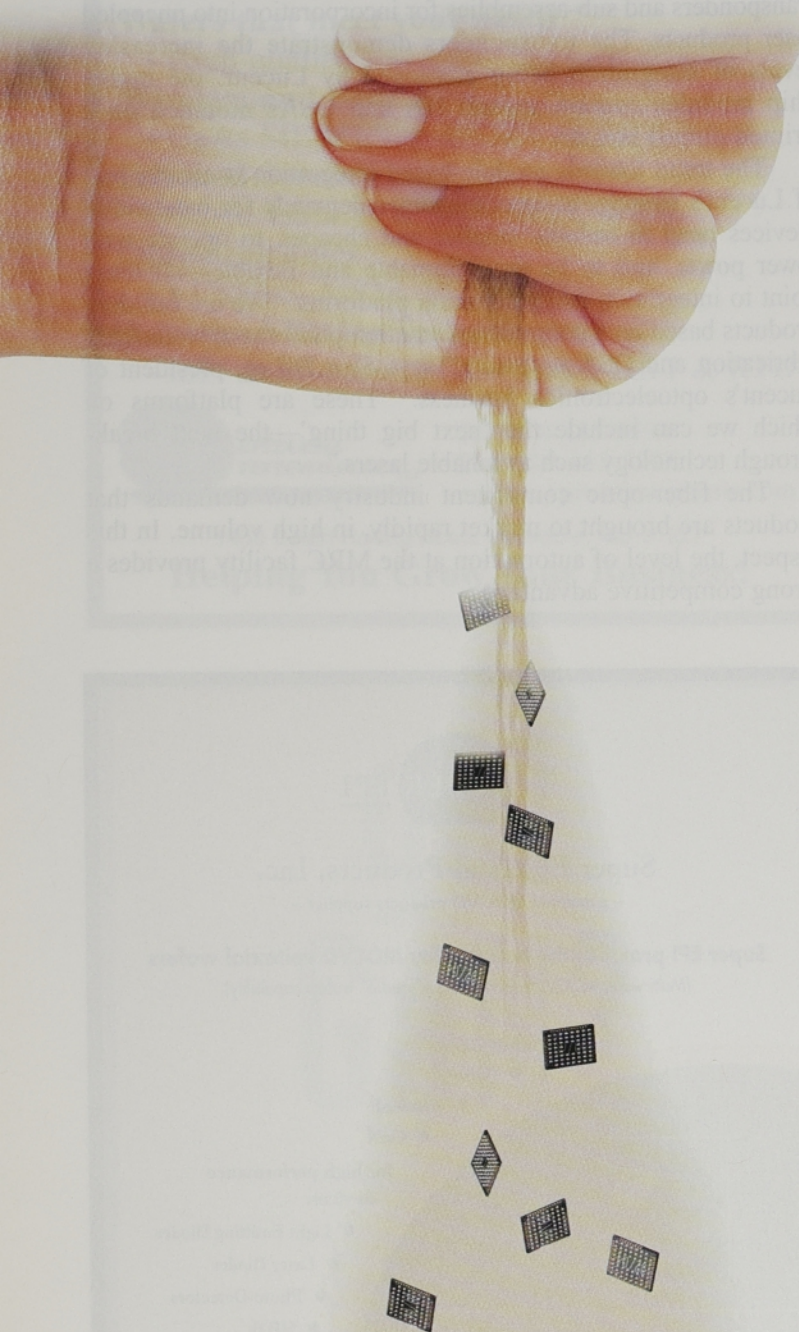
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Sumitomo Forms ExceLight Communications

Sumitomo Electric Industries has spun off its optoelectronic products group from Sumitomo Electric Lightwave into a separate company, called ExceLight Communications, Inc. The new company, which will be located in Durham, NC, is being formed "to give us more flexibility in meeting the demands of the red-hot North American optical communications market", according to a company spokesman. Sumitomo Electric Lightwave, established in 1983 and based in Research Triangle Park, NC, will continue to supply optical fiber cable, connectors, cable assemblies, fusion splicers, and premises cabling systems.

ExceLight will operate as a wholly owned subsidiary of Sumitomo Electric Industries. The products offered include 1480 nm pump lasers, DWDM source lasers, photodiodes, and data links for SONET/SDH, ATM, and Gigabit Ethernet applications. The company will also offer passive components such as wavelength-division multiplexers, optical add/drop modules, couplers, splitters, filters, and fiber Bragg gratings.

Most of the products offered by ExceLight are manufactured by Sumitomo and will carry the Sumitomo brand name. ExceLight will provide design input designed to tailor the products to meet the needs of their customers in North America. According to a company

spokesman, "We recognize that Sumitomo has world-class research and manufacturing capabilities in optical technology, especially lasers and transceivers. But we also believe that meeting customer demand requires a wider range of capabilities best served by a company with more autonomy. We will leverage Sumitomo's considerable strengths even as we expand our products and services beyond that base." ExceLight plans to open a design center in the near future. Sumitomo Electric Industries had sales of \$13 billion last year, distributed over 200 subsidiaries and affiliated companies.

VCSEL Arrays from Emcore

Emcore has released a new family of VCSEL and photodetector arrays for high speed communication transceivers. These included 1×4 and 1×12 oxide-confined VCSEL arrays, which have an aggregate speed of 10 Gb/s and 30 Gb/s respectively, and GaAs photodetector arrays capable of data rates up to 3.125 Gb/s. The VCSEL arrays have a threshold current of 1.5 mA and slope efficiencies of 0.4 mW/mA, and a 250 μm pitch.

Telecom Laser Diode Developments at Furukawa

Furukawa Electric (headquartered in Tokyo, Japan) is embarking on an expansion of its WDM equipment business, which includes high power lasers used to pump EDFAs at telecom wavelengths. This is being augmented by investments in Raman amplifiers, passives and functional optical fiber technologies, and is part of a plan to manufacture the important sub-system optical components required in WDM systems. The company's stated goal is "to develop the WDM sub-systems business into a company mainstay, aimed at becoming a distinguished worldwide sub-system manufacturer".

Furukawa currently provides about 70% of the market for 1480 nm pump lasers, and intends to double its current output of these components to 100,000 units per month by March 2001. The company says that it is experiencing strong demand for its products, both on the domestic front and from North American telecom systems manufacturers, including Nortel Networks, Lucent, Corning and JDS Uniphase. Markets for both 1480 nm and 980 nm laser diodes are showing revenue growth of well over 50% per year [CS 6 (1), p. 74].

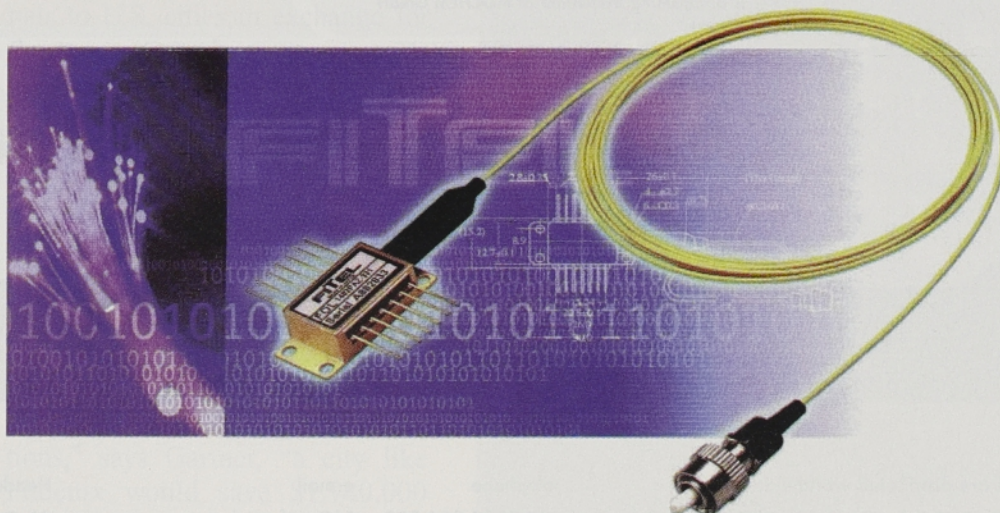
Much of the demand in newly installed optical links is for 40-channel WDM systems, says Furukawa. A key requirement for these multi-channel systems is higher output power from the pump laser diode. Furukawa is address-

ing this, and recently announced a 1480 nm laser operating at a pump power of 300 mW laser (see below).

And while Furukawa has already spent more than \$32 million expanding its pump laser production for the fiscal year (which ends in March 2001), the company will increase this investment to around \$92 million at its Chiba Works facility, 20 km east of Tokyo, over the same period.

As a result of these ramp-ups, total revenues from all optical components including pump lasers are expected to increase from \$460 million by March 2001 to around \$920 million by March 2002.

(continued on page 78)



Furukawa's high power 1480 nm pump laser diode is available with fiber outputs up to 250 mW. A 300 mW version will be in production soon.

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Construction Begins on SLI's New LED Plant

SLI-Opto, a new 70:30 joint venture between miniature automotive lamp manufacturer SLI Inc. and LED lamp manufacturer Stanley Electric, has begun building a \$20 million LED manufacturing facility at SLI's site at Barrie in Ontario, Canada. The new 15,000 sq. ft. plant will produce surface mount LED lamps for assembly into miniature lighting systems for automotive applications, which are marketed under SLI's Chicago Miniature Lamp brand name.

Headquartered in Canton, MA, SLI is the world's largest supplier of LED-based automotive dashboard backlighting, while Stanley Electric is Japan's leading LED manufacturer and the second biggest LED supplier in the world behind Agilent.

According to CEO Frank Ward, the OEM market for LED miniature lamps is among the company's fastest-growing and most profitable sectors. "Over the past three years, the market for automotive interior lighting has doubled—this pace continues and the trend is definitely toward LEDs," said Ward. "As the world's number one supplier of automotive instrumentation lighting and a principal lighting supplier to all major automakers

and their first tier suppliers, we're better positioned to benefit from this trend than our competitors."

SLI will continue to buy LEDs from other sources for its other LED lighting applications. Ward says the ability to manufacture its own LED lamps will give the company better control over product quality and supply, and improve technical support for its North American OEM customers.

Scheduled to begin production in the fall, the new fully-automated facility will employ Stanley Electric's LED die attach, wire bonding and encapsulation processes in a class 10,000 clean room. Initially, the Barrie plant will produce 120 million LEDs per year, ramping up to 600 million/year by the end of 2003. These will be surface mount LEDs (including Stanley's "1608" 0.5 mm thick packages). The Barrie facility will also serve all of SLI's global miniature lighting factories and complement OSA, the company's European LED lamp assembly plant in Berlin. Acquired in 1997, OSA has a capacity for 72 million LED lighting assemblies per year. "When the Barrie plant reaches full capacity, we will increase our total global capacity for finished LED lighting assemblies by 15%," said Ward.

Manufacturers Promote LED Traffic Signals

Two manufacturers of LED traffic signals have introduced financial incentives to speed the introduction of their products. Dialight, the largest LED-based traffic signal maker in North America, and LumiLeds Lighting will offer high-flux LED-based traffic signals at a 40% price reduction. The two companies have a marketing joint venture that aims to stimulate conversion from incandescent signals and to shorten the payback period on municipalities' initial investment in the signals. LumiLeds recently developed a high-flux LED that provides more than 10 times the flux of a conventional high-intensity LED: this requires fewer devices and employs a package that provides more uniform illumination and wider viewing angles compared to earlier signals. The company says it is also more reliable than its previous LED signals.

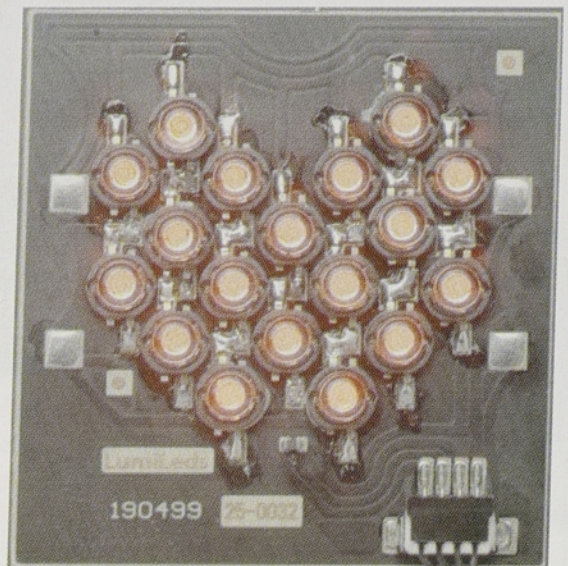
"Notwithstanding the economic benefits of LED signals, notably dramatic energy and maintenance savings, pricing remains a significant obstacle to adoption of the technology," said Gary

Durgin, Dialight's VP of marketing. "The discounted prices we are offering not only make the technology more affordable at the front end, but provide even greater savings over the long term."

Further incentives are being provided by a company from Arizona that is offering free LED traffic signals to U.S. cities in exchange for the money saved on energy costs over the next five years. Scottsdale-based Traffic Technology Inc. (TTI) manufactures Unilight, a 3-color LED signal that costs just \$140. "The energy savings alone will virtually pay for the cost of the Unilight signal," said TTI's William Gartner. Maintenance costs are also substantially reduced as a result of the LED's 5-year lifetime warranty. "With an estimated 850 intersections," says Gartner, "a city like Phoenix would save \$1,940,000 each year in the first 5 years."

Many U.S. municipalities are actively replacing incandescent

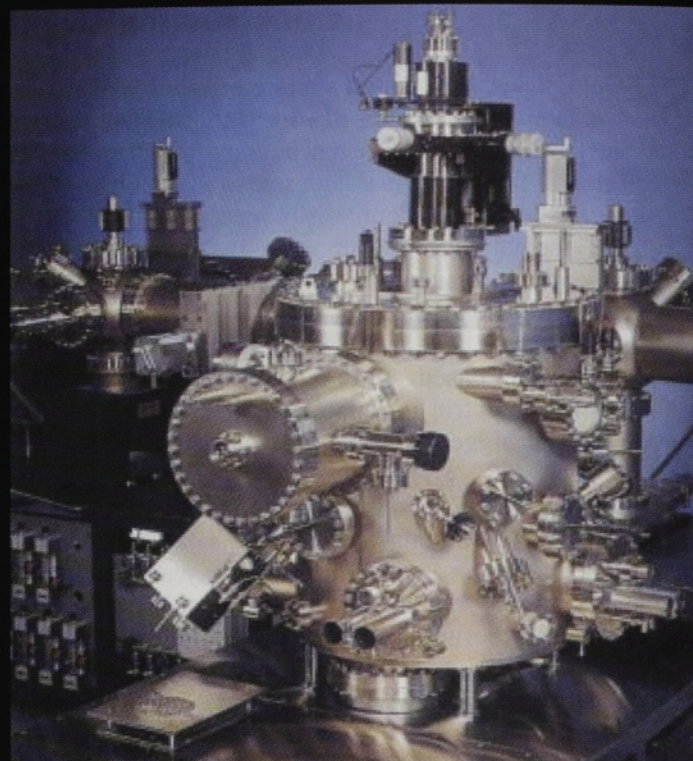
bulbs with green and red LED components, creating signals with mixed LED and incandescent operations, says TTI. The new all-LED fixture maximizes the electrical and maintenance savings available from the LEDs.



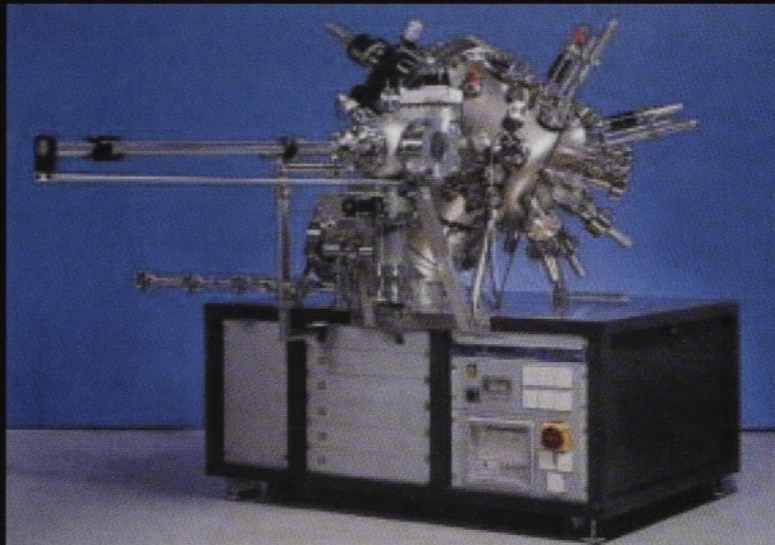
Traffic signals now require just 18 of LumiLeds' high flux LEDs.

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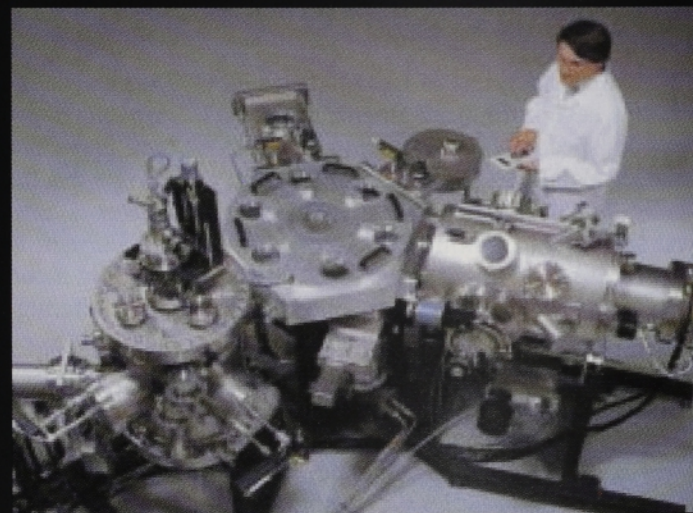
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GELcore Launches AlInGaP LEDs

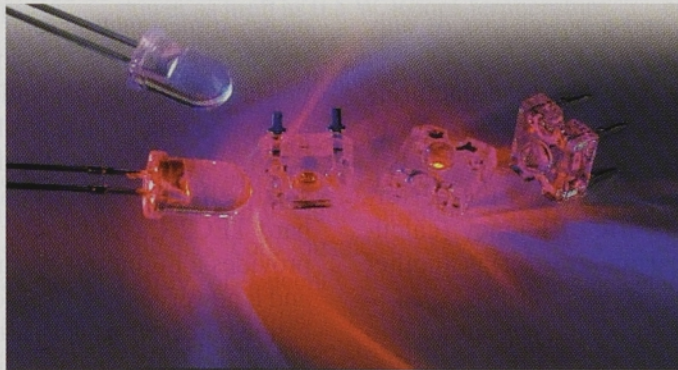
GELcore has introduced its first AlInGaP high brightness LEDs operating in the red (626 nm), red-orange (620 nm) and yellow (588 nm) portion of the spectrum. Set up in 1999 as a joint venture between GE Lighting and Emcore to develop solid-state lighting systems, GELcore says it intends to add the full spectrum of high brightness LEDs, including white, later this year.

"We are currently building a portfolio of high brightness LED products, although moving forward, there will be increased focus on integrated LED systems," said GELcore's Thomas Pozda. "The first illumination system is being tooled and will be released later this year."

GELcore describes its LED activities as forward integrated; the company leverages design and intellectual property in all sectors of the manufacturing chain, from epiwafer growth to LED lamps to packaged systems for end user applications. All of these activities are sub-contracted to other manufacturers. LEDs developed at GELcore will be marketed under the GE brand name.

Target applications for the new AlInGaP devices, which are grown on absorbing GaAs substrates, include traffic signage,

automotive and displays applications. Luminous intensities of between 1.1 cd and 12 cd are available depending on viewing angle (6° – 100°). Currently, standard round 5 mm packages are offered, in addition to $3.8 \times 5.5 \text{ mm}^2$ and larger $4.6 \times 5.2 \text{ mm}^2$ oval packages (see figure) in a variety of finishes (clear, diffuse and tinted and diffused). The company says surface mount devices suitable for automotive applications will also be available later this year.



GELcore Buys LED Signal Manufacturer

GELcore has also acquired its first company—Ecolux, an LED traffic control module manufacturer based in Montreal, Canada. Founded in 1992, the Ecolux production plant has a capacity of 20,000 modules per month for road and rail signal applications. The company's Diolux full-color modules are also designed to allow existing signals to be retrofitted.

"By acquiring Ecolux, we instantly expand the breadth of our offering in the traffic, rail and transit signaling categories," said Michael Petras, president and CEO of GELcore. "This development is the perfect complement for our ongoing plan to be a leading global LED systems provider."

Gentex Reveals Power of New LED Package

Gentex, a manufacturer of LED map lights, has released details of a new package that reportedly increases the LED output power by as much as a factor of two compared to a conventional package. The company has revealed performance data for its new Orca package, following lengthy tests with LEDs from various sources.

Performance gains from the new package design relate in part to the thermal management benefits of heat sinks, says Gentex, which two years ago fielded the first commercial white-light LED illumination system for automotive map lights using a binary complementary combination of discrete AlInGaP amber and InGaP blue-green LEDs. This approach takes advantage of the dominant intensity produced by amber devices, which are far more efficient and currently much cheaper than blue LEDs [CS 6 (2) p. 43].

"For automotive applications where environmental conditions present the greatest challenge to LED systems, the new packaged LED has been validated at

0.5 W of power in fully processed printed circuit board (PCB) assemblies throughout normal temperature ranges," said Gentex's senior research scientist, John Roberts. In less demanding non-automotive environments, the new package is capable of 0.8 W, a considerably higher output than the 0.12 W available from a conventional 5 mm device, Roberts adds.

Gentex has tested all types of commercially-available chips, including TS-AlInGaP, InGaP/SiC, InGaP/sapphire, and AlGaAs chips, with similar results. Roberts says the package allows an LED chip to stay cooler, operate reliably at higher power and produce more light than the same chip used in a conventional LED package, which cannot be readily enhanced with a heat sink. Pilot production, including the proprietary binary complementary white LED assembly, is expected early next year. High power monochrome devices in various colors and infrared, as well as a white LED based on InGaP/phosphor will also be available at that time.

Toyoda Gosei to Triple LED Production

Japanese LED supplier Toyoda Gosei is building a new manufacturing plant aimed at increasing its LED capacity from 35 million units per month to over 100 million units per month by March 2002. Recently, the Aichi-based company forecast a capacity of 50 million LEDs per month by the end of this year [see CS 6, (2), p. 33].

The new \$36.4 million facility is scheduled to begin operating in the spring of 2001. According to general manager of optoelectronics Ryo Onishi, the new plant will manufacture discrete blue, green and blue-green InGaP-based high brightness LEDs.

Toyoda Gosei has also recently set up a 60:40 joint venture with Tokyo-based electronics maker Koha. To be known as TG-OPCEED, the new company will manufacture LED-based automotive lighting assemblies.

Spectrolab, Emcore Set Solar Cell Records

Spectrolab has established a new record efficiency for triple-junction space solar cells of 29%, while Emcore has manufactured devices with 26% efficiency and a power loss of only 8% under a typical 15-year geostationary orbit.

High-efficiency solar cells allow satellite manufacturers to offer increased payloads for the same solar array size or to use smaller, lighter arrays to achieve the same power level. However, exposure to radiation in space degrades the performance of the solar cells, so the end-of-life efficiency (calculated after a lifetime of 15 years in a particular orbit) is another crucial factor to consider.

Spectrolab's record-breaking solar cells are about to go into production, according to David Lillington, the company's acting President. "We will be starting production of this second-generation, radiation-hard triple-junction cell in the third quarter of 2000," he says. "The average maximum power efficiency will be 27.4%, with an end-of-satellite-life efficiency of 24.1% after 15 years in geosynchronous orbit." This corresponds to a power loss of around 12%.

Emcore is currently in production of triple-junction solar cells with an average efficiency of 26%, while the maximum efficiency

observed to date was 26.8%. Dual-junction solar cells with an average efficiency of 23.3% are also in production. The 26% efficiency triple-junction solar cells are being shipped to customers for space qualification. During testing, these cells demonstrated a power loss of only 8% under a typical 15-year geostationary orbit, corresponding to an end-of-life efficiency of 23.9%.

Meanwhile, the third major manufacturer of GaAs-based solar cells, Tecstar, has completed qualification on its radiation-hard TEC2 Cascade solar cell. The production TEC2 solar cell provides a minimum average 24.5% beginning-of-life efficiency, and a power loss of 13% for 15-year geosynchronous orbit applications. Tecstar says that the new solar cell design is in production to meet several significant contractual delivery requirements in the coming months, and that it will also introduce a modified design featuring a monolithically grown bypass diode.

UDC and Aixtron Collaborate on OLED Production Reactors

Universal Display Corporation (UDC), a pioneer of displays based on organic LED technology, has entered into a development and license agreement with Aixtron to develop production equipment to fabricate organic LEDs. OLEDs are believed to be the next generation of technology to replace LCD and CRT technology in future flat panel displays [CS 5(9), p. 43].

Conventional OLED fabrication equipment evaporates the organic molecules at high temperature and pressure. Using an organic vapor phase deposition (OVPD) process developed at Princeton University, the new production process employs a carrier gas stream in a hot-walled reactor at very low pressure to precisely deposit the large, thin areas of organic materials used in full-color OLED displays. UDC and Aixtron will jointly develop the production equipment, to be sold exclusively by Aixtron under license. UDC intends to install a demonstration pre-production system at its 11,000 sq. ft facility in Ewing, NJ next year.

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Applied Optoelectronics Licenses Lucent's QC Laser

Applied Optoelectronics, Inc. (AOI) has entered into a licensing agreement with Lucent Technologies that gives AOI the right to manufacture quantum cascade (QC) lasers for applications in industries other than telecommunications. The agreement marks the first time Lucent has licensed this technology.

The QC laser was invented and demonstrated in 1994 at Bell Laboratories, and operates in the mid-infrared portion of the spectrum where it has been previously difficult to create high-efficiency lasers. This spectral region is important as many chemicals—including pollutants, industrial chemicals, explosives and medical substances—can only be sensitively de-

tected using mid-infrared lasers. AOI wants to develop the QC laser for sensing applications, particularly now that the laser can operate at room temperature with a power as high as 0.5 W. Room-temperature operation is important for the development of compact and portable sensors.

"Through technology licenses such as this, Lucent works with other companies to transform some of its technologies into commercially viable products outside of Lucent's core business," says Dan McCurdy of Lucent's Intellectual Property business. "In the case of QC lasers, while Bell Labs continues to develop its applications in the communications industry and pursue long-term research, AOI and its

customers are pursuing sensor applications in markets such as combustion diagnostics, environmental sensing, medical diagnostics, industrial process control and law enforcement."

AOI recently produced its first QC laser, and expects that the devices will be commercially available in September 2000. The Sugar Land, TX-based company says it already has several orders for the new lasers for use in sensing applications. It is also currently constructing a 24,000 sq. ft. manufacturing facility to house all its production equipment, including several DCA production MBE reactors, in addition to providing additional laboratory and office space.

First Electrically-Injected Organic Laser

Physicists at Bell Labs, the R&D arm of Lucent Technologies based in Murray Hill, NJ, have developed the first electrically-injected organic laser. Previous organic lasers have been optically pumped. The device was fabricated using high-quality crystals of tetracene, an organic molecule with

four connected benzene rings. Emission was in yellow-green portion of the spectrum. One advantage of such devices may be the reduction in manufacturing costs compared to lasers manufactured using inorganic semiconductor materials such as GaAs and InP.

