



COMPOUND

SEMICONDUCTOR

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May 2001

Volume 7 Number 4

GaAs

Manufacturing

- Building a better fab
- Foundries in Taiwan
- Millimeter-wave ICs
- Reliability of InGaP HBTs
- Filtronic exploits PHEMTs

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GaAs bubble deflates

New players make waves at OFC

European start-ups



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information sciences.**

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To find out more, contact Andy Hover at Caswell Technology, Caswell, Towcester, Northants NN12 8EQ. Telephone +44 (0) 1327 356707, fax +44 (0) 1327 356705 or email: andy.hover@marconi.com





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IN

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North America*



With manufacturing sites in both the USA and the UK, IQE has established itself as the world leading epi-wafer foundry, supplying custom compound semiconductor epitaxial structures.

Demand for our products for both the electronics and opto-electronics sectors has soared. Fuelled by growth in internet usage, mobile telephony, data storage and display technologies, many large multinational blue chip companies have turned to IQE as the specialist contract supplier of choice.

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We offer a highly competitive salary and benefits package, including stock options.

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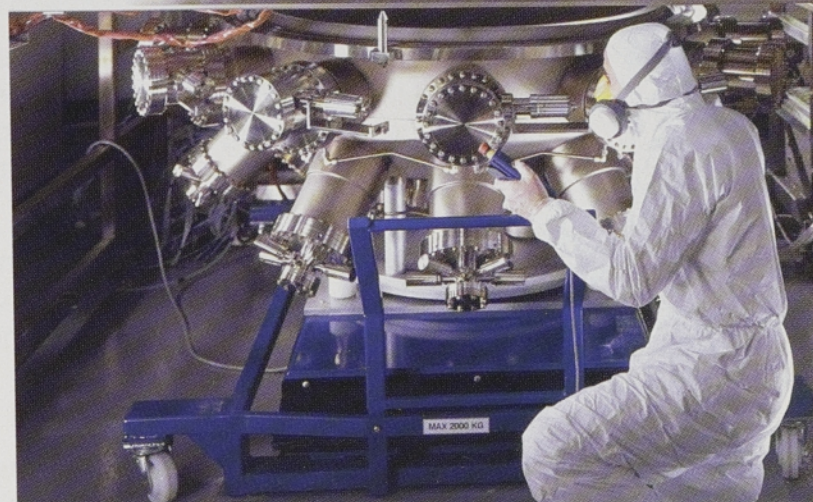
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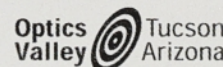
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- ▶ *Epitaxial Engineer*
- ▶ *Optical Engineer*
- ▶ *Semiconductor Laser Engineer*



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Demand for our products for both the electronics and opto-electronics sectors has soared. Fuelled by growth in internet usage, mobile telephony, data storage and display technologies, many large multinational blue chip companies have turned to IQE as the specialist contract supplier of choice.

To meet the increasing demands we are seeing for our wafers, major expansion plans have been put into place. To support these plans we now seek to recruit highly motivated engineers at both our US and UK facilities.

You will have the opportunity to make a major contribution to the leading player in this rapidly growing industry.

We offer a highly competitive salary and benefits package, including stock options.

If you have two years or more relevant engineering experience supported by a sound academic background, then we want to hear from you. Ideal candidates will have previous experience with MOCVD and/or MBE growth techniques.

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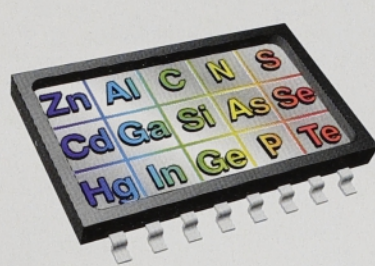
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Optical fiber conference draws over 38 000

Attendance at this year's Optical Fiber Communication conference (OFC) more than doubled compared to last year. Over 38 000 attendees crowded into the show, held late March in Anaheim, California. The 970 plus companies that were exhibiting included a large number of optical component makers, and many new faces (see report, page 49).

Among the component vendors, a number of major themes were in evidence:

- Tunable lasers – these are a key enabler for network flexibility.
- VCSELs – higher power and long wavelength devices are increasing the range of applications for surface emitters.
- High data rates – several vendors showed 40 Gbit/s components, such as modu-

lators and transimpedance amplifiers.

- Integration – small, highly functional components are being made by integrating components in a hybrid manner or by using monolithic integration on InP.
- Automation – vendors emphasized the automated nature of their manufacturing processes, a necessary transition as the industry continues to mature.

Plenary speakers announced for CS-MAX conference in July

Experts in the field of high-volume manufacturing of compound semiconductor devices will share their knowledge with the rest of the industry this summer at the Compound Semiconductor Manufacturing Expo (CS-MAX). As detailed in the box on the right, speakers from the most innovative compound semiconductor fabs, including Vitesse, Nichia and Honeywell, will headline the plenary sessions at the conference.

CS-MAX is a new event for the compound semiconductor industry, designed to play the role that Semicon West and related shows play for the silicon industry – namely, an annual showcase for new ideas about increasing fab productivity. The inaugural CS-MAX will be held at the Hynes Convention Center in Boston, Massachusetts on July 9–11, 2001.

CS-MAX will offer a technical program with approximately 100 papers on high-volume manufacturing of compound semiconductor devices, organized into five tracks: microelectronics, laser diodes and fiber-optic components, LEDs, epitaxy and characterization.

The event will also include the industry's largest equipment and materials

Plenary presentations at CS-MAX include:

"Mainstream Manufacturing: GaAs IC Production in a 6" Fab"
Patrick Jenkins, vice-president, **Vitesse Semiconductor**

"The Fabless RF Components Model: Key Strategies and Tactics"
Bob Van Buskirk, president and CEO, **Stanford Microdevices**

"From 6" Silicon to 6" GaAs with a High Productivity, High Yield Approach"
Richard Kerrigan, general manager & John McEachran, operations manager, **Filtronic Compound Semiconductor**

"The PCAD Program: Advances in Photonic Computer Aided Design"
Matthew Goodman, chief scientist, **Telcordia Technologies**

"Commercialization of VCSEL Technology"
Jim Tatum, VCSEL technology manager, **Honeywell VCSEL Products**

"LED Manufacturing In Taiwan"
Jim Chi, deputy director, **Industrial Technology Research Institute, Taiwan**

"High Volume Production of InGaN-based LEDs at Nichia"
Kiyoshi Komatsu, **Nichia**

exhibit, featuring all of the major suppliers to compound semiconductor fabs. Several workshops, tutorials and free seminars will also be offered.

CS-MAX is sponsored by *Compound*

Semiconductor magazine and Institute of Physics Publishing. More information about the event is given on page 42 of this issue, and is also available on the conference Web site at www.cs-max.com.

Anadigics buys up Telcom Devices

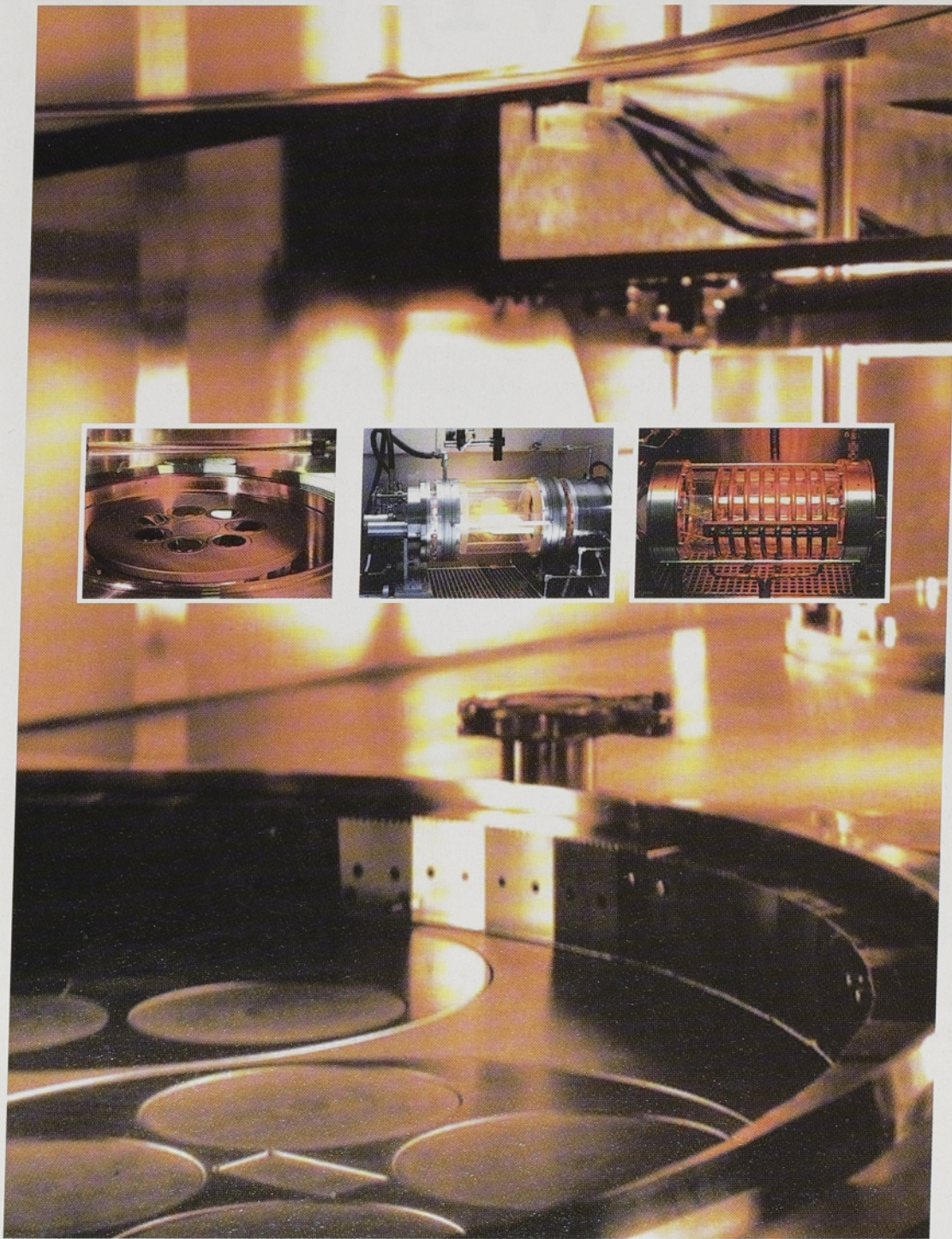
Anadigics has acquired Telcom Devices of Camarillo, CA in a deal valued at up to \$45 million. Telcom Devices is a manufacturer of InP-based photodiodes for the telecommunication and data communication markets.