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Rapid Growth for High Power Devices

TIM WHITAKER

Like most other companies in this industry, High Power Devices (HPD), a manufacturer of high power laser diodes based in North Brunswick, New Jersey, is undergoing a period of dynamic growth. "Sales are doubling every year," says Len Hillis, HPD's marketing director, "and given the present market opportunities, there is no decrease in sight."

HPD specializes in single emitter devices operating at visible and near-infrared wavelengths in the 0.5–5 Watt range. The company currently ships about 5,000 laser diodes per month, many of which are used in medical applications such as cosmetics, surgery and photo dynamic therapy. HPD is in the process of developing laser diodes with novel properties to address several major growth areas—these include printing applications, laser bar arrays and telecommunications (for example, multi-mode 980nm pumps for double-clad fiber amplifiers).

Founded in 1995 by 3 principals, HPD originally occupied a 400 sq.ft. office area in a high technology incubator center directed by Rutgers University. The company moved into its present 10,000 sq.ft. manufacturing facility after the third year of business. "We grew out of the original space almost before we moved into it," says Len Hillis. "Although we are currently enlarging our existing facility, we expect to move to a larger space within one to two years." The company now has sales of around \$5 million and expects to increase its number of employees from 22 to around 30 by the end of this year.

At present, most of the steps needed to manufacture high-power laser diodes are carried out in house. As part of its expansion plans, HPD intends to introduce epitaxial capability and become completely vertically integrated.

Medical Applications

The number of applications requiring high quality, high power laser diodes has increased substantially over the past few years. At present, many of HPD's products are used in medical and cosmetic procedures such as ophthalmic disease treatment, soft radiation therapy for the relief of muscle strain, or even to assist in closing open wounds. HPD's laser diode products are also used for many cosmetic applications such as the removal of hair, spider veins and wrinkles. While many procedures use IR radiation, which is absorbed by soft tissue, photo dynamic therapy (PDT) uses lasers that emit visible

light. The laser light is absorbed in the patient's body by an ingested chemical reagent causing a reaction that has a therapeutic effect; for example, the activated chemical may release oxidizing agents that destroy cancer cells. HPD manufactures visible lasers (in the 630–670 nm range, depending upon the chemical) for this type of application.

Laser diodes have taken over these markets from other types of lasers because they provide smaller, more portable systems that are more compatible with conventional power supplies. Most importantly, laser diodes are relatively cheap. "Manufacturers want to

price their [laser-based] instruments so that every operating room in every hospital can have one," says Hillis. "The major profit margin is in selling consumables, such as the fibers that deliver laser light to the area under treatment, or the chemicals used in PDT." Systems using high power laser diodes have a useful life of several years, even though the lifetime of the laser itself may be in the region of a few thousand hours. This is because the laser source only operates for seconds or minutes for each procedure.

Products and Prototypes

While a number of standard catalog products are available, an important aspect of HPD's business is its custom prototyping service. "Almost all customers want a product that is specific to their needs," says Len Hillis. "HPD is small enough to be very flexible, and can quickly and cost-effectively tailor laser diodes to specific applications." This may include development of devices with specific wavelengths or optical characteristics, as well as specially designed packages where an industry standard package is not appropriate. "Custom prototyping services allow researchers and manufacturers to develop new products and optimize system design without expending the large amount of time and money normally associated with custom laser development."

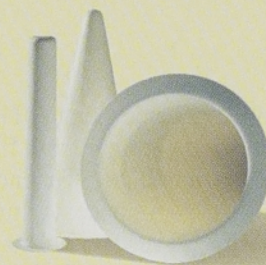
In order to take advantage of rapidly growing opportunities and begin the company's next growth phase, Hillis says that HPD is developing a comprehensive plan to evaluate new emerging technologies and determine requirements for the next generation of laser diode products. By addressing markets such as printing and telecommunications, and by expanding its facilities and workforce, HPD looks set to continue to grow along with the markets it serves.

Systems using high power laser diodes have a useful life of several years, even though the lifetime of the laser itself may be in the region of a few thousand hours.



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Samsung Demonstrates Violet Laser Diodes

Samsung Advanced Institute of Technology (SAIT) recently demonstrated CW operation at room temperature of a nitride-based violet laser diode. An output power of 3.5 mW was attained at a drive current of 80 mA, and the lifetime was about 93 hours at 50°C and 3 mW.

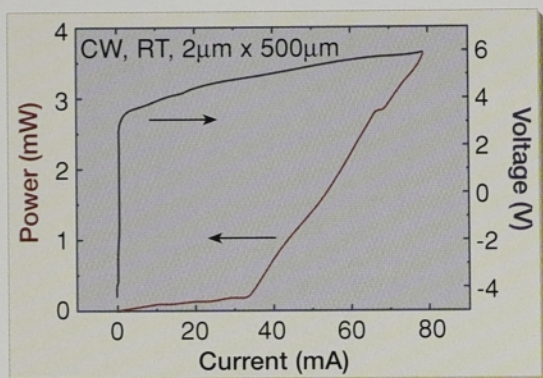


Figure 1. L-I-V characteristics of Samsung's violet laser diode.

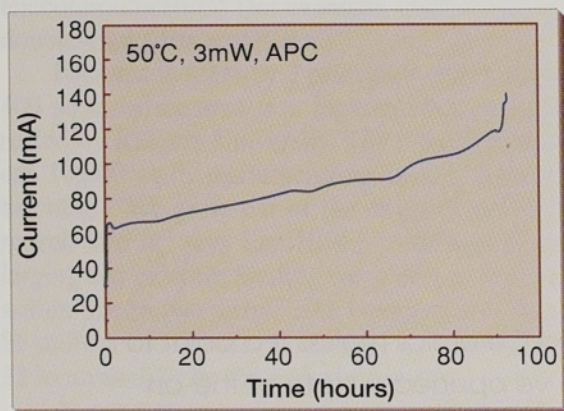


Figure 2. Lifetime test results for the GaN-based laser. Breakdown occurred after ~93 hours.

The laser structures were grown by MOCVD on epitaxially laterally overgrown (ELOG) GaN on sapphire. The ELOG GaN layer was deposited on a stripe pattern consisting of 4-µm windows and 10-µm SiO₂ stripes. This pattern was formed on 2-µm-thick GaN film grown on a c-plane sapphire substrate. The p-GaN was activated at 375°C under UV illumination, which was an important feature of the process. "Using the low temperature activation process, we were successful in obtaining high quality p-GaN," explains Yongjo Park, manager of the compound semiconductor laboratory at SAIT. This resulted in a low contact resistivity of $1 \times 10^{-6} \text{ Ohm.cm}^2$.

In order to form ridge-type laser diodes, the structure was etched using chemically assisted ion beam etching (CAIBE). The area of the ridge laser was $2 \times 500 \text{ µm}^2$. Laser facets were formed by CAIBE, and 2 pairs of quarter-wave TiO₂/SiO₂

dielectric multilayers were employed on both facet surfaces.

Laser Performance

The electrical characteristics of the laser were measured at room temperature under a direct current. Figure 1 shows L-I-V characteristics of one of the lasers with a ridge area of $2 \text{ µm} \times 500 \text{ µm}$. The threshold current was found to be 33 mA, corresponding to a threshold current density of 3.3 kA/cm². The operating voltage of the device at the threshold current was 5.0 V.

Figure 2 shows the results of a lifetime test of CW-operated laser at 50°C in automatic power controlled (APC) mode. The operating current is shown as a function of time under a constant output power of 3 mW per facet. The operating current gradually increases up to 120 mA due to the increase in the threshold current and sharply increases after 93 hours, leading to the breakdown.

Free-standing GaN

SAIT has also successfully fabricated free standing GaN substrates (see Figure 3). "The free standing substrates, which were grown by HVPE, were as large as 1.5 inches in diameter and 300 µm in thickness," says Yongjo Park. "The measured dislocation density was $\sim 10^7/\text{cm}^2$. Now we are trying to optimize process parameters to grow a good performance laser diode on the HVPE GaN substrate."



Figure 3. A 1.5-inch-diameter free standing GaN substrate grown by HVPE.

Rockwell Contract for SiC Power Devices

Rockwell Science Center (Thousand Oaks, CA) has received a \$1 million contract from the U.S. Air Force Research Laboratory to develop high-efficiency, radiation-hardened power electronics for use in space. A major objective will be a modular, high-density power switch made from SiC. This will be a key component in power conditioning and distribution systems in platforms such as the Space-Based Laser, Orbital Transfer Vehicle and Spaced-Based Radar.

SiC power switches can reduce power loss by up to tenfold, in addition to increasing the switching speed and power density compared to earlier power modules. These improvements will allow modules with that weigh around one-fifth of previous versions, says Rockwell. Technologies developed from this program are also expected to have commercial applications in medical electronics, automotive electronics, electrical utilities and aircraft ignition systems.

Cree Demonstrates 28% Efficient InGaN LED, Receives Multi-Million Dollar Contracts

Cree Lighting Company (Durham, NC), formed by the recent merger of Nitres and Cree Inc., has demonstrated a near-UV/violet InGaN-on-SiC LED with a quantum efficiency (QE) of 28%. The overall (wall plug) efficiency was 22%. This considerably improves on the previously result, announced by Nitres, of 20% QE and 12% wall plug efficiency [CS 6(1), p. 16].

LEDs in the UV and near-UV spectrum are used to produce white light sources, which is achieved by using phosphors to convert the wavelength to the visible spectrum and color mixing to make a white light source. During conversion, the high quantum efficiency of the emitter is key to energy efficiency. The new LED emits at 400 nm and has a power output of 17 mW, compared to 12 mW from the previous device.

"These are impressive results and demonstrate the substantial progress Cree Lighting has made to further improve the efficiency of LEDs," says Cree's CEO Neal Hunter.

In more news, Cree Inc. has received multi-million dollar contracts from several Asian and European customers. The first contracts total \$70 million for shipments up to September 2001. Included in these orders is a one-year purchase agreement with Osram Opto Semiconductors for standard brightness, high brightness and its recently-introduced, smaller chip size InGaN-on-SiC LEDs, in addition to SiC wafer products. The Osram agreement is the largest product contract signed in Cree's history.

Cree has also received additional contracts from unnamed Asian customers totaling \$21 million for shipments during the company's fiscal year 2001. These purchase agreements also include Cree's range of InGaN-on-SiC LEDs.

"This latest booking adds to our record backlog for this fiscal year," said Neal Hunter. "These contracts represent the largest orders ever received from each of these respective customers."

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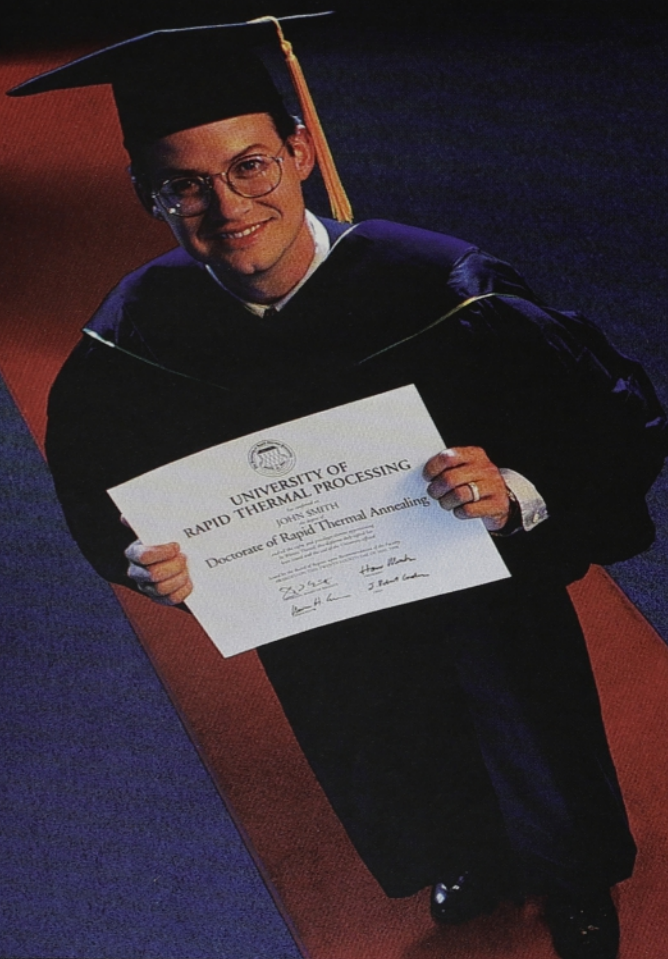
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CIBC World Markets Predicts Accelerated Demand for Analog GaAs

According to figures recently compiled by CIBC World Markets, the worldwide GaAs market for analog applications grew by around 52% during 1999 to reach a total of \$2.45 billion, compared to around \$1.6 billion in 1998. Furthermore, this astonishing growth is going to continue for the next several years—CIBC predicts shipments will reach almost \$3.6 billion during 2000 [see Figure 1]. In 2004, shipments will exceed \$11 billion, a figure that is equivalent to the value of the entire compound semiconductor industry in 1999.

The leading analog GaAs suppliers in 1999 are shown in Figure 2. It should be noted that because the research conducted by CIBC excludes digital and optoelectronic applications, there are some names missing from the list of leading manufacturers, notably Vitesse Semiconductor.

The top fifteen contains five Japanese companies and one European manufacturer, with the remainder coming from the U.S. All of the top ten companies in 1999 had sales exceeding \$100 million. As in 1998, the top two manufacturers were the Japanese companies Fujitsu and Mitsubishi. RF Micro Devices leapfrogged over Motorola into third place and recorded the year's largest increase in revenues of 138%. In 1997, RFMD was not even in the top twelve. Other companies recording growth in excess of 100% were Alpha Industries and TRW. The only company to register a decrease in revenues from '98 to '99 was Raytheon RF Components.

Analog GaAs Market Forecast

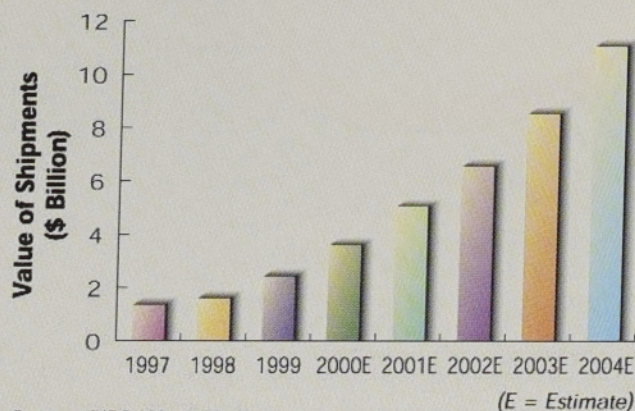
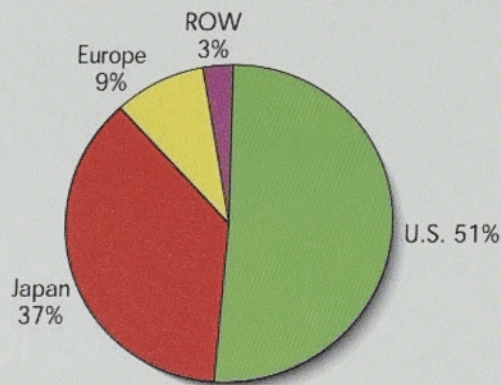
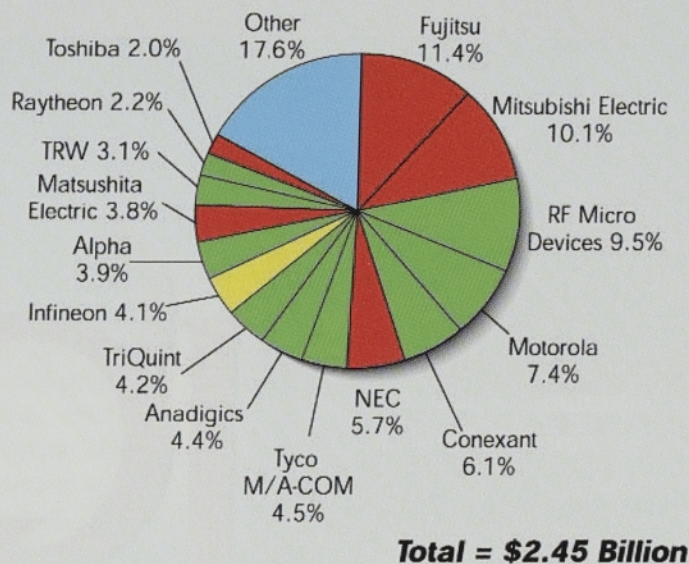


Figure 1. The total analog GaAs market will grow to around \$11 billion by 2004, according to estimates from CIBC World Markets.

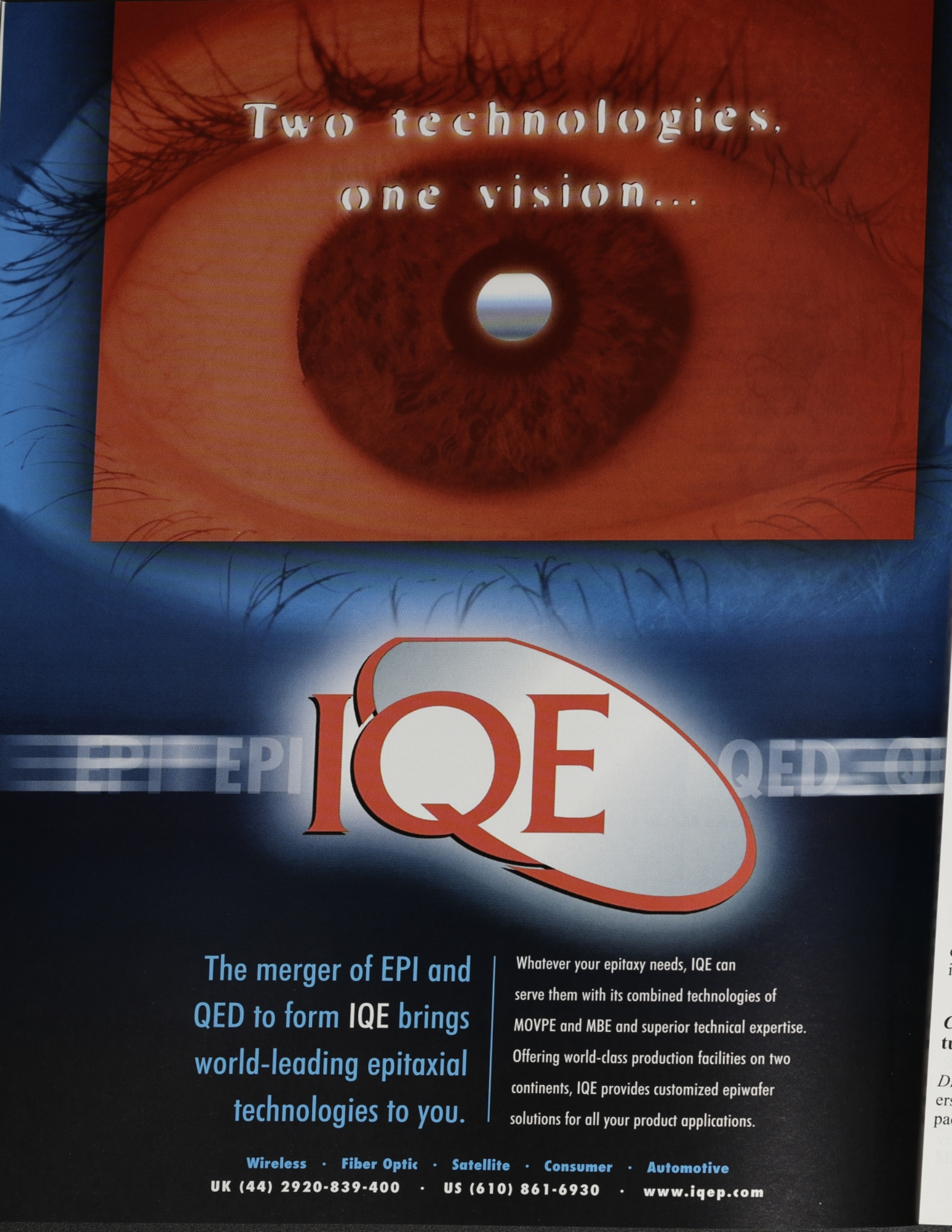
Figure 2 also shows the breakdown by region. U.S. companies accounted for over half of all analog GaAs shipments last year, up from 35% in 1997. Last year, the top three Japanese suppliers—Fujitsu, Mitsubishi and NEC—accounted for almost 75% of that country's total shipments of \$900 million.

Worldwide Analog GaAs Market 1999



Source: CIBC World Markets

Figure 2. The 1999 analog market for GaAs by company (top) and by region (bottom).



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Tracking the Wireless Food Chain

CIBC World Markets tracks and analyzes the performance of companies that participate in the "wireless equipment food chain". At the top of this food chain are system suppliers such as Nortel, Lucent, Qualcomm, Nokia, Ericsson and Motorola. Below these OEMs are companies that supply equipment, generally stand-alone hardware, followed by those supplying subsystems, multi-function modules and transceivers. Supporting these are the RF/microwave device and component manufacturers, including the GaAs fabs, who are in turn supported by substrate, epiwafer and process equipment vendors. Below, Dale Pfau, Managing Director and Earl Lum, Executive Director of CIBC's Wireless Technology Group, provide further insight into this market:

Compound Semiconductor: What's driving the demand for wireless GaAs products?

Dale Pfau/Earl Lum: There is an accelerating demand for broadband communication devices, particularly those providing wireless Internet connectivity. Mobile handset sales continue to grow at a strong rate—last year's total was in the range of 270–280 million units, with a growth rate of 40–45% and we expect that handset shipments in 2000 will reach 425 million units. While the number of new subscribers will continue to rise, we expect that at least half of all shipments will be replacement units, allowing users to switch to emerging 2.5G and 3G services. Another area of extremely strong growth is broadband wireless access.

CS: Can semiconductor manufacturers keep pace?

DP/EL: Most of the major manufacturers are working hard to expand their capacity. Actually, it appears that the prob-

lems may lie with other components especially SAW filters, and also liquid crystal displays and drivers and tantalum capacitors. All three major handset manufacturers—Ericsson, Motorola and Nokia—stated that they could have shipped more handsets in the fourth quarter of 1999, had they had an additional supply of one component or another. The most recent second quarter results continue to indicate that component issues remain within the industry. Of course, this also affects semiconductor shipments because the manufacturer won't buy additional power amplifiers and other RF components and hold them in inventory if they can't get enough SAW filters and other components.

CS: Everyone seems to be building GaAs fabs—is there going to be an over-capacity?

DP/EL: The growth experienced by the system side of the business—more subscribers, new services like 3G and broadband access—will mean that the demand for components should continue to be very strong over the next several years. Also, the number of components in a handset will increase as we go to multi-band and world phone configurations that require more switches, PAs, receivers and other RF building blocks. Even if we have a large number of new six-inch GaAs fabs coming on line in 2001/2002, we don't think this is going to create an over-capacity situation at any time in the near future.

CS: Will there be more integration in handsets?

DP/EL: At the moment there is a craze for power amplifier modules that integrate additional functionality into a 6×6 or 8×8 mm² package. We don't believe we will see a manufacturable single chip solution, with all functions on the same semiconductor material. Instead, we think integration will come through multi-chip module technology.



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Fujitsu to Outsource Part of GaAs Production

Fujitsu Quantum Devices (FQD) has decided to outsource some of its compound semiconductor production. The company is considering four chip manufacturers to produce some of its RF and microwave GaAs products, which are used in wireless handsets and base station components. Fujitsu says external production should account for 35% of total shipments by the end of March 2002. This move is designed to leave the company with more capacity for producing high speed GaAs-based ICs and optoelectronic devices for WDM applications.

"We are currently looking at chip manufacturers in Japan, SE Asia and the US," said Gene Brannock, Executive VP of Fujitsu Compound Semiconductor, the US arm of FQD.

At the same time, FQD is spending approximately \$48.1 million to increase capacity at its facility in the Yamanashi prefecture in Japan. Four-inch wafer output will be increased from the current 4,000 to 5,200 units per month by the end of September. Brannock says the company is targeting a monthly supply capacity of $8,000 \times 4$ -inch wafers by the end of March 2003.

"This increased capacity will result from the outsourcing, in addition to the expansions in our own internal capability," said Brannock. "In total, we are looking at a 25–30% increase in our internal capacity by September. We have a major product focus on 3G activities, both for terminals and base station components, as well as a growing application for Automated Intelligent Cruise Control systems operating at 76 GHz for the Japanese market," he added.

BAE Systems to Acquire Sanders

BAE Systems North America, a subsidiary of the UK defense contractor BAE Systems plc, is to acquire Lockheed Martin's Aerospace Electronics Systems (AES) business, which includes Sanders, for \$1.67 billion. Sanders operates a GaAs fab in Nashua, NH and also manufactures infrared imaging systems using HgCdTe detectors and QWIPs.

Sanders manufactures microwave and millimeter-wave GaAs MMICs, in addition to modules and subsystems used in electronic systems employed in defense, surveillance and electronic warfare. The Sanders GaAs fab is cur-

rently being upgraded to utilize 6-inch GaAs wafers, and was the first to install an X-ray lithography system. A deal was recently struck between M/A-COM and Sanders which allows the two companies to share the Sanders fab [see CS 6(5), p. 6].

Lockheed Martin states that the proposed transaction "advances our strategic initiatives to refocus the Corporation, generate cash and reduce debt". With revenues of \$1.2 billion in 1999, Lockheed Martin's AES business also comprises Fairchild Systems and Space Electronics & Communications.

Stanford Microdevices Signs Foundry Agreement with GCS

Stanford Microdevices (Sunnyvale, CA) has signed a foundry supply agreement with Global Communication Semiconductors (GCS) to develop RFICs for telecommunication and broadband wireless applications. GCS, based in Torrance, CA, will provide Stanford with a high-volume supply of 4-inch InGaP/GaAs HBT devices for products designed at Stanford's centers in Long Beach, CA, Dallas, TX and Ottawa, Canada.

"With its high linearity performance and exceptional thermal properties, the GCS InGaP/GaAs process technology is a technology platform that features outstanding versatility and applicability for our infrastructure-focused components," said Stanford Microdevices' Jerry Quinnell.

Tony Blair Opens Filtronic's 6-inch GaAs Facility



Filtronic Compound Semiconductors' plant in Newton Aycliffe, England was officially opened by the British prime minister, Tony Blair, in a ceremony at the end of June. The plant has undergone a £35 million (~\$56 million) refit since it was acquired from Fujitsu less than one year ago, and is now producing pilot quantities of PHEMT-based ICs on a 6-inch GaAs wafer manufacturing line [see CS 6(4), p. 43 for more information].

Microsemi Announces GaAs HBT Products

Microsemi (Santa Ana, CA) has released new GaAs HBT RFIC products for mobile phone, base station, cable modem and wireless LAN applications. Microsemi, which recently acquired Infineon's HBT group [see CS 6 (3), p. 17], has introduced two 50 ohm internally-matched gain blocks, produced using an InGaP/GaAs HBT fabrication process. Both chips operate at 5 V, and the higher performance variant offers DC to 6 GHz operation and 19 dBm of linear power output.