Anadigics says the acquisition is a key

step in its strategy to provide high performance chip-sets by adding long wavelength PIN photodiodes and unique packaging capabilities to its fiber product line. Telcom Devices' products include digital photodiodes for systems operating at speeds up to 10 Gbit/s and at wavelengths from 1300–1550 nm, in addition to laser backside facet monitors for fiber transmitters and analog photodiodes for optical nodes in cable systems.

"As fiber systems continue to increase in speed from 10 to 40 Gbit/s and beyond, our customers are demanding fully integrated component sets in order to speed their products to market," said Tom Lagatta, vice-president of Anadigics' Fiber Optic Communications Products group. "Telcom Devices' capabilities in InP processing and photodiode design and manufacturing broadens our portfolio of fiber components at these data rates."

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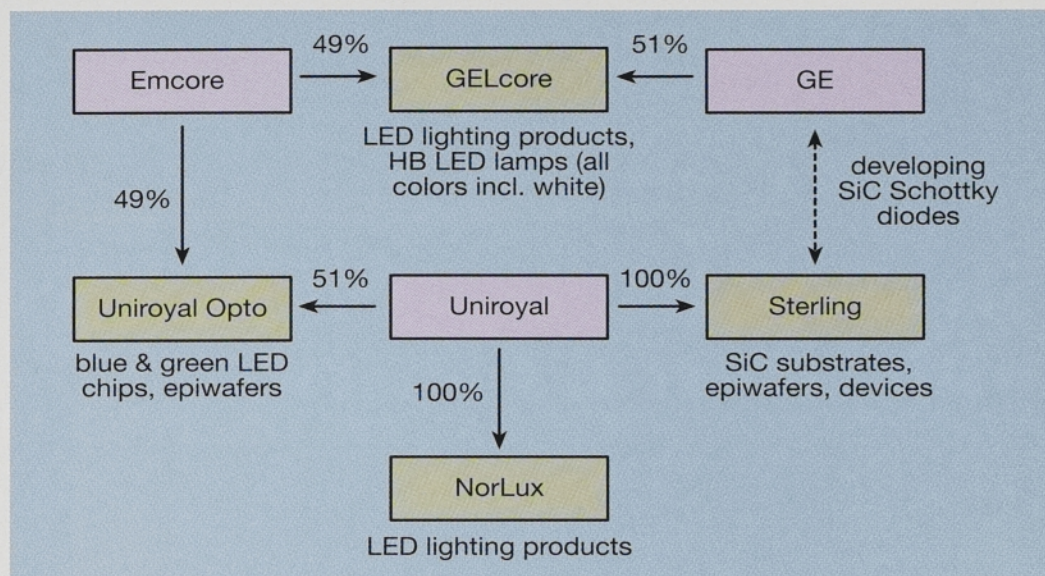
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Leadership Through Better Thin Film Coating Ideas

Uniroyal unveils high output power LEDs

Uniroyal Optoelectronics has demonstrated high-brightness blue LED chips with an output of 3.5 to 4 mW. When conventionally packaged, the lamp power output is expected to be between 8 and 10 mW, making these emitters suitable for outdoor displays, in addition to enabling a number of LED-based biomedical and dental procedures. This high output power elevates these devices into the league of other LED manufacturers such as Nichia and Osram Opto Semiconductors; the latter company produces a shaped blue InGaN chip that offers 8 mW when packaged (see *Compound Semiconductor* February 2001, p7).

Uniroyal has also begun shipping 450 and 470 nm InGaN-on-sapphire blue LEDs with a minimum power output of 2 mW in die form. When conventionally packaged, these devices are expected to result in output power levels between 4 and 5 mW. The 450 nm LED can be combined with a phosphor coating to make white lamps for niche applications such as flashlights and nightlights, while the 470 nm emitter is designed for outdoor video displays, biomedical applications and instrumentation. "Uniroyal Optoelectronics is producing increasingly higher quality products from its facilities in Tampa, Florida," said president and chief oper-



A tangled web: Uniroyal Technology, Emcore and General Electric are involved in several activities related to wide bandgap devices and LED-based products. Percentage figures refer to ownership of subsidiary companies and joint ventures.

ating officer Robert Soran. "We recently doubled the capacity of our high-brightness blue and green LEDs, and we are also nearing completion of the build out of additional capacity for these devices."

NorLux lighting subsidiary

In further news, Uniroyal has formed NorLux, a subsidiary which has been

set up to design custom lighting solutions and applications that leverage high-brightness LEDs. Based in Carol Stream, IL, NorLux is equipped with high-capacity, prototype design and test equipment in a class 10 000 clean room. The new subsidiary aims to speed up the development of solid-state lighting-based applications.

LumiLeds' LEDs optimize backlights

LumiLeds Lighting has introduced a backlight source optimized around its new Luxeon LEDs, a range of large-area, high-power devices employing high-flux chips (see *Compound Semiconductor* March 2001, p11). LumiLeds' packaged LEDs now offer outputs upward of 20 lumens in certain colors (such as its 540 nm green device), and these emitters are being employed in the new backlighting system to enable features not currently available with conventional backlighting technology, says the company. In addition, this is the first source that targets medium to large LCD displays, including those used in PCs. LumiLeds is already working with LCD panel

manufacturers and hopes to introduce Luxeon-powered backlights by the end of the year.

LEDs offer a number of advantages over conventional light sources for this application. Solid-state emitters are more durable than fragile cold cathode fluorescent lamp (CCFL) sources, and at around 10 V their power operation is low enough to significantly reduce electromagnetic interference. LEDs also appear brighter, resulting in NTSC values of up to 130% being produced in the backlight. The NTSC is the color chart definition for typical cathode ray tube screens that defines color saturation e.g. how "red" an object appears. CCFLs exhibit only around 80% of the ideal NTSC value, resulting in paler colors.

Added to this is the ability to "color sequence" the LEDs as a result of the

Luxeon's very fast (100 ns) switching times. A higher resolution is afforded by the fast modulation and sequencing of the red, green and blue LEDs. Energy requirements are also reduced: in CCFL sources, filters are needed to display the required colors, and the LCD display has three different areas per pixel that open and close to show red, green and blue. This makes the LCD display more expensive and power hungry. As LED displays already consist of individual color-separated emitters, the LCD panel requires just one area that opens/closes per pixel and consumes less power.

"This solid-state backlighting solution will allow the LCD display market to go head-to-head with the incumbent cathode ray tube market," explained Mark Pugh, LumiLeds' vice-president of strategic marketing.

GELcore set to expand LED range

GELcore, the joint venture between GE Lighting and Emcore, has introduced new blue, green and blue-green high-brightness LEDs. These InGaN-based devices add

to the company's existing white, 620 nm red, 620 nm red-orange, 605 nm Portland orange and 588 nm yellow amber AlInGaP LEDs introduced last year (*Compound Semiconductor* August 2000, p19).

Applications for the new devices, which are housed in clear standard 5 mm packages, include variable messaging, traffic

signals, exit signage and specialty lighting applications. Several viewing angles offering different luminous intensities are available. GELcore was set up two years ago to develop solid-state lighting systems. The company subcontracts epiwafer growth, chip fabrication and the manufacturing of LED lamps and lighting systems.

NITRIDE NEWS

Sterling develops SiC diodes with General Electric

Sterling Semiconductor, a subsidiary of Romyal Technology, has expanded its R&D contract with General Electric Corporate Research & Development (GE CRD) to include the development and evaluation of silicon carbide Schottky diodes. These devices are "building blocks" that support a wide range of consumer and industrial products, including wireless communications, portable computing and automobiles. Si-based Schottky diodes are sold in quantities of 500 million units per year in North America alone.

SiC-based devices offer the advantage of being able to operate at much higher voltages and temperatures and with greater efficiencies than silicon devices, allowing for simplified electronic designs and packaging in products that use Schottky diodes.