"We are on schedule for rolling out a series of RFICs for mobile connectivity applications, which also includes LNAs and power amplifiers for second- and third-generation systems implementing CDMA, GSM and W-CDMA with advanced module packaging technology," said Microsemi's Dr. Michael Kim.

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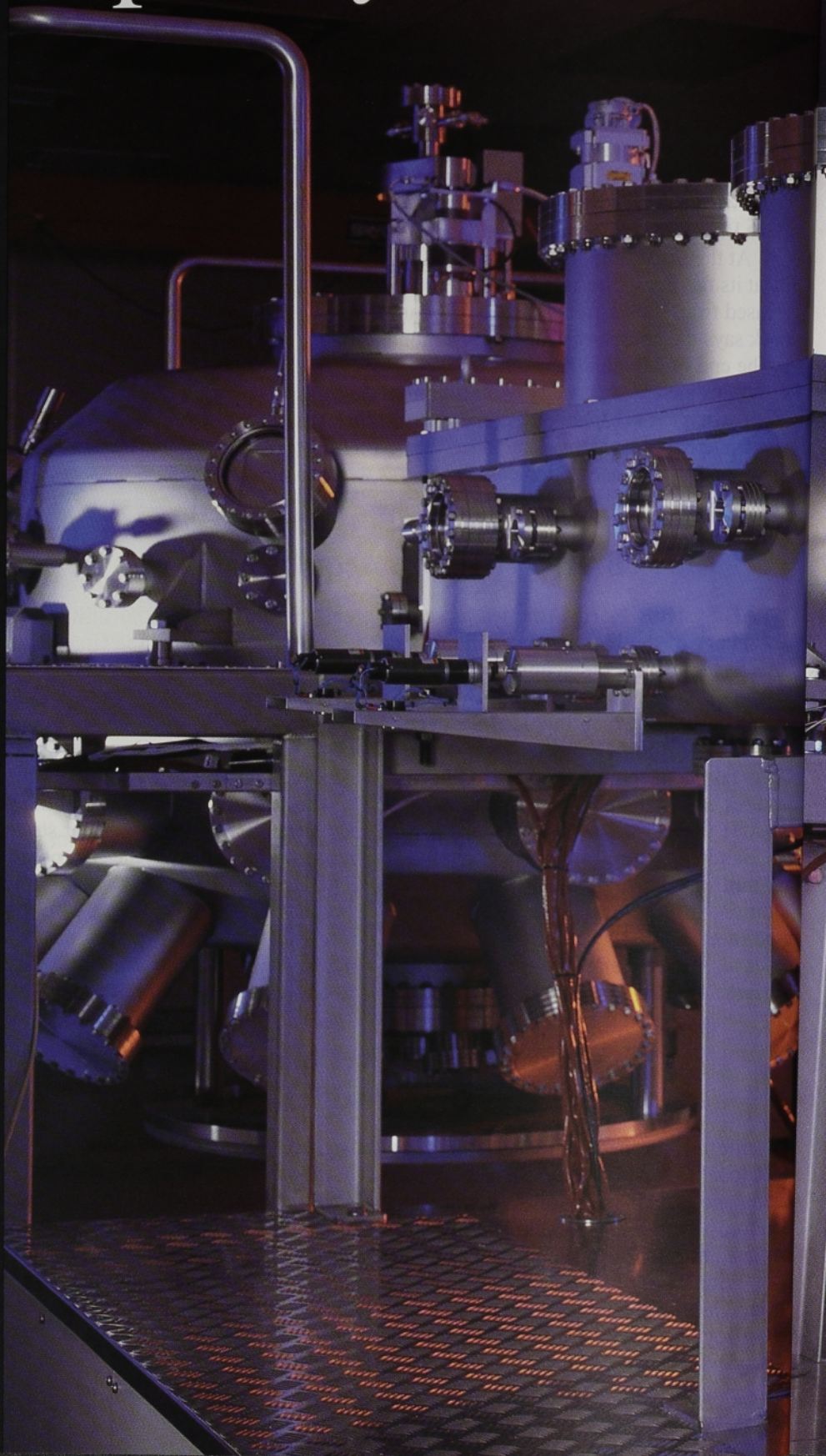
High Yield - VG Semicon's acclaimed ThermoCell™ technology provides process uniformity and reproducibility within 1%. But more importantly the use of ThermoCell™ effusion sources makes the VI50 ten times more stable than its closest competitor, eliminating the costly requirement for daily recalibrations. And with the lowest defect levels reproducibly measured from any effusion source it's no wonder the VI50 with ThermoCell™ technology has been called the most advanced MBE system available today.

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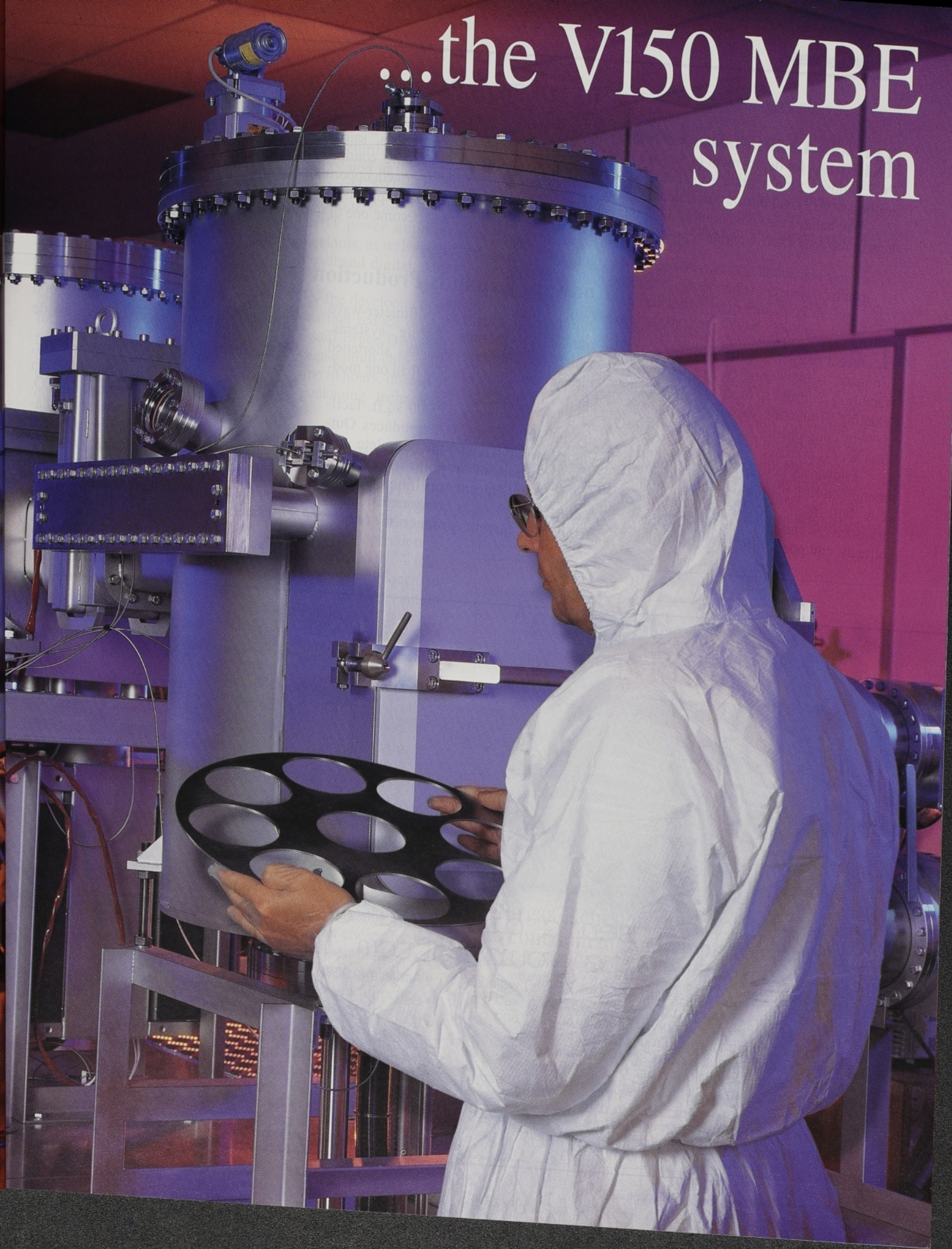
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RFMD Ships PAs to Sanyo

RF Micro Devices (RFMD) has begun shipping 3 V GaAs HBT PAs for deployment in Sanyo's latest dual-band CDMA PCS handset. Shipments are expected to ramp up to the multi-million-dollar level during this calendar year.

"We believe the sub-assembly and contract manufacture markets in the Asia Pacific region represent a high growth area of our

business, and we plan to continue to expand our presence and support in Asia," said Greg Thompson, RFMD's director of worldwide sales. "We continue to believe the CDMA market represents a high-growth opportunity for the company, and Sanyo is one of the leading suppliers of CDMA phones. We anticipate this account will become one of our top 10 accounts this quarter."

Endwave Expands Production

Endwave Corporation, formed by the recent merger of TRW Milliwave and Endgate, is expanding two of its manufacturing facilities to more than double its existing production capacity of RF sub-system components for broadband wireless access systems.

Endwave's new 24,000 sq.ft. flexible manufacturing plant in Diamond Springs, CA will focus on the production of transceivers and modules. This facility is already equipped with three of Agilent's

automated high-speed millimeter-wave transceiver module testing systems, which the company says has shortened measurement times to less than one module per minute.

The company's 12,000 sq.ft. facility in Santa Clara, CA, produces Outdoor Units (ODUs)—the complete outdoor portion of a point-to-point or point-to-multipoint millimeter wave radio. This plant is being expanded to triple its current production output.

Endwave says it has sold over 50,000 millimeter wave transceivers worldwide to date.

"With the Endgate-TRW merger, the company more than doubled in size," said Ed Keible, Endwave's CEO. "Now, with the increased production capacity enabled by the addition of these two new facilities, we are taking another key step in building the critical tools to meet the growing requirements of our customers."



Warning: Arsenic disposal can be hazardous to your bottom line

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Anadigics Develops MCM Pilot Line for HBTs . . .

Anadigics has developed a pilot manufacturing line for multi-chip module (MCM) assembly. Located in the company's 6-inch manufacturing facility in Warren, NJ, the new MCM assembly line is currently being used to develop sample and pre-production quantities of InGaP HBT power amplifier modules for GSM, CDMA, and TDMA standards, as well as advanced cable tuner modules for use in broadband digital cable systems.

"Module technology is a key driver for the development of highly integrated, highly efficient solutions that reduce overall form factor and shorten time to market," said Bruce Diamond, senior VP of Operations. "Anadigics' in-house multi-chip module line shortens module assembly cycle time to hours, instead of weeks, enabling us to evaluate new packaging technology quickly."

. . . and Ships Over 100 Million RFICs

Anadigics has announced shipment of over 100 million broadband RFICs for broadband cable systems and fiber optic networks. The company's 6-inch manufacturing operation in Warren, NJ manufactures receivers for high speed SONET telecom networks, datacom networks, and Internet backbones, as well as highly-integrated tuner ICs and broadband GaAs amplifiers for cable television, Internet, and IP telephony systems. Anadigics' OEM customers include Scientific Atlanta, Nortel Networks, Lucent Technologies, Stratos Lightwave, Cisco Systems and Motorola. More than 1 million GaAs tuner ICs were shipped for use in Motorola's cable modem products in 1999.

Anadigics says that developments in fiber optic infrastructure as well as emerging two-way digital cable services have contributed to a 57% increase in its cable products revenue in the first half of 2000.

Nortel Selects Alpha as Preferred Supplier

Nortel Networks has qualified Woburn, MA-based Alpha Industries as a global preferred supplier, guaranteeing its RFICs and other semiconductor products as first choice for design engineers throughout Nortel's worldwide operations.

"Nortel is a significant Alpha customer, and our sales to them are growing rapidly," said Christopher Conlin, director of worldwide sales and marketing. "Our preferred supplier status takes Alpha's relationship with Nortel to the next level and allows Alpha the opportunity to participate earlier in the design cycle for next generation products."

In more news, Adaptive Broadband has chosen several of Alpha's GaAs IC switches and control devices for its high-speed broadband and wireless LAN systems operating in the 2.4–5.8 GHz frequency range.

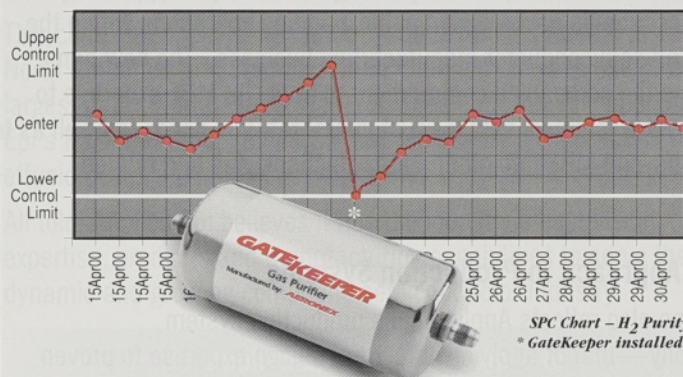
New Satellite LNA from TRW

TRW has introduced a highly-miniaturized LNA down-converter for satellite applications. The new device will reduce the size and weight of payloads serving the Astrolink global broadband telecommunications system, slated to begin service in 2003.

"Our unit is about the size of a matchbook and weighs little more than an ounce, yet contains extensive built-in redundancy for high reliability," said Paul Borzcik, manager of TRW's Astrolink program. "Only five years ago, electronics to perform the same functions would have required a box weighing several pounds."

TRW's LNA satellite downconverter receives at 30 GHz and transmits back to earth at 20 GHz. The package features an integrated microwave assembly consisting of a number of TRW's GaAs ICs designed for Ka band operation. The LNA's small size allows many such devices to be mounted directly in the multi-beam antenna, reducing signal loss between the LNA and antenna. The company says it is now completing the first pre-production batches, with production to begin shortly.

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MORE THAN THE NAME HAS CHANGED

Applied Epi, formerly EPI MBE Products Group, has long been the world leader in Molecular Beam Epitaxy (MBE) components and R&D systems.

Now, the company has a new name and an expanded mission—to become the world's leading supplier of fab-line solutions for the global compound semiconductor industry.

To that end Applied Epi has:

- expanded its vision to include other epitaxy technologies, such as Metal Organic Chemical Vapor Deposition (MOCVD),
- developed the world's highest-capacity MBE production systems,
- increased its production capacity, and
- greatly expanded its sales and service network.

The company now provides best-of-class products for all three segments of the MBE equipment industry—components, R&D systems and production systems. It will expand its epitaxy offerings beyond MBE. And it will back them all with a seasoned and experienced service and support network.

A New Name for a New Mission

EPI MBE Products Group recently changed its name to Applied Epi to better describe its new mission and expanding operations within the compound semiconductor manufacturing business. The new name describes the company's commitment to apply its MBE expertise to develop advanced tool sets for customers' fab-line needs, as well as to expand beyond MBE into other epitaxy technologies and related products.

A New Approach to Production Systems

The name also reflects Applied Epi's production system philosophy—that of applying its epitaxy design expertise to proven models and architecture found within silicon semiconductor manufacturing. That design philosophy enabled Applied Epi to create the world's highest capacity MBE production tools.

The flagship of this new line is the GEN2000. This revolutionary multi-wafer production MBE system is about half the size of existing 4x6" systems, yet it can simultaneously process seven 6-inch wafers. It increases productivity by 75% and reduces production costs per wafer by roughly one-third over existing systems.

This high throughput is made possible by using a "cluster tool" wafer management and transfer system—building upon the concepts used in

high-volume silicon semiconductor manufacturing—to mass-produce epitaxial wafers.

Applied Epi believes that the cluster tool design, coupled with its MBE components and comprehensive service, will give the GEN2000 the longest uptime and the lowest per wafer cost in the industry.

This superior return on investment has captured the attention of leading epitaxial wafer manufacturers. RF Micro Devices, IQE and Filtronic Compound Semiconductors Ltd. have already purchased GEN2000 systems—demonstrating the acceptance of the Applied Epi's design philosophy, and quickly establishing its position within the production MBE market.

**Through a combination of innovation,
throughput and uptime, the GEN2000 delivers
the lowest per wafer cost in the industry.**

An Unsurpassed Knowledge of MBE Applied to Production

Applied Epi's ability to bring such innovations to market springs from its understanding of both MBE technology and customer needs. Name a breakthrough in MBE over the past decade and it likely came from Applied Epi.

Some of the pioneering Applied Epi technologies that have become—and will likely become—MBE industry standards include Valved Crackers, SUMO™ Effusion Cells, Process control Molly™ software, and the UHV cluster tool wafer management system.

Applied Epi is committed to remaining the world's leading supplier of MBE components, and is incorporating many of these industry-standard designs into its growing lines of R&D and production systems.

R&D Systems Continue to Grow

Applied Epi is experiencing tremendous growth in MBE research systems as well. Its MOD GENII system is the leading MBE system for optoelectronic materials. In addition, the company's 930 system has become the preferred choice of the world's leading MBE R&D facilities seeking a robust, reliable and flexible growth platform.

A Time-Proven Approach to New Product Development

Applied Epi has long practiced a customer-centric approach to new product development. The company relies upon specialized in-house capabilities, including a full cadre of specially trained UHV welders and machinists who work hand-in-hand with the company's engineers and designers. This in-house expertise enables Applied Epi to arrive at a finalized design and functioning product on budget in a shorter period of time.

The company will apply this same customer-centric approach as it expands into other epitaxial fields. Applied Epi's established core competencies and expertise in MBE will be applied to new product development in other epitaxial technologies, such as MOCVD.

A Premiere Manufacturing Site Expands

Applied Epi has increased its manufacturing capacity to support its current and planned growth. The company has dedicated more space and resources to specifically support the production of its components, R&D systems and production systems in its state-of-the-art, 75,000-sq. ft. facility in St. Paul, MN. This enables Applied Epi to remain strategically focused on all three manufacturing operations to ensure customers get faster delivery of products, no matter what their epitaxial needs.

A Solid Company Investing in the Industry

In its 15-year history, the company's ability to finance growth and support new product development has created a reputation as an industry leader. This history underlies Applied Epi's confidence that it will fulfill its new expanding mission to become a full-service provider of epitaxy equipment solutions.

Applied Epi's financial strength will fuel this expansion beyond MBE, as well as support current increased MBE R&D and production system manufacturing efforts. Customers will benefit from a broader global support network, comprised of a dedicated sales force and distributors. Sales offices are located in the United States and Europe (U.K.), while distributors serve customers in India, Japan, Korea, Singapore, Taiwan, China, Hong Kong and France.

Applied Epi's customers include companies like Motorola, Lucent Technologies, Sony, Hewlett-Packard, Mitsubishi Chemical, Agilent Technologies, RF Micro Devices, IQE, and Filtronic. Numerous world-leading educational centers for advanced micro-electronics and optics, such as the University of California at Santa Barbara, and

Stanford, Cornell, Tokyo and Osaka Universities, are among customers for components and R&D systems.

The company's customer base will expand as the demand for more complex compound semiconductor structures creates new epitaxy applications for wireless communications, satellite communications, personal computing devices, optical data storage (CD and DVD) and high-efficiency lighting.



Applied Epi has recently added another 10,000 square feet of manufacturing space to speed the delivery time on its new MBE production systems.

The Right Choice for the Future

To support these applications, Applied Epi today can deliver the world's highest capacity MBE production systems, the world's preferred R&D systems, and the world's highest performance MBE components, electronics and software. Next, the company will provide an expanded epitaxy portfolio that includes MOCVD.

This complete package has already made Applied Epi the largest North American manufacturer of MBE equipment, and one of the largest in the world. More than 350 sites currently rely upon Applied Epi's R&D and production systems, while more than 3,500 of its effusion cells are in facilities worldwide.

All told, Applied Epi believes it has the industry's best vision, people, expertise, products and manufacturing capabilities to serve the dynamic and growing compound semiconductor industry.

Applied Epi's new mission—to become the world's leading supplier of fab-line solutions for the global compound semiconductor industry.

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Applied Epi

Accent Acquires Bio-Rad's Semiconductor Division

Bio-Rad Laboratories has sold its semiconductor and optoelectronic metrology business to Accent Semiconductor Technologies, a newly formed company with headquarters in Mountain View, CA, for \$35 million. Bio-Rad will retain an 18% share in the new company, and says the sale reflects its re-focus on core businesses in healthcare and clinical diagnostics.

"The transfer to new ownership is an excellent strategic move both for Bio-Rad

and for the semiconductor business unit," said Bio-Rad's CFO, Tom Chesterman. "Bio-Rad will be able to concentrate on its core businesses, and the semiconductor group will benefit from a new environment well suited to its goals and potential."

Accent will continue to supply semiconductor measurement tools for applications including monitoring of wafer production processes and device research. The operations of the semiconductor and optoelectronic metrology business will

remain essentially unchanged in its current locations; these include the company's UK facilities in York and Hemel Hempstead, and US operations in Mountain View, Cambridge, MA and Albuquerque, NM.

According to Accent's Steve Blight, the new company will split into two divisions concentrating on compound semiconductor and silicon markets. "We have identified compound semiconductors as an important growth area for Accent," he said.

Unaxis Moves Semiconductor Unit to Florida

Unaxis Semiconductors, the business unit of Unaxis AG that includes both Plasma-Therm and BPS, has moved its worldwide headquarters to the site of the former Plasma-Therm facility in St. Petersburg, Florida. Unaxis AG is a Swiss-based technology company that was formed by the recent reorganization of the diversified Oerlikon-Bührle conglomerate. Unaxis Semiconductors is one of several groups within Unaxis IT, the others being data storage, displays, optics and materials—the IT segment makes up around half of the company's sales. Plasma-Therm, which manufactures thin-film etching and plasma-enhanced CVD equipment, was acquired by the Oerlikon-Bührle group in March 2000 to complement the products and capabilities of the BPS group.

WIN Semiconductors Orders Tegal Plasma Etch System

Tegal (Petaluma, CA) has received an order from WIN Semiconductors Corporation, a new Taiwanese company that is currently constructing a 6-inch GaAs fab in Lin Kou for foundry services based on HBT and PHEMT processes. Due to be installed shortly, Tegal's 900 series plasma etcher will be used in the production of GaAs MMICs.

Picogiga Steps Up Production

Picogiga has ordered three additional Riber MBE reactors with a capacity for 7×6 -inch wafers per run. This will allow a 75% increase in productivity, and will double production capacity by the end of 2001. The company is also planning to begin construction of a new facility at the end of the year. "Our present facility will be fully occupied in 2001, and to prepare for future expansion, we have purchased 8,000 m² (~ 87,000 ft²) of land adjacent to the present facility," said Picogiga's chairman, Linh Nuyen. The new Riber reactors will be installed in Picogiga's existing facility.

JMAR Awarded X-Ray Lithography Contract

JMAR Technologies of San Diego in California has received an additional \$3.8 million contract from the U.S. Army Research Laboratory to continue development of a X-ray point source for lithography. X-ray lithography (XRL) is one of the contenders to succeed Deep UV (DUV) lithography in defining circuit feature—currently, production-scale DUV lithography produces features sizes of 0.18 μ m, and is approaching its resolution limit. JMAR's PXS laser plasma XRL system has already defined features as small as 0.07 μ m.

"As the trend toward smaller circuit sizes continues, we believe a lithography system using the PXS light source, which does not require expensive optics, could become in-

creasingly attractive to semiconductor manufacturers as they strive to balance the demand for ever-smaller chips with the need to curb the skyrocketing cost of producing them," said John Martinez, JMAR's chairman and CEO. "This new contract funding should enable us to complete a four-beam PXS module before the end of this year to power a viable, entry-level production lithography device."

JMAR's first two years of funding resulted in the development of a laser capable of 75–125 W of short pulse power, with laser-to-X-ray conversion efficiencies in the 3–6% range. JMAR says that collimation improvements have also increased the X-ray power incident on the lithography mask by up to 40 times.

New Corporate Identities

IQE plc, formed last year by the merger of Epitaxial Products International (EPI) and Quantum Epitaxial Designs (QED), will change its corporate identity. EPI (Cardiff, UK) will now be known as **IQE (Europe) Ltd.** and QED (Bethlehem, PA) will operate as **IQE Inc.** Sales and marketing activities and business transactions conducted in Europe and the Far East will now be managed by IQE (Europe) Ltd., with North American activities handled by IQE Inc.

EPI MBE Products Group of St. Paul, MN has changed its name to **Applied Epi, Inc.** "Our new name acknowledges that our enabling MBE technology is more critical than ever to compound semiconductor manufacturers," said David Reamer, president of Applied Epi.

Emcore Quadruples Epiwafer Production Capacity

Emcore has completed the second phase of expansion at its Somerset, NJ manufacturing facility, and has moved its corporate offices to a new facility nearby. The addition of 7,000 sq. ft. of space will accommodate 10 new Emcore MOCVD reactors for the production of PHEMT and HBT epiwafers, increasing the company's production capability by 400%. This brings the total number of production tools in operation to 18, providing a total annual capacity of 360,000 six-inch wafers. The enlarged facility also doubles Emcore's characterization capabilities. Earlier this year, the company's first phase of expansion nearly doubled the production capacity of four- and six-inch wafers for PHEMT and HBTs [see CS 6(3), p. 20].

Emcore has also increased the capacity of two other divisions. The company's electronic device division has been expanded to increase production of photo-detectors for high speed array transceivers, while the MOCVD tool division now has the ability to manufacture 225 MOCVD reactors per year.

Matheson Builds New Manufacturing Facility

Matheson Tri-Gas is close to completing a new specialty gas facility at New Johnsonville, TN for the manufacture of arsine and phosphine. Expected to be fully operational in the second half of 2000, the facility augments Matheson's existing facility in Gloucester, MA.

The company says the additional capacity is needed to meet increasing demands for compound semiconductor gases. "We are seeing tremendous growth in the MOCVD market due to advances in optoelectronics and communications markets," said marketing director Kevin Finn. "In turn, the demands for purity and capacity for these gases is increasing dramatically."

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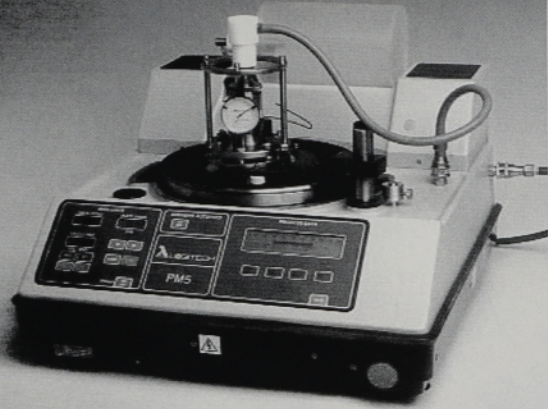
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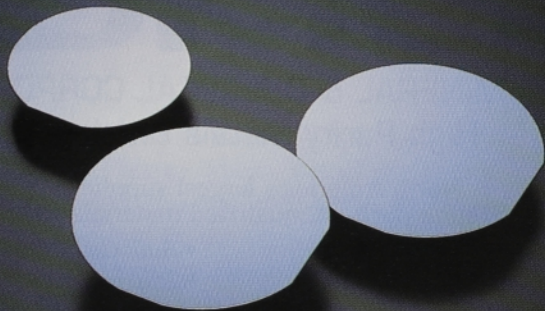
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EMF Expands Metalorganic Capacity, Sells Reactors

EMF (Cambridge, UK) has installed the world's largest gas chromatography (GC) system for the production of group III metalorganic precursors. The patented GC technology, purchased from Eagle Picher for \$3 million, allows the separation of the precursor chemicals from impurities during the production process. "The GC plant increases our metalorganic production capacity to over 2000 kg per year," says Jim Dixon, EMF's sales and marketing director. "We are responding to increased demand for our DEOX grade products." These are high purity trimethylaluminum (TMA), trimethylgallium (TMG) and trimethylindium (TMI). "In applications such as the growth of VCSELs and GaN LEDs, high purity precursors with ultra-low oxygen content are critical," adds Dixon.

EMF has also received an order from Northrop Grumman for two MOCVD reactors for the growth of SiC and GaN. Both systems will be delivered and installed by the third quarter of 2000.

In Brief . . .

DCA Instruments has received an order for a 4 × 4-inch MBE system from **Applied Optoelectronics** (Sugarland, TX) to grow InP based devices. Delivery of this system, the third multiwafer production reactor to this customer, is expected by early 2001.

Oxford Instruments Plasma Technology (Yatton, UK) was awarded first place in a recent customer satisfaction survey by VLSI. The company also topped the bill in process support, product performance and technical leadership. This results from a number of initiatives carried out by OIPT—including after-sales support and increased manufacturing efficiency, in addition to better customer sample characterization following construction of a new applications laboratory.

Universal Systems (San Jose, CA) has received a \$2.6 million contract from **Alcatel's** Optronics unit for wet process systems. Delivery of the company's VLF series of automated wet process stations, scheduled over the next few months, will provide Alcatel with wafer cleaning and related processing of Si, GaAs and InP substrates and devices.

Ericsson Microelectronics has ordered multiple 943GT systems from **KDF**, to be installed at Ericsson's manufacturing facility in Kista-Stockholm, Sweden by the third calendar quarter.

Developments in 980nm Pump Lasers for Advanced Er-doped Fiber Amplifier Architectures

TOBY STRITE and DHRUPAD TRIVEDI
JDS Uniphase

Since the early 1990's, engineers have used wavelength division multiplexing (WDM) and other enhancements to double the data transmittable through an optical fiber strand every 9–12 months. This phenomenal achievement is timely since demand for fiber-optic communication as represented by the Internet was recently doubling every four months. Optical amplification remains the key enabler of optical networking because, being a purely optical process, it is highly bandwidth scalable. The particular success of Er-doped fiber amplifiers (EDFAs) results from the happy coincidence that Er embedded in silica glass provides gain within a narrow band around 1550nm where silica is especially transparent. Gain is realized by pumping erbium-doped fiber at either 980nm or 1480nm. The combination of low fiber absorption and all-optical amplification makes optical networking the lowest cost method for transporting large amounts of data over extended distances. EDFAs remain at the heart of every fiber-optic network deployed, but to maintain the innovative pace demanded by growth of the Internet, amplifier architectures are evolving rapidly.

This article overviews the evolution of EDFAs for increased bandwidth paying special attention to the pump lasers needed to power them.

The Evolution of the EDFA

The most critical EDFA performance parameters are amplified 1550nm output power (typically stated in dBm) and noise figure (stated in dB). Output power is chiefly determined by total pump power

and the amplifier internal loss. The noise figure is defined as the ratio of the signal-to-noise ratio at the input to the signal-to-noise ratio at the output. Proper pumping is a critical determinant of output power and noise figure.

The simplest form of the EDFA, shown in Figure 1(a), employs a WDM coupler to guide pump laser light into the Er-doped fiber gain medium. Such single-stage optical amplifiers are suited for a wide range of applications such as single channel amplifiers, simple WDM amplifiers and low-

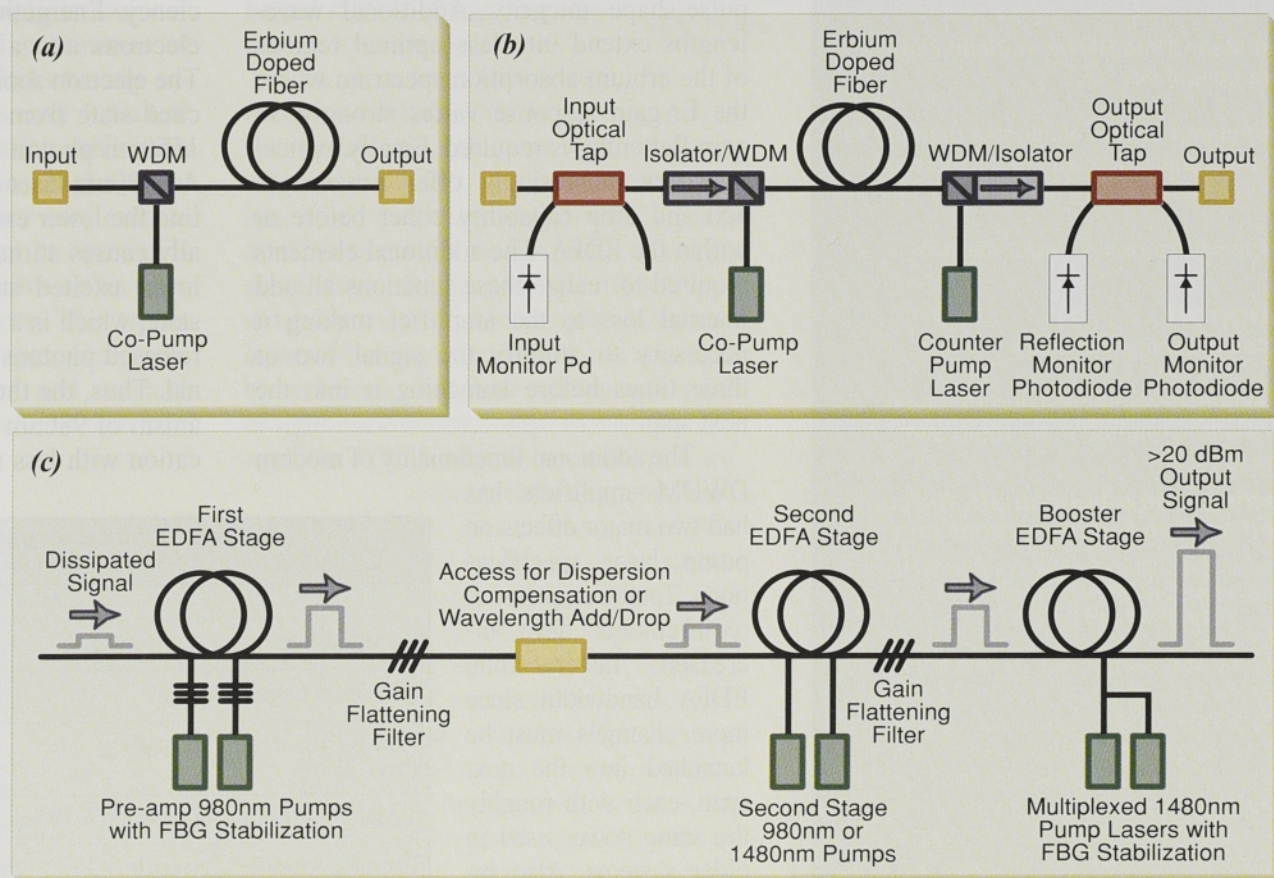
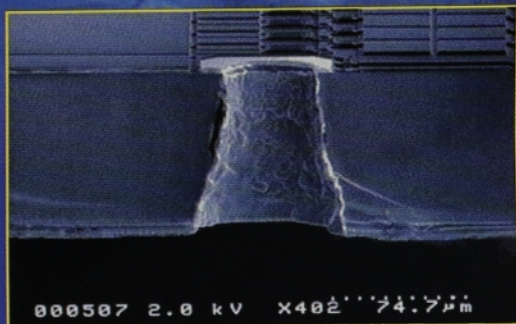


Figure 1. EDFA Evolution. (a) Simple coarse WDM EDFA, ca. 1994. (b) Upgraded single stage amplifier suitable for 16-channel WDM systems, ca. 1997. (c) State-of-the-art DWDM EDFA with increased functionality.

Production Proven GaAs Via Etch for MMIC Device Manufacture



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cost. When only a single pump is used, it is generally a 980nm, since the noise figure remains of critical importance.

Single stage amplifier performance can be improved by adding pump lasers and additional components. An EDFA such as Figure 1(b) is typical of single stage amplifiers. EDFAs typically use both pump laser technologies to arrive at optimum amplification solutions in terms of price/performance tradeoffs. Typically, a co-propagating 980nm pump enters the Er-doped fiber alongside the depleted signal to immediately provide low noise amplification, while a counter-propagating 1480nm pump enters from the rear for maximum pumping effect at the output.

As fiber-optic system bandwidth continues to scale, multiple stage EDFAs resembling Figure 1(c) are needed because all methods of increasing system bandwidth—adding wavelengths, increasing channel data rates and improving network efficiency—require additional EDFA functionality. Specifically, 10 Gb/s data rates require dispersion compensation near or within the EDFA to maintain the pulse-shape integrity. Additional wavelengths extend into less optimal regions of the erbium absorption spectrum where the Er-gain response varies strongly, so gain flattening is required. Finally, optical networks increasingly offer wavelength add and drop capability either before or within the EDFA. The additional elements required to realize these functions all add internal loss to the amplifier making it necessary to amplify the signal two or three times before launching it into the next span.

The additional functionality of modern DWDM amplifiers has had two major effects on pump laser specifications. Total pump power requirements have increased faster than EDFA bandwidth since more channels must be launched into the next span, each with roughly the same power used in older systems. Also increased internal EDFA losses associated with the bandwidth enhancing elements must also be

compensated. Thus, improvements in the power available from individual pump lasers are required. Second, 980nm pump laser wavelength specifications have been tightened since the Er absorption spectrum vs. pump wavelength around 980nm is strongly peaked, making EDFA response more sensitive to variations of 980nm pump laser wavelength than 1480nm.

Comparison of 980nm and 1480nm EDFA Pump Lasers

The 980nm and 1480nm pump laser alternatives provide vital design flexibility for scaling EDFAs to higher bandwidth. These alternatives can be understood by comparing the key performance parameters of each device type for EDFA pumping (Table 1). Broadly, the strengths and weaknesses of each can be related to the pump wavelength or the semiconductor materials comprising the laser.

Pumping erbium at 980nm or 1480nm is a direct trade-off between noise figure and optical conversion efficiency. Energetic 980nm photons excite electrons into a higher Er excited state. The electron soon relaxes into a lower excited state from which it can replicate a 1550nm photon via stimulated emission. A 1480nm laser directly pumps electrons into the lower excited state, but occasionally causes stimulated emission from the lower excited state back to the ground state, which is a source of noise since the released photons are unrelated to the signal. Thus, the three-level pumping mechanism of 980nm lasers produces amplification with less noise, but at the expense

Table 1. Anticipated performance of 980nm vs. 1480nm pump lasers in January 2001

	980nm	1480nm
Pump Wavelength Dependent		
Minimum Noise Figure	<4 dB	5.5 dB
Pump Conversion Efficiency (mW/dBm)	35%	50%
Typical Rated Fiber-coupled Power	170mW	220mW
Semiconductor Dependent		
Diode Laser Quantum Efficiency	0.95 W/A@ 300mW	0.38W/A@ 250mW
Fiber-coupled Wallplug Efficiency	42% W/W	15% W/W

of wasted energy because the electrons must relax unproductively from the higher to lower excited state.

At the beginning of next year, it will be possible to purchase in volume a 1480nm pump laser producing 200–240mW fiber-coupled power from which the EDFA can produce >100mW (>20dBm) of amplified 1550nm output power (assuming 50% pump conversion efficiency). In comparison, the high end of the 980nm market next year will be 170–200mW, which after erbium-doped fiber conversion losses, produces ~35% less amplified power. Since most laser cost lies in the packaging, 1480nm pumps remain the most economical choice for power.

On the other hand, low noise is critical, since it determines how many EDFAs can be cascaded before the signal degradation requires expensive electronic regeneration. When the 1550nm signal is weak, it is especially susceptible to pump related noise, so 980nm lasers are a clear choice in the initial pre-amplification section of EDFAs and anywhere else within the EDFA where signal strength is low.

The material related parameters of Table 1 stem from AlGaInAs having superior physical properties over InGaAsP for high power laser operation. AlGaInAs 980nm laser structures have higher thermal conductivity and fewer loss mechanisms, which permit them to operate at nearly three times the quantum efficiency of InGaAsP 1480nm lasers. The higher drive current and heat dissipation requirements of 1480nm pumps add residual costs to the amplifier, which can convince

an EDFA designer to forego them in favor of 980nm pumps.

The fundamentally better laser performance of AlGaInAs promotes optimism that 980nm chips will scale in power better than 1480nm, but neither laser type has yet run out of steam, and 1480nm manufacturers have managed to retain their lead in power. Both 1480nm and 980nm pump laser suppliers are striving to further improve output power. Among them, JDS Uniphase has achieved >400mW fiber-coupled power (see Figure 2) using prototype lasers engineered especially for high power and high fiber-coupling efficiency. By mid-year 2001, 300mW 980nm pump lasers will be commercially available. Present 980nm designs should scale up to 500mW fiber-coupled power before radical changes in chip design are foreseen.

As discussed above, the complex DWDM EDFAs of Figure 1(c) are highly sensitive to 980nm pump wavelength, so a stable wavelength is specified. Such wavelength stabilization of 980nm pumps is generally achieved using fiber Bragg gratings. The FBG, normally written into the packaged pump laser's fiber pigtail, performs its function by reflecting a narrow wavelength band of light back into the chip. In a proper design, the FBG feedback governs the laser output, stabilizing the output power within <0.05dB and fixing the laser wavelength within a fraction of a nanometer such as the device shown in Figure 3. Of particular importance is that wavelength locking and output power stability be maintained over as wide a range of operating power and temperature as possible, since EDFAs now often drive pumps variably depending on the network traffic at a given time.

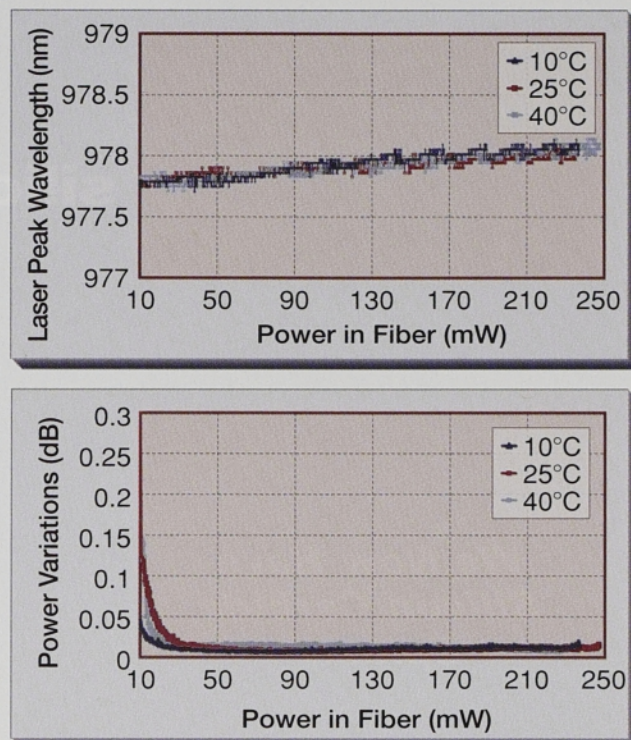


Figure 3. FBG wavelength-stabilized 980nm pump laser. (top) Laser output wavelength is locked within a sub-nm band over a large range of temperatures and operating powers. (bottom) Low-frequency power fluctuations are suppressed well below 0.05dB.

Future improvements in optical networking bandwidth will continue to rely on the ability to transmit more information on a single wavelength, more wavelengths through a single fiber strand, and to more intelligently manage the flow of light through the network. Whether it is upgrading from 10 to 40 Gb/s transmission, or 80 to 160 wavelengths, or all-optical switching, the thirst for bandwidth, and the pump laser power and stability requirements this engenders will continue.

Toby Strite is Director of 980nm Module Marketing, JDS Uniphase. Dhrupad Trivedi is Senior Product Line Manager for Optical Amplifiers, JDS Uniphase. The authors wish to thank their colleagues Stefan Mohrdiek and Berthold Schmidt for their technical contributions to the work presented in this article.

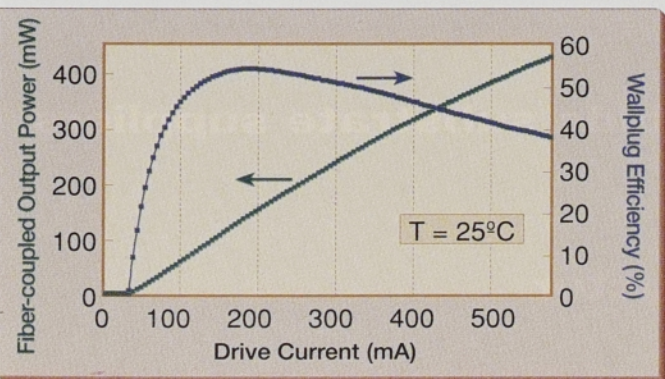


Figure 2. Prototype 980nm laser achieving 400mW fiber-coupled power at >85% chip-to-fiber coupling efficiency. Peak power conversion efficiency is above 50%.

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Commercial Wide Bandgap RF Power Devices—Fact or Fiction?

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Motorola, Inc.

In recent years, the wide bandgap semiconductors silicon carbide (SiC) and gallium nitride (GaN) have received increased attention because of their potential for a wide variety of high power devices [1–4]. Their unique material properties—high electric breakdown field, high saturated electron drift velocity, and, for SiC, high thermal conductivity—give these materials tremendous potential in the power device arena. The data in Table 1 allow a comparison of the basic material properties of silicon, GaAs, 4H-SiC and GaN. The 5–6 times higher breakdown field of both SiC and GaN provides these materials with a clear advantage over Si and GaAs for high voltage, RF power devices.

SiC clearly has an advantage over GaN in thermal conductivity, but the AlGaN/GaN heterojunction that can be grown in the GaN material system enables lateral GaN HFETs to have superior current handling capability compared to lateral SiC devices. Moreover, GaN can be epitaxially grown on SiC, taking advantage of SiC's higher thermal conductivity. In this paper, wide bandgap RF power devices will be discussed in terms of fabrication and state-of-the-art experimental performance, and the results will be compared with those of Si and GaAs devices. In addition, the challenges facing wide bandgap RF power devices as they move toward commercialization will be discussed.

Property	Si	GaAs	4H-SiC	GaN
Bandgap (eV)	1.11	1.43	3.2	3.4
Relative Dielectric Constant	11.8	12.8	9.7	9.0
Breakdown Field (V/cm)	6×10^5	6.5×10^5	35×10^5	35×10^5
Saturated Velocity (cm/sec)	1×10^7	1×10^7	2×10^7	1.5×10^7
Electron Mobility (cm ² /V.s)	1350	6000	800	1000
Hole Mobility (cm ² /V.s)	450	330	120	300
Thermal Conductivity (W/cm.K)	1.5	0.46	4.9	1.7

Table 1. Comparison of properties of various semiconductor materials.

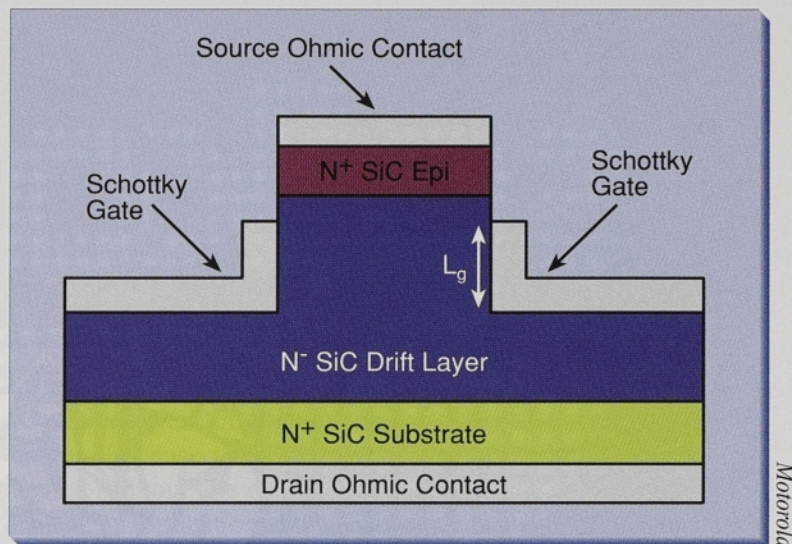


Figure 1. Cross-sectional view of a SiC static induction transistor (SIT). Current flows vertically from source to drain.

RF Power Devices

A. SiC Static Induction Transistors (SITs)

SiC SITs, similar in design and operation to silicon SITs [5], are a vertical device with an ohmic source contact on the top and an ohmic drain contact on the back of the wafer (Figure 1). Between these two N⁺ regions is an N⁻ epitaxial drift layer whose doping is one of the factors that determines the device breakdown voltage and pinch-off voltage. Trenches are etched to define the channel region and Schottky gate contacts are formed in the bottom and along the sidewalls of the trench. Majority carriers flow from the source contact to the drain contact through accumulation layers in the n-type channel region. By applying a negative voltage to the gate contact, the current flow can be modulated and even decreased to zero when the depletion regions under each gate electrode meet in the middle of the channel.

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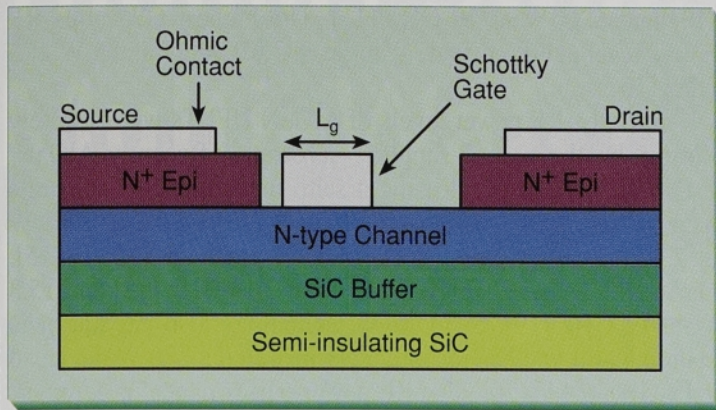


Figure 2. Cross-section of an RF SiC MESFET. Current flows from source to drain in the N-type channel layer.

Although SITs generally have the lowest operating frequencies and lowest RF power densities compared with other wide bandgap RF power devices, they have achieved some of the highest total output powers. 4H-SiC SITs have achieved 400 W pulsed power at 1.3 GHz, 78 W pulsed power at 2.9 GHz, and 47 W pulsed power at 4 GHz [6]. In addition, a one-kilowatt, 600 MHz SiC power module containing four SITs with a total source periphery of 94.5 cm has been demonstrated [7].

B. SiC MESFETs

Unlike SITs, SiC RF MESFETs are lateral devices, similar to GaAs MESFETs, with both source and drain contacts on the top surface of the wafer (Figure 2). Source and drain ohmic contacts are typically placed on top of an N⁺ epitaxial layer and are separated by a more lightly doped N-type channel region. The majority carriers flow in the channel from source to drain and are controlled by a Schottky gate contact. Device isolation can be achieved either with a P⁻ buffer layer on a conducting substrate or with a high resistivity substrate to achieve higher cut-off frequency devices [8].

The highest SiC MESFET power density achieved using a conducting substrate is 3.3 W/mm with $V_d = 50$ V at a frequency of 850 MHz [9]. Using a semi-insulating substrate, 5.6 W/mm has been achieved with $V_d = 60$ V at a frequency of 3.5 GHz [10]. These two results illustrate the significant increase in frequency performance that can be achieved by using a semi-insulating, rather than a conducting substrate. The highest total power reported for a single SiC MESFET (48 mm) is 80 W at 3.1 GHz with $V_d = 58$ V [10]. Under pulsed conditions this same 48-mm MESFET achieved 120 W at 3.1 GHz. Under pulsed test conditions another SiC MESFET achieved 6.3 W at 10 GHz [11].

C. AlGaIn/GaN HFETs

AlGaIn HFETs (Figure 3) are also lateral devices, but contain a more complex material structure than the SiC MESFET. Because GaN substrates are not readily available, the GaN epitaxial channel layer is grown with an interposed nucleation layer on a sapphire or on a high resistivity SiC substrate [12–14]. Sap-

phire has been a good substrate for device development and for demonstration of high frequency performance, but it has a very low thermal conductivity (0.42 W/cm.K) compared to that of SiC (see Table 1). Wider bandgap Al_xGa_{1-x}N is grown on the channel layer forming a quantum well at the interface.

The very high sheet carrier density ($\sim 1 \times 10^{13}$ cm⁻²) in the quantum well gives the AlGaIn HFET very high current carrying capability and high transconductance, both of which are very attractive for high frequency power devices. AlGaIn HFETs have achieved the highest f_T and f_{max} values—28 GHz and 82 GHz respectively—of any wide bandgap semiconductor RF device. Recently, an AlGaIn HFET on a 4H-SiC substrate has achieved the highest RF power density ever reported for a wide bandgap semiconductor device, 9.1 W/mm at 10 GHz [15]. A flip-chip mounted, 2 mm AlGaIn HFET achieved 9.8 W at 8.2 GHz.

Performance Comparison

Three important parameters for comparing RF device performance are operating frequency, power density, and total output power. The relative operating frequency of these three wide bandgap devices can be compared by plotting f_{max} versus transconductance, because device transconductance is an important factor in determining f_{max} (Figure 4). The SiC SITs have the lowest reported transconductance and therefore, the lowest f_{max} values. Because the maximum useful operating frequency of a device is about one order of magnitude below f_{max} , SITs are relegated to applications with operating frequencies below 1 GHz. On the other hand, AlGaIn/GaN HFETs have the highest transconductances and the highest f_{max} values, and therefore are suitable for applications above 10 GHz. SiC MESFETs have f_{max} values between these two extremes. The data for SiC MESFETs clearly show the advantage of using semi-insulating substrates to achieve higher frequency performance. Even though the MESFETs on conducting and semi-insulating substrates have comparable transconductances, those on semi-insulating substrates have 2–3 times higher f_{max} because of the lower parasitic gate capacitance.

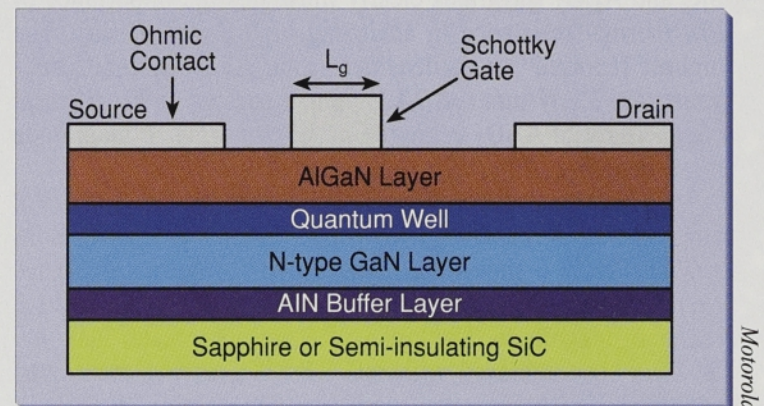


Figure 3. Cross-section of an AlGaIn heterojunction FET (HFET). Current flows in the quantum well from source to drain.