Under its contract with Sterling, General Electric will demonstrate Schottky diodes using Sterling's SiC wafers and epitaxy, applying GE technology developed in part under previous initiatives such as the "Megawatt" device program sponsored by the Defense Advanced Research Projects Agency. The effort is focused on perfecting device design and demonstrating the relationship between device performance and yield, and the characteristics of silicon carbide wafers.

The R&D contract with GE CRD is a subcontract to a grant awarded to Sterling in 1999 by the US Defense Department to develop technology for SiC wafer production under Title III of the Defense Production Act. The GE CRD-Sterling relationship is non-exclusive for both parties.

Cree unveils new 3 inch 4H-SiC wafers

Cree has introduced a new 3 inch diameter n-type 4H-SiC wafer to complement its existing 3 inch n-type 6H-SiC wafers. In addition, Cree has demonstrated a 3 inch semi-insulating 4H-SiC substrate, which it says will allow scaling of RF and microwave products for commercial production. The availability of 3 inch wafers more than doubles the available device area per wafer compared to existing 2 inch SiC wafers, and is expected to significantly reduce the cost of devices made from SiC.

"The addition of n-type 4H to our 3 inch product family, and the demonstration of 3 inch semi-insulating wafer capability, results from Cree's commitment to converting world-class research into products that respond to the needs of the commercial market," commented Robert Glass, general manager of Cree's materials business.

Japanese groups boost SiC MOSFETs

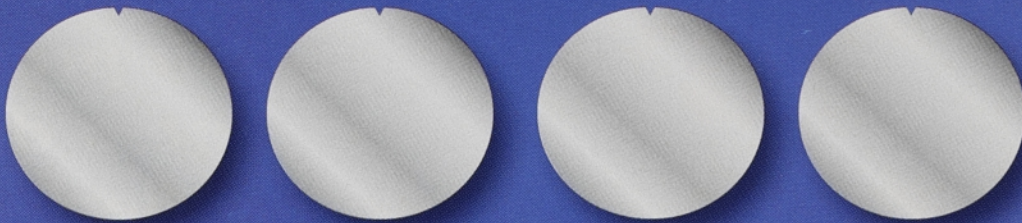
The electronics technology research laboratory of the Ministry of Economy, Trade and Industry has developed a silicon carbide MOSFET with one-tenth the internal resistance of previous devices. The lab lowered the internal resistance by reducing the defects in transistor gates and devising a structure that facilitates current flow deep within the substrate, eliminating resistance due to surface defects. Lowering internal resistance in turn reduces energy loss, a significant factor in the development of SiC MOSFETs for applications such as electric vehicles and industrial power generation equipment.

The Electrotechnical Laboratory and the Research and Development Association for Future Electron Devices have jointly developed a silicon carbide MOSFET, which achieves a channel mobility of $140 \text{ cm}^2/\text{Vs}$. The joint research group has devised a new oxide film formation technique and a unique buried channel structure to boost the flow of electrons. The group has also developed an ultra-high-temperature, ultra-speed thermal processor that incorporates a unique post-ion-implantation thermal processing system, and has succeeded in reducing the source drain's sheet resistance to 38Ω . The prototype SiC MOSFET will pave the way to significantly reducing power losses in SiC-based large power converters.

The Power Electronics Research Cen-

ter of the National Institute of Advanced Industrial Science and Technology has successfully fabricated an interface-controlled enhancement buried-channel 4H-SiC MOSFET that achieves a channel mobility of $140 \text{ cm}^2/\text{Vs}$ at a threshold voltage of 0.3 V. The MOSFET has a thermally grown gate oxide in 4H-SiC, which is prepared by dry oxidation with H_2O annealing. The buried channel region was created by nitrogen ion implantation at room temperature followed by annealing at 1500°C . The lab has found the optimum doping depth of the buried channel region at $0.2 \mu\text{m}$. SiC is expected to be used as a next-generation power electronics semiconductor material, which should achieve resistance levels less than 1/100 of those of conventional silicon devices.

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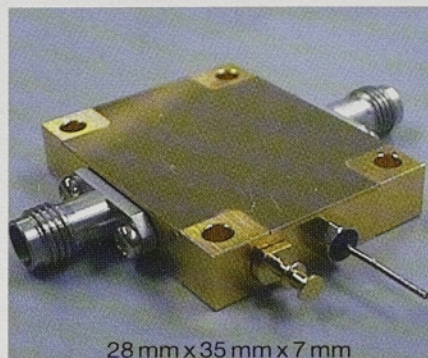


Yokogawa introduces 50 Gbit/s HBT ICs

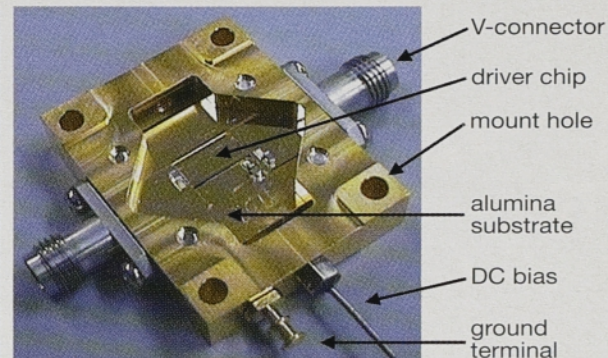
Yokogawa Electric Corporation, a manufacturer of instrumentation, process control and automation systems, has developed 50 Gbit/s modulator driver and 2:1 multiplexer ICs based on its own InGaP/ InGaAs HBT process. In partnership with Ando Electric, which became an affiliate of Yokogawa in late February, the new ICs will be used in the design of measurement and test systems for WDM networks operating at 40 Gbit/s.

The companies are working together to combine Ando's optical expertise in the measurement systems field with Yokogawa's compound semiconductor device technologies. Products and services will address measuring instruments for optical communications (covered mainly by Ando), measuring instruments for radio communications networks and multimedia equipment (covered mainly by Yokogawa) and automatic test equipment for semiconductor testing and device handling, which both companies will cover.

Yokogawa has a 4 inch GaAs fabrication line that can process about 500 wafers per year, according to Akira Miura, general manager of the development project center within the corporate R&D center. "The new ICs will be used in measuring equipment within our own company," says Miura. "We will also sell modules for network applications." The module, measuring 28 × 35 × 7 mm, is shown in the photo, both with and without its cover.



28 mm x 35 mm x 7 mm



Yokogawa has used GaAs HBT technology to realize a 50 Gbit/s modulator driver IC.

Comparison of 50 Gbit/s driver technologies

	SiGe HBT	GaAs HBT	InP HEMT
Integration scale	Excellent (LSI)	Poor (MSI)	Poor (MSI)
Phase noise	Excellent	Excellent	Poor
Breakdown voltage	Poor (1–2 V)	Excellent (8–10 V)	Excellent (8–10 V)
Low-frequency characteristics	Excellent	Excellent	Poor
High-frequency characteristics	Good (100 GHz)	Excellent (300 GHz)	Excellent (300 GHz)
Reliability	Unknown	Good	Unknown
Temperature stability	Unknown	Good	Unknown

According to Yokogawa, GaAs HBT-based driver ICs feature lower jitter and higher output power than devices based on InP HEMTs or SiGe bipolar transistors. The table compares the different technologies for fabricating 50 Gbit/s modulator drivers. Yokogawa's modulator driver has an output voltage of $>2.5 V_{pp}$ with a gain of 9 dB. The supply

voltage is +7 V, the power consumption is 0.65 W, and the frequency response (–3 dB) is 15 kHz to 35 GHz. Very recently, the company achieved 4 V_{pp} operation for its driver IC. The 2:1 multiplexer is packaged in a 20 × 50 × 9 mm module, and has input and output voltages of 0 V and –0.5 V, with a supply voltage of –6 V and 1.2 W power consumption.

RF Micro Devices expands WCDMA alliance

RF Micro Devices has signed a memorandum of understanding to expand its alliance with Qualcomm CDMA Technologies (QCT) to develop WCDMA power amplifier modules for inclusion in QCT's MSM5200 IC family. The two companies recently announced the first generation of PA5200 power amplifiers to the CDMA market following qualification and volume production shipments in October 2000. RFMD's GaAs PAs are used in conjunction with QCT's MSM5200 Mobile Station Modem (MSM) baseband, transmit processor, receiver processor and power management devices to form a

complete, integrated WCDMA module. QCT says it has shipped more than 133 million MSM chips worldwide.

"The joint development efforts between Qualcomm and RFMD continue to result in the most advanced and highly integrated wireless power amplifier products available," said Johan Lodenius, QCT's senior vice-president of marketing and product management. "The alliance allows Qualcomm to maintain its leadership in offering manufacturers worldwide the best performing and most cost-effective power amplifiers available in the CDMA marketplace."

Vitesse to purchase Danish design house

Vitesse is to acquire Exbit Technology, a fabless semiconductor company located at Herlev in Denmark that develops high-speed chip-sets and IP cores for the communications and networking industry. The company is developing Gigabit and 10 Gigabit Ethernet switching and routing technology with a view to providing complete systems solutions for the networking equipment manufacturers. The transaction will be accounted for by the exchange of 4.4 million of Vitesse shares, and should be completed by the end of June.

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2 *An hydraulic trolley is rolled underneath and takes the weight of the bottom half of the growth chamber. The four locating bolts are quickly removed.*

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3 *The trolley is lowered at the touch of a button and the entire lower section of the growth chamber is wheeled out for easy cleaning and source loading.*

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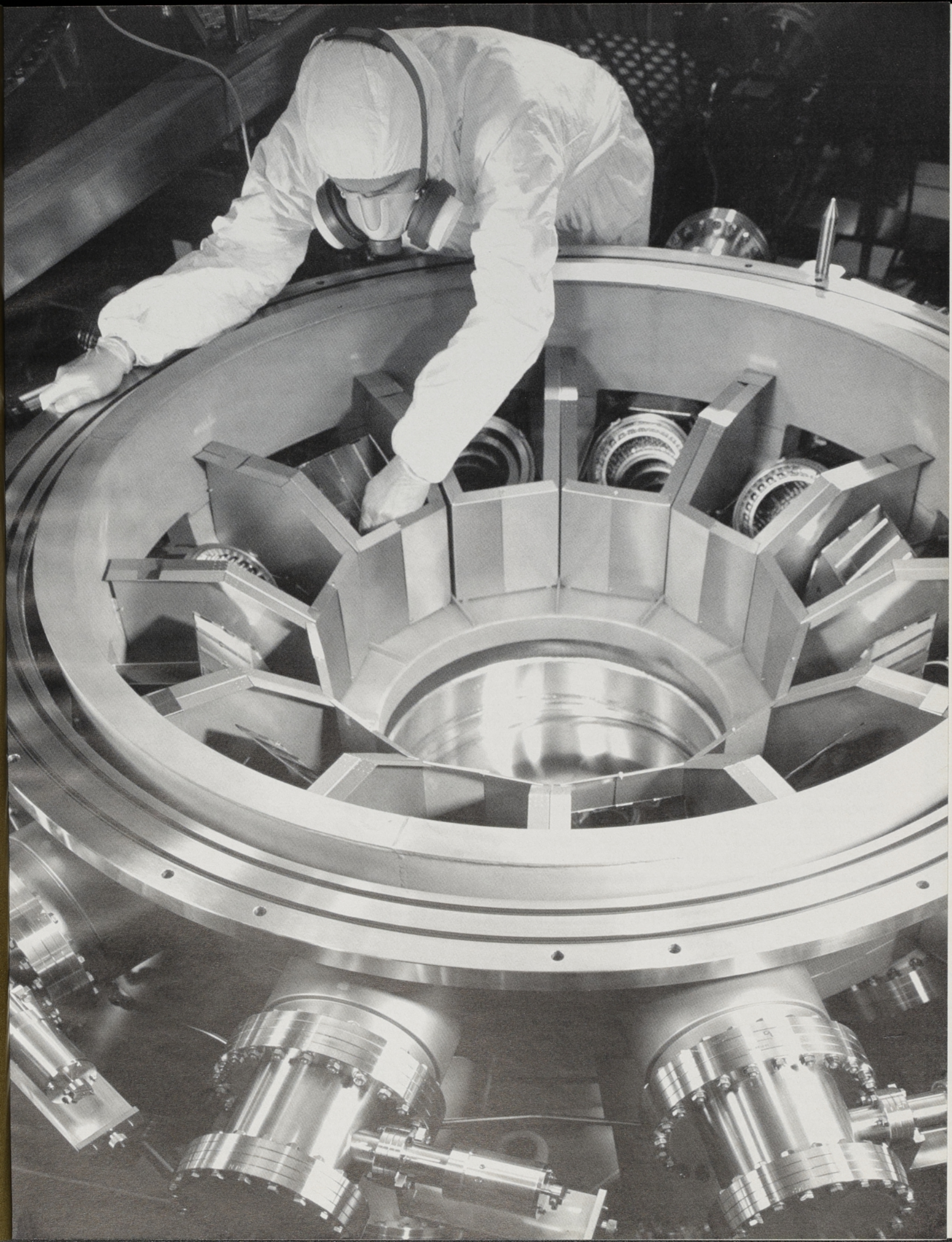


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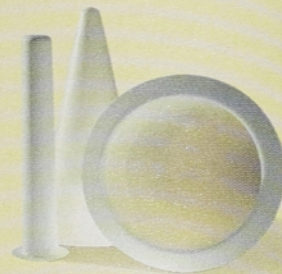
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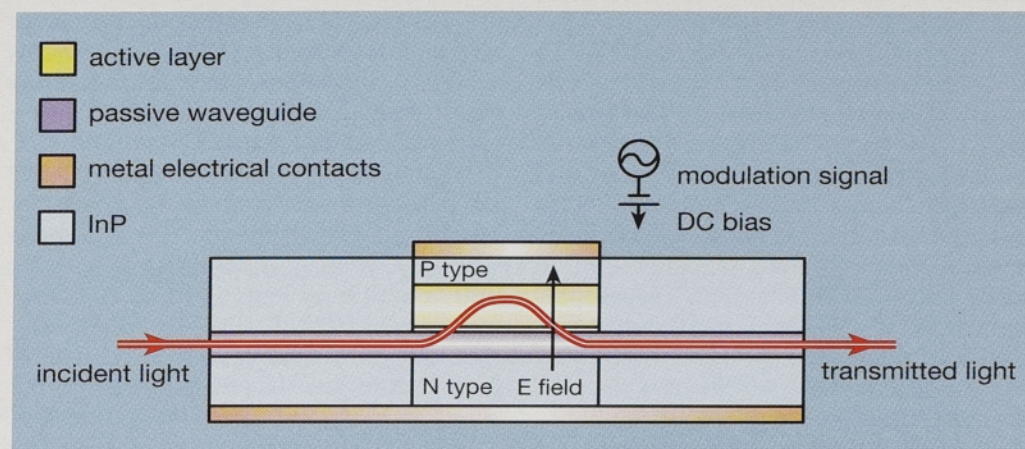
CyOptics is expanding its fabrication facilities to a total of 35 000 sq. ft to provide additional capacity for the manufacture of InP-based components such as lasers and modulators. Located at Yokneam in Israel, the company's new facilities will include an InP wafer fab for chip production, as well as optoelectronic packaging capabilities for 40 Gbit/s devices used in ultra-long haul transmission.

Since its inception in 1999, CyOptics has received a total of \$77 million in investments, which it has used to develop InP-based electroabsorption modulators and pulse generating lasers, and to expand its manufacturing capability. The company performs all InP manufacturing, including wafer growth, characterization and device packaging, in Israel.

"Expanding our manufacturing infrastructure will enable us to meet our customers' needs for real-world, high-volume manufacturing of 40 Gbit/s components," said Dror Motovilov, CyOptics' vice-president of operations. "First qualification devices from these facilities are expected in the third quarter of 2000, with full-scale manufacturing in 2002."

The InP advantage

CyOptics' pulse generating laser (PGL) can be used in RZ (return-to-zero) schemes for long-haul DWDM networks operating at 10 Gbit/s and above. RZ systems are likely to replace non-return-to-zero (NRZ) transmitters, which at low frequencies employ a directly modulated CW laser. At high data rates, these lasers



InP becomes opaque when an electric field is applied. This effect, known as electroabsorption, can be used to modulate light sources at very high frequencies.

are subject to chirp (frequency changes), limiting the distance the signal can travel. This is typically overcome for higher data rates and longer transmission distances by employing an external modulator, which acts as a shutter to the CW laser light.

In the case of high-speed RZ transmitters, the two functions – pulse generation and data modulation – are handled separately. A conventional RZ transmitter needs a high-power laser and two modulators, one to create a train of RZ pulses, and the second to modulate this train. These modulators are typically made from LiNbO₃.

In comparison, CyOptics' PGL is a compact InP component that directly generates a stream of modulated RZ pulses. This stream subsequently has information added to it with a modulator – effectively

eliminating the second modulator.

CyOptics' device is an InP electroabsorption modulator that operates at 40 Gbit/s. This component takes advantage of the electroabsorption effect in InP materials. As a reverse bias is applied, InP becomes opaque to light, and this can be used to modulate the light from a laser source at high frequency (see figure).

The company's InP electroabsorption modulator is much smaller than a conventional LiNbO₃ modulator, which requires a 5 inch package at this frequency. InP modulators are typically one sixth of this size, and operate at the much lower voltage of 3 V. CyOptics says that its PGLs and electroabsorption modulators may be hybrid or monolithically integrated, leading to a much smaller overall transmit component.

Optical companies receive first-round funding boost

Qusion Technologies, an optical component manufacturer founded late in 1999, has raised \$9.25 million in first-round venture capital funding from four major investment companies. The company says the financial injection will accelerate production of InP-based transceivers with a view to developing components for 40 Gbit/s systems.

Qusion is currently undergoing a major expansion of its 33 000 sq. ft manufacturing facilities in South Brunswick, NJ, which include a 4000 sq. ft class 1000

clean room and class 100 clean room space for photolithography. The company aims to integrate lasers, modulators and detectors onto a single chip, and expects to demonstrate fully integrated transceiver modules by the end of the year.

VSK Photonics

VSK Photonics, a start-up fiber-optic component company formed at the end of last year, has received first-round funding totaling \$18 million from Morgenthaler Ventures and Intel Capital. The

investment will provide VSK, which is located in Irvine, California, with further manufacturing resources to develop InP-based 40 Gbit/s optoelectronic components and modules.

At this early stage of its development VSK is understandably maintaining a low profile. While few details of its facilities are currently available, VSK will follow a vertically integrated approach, from epitaxial growth through to packaging, that will most likely include manufacturing of photodetectors, modulators and lasers.