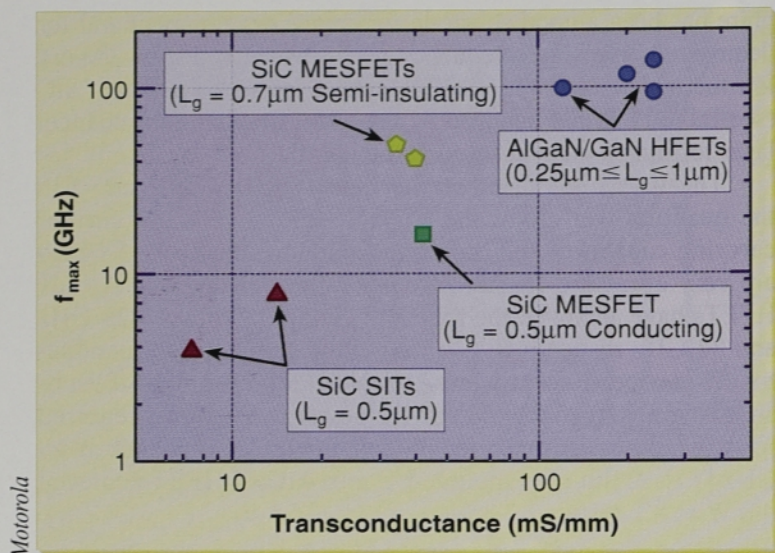


Figure 4. Maximum frequency of oscillation (f_{max}) versus device transconductance for SiC SITs, SiC MESFETs and AlGaIn/GaN HFETs.

The high breakdown field of wide bandgap semiconductors (SiC and GaN) enables devices with higher RF power densities than the narrower bandgap materials (Si and GaAs). As shown in Figure 5, Si and GaAs FETs have power densities near and below 1 W/mm, while the wide bandgap devices have power densities above 1 W/mm for comparable operating voltages. The highest power densities reported for SiC SITs, SiC MESFETs, and AlGaIn/GaN HFETs are 1.3 W/mm, 5.6 W/mm, and 9.1 W/mm, respectively.

When comparing the power density of different devices, it is important to also know the total power capability of the device, because larger devices generally have lower power densities than smaller devices. This is clearly illustrated in the GaAs data in Figure 5, because the lowest power density device (0.56 W/mm at 15 V) has a significantly higher total power capability (200 W) than the other GaAs devices [16]. Recently, however, a 100 W AlGaAs HFET with a field-modulating plate has been demonstrated with a power density of 1.16 W/mm at a drain bias voltage of 30 V [17]. The AlGaIn/GaN HFET data on SiC and Al_2O_3 substrates clearly illustrates the importance of low thermal resistance in achieving high power density. The highest reported power densities using Al_2O_3 and SiC substrates are 3.1 W/mm and 9.1 W/mm, respectively. The thermal conductivity of Al_2O_3 is approximately an order of magnitude lower than that of SiC.

Another basis for comparing RF power devices is the total power handling capability that each technology has demonstrated. Figure 6 shows the highest total RF powers that have been achieved—note that the power axis of this graph spans 3 orders of magnitude. The highest RF powers, greater than 400 W, have been achieved with SiC RF SITs, as was mentioned previously [6,7]. However, these very high power levels have been achieved at frequencies equal to or less than 2 GHz with the devices operated in the pulsed-mode. A 4H-SiC MESFET operated in the pulsed-mode has achieved 120 W at 3.1 GHz

[10] and 6.35 W at 10 GHz [11]. The highest CW-mode RF power level achieved with a single SiC MESFET is 85 W at 3 GHz [10].

Initially, RF power levels of AlGaIn HFETs were severely limited by the use of sapphire substrates. Recently AlGaIn/GaN HFETs fabricated using a semi-insulating SiC substrate have achieved total output powers of 9.1 W, 9.8 W, and 8.3 W at 7.4 GHz, 8.2 GHz, and 10 GHz, respectively [10, 14–15]. GaAs HFETs have achieved 240 W at 2.14 GHz [18] and 15.8 W at 12 GHz [19]. Si LDMOS technology also has not been standing still and has recently demonstrated a 220 W device at 2.12 GHz, 28 V [20]. The RF power performance of commercially available Si LDMOS FETs is included in Figure 6 for comparison [21].

Commercialization

No one questions the commercial value of wide bandgap GaN-based blue LEDs and lasers. Many companies worldwide are pursuing short wavelength lasers for increased data storage density. The commercial value of wide bandgap switch-mode and RF power devices is less clear. The biggest difference in these two applications is that the wide bandgap photonic devices face little competition from alternative technologies that perform the same function. However, in both the switch-mode and RF power markets wide bandgap power devices face stiff competition from well entrenched, mature semiconductor technologies, silicon and GaAs. For a new technology to gain a foothold in the market place it must offer all of the attributes of the mature technologies that customers have come to expect such as proven reliability, multiple dependable sources, accurate device models, and low cost. In addition the new technology must offer a significant performance improvement at a reasonable cost. This cost requirement is less stringent for military systems and therefore expensive new technologies often

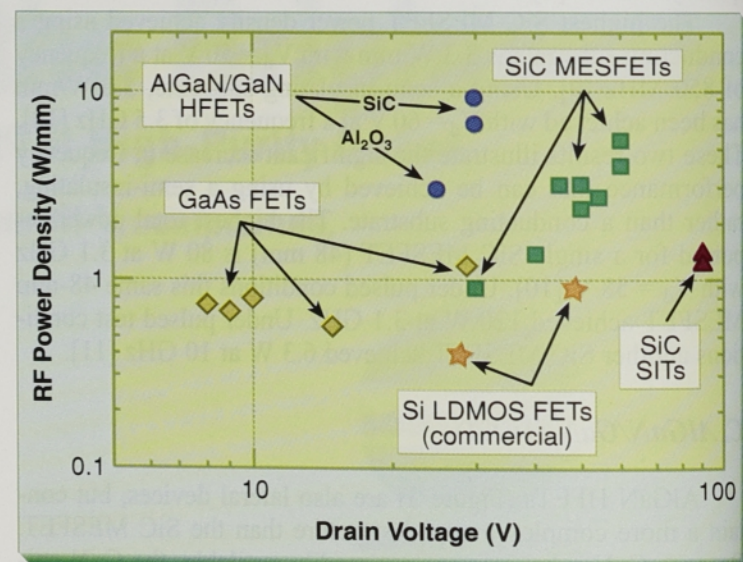
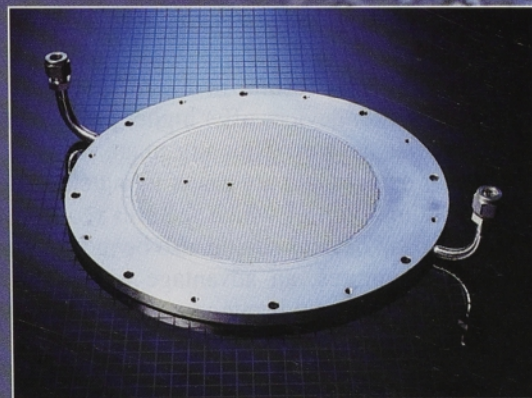
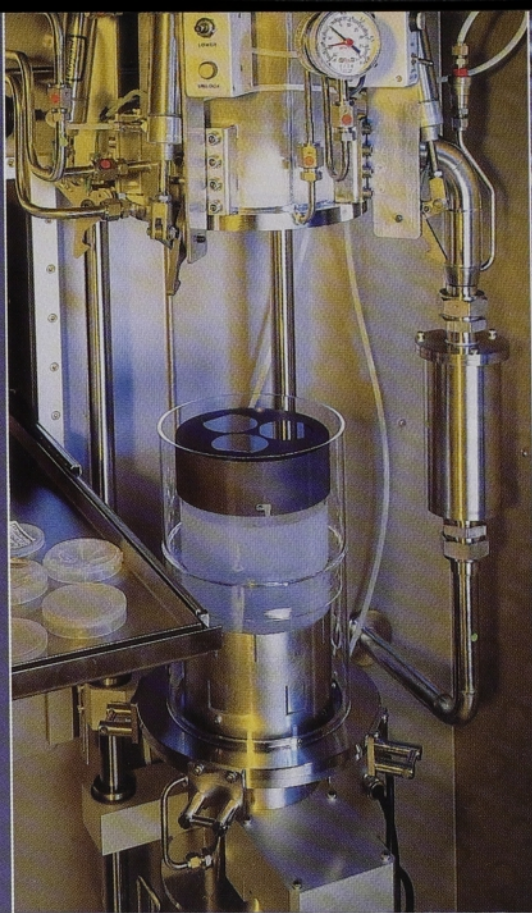


Figure 5. RF power density as a function of operating voltage for SiC SITs, SiC MESFETs and AlGaIn/GaN HFETs.

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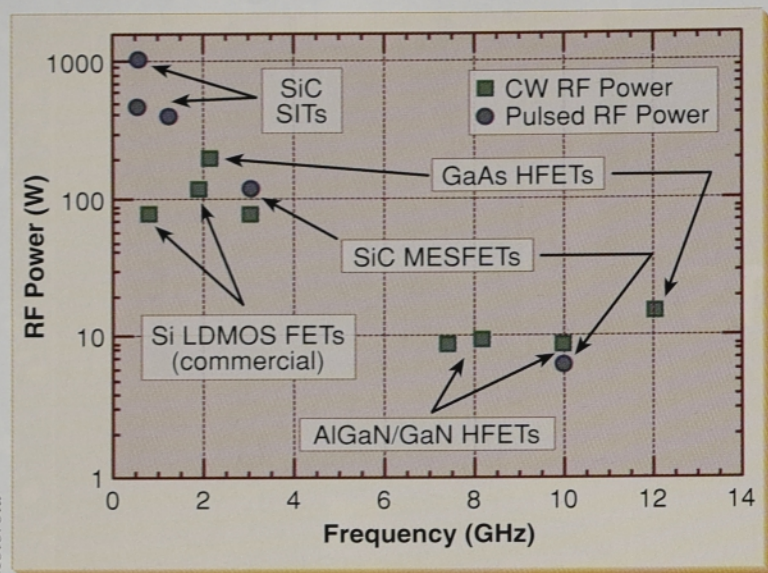


Figure 6. Total RF output power as a function of operating frequency for SiC SITs, SiC MESFETs and AlGaIn/GaN HFETs.

are first utilized here. In contrast, the commercial market wants devices with improved performance at preferably lower cost. Recently, the first commercially available SiC RF power device has been introduced by Cree, Inc. This device delivers 10 W of output power from 400 to 2500 MHz with a gain of 12 dB at a drain bias of 48 V [22].

The experimental results in Figure 5 clearly show that wide bandgap power devices offer higher power density than Si and GaAs power devices. This advantage leads to physically smaller power devices that are easier to match and require less power combining, both of which features reduce system loss. The wide bandgap devices should also be more tolerant of high operating temperatures, an advantage especially to military systems. However these advantages are achieved only at operating voltages above about 10–20 V. This fact relegates wide bandgap RF power devices to base-station and infrastructure applications. The RF semiconductor content in these applications, valued at approximately \$600 million/year at present, is mostly Si LDMOS.

Given the performance advantages of wide bandgap devices and the availability of a large market, what are the technical challenges facing the technologies? Many of these challenges are not very different from those facing other semiconductor technologies. In order to achieve high device yield the starting material and fabrication processes must be controlled sufficiently to ensure reproducibility of device specifications. In addition starting material and packaging costs must be kept as low as possible.

The wide bandgap technologies offer some interesting challenges and possibilities in these areas. Assuming that the high thermal conductivity of the SiC substrate is required, only 50-mm semi-insulating and conducting wafers are currently available. Larger diameter 75 mm and 100 mm wafers have been demonstrated in R&D. SiC substrates have a unique defect called a micropipe, which is a small hole (0.5–2 μm in diameter) that extends through the wafer. If present in or near device

channel regions, micropipes are a “killer” defect. The lowest micropipe density reported to date is 0.5/cm² in R&D material. Production grade substrates have micropipe densities 1–2 orders of magnitude higher.

Also, commercially available SiC epitaxy has very wide specifications on thickness uniformity ($\pm 25\%$) and on doping density ($\pm 50\%$). The cost per unit area of a semi-insulating SiC starting wafer with epitaxy is 25 times that of a GaAs wafer. Clearly the quality and cost of SiC substrates and epitaxy will have to be improved significantly in order to achieve low die cost. Finally, high power density, wide bandgap devices may benefit from lower package costs, because smaller packages will be required for equivalent RF output power.

Conclusions

Wide bandgap devices offer higher RF power densities than Si and GaAs devices, and the total available market for such devices is approximately \$600 million per year. The amount of this market that wide bandgap power devices will capture is totally dependent on their cost for performance as compared to that of Si and GaAs devices. With the introduction of the first commercial SiC RF power MESFET by Cree, Inc., the competition among these RF power technologies will certainly intensify.

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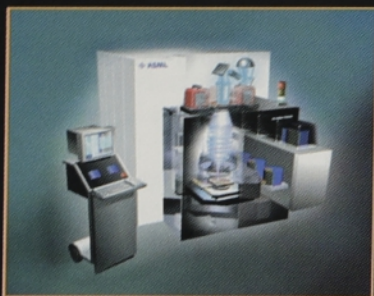
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Recent Progress in the Development of III-V Solar and Thermophotovoltaic Cells

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In recent years, multi-junction solar cells have been widely used for space applications, mainly due to their high efficiency and low degradation under electron and proton irradiation in space. U.S. companies such as Spectrolab, Tecstar and Emcore manufacture multi-junction solar cells with an annual production capacity exceeding 1 MW. All of these companies use a dual- or triple-junction solar cell concept originally developed by the National Renewable Energy Laboratory (NREL) in the early 1980's. This cell concept is based on monolithically grown solar cells fabricated from $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$, GaAs and germanium. These materials all have nearly the same lattice constant and therefore can be grown on one substrate with a low dislocation density. Multiwafer MOVPE reactors are used for the large-scale production of these solar cells.

Another potential market for III-V solar cells in the future is in terrestrial solar concentrator systems for large-scale electricity production. These systems will typically work at high illumination intensities, equivalent to 500–1000 suns. In this case, the costs of the photovoltaic receiver are not price limiting, and expensive high-efficiency III-V solar cells can be used. Today's production capaci-

ties of III-V space solar cells would be sufficient to produce more than a GW of electrical power per year if used in such concentrator systems. For comparison, the current yearly production rate of flat plate solar modules is in the range of 200 MW.

At high concentration levels, III-V semiconductors are the technology of choice. High efficiencies (>30%) can be reached and the degradation of the cell

performance at high working temperatures is much smaller compared to Si. On the other hand, the development of III-V multi-junction solar cells for high concentration ratios is a big challenge for the cell manufacturer. Current densities in the order of several A/cm^2 have to be conducted at a low resistance, and tunneling junctions with high peak-tunneling currents have to be found. The development of appropriate solar cells is one of the key areas of interest in the III-V group at the Fraunhofer ISE. New solar cell structures based on a $\text{Ga}_{0.83}\text{In}_{0.17}\text{As}$ bottom cell grown lattice mismatched on GaAs substrates have been developed [1,2] and high efficiencies up to 31% at 300 suns and >29% at 1000 suns (AM1.5d)[‡] have already been achieved.

Another key focus at the Fraunhofer ISE lies in the development of low-

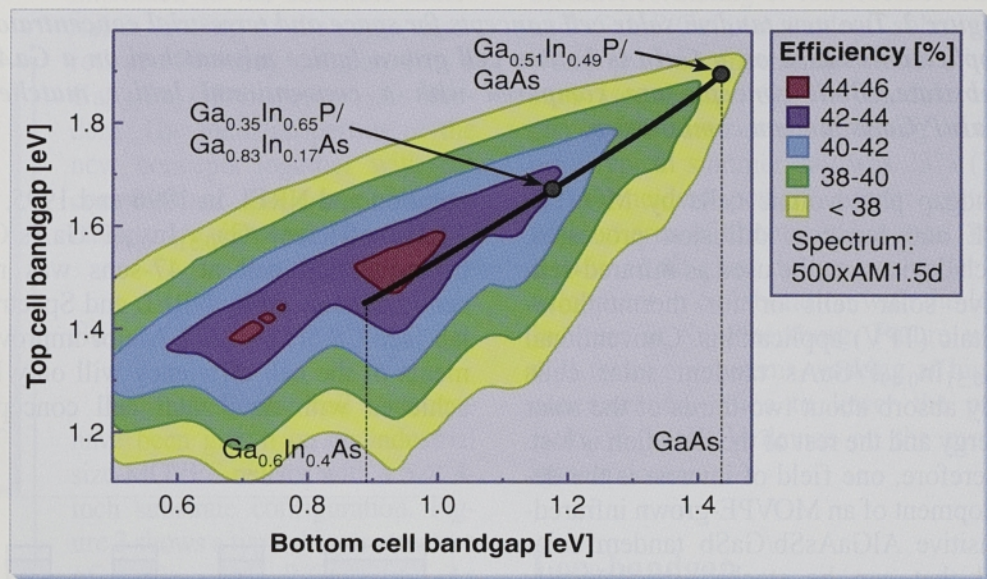


Figure 1. Theoretical efficiency limits for monolithic tandem solar cells according to the bandgaps of the top and bottom cells. A concentration of 500-suns at AM1.5d was assumed.

* The Fraunhofer Institute for Solar Energy Systems (ISE) in Freiburg, Germany, is a non-profit research institute dedicated to meet the demands of its customers from research groups to large industrial companies. A close collaboration in the field of Epiwafer production and prototype development for III-V optoelectronic devices by MOVPE, LPE and low-cost diffusion processes is offered. For more information, see <http://www.ise.fhg.de/Folders/Photocells>.

‡ The air mass 1.5 (AM1.5) spectrum represents the solar spectrum after passing through the Earth's atmosphere and is used to compare performance of terrestrial systems. The global spectrum (AM1.5g) includes direct and diffuse radiation and is used for flat plate applications. Concentrators can only focus the direct irradiation and therefore the AM1.5d spectrum is used.

conventional	new concepts for ...	
	space	concentrators
Ga _{0.51} In _{0.49} P top cell	Ga _{0.51} In _{0.49} P top cell	Ga _{0.35} In _{0.65} P top cell
GaAs bottom cell	Ga _{0.95} In _{0.05} As bottom cell	Ga _{0.83} In _{0.17} As bottom cell
GaAs, Ge substrate	Ga _{1-x} In _x As buffer layer	Ga _{1-x} In _x As buffer layer
	GaAs, Ge substrate	GaAs, Ge substrate
• lattice matched	• GaInP and GaInAs lattice mismatched	• GaInP and GaInAs lattice matched
• 300 < λ < 900 nm	• substrate mismatched	• substrate mismatched
	• 300 < λ < 950 nm	• 300 < λ < 1050 nm

Figure 2. Two new tandem solar cell concepts for space and terrestrial concentrator applications based on a GaInAs bottom cell grown lattice mismatched on a GaAs substrate. Both concepts are compared with a conventional lattice matched GaInP/GaAs tandem combination.

bandgap photovoltaic cells by MOVPE, LPE and low-cost diffusion processes. Such devices can be used as infrared-sensitive solar cells or for thermophotovoltaic (TPV) applications. Conventional Ga_{0.51}In_{0.49}P/GaAs tandem solar cells only absorb about two-thirds of the solar energy and the rest of the radiation is lost. Therefore, one field of interest is the development of an MOVPE-grown infrared-sensitive AlGaAsSb/GaSb tandem solar cell that can be stacked mechanically under a Ga_{0.51}In_{0.49}P/GaAs tandem [3]. This would lead to an additional theoretical efficiency gain of about 13% at 500 suns (AM1.5d) and to an overall efficiency exceeding 40% for the 4-junction device.

TPV cells are used to generate electricity from a hot radiator with a temperature in the range of 1000–1400°C. The radiator emission is mainly in the long wavelength range and low-bandgap photovoltaic cells from materials such as GaSb (0.72 eV) or GaInAsSb (0.55–0.6 eV) are used. Different concepts like the use of low-cost polycrystalline GaSb are currently under investigation [6].

New Tandem Solar Cell Concepts

Ga_{0.51}In_{0.49}P/GaAs tandem solar cells with efficiencies of 30.3% at 1-sun AM1.5g, and 30.2% at 150-suns AM1.5d, have been reported by Japan Energy Cor-

poration and NREL in 1996 and 1995. A 32.3% efficient Ga_{0.51}In_{0.49}P/GaAs/Ge triple-junction cell at 47-suns was recently announced by NREL and Spectrolab [see CS 5(9), p. 42]. Major improvements of the cell efficiency will only be achieved with new solar cell concepts

based on new material combinations. The bandgaps of Ga_{0.51}In_{0.49}P (1.88 eV) and GaAs (1.42 eV) in fact are far from being ideal for the conversion of sunlight into electricity. Especially for concentrator applications, a major improvement of the efficiency can be achieved by lowering the bandgaps of both the top and bottom cells (see Figure 1).

A new possible material combination is a Ga_yIn_{1-y}P/Ga_{1-x}In_xAs tandem where both materials are grown lattice matched to each other. In this case, the bandgaps of the top and bottom cells decrease with increasing In-content (see black line in Figure 1) leading near to the maximum achievable efficiency for any tandem combination of materials. Unfortunately, the Ga_{1-x}In_xAs material is not lattice matched to any well known substrate material and therefore has to be grown on a metamorphic buffer layer on GaAs or Ge. Such Ga_{1-x}In_xAs structures are well known from the development of advanced metamorphic HEMTs.

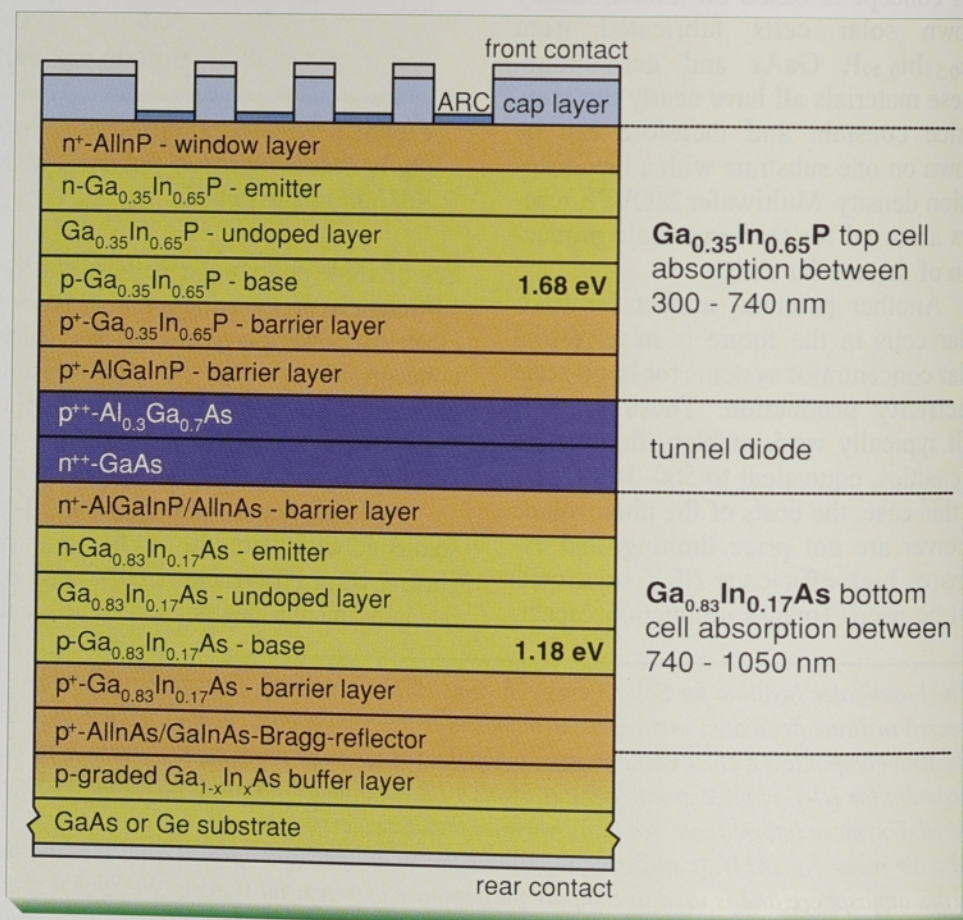


Figure 3. Structure of a Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As tandem solar cell. Active layers are shown in yellow, barrier layers in orange and the tunneling diode in blue.

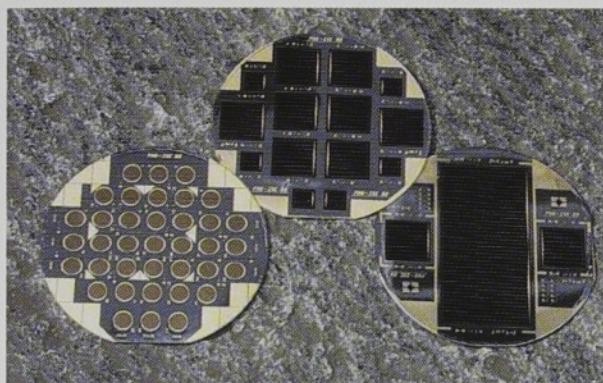


Figure 4. Different tandem solar cells with areas ranging from 0.13 cm² to 8 cm².

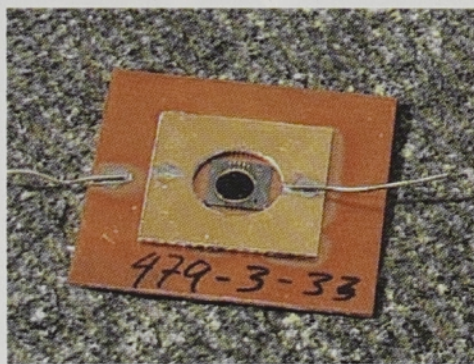
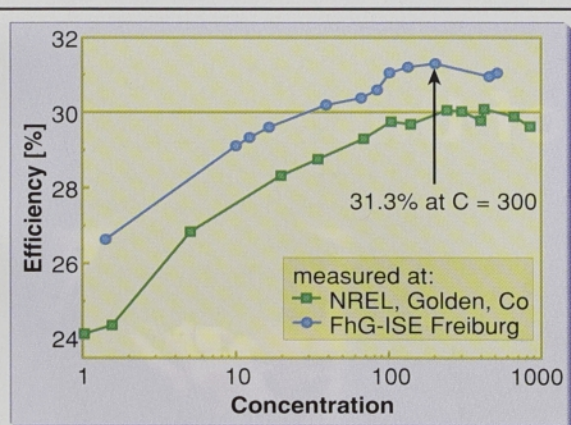


Figure 5. (bottom) A $\text{Ga}_{0.35}\text{In}_{0.65}\text{P}/\text{Ga}_{0.83}\text{In}_{0.17}\text{As}$ tandem concentrator cell and (top) cell performance measured under concentration at NREL and ISE laboratories.