OIF adopts more short reach interface standards

The Optical Internetworking Forum (OIF) is continuing its adoption of high bandwidth very short reach (VSR) interfaces. Two new 10 Gbit/s VSR interfaces were recently agreed with the aim of reducing the cost of the high bandwidth data links required in local environments such as central offices. As shown in the table below, VSR3 and VSR4 complement the two short distance link standards adopted recently (see *Compound Semiconductor* March 2001, p6).

The VSR3 standard (VSR OC-192 four-fiber interface based on parallel optics) employs four parallel channels at 2.5 Gbit/s and uses 850 nm VCSELs. VSR3 links with four fibers in each direc-

tion will use 8 of the 12 fibers in a multimode ribbon. Four-fiber solutions are also being specified in the ANSI Fibre Channel standard and Infiniband.

VSR4 (Serial shortwave VSR OC-192 interface for multimode fiber) is for 10 Gbit/s data links over 50 μ m multimode fiber at distances up to 85 m, or up to 300 m with high bandwidth (2 GHz.km) multimode fiber. VSR4 is a serial interface standard that describes the use of a single 850 nm VCSEL and PIN photodiode device, and is a similar interface to that under consideration by IEEE for 10 GbE, expected sometime this year (see *Compound Semiconductor* February 2001, p69).

10 Gbit/s very short reach (VSR) standards

Standard	Format	Wavelength	Fiber type	Distance
VSR1	12 channels @ 1.25 Gbit/s	850 nm	62.5 μ m core multimode ribbon	300 m
VSR2	1 channel @ 10 Gbit/s	1310 nm	Installed single mode	600 m
VSR3	4 channels @ 2.5 Gbit/s	850 nm	Single 12 fiber ribbon (4 in each direction, 4 dark)	300 m
VSR4	1 channel @ 10 Gbit/s	850 nm	50 μ m multimode fiber	85 or 300 m (high bandwidth fiber)

Agility showcases 10 mW tunable laser

Agility Communications has developed a prototype monolithic 10 mW tunable laser. Discussing the device at this year's Optical Fiber Conference, chief development engineer Greg Fish described a packaged monolithic laser capable of rapidly tuning to more than 90 ITU channels. This is the first such widely-tunable monolithic laser to graduate from laboratory curiosity to sampling device. Agility's existing commercial product, a sample-grating DBR tunable laser, offers 4 mW of output power.

Fabricated and alpha-tested at the company's manufacturing facility in Santa Barbara, California, Agility's device employs a monolithic architecture based on InP to integrate a DBR laser and electroabsorption modulator, which simplifies

automation by reducing the number of chips to be connected and packaged. The device operates over the entire C-band (1530–1565 nm) and is the first prototype of its kind.

"Under rigorous production testing in our manufacturing facilities, Agility can provide the data and results to substantiate the full capabilities of a monolithic 10 mW, widely-tunable laser," said president and CEO Ron Nelson. "Our first product supported the needs of the metro market, and with this new high-power capability Agility can now address the long-haul market. Because Agility can integrate components at the chip level, our all-monolithic architecture delivers high power, functionality, and can be manufactured at the lowest possible price."

Companies agree on module standards

Several companies are collaborating on multi-source agreements (MSAs) to set standards that will speed the insertion of the fiber-optic components used in data and telecommunications systems. Agilent and Mitel Semiconductor are developing four-channel parallel fiber-optic modules operating at 10 Gbit/s. The parallel optic module features four transmit and four receive channels in one package, with each channel operating at 1–2.5 Gbit/s, for an aggregate bandwidth of 4–10 Gbit/s in each direction.

This year the two companies will agree on a common package, and optical and electrical interfaces for modules employed in 10 Gbit/s very short reach (VSR) connections and those recommended by the industrial consortium InfiniBand. A 12 channel MSA was recently announced between Mitel, Agilent and W L Gore (*Compound Semiconductor* April 2001, p22). Mitel and Agilent expect that the design and manufacturing expertise developed for the 12 channel product will be applied to the new four-channel transceiver.

Agilent and Agere support 10 GbE

Agilent is also working with Lucent spin-off Agere to develop physical standards for 10 Gigabit Ethernet (GbE) fiber-optic transceivers. The MSA is the first to support the proposed IEEE 10 GbE standard, and specifies a uniform form-factor, size, connector type and number of electrical pin-outs. A third company, Tyco Electronics, will produce a 70 pin electrical connector that attaches the transceiver to a printed circuit board.

Specifically, the agreement covers four types of transceiver, including 850 and 1310 nm serial, 1310 nm wide (also known as coarse) WDM and 1550 nm serial (*Compound Semiconductor* February 2001, p69). A stipulation is that modules do not exceed 1.5 $\times$ 4.8 inches or be higher than 0.7 inches – dimensions that will allow high port densities on typical line cards. The companies expect to begin shipping the transceivers in 2001. According to senior program manager at Agere, Ed Cornejo, the new design will address the major 10 Gbit/s design challenges including heat dissipation, manufacturing issues, pin assignments and flexibility with regard to other technologies.

JDSU and Alcatel extend deal

JDS Uniphase is set to extend the supply of its 980 nm laser diode chips and pump stabilizers to Alcatel Optronics through to the year 2003. Alcatel will use the 980 nm chips, which are manufactured by the former SDL, in its pump modules which are used in submarine DWDM fiber networks.

The decision to extend the agreement follows the successful joint qualification

and production of a new laser diode, which when packaged in Alcatel's submarine-qualified pump module will provide 200 mW of output power and reliable operation for over 25 years. A range of pump wavelengths are available from 972–984 nm. In addition, the power consumption of the total system at 200 mW operation has been reduced by lowering the drive current to 450 mA.

Infineon develops new 1300 nm VCSELs

Infineon has developed 1300 nm VCSELs at its corporate research center in Munich, Germany. The new devices operate in CW mode with a power of 1 mW and 2 mA threshold current at room temperature, and are designed to replace edge-emitting lasers and provide a reliable low-cost source using either multimode or single-mode fiber. The company says bit-error-

free (BER $<10^{-11}$) transmission has been achieved up to 10 Gbit/s.

Leveraging production of existing 850 nm VCSELs, Infineon's long wavelength variant is grown by MBE on GaAs substrates and consists of an InGaAsN multi-quantum well active region. Laser action is achieved up to +80°C. Samples will be available in 2002.

Luminent expands its operations

Luminent, the fiber-optic component spin-off from network equipment manufacturer MRV Communications, has completed the integration of its recently acquired Asian subsidiaries, Fiber Optic Components Inc (FOCI) and Optronics International Corporation (OIC). The acquisition of OIC – now known as Luminent-Hsinchu Active Component Division – completes the company's goal of offering the full gamut of active components, including lasers, LEDs and transceivers for fiber-to-the-home, metro core and metro access markets (*Compound Semiconductor* Nov 2000, p32). FOCI, which manufactures passives components such as coarse WDM modules, fiber gratings and thin-film filters, will form Luminent's Passive Component Division and elevate the company to the ranks of the few manufacturers that combine active and passive technologies for single-mode fiber-optic networks.

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Irish start-up to develop VCSELs

The National Microelectronics Research Centre (Cork, Ireland) has spun-off a new company called FireComms to make resonant cavity LEDs (RCLEDs) and visible VCSELs for use in datacom and telecommunications applications. Leveraging eight years of intellectual property and expertise attained at the center, FireComms will initially produce prototype visible VCSELs and RCLEDs on GaAs substrates for use as sources for plastic

optical fiber links. Future plans for high-volume manufacturing are based on a fabless approach.

Plastic optical fiber links potentially offer a low-cost way to connect consumer products such as computers, audio visual equipment and central computer systems in automobiles over short distances with high bandwidth. FireComms hopes to access a large potential market for the visible sources required for such links,

which include 650 nm RCLEDs, and VCSELs at the longer wavelength of 670 nm. So far, plastic optical fiber links have demonstrated data transfer rates of 3 GHz over 100 m using special plastic fiber (see *Compound Semiconductor* August 2000, p65). Plastic optical fiber links could also become important to connect devices in future technologies for automotive, telecommunications consumer electronics manufacturers.

Alcatel breaks the 10 Tbit/s barrier

Alcatel has exceeded the 10 Tbit/s barrier, setting the record for transmission capacity over a single optical fiber. This data rate is the equivalent of 160 million phone calls per second or over one million ASDL Internet connections per second. In an-

other demonstration, the company transmitted 3 Tbit/s (300 channels $\times$ 10 Gbit/s) over a 7300 km span – a distance equivalent of Japan to Hawaii. The results were obtained at Alcatel's lab and presented during the recent OFC conference in Anaheim, California.

Alcatel employed its Teralight fiber to demonstrate the unidirectional transmission over 256 channels, each one modu-

lated at a rate of 40 Gbit/s, reaching a total throughput of 10.2 Tbit/s over a distance of 100 km. This is almost twice as much data as was transmitted in a demonstration by Alcatel last year (*Compound Semiconductor* Sep/Oct 2000, p43). Alcatel performed the error-free transmission using dual-stage hybrid Erbium/Raman amplifiers operating at 40 Gbit/s data rates with forward-error correction.



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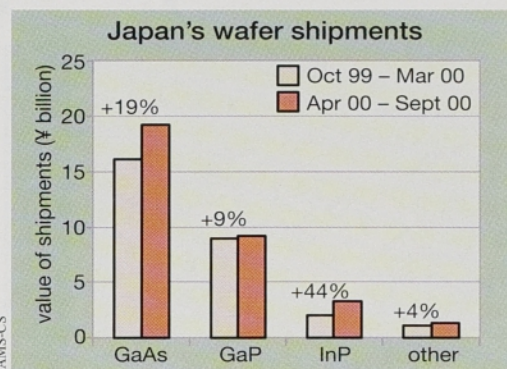


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Japanese wafer shipments hit ¥33.3 billion

Total shipments made by Japanese suppliers of compound semiconductor wafers reached ¥33.3 billion (\$274 million) in the six-month period from April to September 2000. The figures, which were supplied by the Japanese Manufacturers' Society of Compound Semiconductor Materials (JAMS-CS), indicate that total shipments increased by just over 17% compared with the previous six-month period. For the April–September 2000 period, 61% (¥20.3 billion) of wafer shipments were for domestic use, with the balance being exported from Japan. Total shipments for



Wafer shipments by Japanese suppliers, showing the fast growth in InP sales.

the whole of the fiscal year 1999 (ending in March 2000) were valued at ¥55 billion, up almost 22% from the previous year.

As shown in the graph, GaAs wafer shipments represent just under 58% of the market, and showed strong growth recently – reaching ¥19.3 billion between April and September 2000. GaP shipments grew slightly while InP shipments grew rapidly, driven by the demand from DWDM networks. In fact, reports indicate that InP wafer shipments reached ¥700 million in January of this year, and were close to ¥800 million in February.

Sharp builds new laser plant in Hiroshima

Sharp is to spend ¥18.7 billion (\$154 million) on a new factory that will make semiconductor lasers for use in CD and DVD players and in data storage units for personal computers. Construction of the 14 000 m² plant in Mihara, Hiroshima Prefecture, will begin in June, and production is due to start in September next year.

It will have an initial monthly output of 5 million units, and a maximum capacity of 14 million units per month. Sharp currently produces 1.4 million semicon-

ductor lasers per month at a plant in Nara Prefecture. The company also plans to invest an additional ¥12 billion by the end of 2005 to build a second factory on an adjacent site in Mihara.

Sharp is expanding its output despite a 30% fall, to ¥180–200, in the price of lasers for DVD players. The company aims for almost ¥60 billion in sales from its semiconductor laser division in the year ending 31 March 2001, and hopes to expand the figure to ¥100 billion by fiscal 2005.

Toyoda Gosei makes commercial blue laser

Toyoda Gosei, a supplier of nitride-based LEDs, is poised to join its rival Nichia as a commercial supplier of short-wavelength, bluish-purple laser diodes. Having developed a manufacturing technology for the laser, Toyoda Gosei plans to start sample shipments this fall. The device has a wavelength of 410 nm with a 3 mW output, and an estimated life of more than 5000 hours under continuous oscillation at room temperature.

The basic research for the GaN-based laser was carried out under the direction of Isamu Akasaki and Hiroshi Amano of Meijo University – and it was funded in part by the Japan Science and Technology Corporation (JST). The research, which took seven years and cost about ¥700 million (\$5.8 million), yielded several technological breakthroughs.

Toyoda Gosei developed a growth technique to improve the quality of the multi-quantum-well layers, included an optical waveguiding structure into the device, and developed a packaging technology that excels in heat radiation. The manufacturer has filed about fifty patent applications in connection with this GaN-based laser research.

Short-wavelength laser diodes are likely to be used as the light source in next-generation, high-capacity DVD players, and could also be used in applications such as laser printers and full-color projector-type laser displays.

Oki to produce more 10 Gbit/s components

Oki Electric Industry Company plans to spend ¥3–4 billion in fiscal 2001 (ending March 2002) to boost production of 10 Gbit/s components. The money will fund the expansion of the company's Tokyo production facility and increase output of modulator driver chips to 30 000 units a month – about 75% over current levels. It will also double production of laser diodes used in optical-fiber defect detection to 10 000 units per month by the summer.

Oki expects optical component sales to double to ¥30 billion in 2001. Although the US economic slowdown has hurt many components vendors, Oki believes that its devices are in high demand for use in undersea cables and other backbone infrastructure applications, and that the slowdown will have less effect on its own sales.

Matsushita enters the LED lighting business

Matsushita Electric Works is planning to begin selling lighting products based around white LEDs. The company will begin retail sales this year of lamps that use the energy-efficient and long-lasting light sources, and will supply component modules to other lighting manufacturers. It plans to offer 40 products by the summer, and to launch a similar number of new products next year.

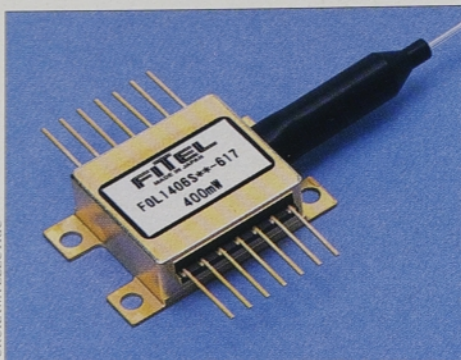
White LEDs now produce 15 lm/W, have a lifetime of 10 000 hours and cost about ¥65 each. If current technological trends continue then by 2003 white LEDs are expected to emit 40 lm/W, last 20 000 hours and cost less than ¥20 each. This product will therefore offer a very attractive alternative for users of incandescent and halogen lighting.

Sanyo creates a thin laser for DVD players

Sanyo Electric has developed a thin semiconductor laser for use in compact, lightweight DVD players and DVD-ROM drives. Compared to CD lasers, the optical sources used in DVD players require a higher operating current, which also creates more heat, so manufacturers must make the laser semiconductors in cylindrical form to maximize heat dissipation.

Sanyo's new unit produces light more efficiently, lowering the operating current, and it also has superior heat-radiating properties, eliminating the need for a cylindrical form. The new laser is 2.4 mm thick and weighs just 0.2 g (less than half the size and weight of cylindrical lasers). A Sanyo affiliate, which produces 800 000 cylindrical DVD lasers a month, will begin shifting production to thin lasers at year-end. By next spring, it plans to end production of cylindrical lasers and boost output of thin lasers to 1.5–2 million units per month.

Furukawa and Mitsui join forces to pump up the power



Fitel launches a 400 mW pump.

Furukawa Electric and Mitsui Chemicals have started joint development of a new, high-power 980 nm laser chip for use in EDFAs. The two companies plan to produce 980 nm modules, with an output of 250 mW, by fall 2001, and will increase the

module power to 350 mW by early 2002. This venture will use Furukawa's stabilization technology and Mitsui Chemicals' expertise to improve output power.

Furukawa Electric is already established as the leading supplier of 14xx nm pump lasers, used to pump both EDFAs and Raman amplifiers. The company claims a market share of nearly 70% for these products and has a production capacity of 100 000 modules per month at its plant in Chiba. At the recent Optical Fiber Communication conference (OFC), Fitel Technologies (Furukawa's US subsidiary) launched the company's newest 14xx nm product – a 400 mW module. This is claimed to be the highest power 14xx nm pump on the market, with samples available in June, and volume production scheduled for the end of this year.

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DWDM market to reach \$34.6 billion by 2009

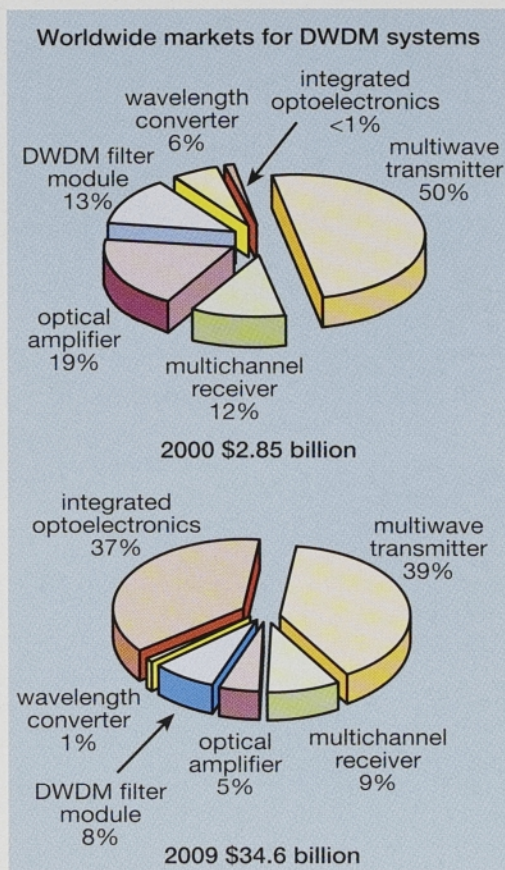
Fed by the continuing strong demand for bandwidth, the market for major components used in dense wavelength-division multiplexing (DWDM) systems and optical add/drop multiplexers will grow ten-fold to \$34.6 billion by 2009, up from \$2.85 billion last year. According to a study by ElectroniCast of San Mateo in California, more than half (54%) of these components – which include laser diodes, amplifiers and photodiodes for receivers – will be required for the North American market.

DWDM component technologies have advanced to the point that DWDM networks are now the clear economic winners in undersea cable and long-haul terrestrial networks. Technology advances and falling gigabit-kilometer prices also mean that WDM will increasingly be applied to shorter-distance links.