Besides the advantage of higher conversion efficiencies, the new material combination also offers the potential to be very radiation hard. This is one of the key arguments for space applications where the cell efficiency degrades with time under proton and electron irradiation. First experiments show that $\text{Ga}_{1-x}\text{In}_x\text{As}$ single-junction solar cells are at least as radiation-hard as GaAs devices [4]. The damage of the GaInP

top cell decreases with higher In-contents up to InP, which is the most radiation hard high-efficiency solar cell material known today.

Another concept has been developed for the illumination conditions in space. In this case a $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ top solar cell is grown lattice mismatched to an underlying $\text{Ga}_{0.95}\text{In}_{0.05}\text{As}$ bottom cell, grown on GaAs. This material combination with a smaller mismatch to the substrate material is leading to the same theoretical efficiency compared to a $\text{Ga}_{0.35}\text{In}_{0.65}\text{P}/\text{Ga}_{0.83}\text{In}_{0.17}\text{As}$ tandem. The main properties of the new concepts together with the conventional $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ tandem are shown in Figure 2.

Solar Cells

Different solar cell structures have been grown on an industrial size MOVPE reactor with a 5×4 -inch substrate configuration. Figure 3 shows a typical layer structure of a $\text{Ga}_{0.35}\text{In}_{0.65}\text{P}/\text{Ga}_{0.83}\text{In}_{0.17}\text{As}$ tandem solar cell. The high-energy photons between 300 and 740 nm are absorbed by the $\text{Ga}_{0.35}\text{In}_{0.65}\text{P}$ top cell. Radiation between 740 and 1050 nm is collected by the $\text{Ga}_{0.83}\text{In}_{0.17}\text{As}$ bottom cell with a bandgap energy of 1.18 eV. The two subcells are connected by a highly doped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ interband tunneling diode.

Solar cells with an area between 8 cm² for space and 0.13 cm² for concentrator applications have been produced on 2-inch wafers (see Figure 4). Up to now the efficiency of the new concepts in Figure 2 is between 27.6% and 28.0% at 1-sun AM1.5g terrestrial illumination conditions. Further optimization of the cell structure and GaInAs buffer layers has to be performed to increase the device performance of the new concepts. However, a significant advantage is becoming apparent under concentrated sunlight.

Figure 5 shows a typical concentrator cell together with the measurement of the

cell performance under concentration. A record efficiency of 31.3% at 300-suns has been determined at Fraunhofer ISE. The efficiency measured at NREL was slightly lower but still >29% at 1000 suns, which is the best value of any solar cell under such high concentration ratios today. These cells are therefore well suitable for the use in next generation photovoltaic concentrators working at high illumination intensities.

Initial outdoor experiments have been performed with a small concentrator module, consisting of four Fresnel lenses and GaInP/GaInAs tandem solar cells working at a concentration ratio of 123 suns (see Figure 6). The module efficiency measured at our Freiburg facility on a typical summer day was 23% (763 W/m² incident power). Larger systems with an area of about 1 m² in total, realized in an all-glass design, are under development in collaboration with the Ioffe Institute in St. Petersburg. Future work will focus on systems working at higher concentration ratios to lower the price ratio of the III-V device on the overall system costs.

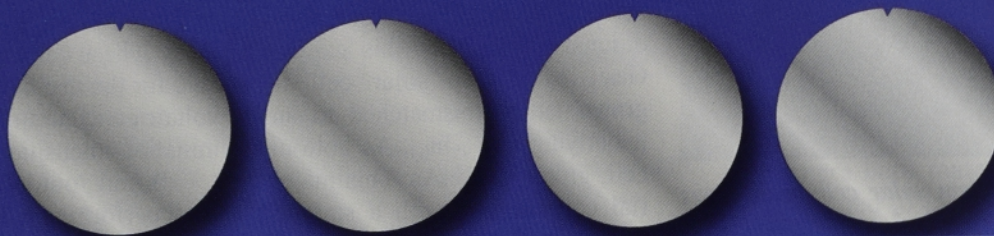
Low-bandgap Thermophotovoltaic Cells

Recently a renewed interest in thermophotovoltaic (TPV) electricity generation has emerged. Here, low energy radiation emitted from a heated radiator is absorbed by a TPV cell and converted into electricity. The choice of photovoltaic



Figure 6. A small (64 cm²) concentrator system with four $\text{Ga}_{0.35}\text{In}_{0.65}\text{P}/\text{Ga}_{0.83}\text{In}_{0.17}\text{As}$ tandem solar cells working at a concentration ratio of 123.

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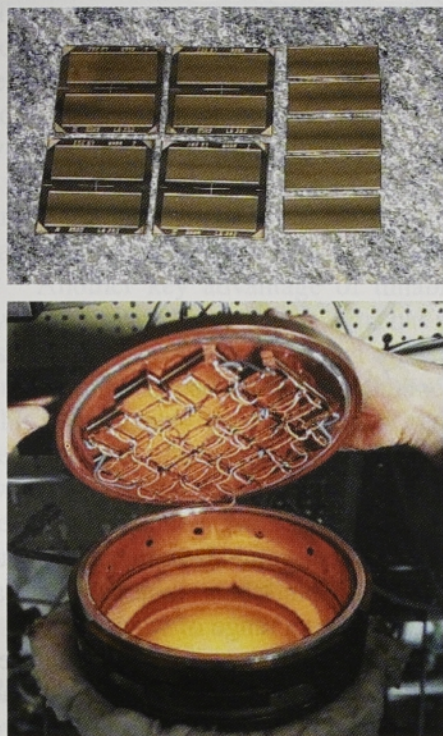


Figure 7. (top) Several $1 \times 2 \text{ cm}^2$ TPV GaSb cells and (bottom) a thermophotovoltaic generator.

cells for TPV systems depends on the type of radiator (selective or broadband) used. It is important to note that relatively low (up to 1400°C) radiator operating temperatures are preferable. High-temperature radiators are technically more complicated and not reliable. Moreover, the operation of radiators below 1400°C is important from an ecological point of view because of a strong emission of poisonous NO_x at higher temperatures.

Different TPV cells, for example relatively inexpensive Si cells, can be used in TPV systems in combination with selective radiators. However, these generators have a low power density and there are no such TPV systems of practical importance today. On the other hand, if low-temperature TPV systems with non-selective broadband radiators are considered, low-bandgap TPV cells (0.5–0.7 eV) are required

The main concept developed at the Fraunhofer ISE for low-bandgap TPV cells is the use of strong built-in electric fields in the emitter [5]. These fields (up to 8 kV/cm) are formed due to a specific steep Zn diffusion profile regulated through the Zn diffusion parameters and precise etching. Optimization of Zn dif-

fused emitters in TPV cells leads to an essential improvement of the device performance. Formation of strong built-in electrical fields in the emitter provides a dramatic decrease of the surface recombination influence resulting in an increase of the generated current and voltage. This concept was successfully used for PV cells made of various materials including GaSb (0.72 eV) and InGaAsSb (down to 0.55 eV).

In the case of GaSb, only Zn diffusion is used and no epitaxial growth is necessary. Moreover, recent research in cooperation with the Rensselaer Polytechnic Institute (Troy, NY, USA) has shown that polycrystalline GaSb with small grains (down to $\sim 100 \times 100 \mu\text{m}$) can be effectively used for the fabrication of high-efficiency TPV cells [6]. Polycrystalline GaSb can be easily grown in large quantities from a melt at very high growth rates. Moreover, unlike for single crystal GaSb, special optimization of the growth conditions is not necessary. These results are very significant for low cost TPV applications due to the inexpensive nature of polycrystalline GaSb and the relatively simple diffused junction fabrication technology. Figure 7 shows several GaSb TPV cells (bottom) together with a prototype TPV generator fabricated at Fraunhofer ISE (top).

Our calculations based on the measured GaSb TPV cell parameters show, that cell efficiencies up to 30% can be achieved assuming a blackbody temperature of 1300–1500 K and a perfect band edge filter which reflects light with energy lower than the GaSb bandgap (Figure 8).

Zn-diffused emitters were also fabricated in $\text{n-In}_{0.15}\text{Ga}_{0.85}\text{As}_{0.17}\text{Sb}_{0.83}$ (0.55 eV) epitaxial layers grown on GaSb substrates at AstroPower (Newark, DE, USA) using the liquid phase epitaxy technique. Similar to GaSb cells, built-in electric fields resulted in excellent cell parameters without passivating Al-GaAsSb window layers [7].

In summary, very good results have been achieved for TPV cells with a relatively simple design (substrate/diffused

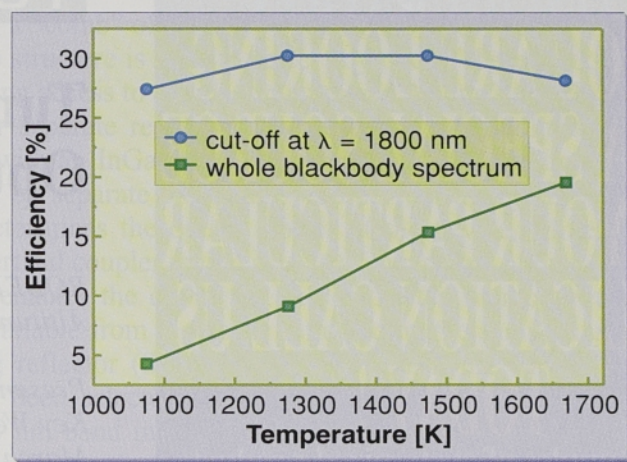


Figure 8. Calculated efficiency of a GaSb TPV cell with the optimized structure as a function of the blackbody temperature. The calculations are based on measured device parameters of the TPV cell. An efficiency of ~30% can be achieved using a band edge filter to reflect light with energy below the GaSb bandgap of 0.72 eV (i.e. $\lambda > 1800 \text{ nm}$). The blackbody illumination of the cell was “scaled” by a factor of 0.6 to take into account optical losses in a TPV system.

layer for GaSb or substrate/epitaxial layer/diffused layer for InGaAsSb). This design allows the use of low-cost technologies like diffusion from the vapor phase or liquid-phase epitaxy. However, further increase of efficiency requires fabrication of low-bandgap tandem TPV cells. Obviously, their design must be similar to the design of high-bandgap tandem solar cells like the one in Figure 3. This requires more complicated growth techniques like MOVPE, and initial experiments to fabricate such cells were recently started at Fraunhofer ISE [3].

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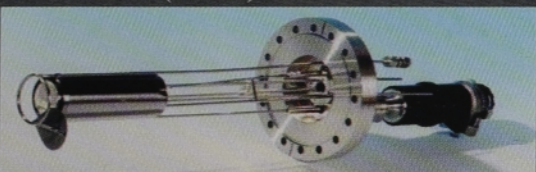
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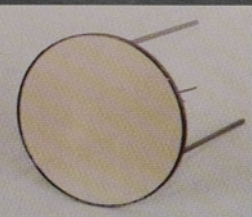
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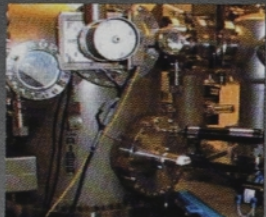
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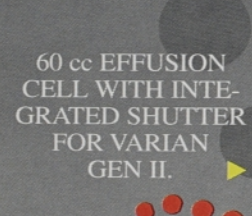
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FORUM - TUNABLE LASERS

Tunable Lasers and Future Optical Networks

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

The high data capacity provided by dense wavelength division multiplexing (DWDM) optical fiber links is the reason that the Internet exists in its current form. DWDM has been instrumental in allowing network operators to send multiple signals down a single fiber, enabling a huge growth in network resources for no extra fiber deployment. With the expected exponential growth of traffic, it is clear that optical network capacity installation must continue apace by scaling dramatically. In addition, in a manner analogous to the management of electricity, key to satisfying the requirements of future optical-networks will be the ability to supply bandwidth on demand.

Allocating Capacity Dynamically

Currently, optical networks employ fixed lasers emitting at particular wavelengths to achieve data multiplexing and higher bandwidth. But crucial to providing this bandwidth, while at the same time avoiding bottlenecks, is the ability to assign and re-assign wavelengths as needed throughout the network—providing bandwidth when and where needed. Allowing more flexibility in the way fiber capacity is provisioned is the driving force behind the requirements of next generation optical networks. In future, service providers will require a 10-fold scalability beyond a network's initial installed capacity, in addition to rapid service activation to allow high capacity links to be deployed as needed. These

stringent requirements can be elegantly met by tunable lasers—sources that can be tuned over a range of wavelengths.

The immediate use for tunable lasers in existing networks is for inventory management and "sparing". Sparing involves the use of tunable lasers as back-up replacements for fixed wavelength devices in DWDM. While the retention of fixed wavelength replacements was manageable when just four or even eight wavelengths were in use, network operators now need to carry a large inventory of spares to cover the range of transmitters with closely spaced wavelengths covering as many as 80 different channels. This also means a large number of transmitter boards containing other essential components such as laser drivers, modulators and driver ICs. For each wavelength channel operating at 10 Gbps, this could cost as much as \$50,000. Instead, using a tunable laser, one board can be held as backup and tuned to the wavelength of the faulty fixed wavelength laser. These same boards can then migrate to replace all fixed wavelength lasers in the network, as their cost approaches that of a fixed laser.

While inventory reduction represents the immediate driver for tunable lasers, a number of exciting new possibilities are also enabled by these devices. One such is optical-add-drop multiplexing or OADM, which uses passive optics to

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allow chosen wavelengths to be added or diverted without converting to electrical signals in the process. OADM has the potential to be the major revenue source for carriers. In future, point-to-point capacity will become a commodity, and carriers will profit from being able to provide service where and when it is needed. For example, a carrier might supply a 10 Gbps link for a number of hours, before redistributing the data capacity to another point in the network.

Another key advantage of tunable lasers is the ability to switch at nanosecond speeds. This has enabled new schemes such as fast packet switching, which allows the nodes on a network ring to only use a wavelength channel when transmitting data. This considerably reduces network resources and represents the best way to facilitate network infrastructure. Fast packet switching is not as far away from commercial reality as is generally assumed. MCI has stated that there will be tunable lasers in its network this year, and it is likely that optical routing will follow rapidly in 2001 and fast packet switching a year later.

Requirements for Tunable Lasers

Reducing the number of lasers required as backups dictates a wide tunability, at least across the C and L bands. In addition, a replacement tunable laser once installed should become a permanent fixture of the network. And while tunability is obviously attractive, it is only usable if the power or linewidth is sufficient for the application. A further requirement is that the cost must be comparable to that of a distributed feedback (DFB) laser. And, importantly, second sourcing must be possible to provide seamless component insertion. Because each tunable laser technology, and tunable laser, is both complicated to control and subtly different in operation, this second sourcing issue dictates standardization at the electronic module level. Production at this module level is also becoming much more important as the amount of engineering that companies now wish to undertake has diminished as they ascend the food chain. Therefore, butterfly packages are unlikely to be the standard, both because tunable lasers differ depending on the supplier, and because most customers prefer the simplicity of a "digital signal in, wavelength out" module. In any event, the laser module must also demonstrate standard telecommunication performance, with a power output of 10 dBm (10 mW) at the system level.

Altitud's Grating Coupled Sampled Reflector

There are several approaches to tunable lasers on the market, including DFB laser arrays, distributed Bragg reflector (DBR) lasers, tunable VCSELs and external cavity lasers. At Altitud, we have chosen to concentrate on the DBR as a device route (see Figure 1). DBRs use standard processes developed over the past twenty years for DFBs and other telecommunications lasers, in addition to standard packaging.

The device developed at Altitud is based on a sample grating DBR (specifically, the Grating Coupled Sampled Reflector or GCSR). This design has a grating at the rear of the structure,

producing a "comb" of reflected peaks. A vertical coupler filter within the structure is used to select any one of these peaks, in effect giving access to a wide tuning range. Altitud's GCSR employs four separate regions fabricated from a monolithic InP structure with an InGaAsP QW quaternary active region, each controlled by separate electrodes. The current through the gain section determines the optical power of the device, while the second, vertical coupler region acts as a coarse tune of up to 100 nm. This enables the choice of one of the ten or more wavelengths available from the peaks reflected by the sampled grating Bragg reflector (S-DBR in figure). Once the wavelength range has been selected, the grating region tunes the current across a 4 nm band in the same way as that of a DBR, and a phase region gives the fine control at the GHz level.

In this device, the control of power and wavelength is managed at the module level and the power output can be +10 dBm and higher. This translates into less engineering for the customer, and a cost that is close to that of a standard DFB laser. Packaging, including the integration of cooler, isolator and optics, is performed using a precision laser welding production process. While still relatively new, Altitud has tested these chips for more than 130,000 device hours, showing that a lifetime of around 20 years is certainly attainable.

Chip manufacture, packaging and quality assurance processes are performed at Altitud's facility in Stockholm, which is a new combined manufacturing and headquarters facility leased from Mitel [see CS 6(2), p. 8]. At present, a capacity shortage is occurring in the industry, and Altitud's goal is to ramp-up capacity and increase yields as quickly as possible. The company aims to achieve this by bringing some of the manufacturing discipline and economies of scale found in the silicon industry to InP lasers. The new site employs class 10 and class 100 clean rooms, and growth is currently performed on 2-inch wafers.

Applications for Tunable Lasers

The functionality of an optical network is produced by changing the route of an optical signal. This can be achieved at the transmitter by simply changing the wavelength and using either passive or tunable WDM filters at each node to determine the

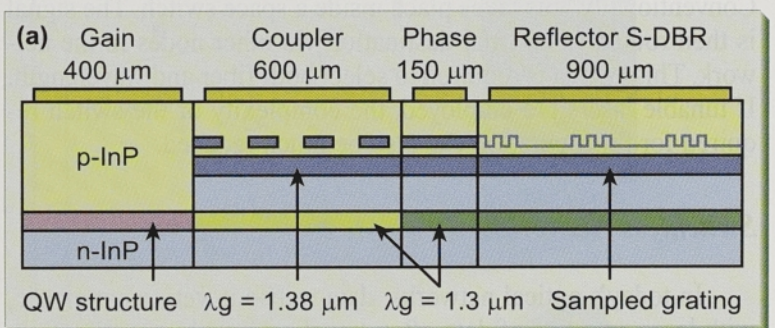


Figure 1. The grating coupled sample reflector (GCSR) from Altitud employs four separately controlled regions fabricated in a monolithic InP structure with an InGaAsP QW quaternary active region. The design allows tuning across a 100 nm range.

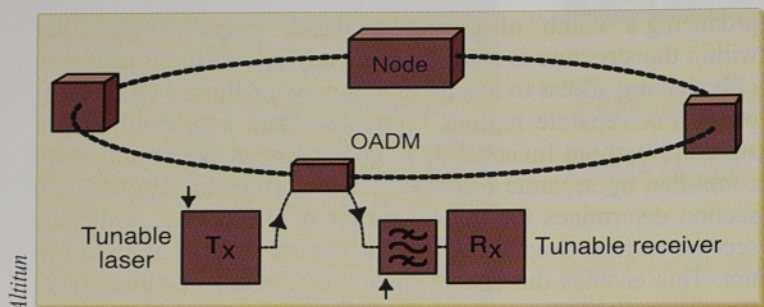


Figure 2. A ring network uses tunable transmitters and receivers (Tx and Rx respectively) to manage capacity. The destination of signals on the ring is determined by carrier wavelength. Wavelengths can be added or dropped from the ring without electrical conversion using an optical add-drop multiplexer (OADM). If the system uses tunable lasers, signals can be sent to any of the nodes on the ring.

signal route. This signal routing is commonly implemented using ring or mesh systems.

Ring Networks

In a simple ring system such as is suitable for metropolitan networks, signals are routed to different points (or nodes) on the ring. The destination of a particular signal is determined by its carrier wavelength. Wavelengths can be added to or dropped from the ring without electrical conversion using an optical add-drop multiplexer or OADM (Figure 2). If the transmitter contains a tunable laser, then it is able to send signals to any of the nodes on the ring.

Mesh Networks

The same process can be achieved with mesh networks. Mesh architectures are increasingly favored in the backbone network to provide short term connections and make efficient use of bandwidth and fiber infrastructure. Usually, these systems employ optical cross-connects (OXC) to route the signals. OXCs can demultiplex (demux) a digitally modulated signal on a carrier wavelength, and transfer this signal onto a different wavelength and fiber to reroute it to another point in the network. Conventionally, this takes place inside a space switch. The signal is then routed to its final destination via other nodes in the network. This switch is required to select both fiber and wavelength. If tunable lasers are employed, the complexity of the switch required for this operation can also be much reduced.

Switchless Networks

In today's optical networks, data traffic is very asymmetric, with large amounts of data often traveling in only one direction. This places even more demand on the network to supply bandwidth as and where needed. In order to compensate for this, carriers must offer links to a particular point on demand, but the problem remains that OXCs can easily become very complex

under these circumstances, with $2,000 \times 2,000$ nodes becoming common. This problem will be addressed by networks currently under development. Known as switch-less networks, these systems also use tunable lasers.

Just such a switch-less reconfigurable all-optical network has been demonstrated by Norwegian national operator Telenor. This employs Altium's tunable lasers, and uses inexpensive passive optical wavelength elements to route signals at each node instead of a space switch. By altering the wavelength of the tunable laser, a specific path is chosen across the network, delivering the signal to its destination without processing, switching or reconfiguration of any of the intermediate nodes. The tunable laser and tunable receiver at the end points carry out the switching function (see Figure 3).

Larger networks can be made by connecting these switch-less mesh networks together, with the advantage that the main long haul cross-connect layer can be greatly simplified. The cross-connect layer is still required and is connected to switch-less sub-networks where all switching is done simply by changing wavelengths by passive routing (Figure 4). In Telenor's demonstration network, each node is spaced at 60 km (40 mile) intervals. With a hundred laser wavelengths available from the Altium tunable laser, this switchless mesh network can support up to sixteen nodes with acceptable traffic patterns, which can approximate to a regional or even a national network. Importantly, this demonstrates that switch-less mesh architectures are scaleable to large sizes.

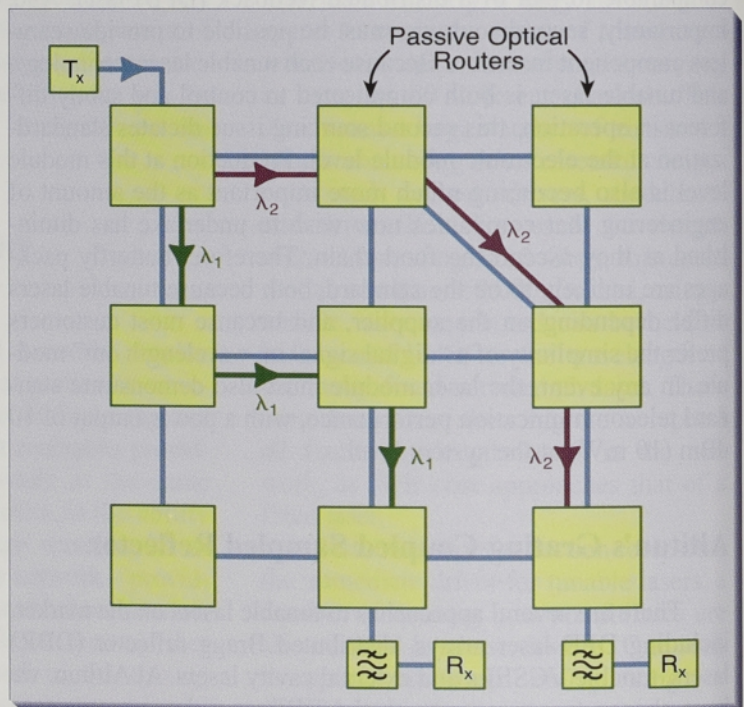


Figure 3. A mesh network can be configured with tunable lasers to send a signal via passive optical routers to any point on the mesh, where it can be detected by a tunable receiver. Regional and national networks require that a route corresponds to a particular wavelength, and the mesh is effectively switch-less.

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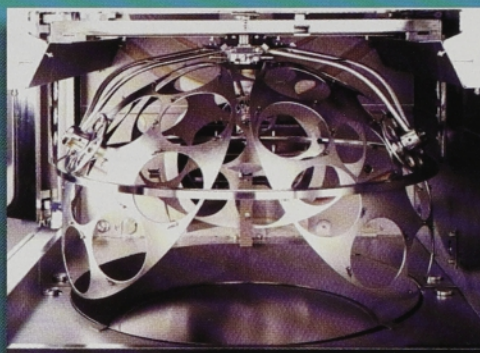
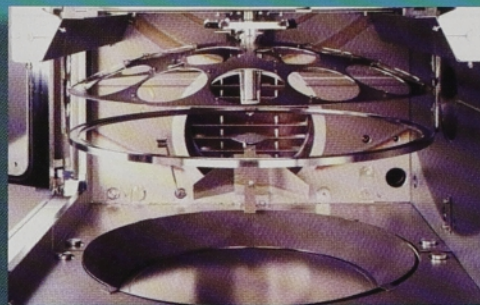
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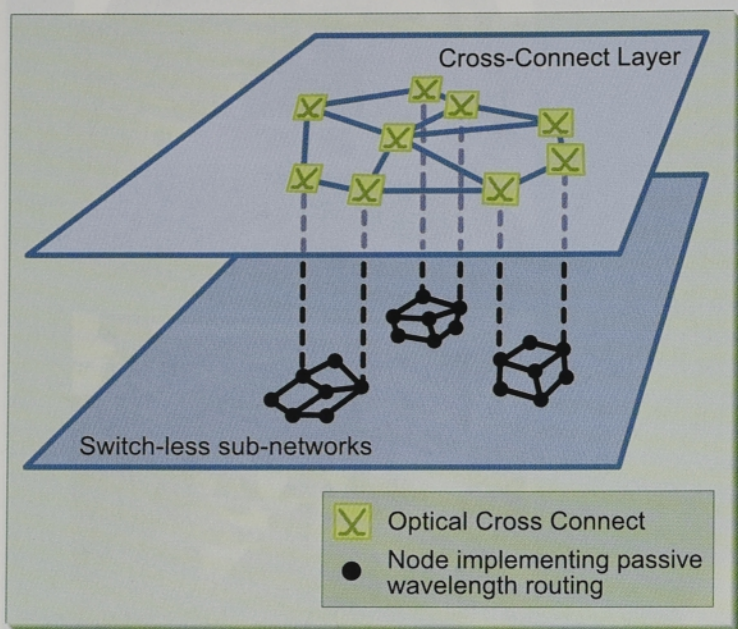


Figure 4. Larger networks can be made by connecting switch-less mesh networks together, with the advantage that the main cross-connect layer can be greatly simplified. The cross-connect layer is linked to switch-less sub-networks, where all switching is performed by passive routing.

Fast packet switching

The systems described above are based on routing an entire wavelength through a system. These systems must also be capable of allotting two-way connections to particular points for time scales that could last for hours or days. However, the ultimate use of capacity will be realized when an optical "packet" can be routed by wavelength. Taking advantage of the tunable laser's ability to switch at nanosecond intervals, this is called fast packet switching. In one approach, nodes are uniquely identified by a single wavelength, and data is routed to a particular node by testing when that line (or wavelength) is free to send data. One elegant way to determine if a wavelength is free is to use sub-carrier tones in the range of 3–4 GHz, multiplexed onto each packet, with each wavelength associated with a unique sub-carrier tone. This allows the wavelengths on the ring to be easily and rapidly detected without the need for fast optical measurements.