Optoelectronics set to dominate

The fastest-growing segment will be for integrated optoelectronic components, which include OEICs and photonic ASICs using hybrid integration schemes at first, followed by integration of active chips and passive waveguides. These will make up 37% of the overall market by 2009 (see figure).

Although the DWDM filter module is a key element of the high-capacity fiber



By 2009 the global market for DWDM components will exceed \$34 billion. The biggest gains will be made for transceivers and integrated optoelectronic components.

network, its cost per channel is moderate compared with the transmitter and receiver, according to ElectroniCast's president, Stephen Montgomery.

"While the per-channel cost of transmitter/receiver [T/R] pairs at a fixed wavelength will drop more rapidly than the filter cost, there will be a strong countering trend towards the deployment of higher-data-rate, more expensive T/Rs," said Montgomery. "The combined T/R and integrated optoelectronics share of the global DWDM component consumption was 62% in 2000. This will grow to 85% or a total value of \$29.4 billion in 2009."

In addition, the multiwavelength transmitter set, which can contain several lasers at different wavelengths, is an important element of DWDM systems. "The transmitter set and the DWDM filter module must provide the required number of wavelengths/channels, with the precise spacing between channels and very narrow optical width per channel," explained Montgomery. "Only extremely small amounts of drift are permitted during any operation. By contrast, the photodiodes in the receiver require less precise control."

DWDM Products Global Market Forecast is available from ElectroniCast. See "www.electronicast.com" for details.

High-brightness LED market is set to triple over next five years

No let-up is expected in the robust sales of high-brightness LEDs in the next five years, leading to a market exceeding \$3.4 billion in 2005. This is compared with sales of \$1.2 billion in 2000.

According to a report from Strategies Unlimited (Mountain View, CA), the worldwide market for high-brightness LEDs now accounts for 42% of the total LED market.

Behind these market gains have been the recent advances in InGaN-based blue, green and white LEDs, led by companies such as Nichia, Toyoda Gosei, Cree and Osram Opto Semiconductors.

High-brightness yellow, orange and red LEDs (made from AlInGaP, AlGaAs or InGaP) are available from various manu-

facturers, notably Agilent and LumiLeds, Osram Opto Semiconductors and Toshiba. Other major suppliers include Stanley Electric, Matsushita Electric, Sharp and Citizen Electronics.

In addition, the year 2000 saw the emergence of new suppliers such as AXT and Uniroyal Optoelectronics, along with a number of new Taiwanese start-ups. Established Taiwanese chip suppliers such as UEC and Epistar, which make AlInGaP-based devices, experienced double-digit growth.

Market penetration

Although high-brightness LEDs are penetrating all market sectors, large, full-color outdoor LED video displays and automo-

bile center high-mounted stop lamps have made significant inroads.

Interior LED lighting also features in more than half of European-made cars. These employ blue, green, white and amber high-brightness emitters for instrument panel illumination. Efficient LED traffic signals have also experienced dramatic market growth.

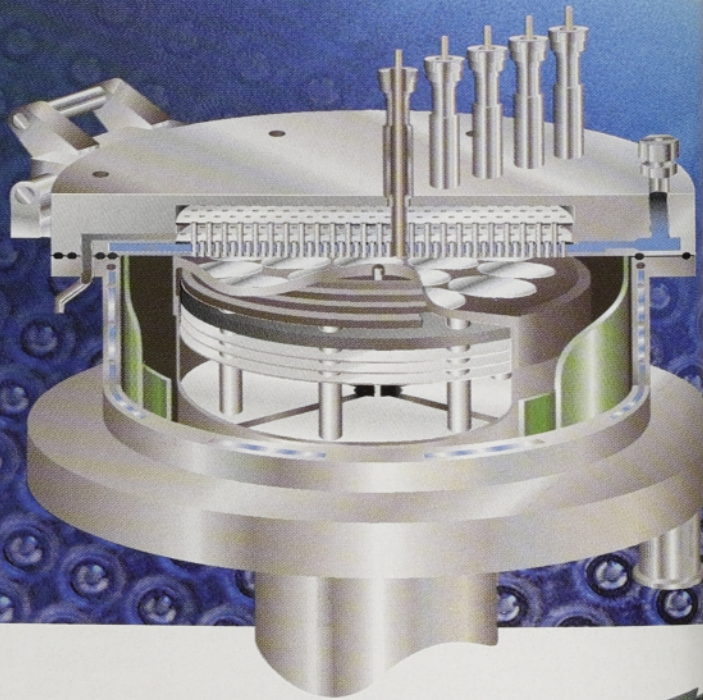
More recent applications include backlights for the small LCD displays used in mobile phones and PDAs. A niche market is also emerging for specialty lighting in retail and decorative applications.

High-Brightness LED Market Review and Forecast – 2001 is available from Strategies Unlimited. For more information see "www.strategies-u.com".

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Slower growth for handsets predicted in 2001

Gartner Dataquest (San Jose, CA) is projecting worldwide mobile phone sales in excess of 506.5 million units in 2001, a 23% increase on last year. However, the growth rate is slower than in 2000, said the company, when sales of mobile phones were up 38% over 1999.

"The rapid annual growth rates of the past several years concealed numerous operational and strategic weaknesses among handset manufacturers," said Bryan Prohm of Dataquest's Worldwide Telecommunications Group. "However, these deficiencies are now being fully exposed thanks to a more challenging business environment. Supply has finally surpassed demand, and although sales growth will continue, only those manufacturers with a strongly differentiated product offering will continue to thrive."

The market will continue to grow steadily through to 2005, when 740 million units will be sold worldwide – more

than a third (280 million units) to the Asia-Pacific and Japan region. Western Europe will retain its number two position with 207 million units.

"The market is in a curious position," said Dataquest's senior telecom analyst Peter Richardson. "High levels of stock carried over from last year are depressing new sales from manufacturers in the first

"Only those manufacturers with a strongly differentiated product offering will continue to thrive"

quarter, but sales in Europe and Asia-Pacific remain strong, underlining our belief that annual sales of more than 500 million units are still possible."

For more information contact Tom McCall at Gartner Dataquest (San Jose, CA). Tel. +1 408 468 8312; e-mail "tom.mccall@gartner.com".

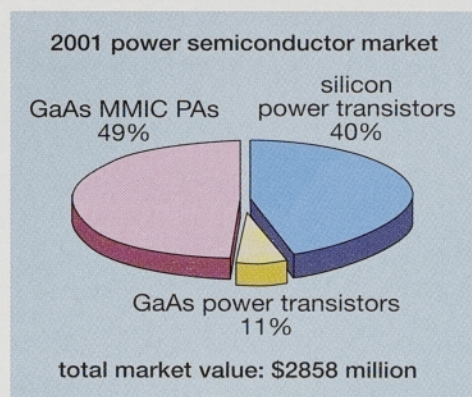
Power semiconductors maintain stronghold

Despite turbulent technology stock markets in the first quarter of the year, Allied Business Intelligence (Oyster Bay, NY) is predicting that the power semiconductor industry will remain vibrant. The market for power semiconductors – including silicon and GaAs power transistors, together with GaAs PA MMICs used in wireless applications – will increase from \$2.85 billion in 2001 to \$8.4 billion in 2006.

Although the narrow-band cellular infrastructure/handset arena represents the most financially attractive market, broadband wireless access and industrial, scientific and medical (ISM) band applications also merit attention.

Fueling the wireless data revolution will be the proliferation of 2.5G/3G systems and broadband wireless local loops, said ABI's Natalie Amiana. "The natural evolution from voice to data has inspired profound changes in the cellular handset and infrastructure market – crucial areas for GaAs transistors, MMICs, power modules and silicon power transistors," she said.

Amiana predicts that 3G will lead to increased component integration as tier-one manufacturers slash product life cycles, and also because new handset manufacturers generally lack RF design experience. "These changes will renew



In the next five years, GaAs MMICs will dominate the power device market – mainly for use as power amplifiers in cell phones.

the popularity of power modules, and force component suppliers to adopt alternative strategies," she said.

Emerging applications such as LMDS, WLANs and MMDS will also bring new life to the power IC and transistor market. "This will shift the emphasis away from cellular/PCS/3G, and reward companies that have a broader focus," said Amiana.

Wireless Power Devices: Transistors, ICs and Power Modules is available from ABI – see "www.alliedworld.com".