One application of this approach would be to route the large amounts of data now generated in metropolitan areas. Backbone technologies, which are now operating at Tbps rates, need to connect to asynchronous digital subscriber line (ADSL) and cable modem accessing systems that operate at lower rates (i.e. Mbps). To accommodate this, carriers are developing high capacity WDM metropolitan area networks or MANs, which can be provisioned with fast package switching.

The fast packet switching approach is, however, still at the laboratory test bed stage. One such system is called Hornet (Hybrid Opto-electronic Ring Network), currently under development at Sprint Advanced Technology Laboratories in Stanford (CT) and Stanford University's Optical Communications Research Laboratory. Hornet is a ring network optimized for data traffic with a circumference of 100 km (60 miles). Based on the number of wave-

lengths accessible to a C-band rapidly tunable laser supplied by Altium, this network can support up to a hundred access points.

Market Developments

DWDM systems are developing at a very rapid pace, and tunable lasers will play an important role in these systems in future. At present, 40 Gb/s data rate systems are in design for long haul applications, and 10 Gb/s long haul systems are now becoming available. In addition, volume growth from new entrants at 2.4 Gb/s and 10 Gb/s for metro markets will also be significant.

In addition to the new generation of optical network architectures described, there are a number of additional market segments where tunable lasers will compete or dominate in future. Sparing or cold backup is the most immediate. Tunable sources can also be used as direct replacements for fixed wavelength lasers. This should add to network flexibility, as new wavelengths can be introduced and the system relatively easily reconfigured as requirements dictate or as systems scale. A further application for these devices is in network management, where tunable lasers can be used for restoration or "hot backup" (providing back-up bandwidth on demand) and flexibly provisioning capacity as required. This wavelength routing can be carried out by tunable transmitters in conjunction with optical add-drop of wavelengths, or by tunable lasers with OXCs. Lastly, a sector exists for fast-packet switching, again either distributed through the network, as in the case of Hornet, or as stand-alone core routers.

The potential market for tunable lasers used as backups is in the region of tens of thousands of units, while fixed laser replacement is much greater—more than 100,000 annually. When optical cross-connect (OXC) applications and fast packet applications finally appear commercially, they will likely amount to a market consisting of several hundred thousand units.

In a 1997 study, Electronicast estimated that several hundred thousand DWDM lasers would be needed by 2003, while by early 1999, CIBC assumed this figure to be nearer 400,000–500,000 units. The most recent report by RHK now puts the value at 2.5 million DWDM units. The conclusion is that the market has taken off much faster than predictions, and of that market, the proportion of tunable lasers is likely to be large. A conservative figure for tunables would be 20% of the DWDM market by 2003, and the ability to reach shipments of many hundreds of thousands of tunable lasers by this time is likely to be constrained as much by the ability of suppliers to ramp capacity as by market demand.

Conclusions

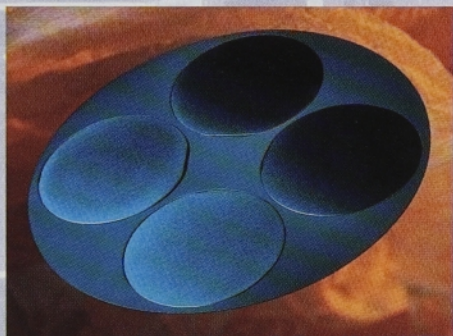
Tunable lasers will represent a hot area for bandwidth provisioning in the new generations of optical networks. These devices are truly enabling for reconfigurable networks, and this "resource management" will represent the main revenue source for network carriers. The future will definitely include tunable lasers for fast optical switching, and there are already a number of companies looking at this architecture. At Altium, we believe the future of the tunable laser as a mainstream product is inevitable.

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Red VCSEL Technology

While 850 nm data communication VCSELS operating in the near-infrared are now a commercial reality, opportunities exist for short wavelength red VCSELS in home data links. However, technological challenges still need to be overcome before these devices match the success of their infrared counterparts.

JOHN D. LAMBKIN*

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Advances in VCSELS have led to commercial applications in data communications at 850 nm [1]. Research is also being directed towards VCSELS operating at 1.3 and 1.55 μm as sources for long-haul telecommunications [2]. While potential exists for devices at shorter wavelengths, such as 780 nm devices for CD and CD ROM lasers containing simplified optics, another important potential application is for red (~ 650 nm) VCSELS. These devices could find use in high speed data links for the home and small business premises markets using plastic optical fiber (POF).

In fact, the demand for transporting digital data between consumer products has prompted the consumer electronics industry to develop and define several new standards for high-speed data interconnect cables and associated protocols such as IEEE 1394. The IEEE 1394 standard includes specifications for copper twisted wire pairs carrying data rates of 100, 200 and 400 Mbps. These high data rates nevertheless limit the span between devices to a maximum distance of only 4.5 m, and also limit the total number of devices that can be linked.

POF addresses this limitation: it has the same cost structure as copper wire, and 3 Gbps data links in excess of 100 m in length have been demonstrated using graded index (GI) fiber. The ideal high-speed source for GI-POF is the VCSEL, or an array of VCSELS in the case of a parallel interconnect. Moreover, an attenuation minimum at 650 nm in the POF favors a VCSEL operating in the red wavelength. The device's high speed, planar geometry and circular beam profile also make it attractive for use with fibers, and a low operating current of a few mA would enable transceivers with low power consumption, an advantage compared to edge-emitting lasers and conventional LEDs.

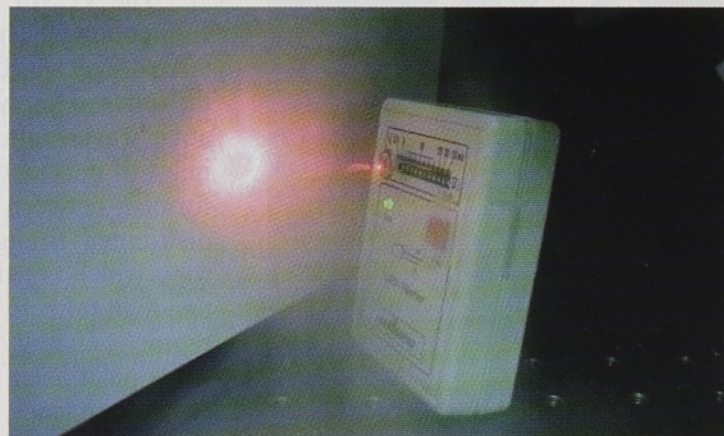


Figure 1. Demonstration VCSEL mounted in an uncapped TO can from the European collaboration on red VCSEL technology (BREDSELS). The project produced devices operating at a wavelength of 673 nm that achieved marginally over 2 mW at room temperature.

In addition, further benefits could be derived from the successful commercialization of red VCSELS; these include replacements for other types of lasers in bar code readers, laser scanners and printers, and as sources for DVD drives.

However, technological difficulties still need to be overcome before these short wavelength devices match the success of their infrared cousins. Some of these hurdles have been addressed in a European Long Term Research project known as BREDSELS-23455** (Bright Red Surface Emitting LaserS), which has succeeded in producing red VCSELS (see Figure 1). The main results of this project form the latter part of the article.

VCSELS vs. Edge-Emitting Lasers

The beneficial properties of VCSELS can be fully appreciated by noting some of the problems associated with edge-emitting lasers. The transverse and lateral modes of edge-emitting

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FORUM - VISIBLE VCSELS

devices are governed by the cross section of the gain region, which is very thin in the transverse direction for carrier confinement, and laterally wide to achieve a reasonable output power. This produces highly elongated near and far fields that do not couple efficiently into the circular mode of an optical fiber, thus making laser fiber pig-tailing a complex and costly affair.

The length of an edge-emitting laser also excites a large number of lasing modes, which in turn leads to modal dispersion within a fiber. Finally, VCSELS offer manufacturing and yield benefits: in an edge emitter, the laser cavity is formed using cleaved crystal facets, which must be broken out of the wafer and packaged if the device is to be tested.

The VCSEL circumvents the above shortcomings. These devices are characterized by a short optical cavity length of the order of λn , where λ is the laser operating wavelength and n is the refractive index of the cavity material. The cavity is formed between two highly reflecting distributed Bragg reflector (DBR) mirrors, which consist of alternate $\frac{1}{4} \lambda$ low and high refractive index layers. The gain region generally consists of quantum wells positioned at the anti-nodes of the cavity resonance.

The VCSEL's geometry is such that the optical cavity is defined normal to the wafer surface; hence, the laser is surface emitting. The surface-normal emission means that subsequent process steps (mesa etching, ion implantation or lateral oxidation) are used to define a circularly-symmetric optical aperture. The resulting transverse mode therefore produces low divergence circular beam profiles that are ideal for coupling into optical fibers. The very short cavity length also ensures support of only one longitudinal mode.

Finally, the VCSEL's geometry also means that the lasers can be tested on-wafer, and subsequently packaged using manufacturing processes similar to those used for LEDs. Indeed, from a manufacturing perspective the VCSEL is treated as a sophisticated LED. In many respects, it is cost benefits rather than technical superiority that has enabled the VCSEL device to become a commercial commodity.

Beyond 850 nm VCSELS

The VCSEL concept was first proposed by Iga *et al* at the Tokyo Institute of Technology (Japan) in 1979 [3]. The first pulsed room temperature devices were produced in 1984 [4], and were followed by CW devices in 1988 [5]. The following decade saw a subsequent steady improvement in device characteristics, which culminated in the mass production of the 850 nm VCSELS we see today.

A similar progression has also been witnessed in the development of visible VCSELS. The first red VCSELS, with a wavelength at 657 nm, were reported in 1992 by Schneider *et al* [6] from the Sandia National Laboratories (Albuquerque, NM). Although this demonstration was obtained using pulsed photo pumping techniques rather than electrical injection, the Sandia group had nevertheless identified the basic epitaxial structure that is still being optimized and developed.

To attain the short wavelength of 650 nm, it is necessary to use strained $\text{In}_x\text{Ga}_{(1-x)}\text{P}/\text{In}_x(\text{Al}_y\text{Ga}_{(1-y)})_{(1-x)}\text{P}$ quantum wells in an $\text{In}_{0.48}(\text{Al}_y\text{Ga}_{(1-y)})_{0.52}\text{P}$ optical cavity, lattice matched to GaAs. These phosphide-containing materials are also used in edge-emitting visible lasers and bring their own material idiosyncrasies. In comparison to the large direct bandgap discontinuities (1.4 eV) available to GaAs/AlGaAs hetero-junctions used in 850 nm VCSELS, the phosphide alloys can only provide a total discontinuity of 0.6 eV. This means that phosphide-containing active regions tend to suffer from excessive carrier leakage via electron thermalization over the low conduction band barrier [7], which results in lasers with poor thermal stability. This problem lies at the heart of making viable red VCSELS, and becomes more acute as the VCSEL operating wavelength is shortened.

These limitations are made worse by problems with epitaxy. AlGaInP alloys grown by MOVPE are noted for the tendency of the cations to order on the group III sub-lattice, producing alternate In and Ga rich (111) planes. This sub-lattice ordering results in a shrinking of the bandgap, which leads to even smaller

band edge discontinuities. This effect is significantly reduced by deliberately growing the structures on GaAs substrates with a large misorientation towards the $\langle 111A \rangle$ direction. In addition, achieving large p -type carrier concentrations in high Al-containing InAlGaInP alloys is also non-trivial. The problem is also exacerbated by the use of Zn as the common p -dopant, which tends to diffuse readily during device operation.

Once the active regions have been grown, DBR mirrors can be formed from $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}/\text{AlAs}$ quarter wavelength mirror pairs. To prevent the mirrors from absorbing at these short emission wavelengths, a high Al concentration (50%) is needed in the high refractive index layer. This effectively halves the refractive index step available in structures at 650 nm compared to 850 nm devices and requires an increased number of mirror pairs, in the region of 50 pairs for the n -type bottom mirror and 35 pairs for the p -type top mirror, to achieve high reflectivities.

Schneider *et al* [8] have also investigated the use of InAlP/InAlGaP DBR mirrors as an alternative to AlGaAs/AlAs mirrors, but the need to maintain perfect lattice matching in these quaternary structures throughout the growth of thick mirrors makes their use impractical.

Developments in Red VCSELS

The first report of electrically-injected visible VCSELS was made in 1993, again by the Sandia group [9]. The VCSEL structure used a long 8λ cavity with 3 quantum wells and Mg as an alternative to Zn as the p -dopant. The $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}/\text{AlAs}$ quarter wavelength mirror pairs were C-doped and employed 10 nm $\text{Al}_{0.75}\text{Ga}_{0.25}\text{As}$ interfacial layers to reduce the series resistance of the mirrors. The VCSELS were simple circular mesa dry-etched posts (5–20 μm in diameter) with annular Ti/Au contacts made to a highly-doped GaAs top contact layer. Room temperature lasing at 650 nm was achieved using pulsed operation with an external quantum efficiency of 1.8%.

Although other groups had started an effort in red VCSELS [10, 11], the Sandia group were also the first to achieve CW lasing at room temperature [12]. These results were achieved by using thinner quantum wells and barriers to improve the overlap between the standing wave and the gain region. They also employed lower p -doping in the DBR mirror to reduce free carrier absorption and the use of graded interfaces in the DBR to lower the series resistance of the p -mirror. Mesa devices with a diameter of 15 μm and an annular contact inside diameter of 5 μm gave a threshold current (I_{th}) of 5 mA (current threshold density $J_{\text{th}} = 2.8 \text{ kA}/\text{cm}^2$) at a voltage of 2.4 V. The maximum output power was 25 μW at 670 nm, although the L-I curve rolled over quickly at $< 2 I_{\text{th}}$.

By reducing the length of the cavity to 1λ and using strained AlAsP interface layers between the arsenide-containing Bragg layers and phosphide-containing cavity layers, further improvements in device performance were obtained [13]. However, the performance of these mesa post VCSELS was limited by a poor temperature stability. Devices were subsequently fabricated with a deliberate blue shift between the gain peak with respect to the cavity mode. In this instance the coincidence of the gain and cav-

ity peaks—the condition for minimum threshold current density—occurs at elevated temperatures and improves the laser's performance at higher temperatures.

Despite these design strategies, the thermal performance of red VCSELS remained poor. For example, 15 μm diameter mesa devices emitting at 675 nm would cease to operate in CW mode at heat-sink temperatures greater than 50°C, despite delivering an impressive 2.8 mW of power at room temperature [14].

Lateral Selective Oxidization

A significant increase in output power, reduction in threshold current and an improved thermal performance was achieved, however, by using lateral selective oxidation. This was a technique first demonstrated in visible VCSELS by the Sandia group [15].

The principle of lateral oxidation of VCSELS is shown in Figure 2. The mesa etched side-wall of the top p -type DBR mirror exposes a single $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$ layer with an Al composition x between 0.98 and 1.0. Exposure of the mesa to steam causes this layer to oxidize laterally toward the centre of the mesa, and is then used to define a current aperture close to the active region. To prevent oxidation of the entire p -type mirror, the Al composition of the low refractive index $\frac{1}{4}\lambda$ layers must be reduced to $x = 0.95$, a composition that does not oxidize significantly. This reduction in refractive index contrast must then be compensated by an increased number of mirror pairs to maintain the desired reflectivity.

The use of selective oxidation for red VCSELS is essential if devices are to meet realistic system specifications. The Sandia group demonstrated the importance of selective oxidation by achieving an impressive 3 mW of power at room temperature at

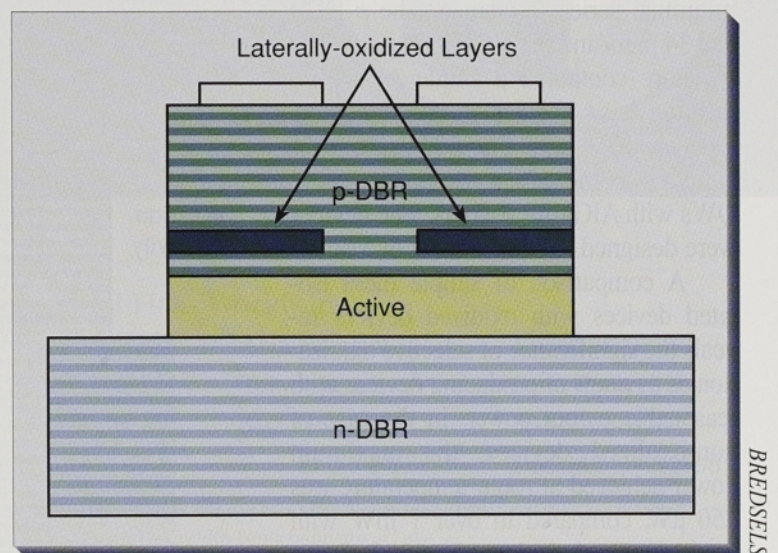


Figure 2. Lateral-oxidization, which uses steam to oxidize the mesa etched side-wall of p -type DBR mirror, exposes a single $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$ layer with an Al composition x between 0.98 and 1.0, resulting in a current aperture near the active region. This significantly increases the output power, reduces threshold current and improves thermal performance of the VCSEL.

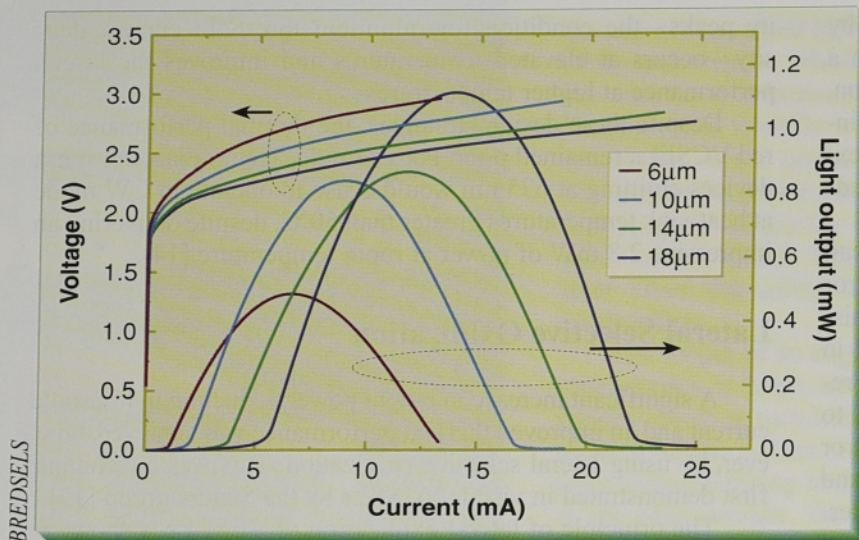


Figure 3. Continuous wave LIV characteristics for 633 nm VCSELS operating at room temperature as a function of oxide aperture diameter.

approximately 665 nm [15]. However, the BREDSELS [16] collaboration has elucidated the function of selectively-oxidized apertures and their effects on visible VCSELS.

BREDSELS' Oxide Aperture Device

The epitaxial VCSEL structures investigated by the BREDSELS group were grown by low-pressure MOVPE on GaAs substrates orientated 10° away from the (100) axis towards $\langle 111 \rangle_A$ in a multi-wafer (7×3 -inch) reactor. The DBR mirrors consisted of $\frac{1}{4}\lambda$ layers of $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}/\text{Al}_{0.95}\text{Ga}_{0.05}\text{As}$ with graded interfaces to minimize series resistance. The p -DBR had 34 pairs and the n -DBR 54 pairs. The structure contained a single AlAs oxidation layer adjacent to the active region on the p -side. The 1λ cavity contained 4 compressively-strained GaInP QWs with AlGaInP barriers. The devices were designed for emission at 665 nm.

A comparison of simple mesa isolated devices with oxidized devices reveals the significance of selective oxidation as a means of producing devices with reasonable output power. In the case of non-oxidized devices, the maximum power achieved at room temperature was $150\text{ }\mu\text{W}$, compared to over 1 mW with oxide-confined devices. Figure 3 shows typical room temperature CW light-current-voltage (LIV) curves for a range of selectively oxidized devices with oxide apertures ranging from 6 to $18\text{ }\mu\text{m}$ in diameter. Typical threshold current densities are less than $2\text{ kA}/\text{cm}^2$, the maximum output power is over 1 mW and the operating

voltage is $\sim 2.5\text{ V}$. In all cases, this is close to the best performance for VCSELS operating at this wavelength.

The main function of the selective oxidation aperture is to create a lateral path by which heat can be removed from the gain region, and thereby minimize the rise in temperature above the ambient. This lateral path is available because the selective oxidation simultaneously permits a wide diameter mesa and narrow current aperture; the bulk of the mesa can then act as a good heat sink for the active region at its centre. This effect can be quantified using a simple finite element thermal model to calculate the temperature profile of a device for a given input current. This model uses a phenomenological approach and includes heating effects due to contact resistance, resistive losses in the DBRs, non-radiative recombination and photons that are re-absorbed in the DBRs. The model assumes that all of the heat generated is dissipated by conduction to the back of the substrate, which is held at the ambient temperature (20°C for all the results presented here).

Figure 4 shows the calculated temperature profile for a device with a $15\text{ }\mu\text{m}$ diameter aperture in a $49\text{ }\mu\text{m}$ mesa biased at 10 mA and 3 V . This shows that the maximum temperature is in the active region. Heat diffuses away from this region both directly downwards towards the substrate, but also indirectly through the unpumped regions of the mesa. For geometries in which the active region accounts for the majority of the mesa diameter, the temperature profile grades monotonically downwards through the structure, since heat generated in the top stack must diffuse through the active region to the substrate.

Our results show that for an $8.5\text{ }\mu\text{m}$ aperture, a mesa diameter greater than $25\text{ }\mu\text{m}$ will no longer provide any further heat sinking benefit. On the other hand, a mesa diameter of $8.5\text{ }\mu\text{m}$,

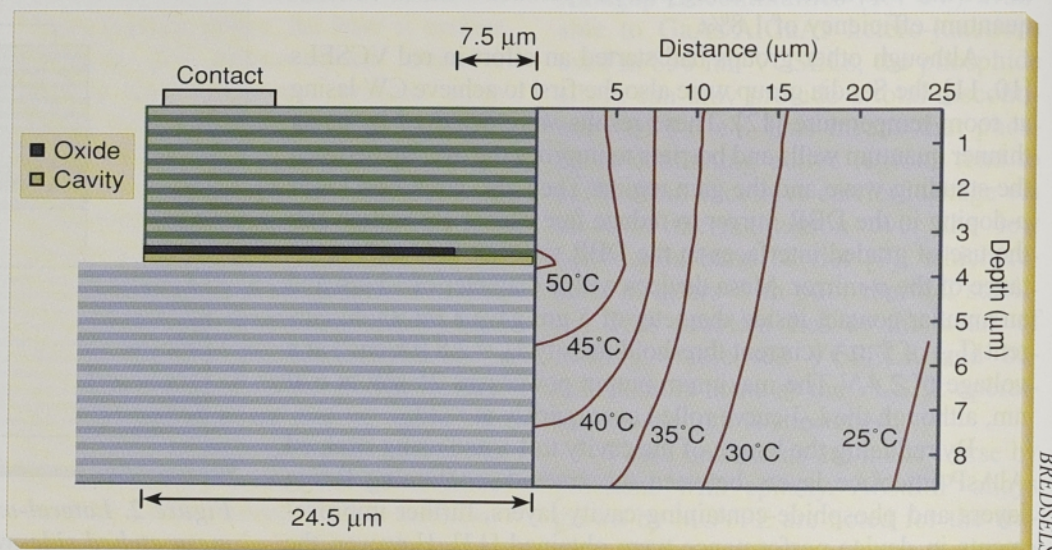
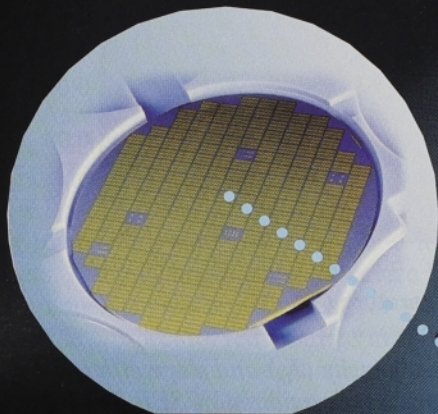


Figure 4. Calculated thermal profile (shown on the right in $^\circ\text{C}$) within an oxide-confined VCSEL with a $15\text{ }\mu\text{m}$ oxide aperture and $49\text{ }\mu\text{m}$ mesa diameter. The maximum temperature is in the active region. Heat diffuses away from this region both directly downwards towards the substrate, but also indirectly through the non-pumped regions of the mesa.

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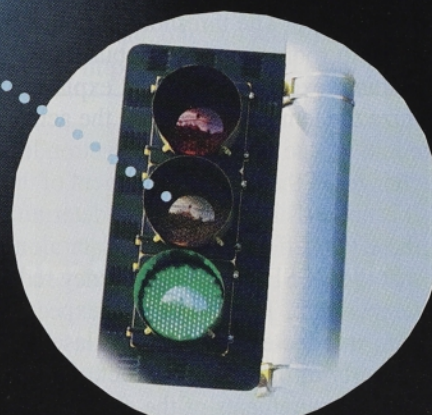
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i.e. an non-oxidized device, shows a temperature rise in excess of 100°C, which ably demonstrates the importance of selective oxidization in terms of providing increased heat sinking.

Free Carrier Absorption

Despite the use of selective oxidation as a means of significantly improving the VCSEL's output power, these devices nevertheless show a rapid and linear reduction in output power as a function of temperature of about $-2\%/^{\circ}\text{C}$. In fact, a 663 nm selectively oxidized device with an output power of 1 mW at room temperature ceases to lase above 35°C. Thus, to achieve devices with an improved thermal performance, it is necessary to understand the physics underlying the reduction of peak power with increasing temperature. The first step is to directly measure the effects of temperature upon the active region by measuring the L-I characteristics at different ambients under pulsed conditions to prevent any Joule heating.

Figure 5 shows the threshold current density (J_{th}) and slope efficiency (η_d) as a function of the ambient temperature. The threshold current density is less than 2 kA/cm² close to room temperature but starts to increase rapidly once the ambient exceeds 60°C, and explains why it is essential to minimize the temperature rise in the active region. This increase in J_{th} could be due to increasing electron leakage out of the cavity, or to changes in the relative alignment of the gain and cavity resonance. It is not possible, however, to determine the relative magnitudes of these two effects from this data alone. Also note from Figure 4 that the VCSEL's slope efficiency reduces rapidly with increasing temperature. This result is unexpected, as no equivalent effect is seen in edge-emitting visible lasers, and it implies that this is a property of the VCSEL structure rather than just its gain region.

Measurements of the slope efficiency of VCSELs as a function of different wavelengths [16,17] reveal that a major factor contributing to the device's poor thermal performance is free carrier absorption. This results from excessive carrier leakage from the active region. In an edge-emitting visible laser, the excess carrier leakage manifests itself as an increase in threshold current, but has little effect on the extraction efficiency. However, in the case of the VCSEL, the free carriers also give rise to additional absorption in the *p*-type DBR, exacerbating the situation. The absorption leads to a reduced mirror reflectivity, which must in turn be compensated for by a larger gain via an increase in injection current. This bigger value of current leads to additional carrier leakage, and a detrimental feedback loop ensues. The key to achieving good thermal behavior in red VCSELs is to minimize the carrier leakage and free carrier absorption.

Temperature Dependence on Output Power

In light of the evidence collated, a new VCSEL was grown and tested. In the new design, a 10 μm selectively oxidized aperture was found to give the best power output: from a constant

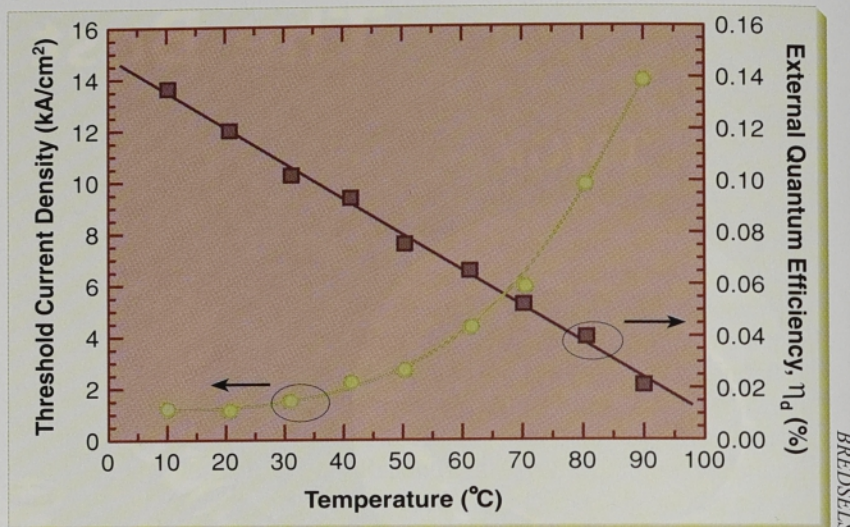


Figure 5. The threshold current density (J_{th}) and slope efficiency as a function of temperature for a selectively oxidized VCSEL. The J_{th} value is less than 2 kA/cm² near room temperature, but the rapid increase above 60°C explains why the temperature rise in the active region must be minimized.

mesa diameter, a 673 nm device achieved marginally over 2 mW at room temperature. This represents a significant improvement on previous devices.

The maximum output power reduces linearly with temperature, and this temperature coefficient varies as a function of aperture size. The best temperature performance is obtained with an aperture of 5 μm with a normalized temperature coefficient of 21.6%/°C, which enables the device to continue lasing up to 60°C. Again, this significantly improves on the previous design.

The deterioration in performance for devices with smaller apertures is caused by scattering losses, while for larger aperture devices, it is the reduced efficiency in heat sinking provided by the oxide aperture. The consequence of this behavior is that the most temperature-tolerant device is not necessarily the device that is optimized for maximum output power at room temperature.

Prospects and Conclusions

Domestic or office-based high-speed POF networks (> 400 Mbps) probably offer the greatest commercial potential for red VCSELs. Indeed, companies such as Mitel [18] and Toshiba [19] have recently published VCSEL results not dissimilar to those presented here, with the stated aim of producing high-speed optical sources for POF data communication. However, the device characteristics described here still do not meet realistic system specifications. In particular, the thermal performance of red VCSELs needs further improvement, i.e. reasonable output powers (300 μW) are needed up to temperatures of 70°C. Devices that meet these specifications will probably only be available by 2002 at the earliest.

For VCSEL POF networks in automotive, aerospace or other industrial applications, the temperature specification is even greater. In addition, there is also a need to achieve this at wave-

lengths between 650 and 660 nm. These enhancements are likely to be met by a combination of refinements in the quality of growth, low leakage active region designs and improved packaging strategies, such as substrate removal. An additional strategy to reduce the effect of free carrier absorption will also be to replace the top semiconductor DBR with a dielectric mirror and use intercavity contacts. That red VCSELS can meet these future data rate specifications is not in doubt—a maximum of 3 dB bandwidth at 4.5 GHz has already been demonstrated [18].

As well as meeting the system temperature and wavelength specifications, there is still considerable work to be done assessing device reliability. Initial life-time measurements made on the BREDSLS devices indicated that the degradation mechanisms for red VCSELS are similar to those for edge-emitting visible lasers. Also, the optimization of device life will be a more complex issue than has been the case for 850 nm VCSELS.

The prospect for red VCSELS in applications such as DVDs, printers and bar code readers is less clear. For POF's, it is hoped that red VCSELS will facilitate the emergence of domestic fiber networks in the same way that 850 nm VCSELS have facilitated local area networks. However, for these other non-POF applications, alternative sources are already available. Hence, for red VCSELS to penetrate these markets they must show a significant improvement in both cost and reliability.

The author would like to acknowledge the collaborators of the ESPRIT Long Term Research programme BREDSLS-23455 Bright Red Surface Emitting LaserS and the support of the European Commission.

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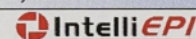
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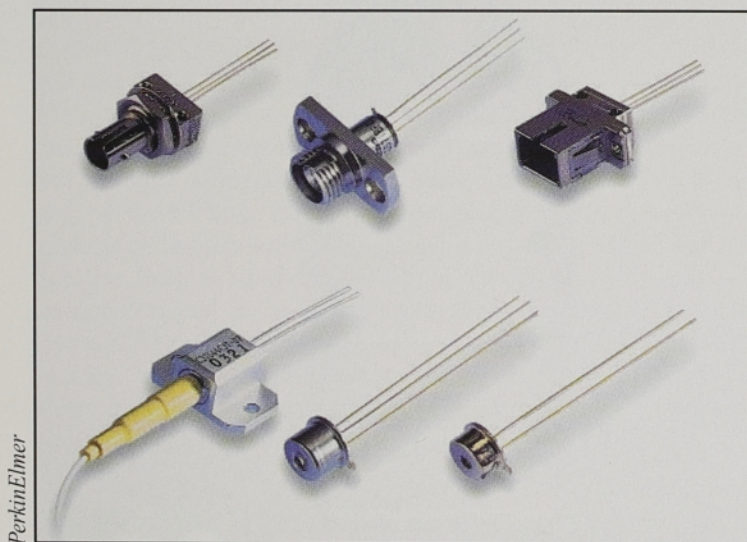
PerkinElmer Optoelectronics

EG&G's recent acquisition of the PerkinElmer name has led to PerkinElmer Optoelectronics—a company committed to serving telecommunications and optoelectronics markets.

RICHARD DIXON

PerkinElmer Optoelectronics came into existence last year when EG&G, a manufacturer of a wide variety of optoelectronic products, acquired PerkinElmer's Analytical Instruments business and the PerkinElmer name. Subsequently, EG&G sold its Technical Services division, and with it the EG&G name. In September 1999, the company announced its intent to change its name to PerkinElmer, Inc., a \$1.7 billion company with headquarters in Boston, Massachusetts.

PerkinElmer Optoelectronics is now one of four businesses within the company, the others being Life Sciences, Fluid Sciences and Instruments. Within the Santa Clara, CA-based Optoelectronics unit, a strategic business enterprise (SBE) was recently formed to focus on products for telecommunications applications. Known as Telecom, this unit is one of three SBEs within Optoelectronics and specializes in laser diodes, optical multiplexers, receivers and detectors. The other two are the Specialty Illumination SBE, which supplies a diverse range of high performance lighting products including IREDs, and the Imaging SBE, which manufactures CCD cameras, photomultipliers, thermopile detectors, IREDs and amorphous Si technology.



PerkinElmer Optoelectronics manufactures a broad line of detectors, including InGaAs photodiodes and APDs for UV, visible and NIR applications.

According to John Engel, president of Optoelectronics, this enterprise is placing a strong emphasis on the rapidly growing markets for telecommunications components, in particular using its vertically-integrated manufacturing capabilities and high-volume optoelectronic packaging facilities, in addition to its test and measurement expertise. "The Telecom business enterprise leverages fundamental technology and considerable experience in sensors and high-speed PIN and avalanche photodiode detectors," he says.

Within Optoelectronics, the Telecom enterprise is demonstrating the highest growth rates of all the divisions at PerkinElmer, and expects 2000 sales of around \$100 million. In total, the Optoelectronics group contribution accounts for around 30% of total company sales, second only to the Instruments division.

Operations

The Optoelectronics Telecom SBE maintains vertically integrated manufacturing facilities in Montreal and Quebec in Canada, St. Louis, MO and in Wokingham in the UK. In addition, it has a number of high volume manufacturing plants in the far East, including Manila in the Philippines and Batam in Indonesia. Epiwafers are grown at the Montreal site and processed into chips. These are subsequently sent to the Manila facility for assembly into various micro-optoelectronic packages. Both Batam and Manila sites are currently being expanded to address the strong demand in the telecom market. The Wokingham facility produces fiber optic test and measurement equipment, which the company says is used in 90% of all chromatic dispersion testing.

Bragg Photonics

PerkinElmer also recently took a 13% equity stake in Montreal-based fiber-grating manufacturer Bragg Photonics, and has the option to increase the stake to 26%. Bragg's technology provides PerkinElmer with several DWDM and optical add-drop multiplexing (OADM) technologies. This includes laser wavelength stabilization, dispersion compensation, signal equaliza-

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tion in EDFAs and optical cross-connect switches used in all-optical network architectures.

Telecom Products

The Telecom SBE recently released a 2.5 Gb/s InGaAs APD and related APD receiver module, in addition to an InGaAs mux array for use in DWDM channel monitoring. Its other products include high-speed InGaAs PIN photodiodes and avalanche photodiodes (APDs), InGaAs and APD hybrid microelectronic receiver modules, photodiode linear arrays (for DWDM channel monitoring) and custom packaged laser diodes. In addition, a range of fiber optic and cable test equipment is available.

Detector Arrays

PIN detector arrays are manufactured for a range of applications. These include fiber optics, WDM, near-infrared (NIR) spectroscopy for industrial chemical and medical analysis, NIR imaging for food and paper sorting/inspection/quality control, NIR astronomy and far-field analysis.

The MXA-256-X detector series comprises a hybrid focal plane InGaAs PIN photodiode array with a wavelength response in the 800–1700 nm range. The array has 256 elements configured in a linear orientation with standard array length of 0.5 mm. Included in the assembly are a single-stage thermoelectric cooler, silicon multiplexer, bias resistor and bypass capacitors.

Receivers

For digital communication applications, PerkinElmer's receivers incorporate an InGaAs APD photodiode or InGaAs PIN photodiode with a GaAs transimpedance amplifier (TIA) in an 8-pin mini-DIL package. Both devices conform to SONET requirements of 155, 622 Mb/s and 1.2 Gb/s receivers used in 1310 nm and 1550 nm long- and intermediate-range and short-range applications. A compact TO-46 package version (the SR TO-46 Series) is also available for data rates up to 622 Mb/s in the same wavelength options.

A TIA featuring automatic gain control provides a cost-effective up-grade for PIN photodiodes for ATM-SDH transmission equipment, Fibre Channel or 100 Mb/s Ethernet. Re-

ceiver modules are available in an industry-standard package with either multimode or single mode-fiber or pigtail connections.

For OC-48 (2.5 Gb/s) requirements, the company's SRBA2.5 series of receivers incorporate a high speed 30 mm InGaAs APD photodiode with a high performance GaAs TIA in an 8-pin butterfly package operating at 1310 nm and 1550 nm.

Laser Diodes

Applications for the company's laser diodes include UV curing, smoke detection, materials processing and range finding. CW laser diodes typically operate at 905 nm, and feature a built-in photodiode monitor for power output control. Packaging is in the form of a 9 mm CD header designed for free space communications and range finding.

PerkinElmer manufactures pulsed laser diodes with MQW strained InGaAs active regions. These demonstrate peak output powers in the 5–175 W range, when operated with a 160 ns pulse width. Significant increases in peak power are attainable at shorter pulse widths (up to 500 W at 10 ns). Pulsed double heterostructure (DH) laser diodes with output powers of 4, 8 and 40 W are also offered as standard products. These devices take advantage of an increase in the maximum permitted emission levels for eye safe operation using InGaAs-based lasers compared to AlGaAs and shorter wavelength lasers.

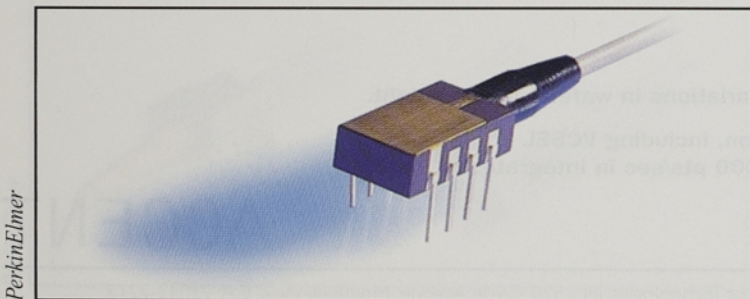
LPE-grown laser diodes consisting of a single heterostructure and operating at 905 nm offer output powers from 2 to 210 W, and are available in a coaxial package design. Applications include high-speed switching, therapeutic medicine, obstacle sensing and general-purpose range finding.

Longer wavelength pulsed diodes in the 850–1300 nm range can be supplied with fiber optic pigtail connections. A fiber alignment process yields highly stable fiber-to-laser diode positioning, for fiber optic instrumentation, laser simulation and range determination.

The Future for Laser Pumps

At present, PerkinElmer has no pump laser product for telecommunications applications. "For detectors and receivers, we are vertically integrated at our Montreal facility," explains John Engel. "To manufacture pump lasers, we would prefer to leverage our excellent optoelectronic packaging and the high-volume manufacturing capability at sites such as Manila and Batam. We would not grow the base structure, but integrate purchased chips into higher level hybrids or sub-assemblies." Engel adds that while this describes the company's short term objectives, in the longer term PerkinElmer will broaden its options.

PerkinElmer has a diverse range of high technology products, and the company's focus on optical networking reflects both its epitaxial manufacturing capabilities and its captive high-volume module-level packaging assembly plants in the far East. As John Engel puts it; "We have an excellent set of assets that we can use to address these new high growth markets."



PerkinElmer's receivers incorporate a high speed InGaAs PIN photodiode with a GaAs TIA in an 8-pin package for digital communications applications.

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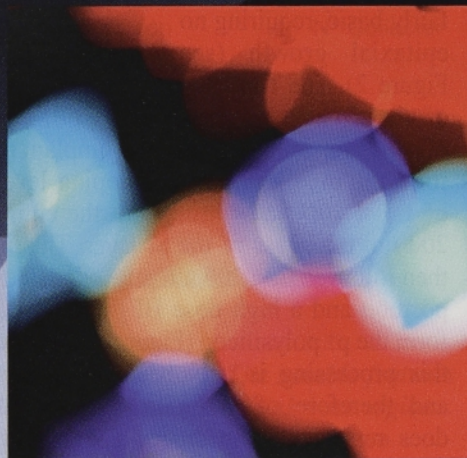
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ROBERT A. METZGER

As RF telecommunications markets continue to grow, competition becomes greater and greater. Not only are GaAs-based products competing with Si-based products, but within the Si arena itself, this same competition drives both continued performance enhancements, while at the same time demanding cost reductions through the implementation of less demanding and sophisticated processing techniques.

An example of this evolution within the Si arena is seen in the Si BJT. High performance commercial devices that can compete with GaAs-based devices have been available for several years. However, these high performance characteristics have come at a cost: sophisticated processing elements are required, including self-aligned double-polysilicon structures, shallow and/or deep trench isolation, epitaxial bases, or in some cases, SiGe bases. While these processes have allowed Si BJTs to exhibit GaAs-like performance, the other major perceived benefit of Si—its supposed lower cost—is often lost due to the need for sophisticated and expensive processing.

Researchers at Toshiba's LSI Research & Development Center are addressing this performance vs. cost conflict by developing a lateral bipolar transistor fabricated on thin-film SOI substrates. These new devices maintain a high level of RF performance, while at the same time dispensing with the sophisticated processing normally associated with high performance Si BJTs [1].

The basic layout of the lateral bipolar transistor device is shown in Figure 1. The starting material consists of a fairly standard SOI substrate using 200 nm of epitaxial Si atop a 400 nm buried oxide (BOX). Designed specifically for high RF

performance, low noise applications, a combination P⁺ poly/CoSi₂ base electrode is used to achieve a low base resistance of only 270 ohm.

The processing required for the lateral bipolar transistor is fairly basic, requiring no epitaxial growth (see Figure 2). The first step of the process consists of a blanket double phosphorus implant to form the n-collector with a doping level of $1.5 \times 10^{17} \text{ cm}^{-3}$ throughout the entire 200 nm thickness of the Si layer. This is then followed by a 200 nm polysilicon deposition and a high dose BF₃ implant to form the p⁺ polysilicon (Figure 2a). While this processing is very basic in nature, and therefore of minimum expense, it does result in some device degradation for certain operating regimes.

During boron thermal activation in the polysilicon, the B diffuses into the n-collector region to form a p-n junction at a depth of about 65 nm below the polysilicon-silicon interface. This penetration of the junction depth decreases the cross-sectional area of the collector region, and results in an increase in collector resistance and premature appearance of the Kirk effect due to increase in collector current density. As a result, the f_t of the transistor will degrade more abruptly at higher collector currents than might normally be expected.

The base is defined by etching through the entire p⁺ poly layer and halfway through the single crystalline silicon (Figure 2b). The remaining silicon film thickness is about 120 nm and the intrinsic base is formed by angled B and BF₃ ion implantation, forming a

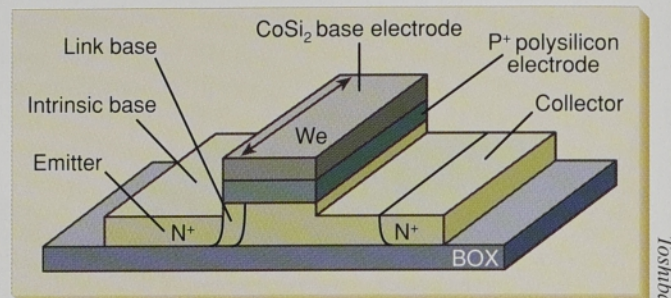


Figure 1. Schematic of a lateral bipolar transistor; the emitter, intrinsic base and collector region are formed laterally in a thin film SOI.

base region with a doping level of $5.0 \times 10^{18} \text{ cm}^{-3}$ (Figure 2c). This implant also forms a very short (7 nm) link base region that connects the intrinsic base to the p⁺ polysilicon base contact region (Figure 2d). This link is typically half the length of that found in a conventional vertical bipolar transistor, thereby decreasing base resistance and in turn, improving RF and noise performance.

After the formation of polysilicon side-walls (Figure 2e), the emitter and collector contact regions are formed by ion implantation. The resulting emitter concentration is on the order of $2 \times 10^{20} \text{ cm}^{-3}$, and the base width is 150 to 200 nm. The last step of the process consists of a TEOS SiO₂ deposition and etch-back process to expose the top of the base polysilicon region, upon which a standard Co salicide process is performed. This salicide process reduces the base sheet resistance from 250 ohm/□ for a poly-only base electrode to 5 ohm/□ for the salicided base electrode (Figure 2f).

With this relatively basic lateral bipolar process, combined with the small junction areas that are possible in an SOI structure (and therefore reduced junction capacitances, in which the emitter-base capacitance is only 1.5 fF and the collector-substrate capacitance

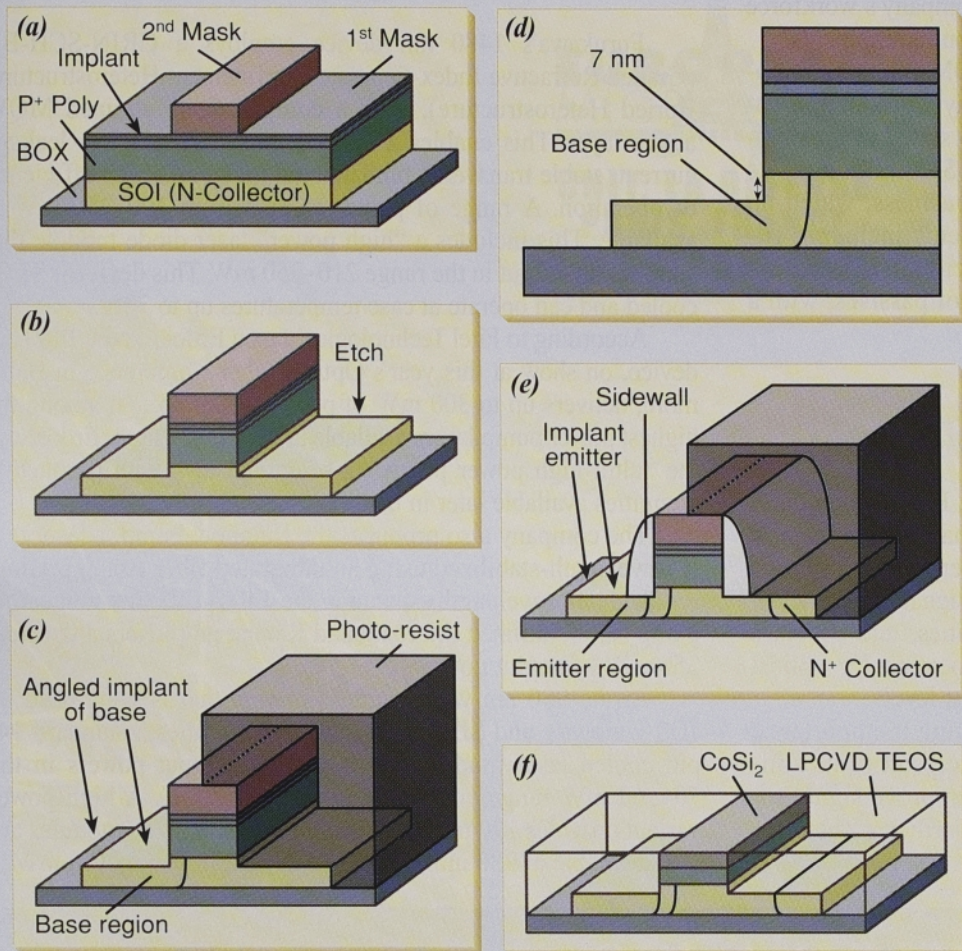


Figure 2. Fabrication process for the 67 GHz bipolar transistor. The notable features are the silicided p^+ polysilicon base electrode and the short (7nm) link base region that connects the intrinsic base and external base electrode. Both contribute to reduced base resistance and improved RF and noise performance.

is 2.5 fF), devices with emitters of $0.12 \times 3.0 \mu\text{m}^2$ exhibit an impressive f_{max} of 67 GHz, one of the highest values reported to date for an SOI-based BJT. The effect of the silicided base contact increases f_{max} by nearly a factor of three as compared to the poly-only process. As expected, due to the small cross-sectional area of the collector and the resulting higher resistance and current crowding, f_t is degraded, with a maximum value of 11 GHz. Further refinements in both collector doping and width may be needed to improve the value of f_t . With a BV_{CEO} of 5.3 V, the device should be well suited to systems with operation voltages in the 2.0–3.3 V regime. As anticipated from the excellent f_{max} and low base resistance values, a minimum noise figure of 1.28 dB was obtained at 2 GHz

operation, making this device quite competitive with both GaAs and SiGe-based devices.

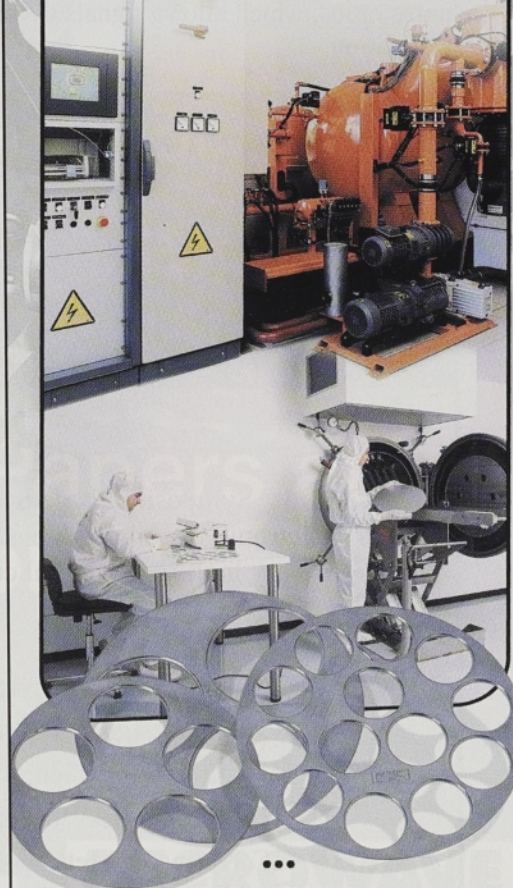
What these characteristics clearly show is that high performance, low noise devices can be manufactured with fairly simple processes requiring no epitaxial growth. These devices will be able to compete with both GaAs and SiGe parts, and should also be cost competitive as a result of the relatively unsophisticated processing.

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(continued from page 15)

Plans also include relocating a part of the company's workforce to Chiba to accommodate the extra production requirements.

Similar sharp ramp-ups of various WDM-related components, including a doubling of the company's production capacity for functional optical fibers, are also slated in the coming months. The company will spend over \$18 million on its passive WDM component manufacturing business, which up to now has provided for internal requirements including filters, fiber Bragg gratings and planar light circuits. The intention is to continue high volume production of passives, with a view to merchant sales.

On the Western Front . . .

Furukawa's wholly owned US subsidiary, Fitel Technologies (Clinton, NJ), recently bought a majority share in Optigain, a manufacturer of EDFAs and optical amplifiers based in Peace Dale, Rhode Island. This new site will be designated a center of excellence for the company's Raman activities, and provides Fitel with a development and production location for optical equipment both at the component and modular level.

Raman distributed amplification is gaining in importance in long-haul transmission systems. This is a result of its ability to increase bandwidth per channel and improve signal-to-noise ratios, which allows signals to travel further without regeneration.

1480 nm Pump Laser Modules

Furukawa's 1480 nm device employs a GRIN-SCH-BH (Graded Refractive Index-Separate Confinement Heterostructure-Buried Heterostructure), with a compressively strained MQW active layer. This enables a laser demonstrating a low leakage current, stable transverse fundamental mode and high efficiency of operation. A range of power outputs from 100–250 mW is available. This includes a "high power" laser diode module that supplies an output in the range 210–250 mW. This device is TEC-cooled and can operate at case temperatures up to 70°C.

According to Fitel Technologies' Jason Erdos, a new 1480 nm device, on show at this year's Optical Fiber Conference in Baltimore, delivers up to 300 mW of power. This makes it among the highest power pump lasers available at this wavelength. Erdos says the "ultra high power pump" is sampling now, with production quantities available later in the year.

The company also produces the Rainbow Pump, a laser that is wavelength-stabilized using an integrated fiber Bragg grating. Available in wavelengths spanning the 1400–1500 nm range, this pump can be utilized in broadband Raman amplifiers and offers 250 mW of output power.

At the 980 nm wavelength, a market that is dominated by JDS Uniphase and SDL, Furukawa also supplies a standard 14-pin cooled laser diode. This operates at output powers in the 70–160 mW range, at temperatures up to 75°C. A high power variant provides 190 mW, and wavelength-stabilized modules are also available at 980 nm and 974 nm operating up to 130 mW.



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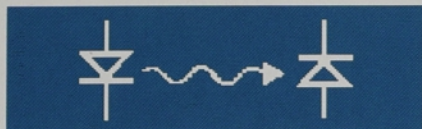
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