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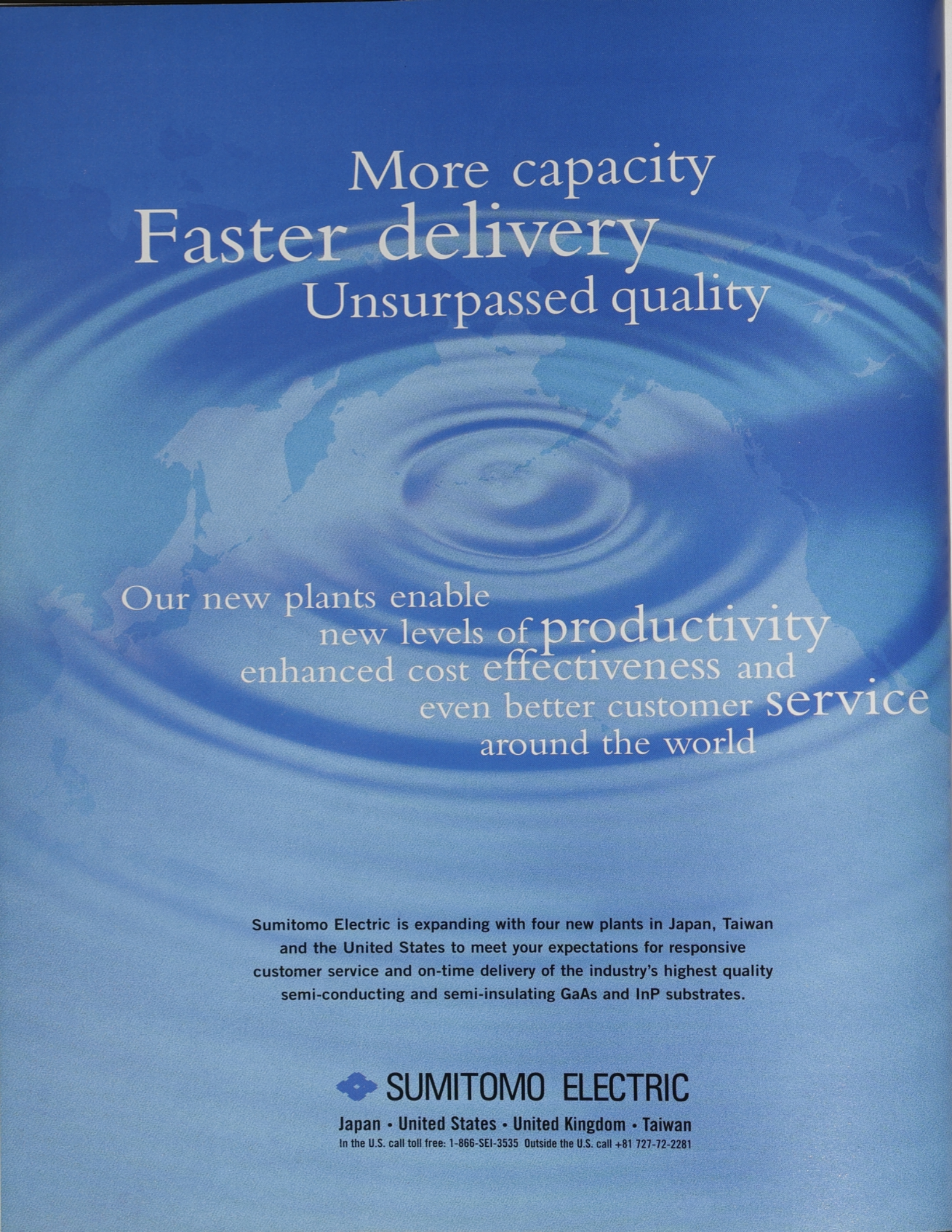
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IQE supplies InP and metamorphic wafers

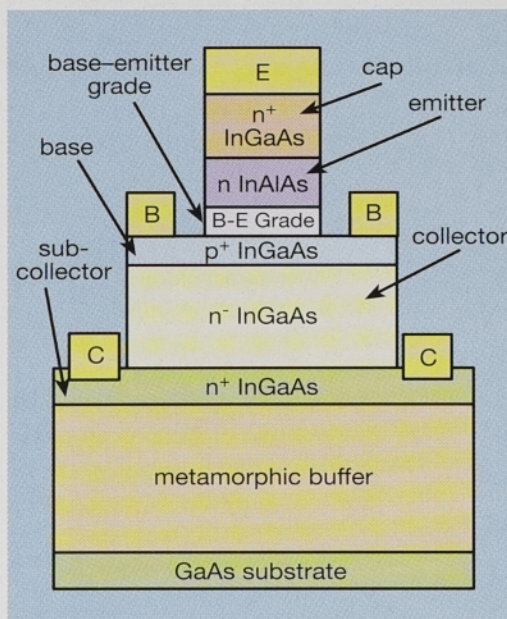
IQE are to begin supplying production quantities of a range of InP HEMT epiwafers, as well as metamorphic HEMT and HBT epiwafers on GaAs substrates, designed for fiber optic and wireless communications applications.

"It is well known that InP-based electronic structures provide significant performance advantages over today's GaAs-based structures, and that the high-volume commercialization of such devices is imminent," explains IQE's chief technology officer, Tom Hierl. "The metamorphic approach represents an attractive alternative to InP-based electronics and is potentially the lowest cost solution to requirements for next generation applications."

InP HBT wafers

Hierl notes that the company's Be-doped InP HBTs have demonstrated f_t and f_{max} values of over 210 and 300 GHz, respectively, in compositionally-graded structures doped at a level of $4 \times 10^{19}/\text{cm}^3$ in the base region. In addition, a high breakdown voltage of 6 V has been achieved at a current density J_c of $1.1 \text{ A}/\text{cm}^2$. The company's commercial partners have obtained f_t and f_{max} values of over 150 and 250 GHz on less complicated DHBT wafer designs with the same base doping.

"Although IQE offers both MBE and



IQE's metamorphic HBT epiwafer structure employs a buffer layer to accommodate lattice misfit strain between the GaAs substrate and InGaAs sub-collector region.

MOCVD growth technologies, we have found that MBE offers a decided advantage over MOCVD for obtaining high base doping levels in InP HBT structures," says Hierl. "Our customers can choose between beryllium and carbon base doping. We have provided a number

of structures which are currently undergoing testing; these feature base carbon doping levels up to $8 \times 10^{19}/\text{cm}^3$."

Metamorphic HEMTs and HBTs

Metamorphic HEMT epiwafers employ a buffer layer between the GaAs substrate and the active region to accommodate the difference in lattice constants. According to Hierl, GaAs substrates are less expensive, mechanically stronger, of higher quality and available in larger diameters than InP. GaAs substrates also benefit from more mature backside processing.

"The metamorphic approach enables the production of a wider range of epitaxial structures due to the flexibility of designing the buffer layer for a range of active region lattice constants," says Hierl. "As a result, metamorphic HEMTs that operate at higher frequencies than a GaAs PHEMT and at higher power densities than InP HEMTs can be designed. The metamorphic approach also offers a GaAs HEMT solution to those customers using 6 inch diameter processing equipment."

IQE is also developing metamorphic HBTs. The structure consists of a single heterojunction HBT with $1 \times 10^{19}/\text{cm}^3$ p-type doping in the InGaAs base (see figure). This device has achieved a current gain of 320, compared with 360 on structures grown lattice-matched to InP.

JMAR buys XRL stepper supplier SAL

JMAR Technologies (San Diego, CA) is to acquire Semiconductor Advanced Lithography (SAL), a supplier of X-ray lithography stepper systems based in South Burlington, Vermont. JMAR manufactures a collimated laser plasma source that directs 25 W X-rays onto a mask/wafer target. Known as the picosecond X-ray light source (PXS), this short wavelength (1 nm) beam can be used in X-ray lithography (XRL) steppers to directly write patterns with line-widths smaller than $0.13 \mu\text{m}$, making it suitable for high-frequency GaAs circuits.

In comparison to the other systems available for high-frequency IC line definition – including deep UV and direct-write electron beam lithography proces-

ses – XRL requires relatively inexpensive optics. It also offers the potential for high throughput and is scalable to sub-100 nm features sizes. JMAR expects a JMAR/SAL lithography unit to be ready for GaAs manufacturers before the end of 2002, with a price tag between \$6 and \$10 million depending on configuration and performance.

"Before the advent of JMAR's patented highly-efficient laser plasma X-ray source, XRL had failed to gain market acceptance due to a lack of adequate or acceptable X-ray source performance characteristics," said John Martinez, JMAR's chairman and CEO. "We believe that JMAR's PXS technology successfully overcomes those shortcomings."

EpiWorks raises \$13.5 M in financing

EpiWorks, a manufacturer of compound semiconductor epiwafers based in Champaign-Urbana, IL, has received \$13.5 million in financing from leading investors, including CIBC World Markets. The company raised \$8.5 million in working capital by offering series C preferred stocks.

EpiWorks also secured over \$5 million in debt financing from other sources to expand its new production facility and equipment set. Founded in 1997, the company employs low-pressure multi-wafer MOCVD systems capable of volume production of 50, 100 and 150 mm epitaxial wafers for optoelectronics applications.

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MATERIALS & EQUIPMENT

Unaxis opens R&D facility in Florida

Unaxis Semiconductors has opened a 43 000 sq. ft R&D facility, including a 15 000 sq. ft class 100 laboratory, located at St Petersburg, FL. Unaxis manufactures etching equipment for compound semiconductor processing, photomask fabrication and other applications and is a subsidiary of Swiss-based Unaxis AG.

Novalux orders suite of Accent systems

Accent Optical Technologies (Bend, OR) has shipped a complete suite of process control systems to laser manufacturer Novalux (Sunnyvale, CA). These systems will be employed in Novalux's recently opened class 10 clean room, which is used to process 4 inch GaAs wafers. According to president and CEO Bruce Rhine, the company is ramping up production by 400% over the next six months to keep up with a significant rise in customer orders.

Nimtec changes to Nikko Materials

Nimtec has changed its name to Nikko Materials. Based in Chandler, AZ, Nikko Materials is a supplier of InP and CdTe wafers for a range of compound semiconductor applications, and manufactures high-purity metals, sputtering targets and anodes. The company says the change reflects the wish of parent company Japan Energy Corporation to bring its subsidiaries under the Nikko Materials banner.

Opto Tech goes for Tegal etch systems

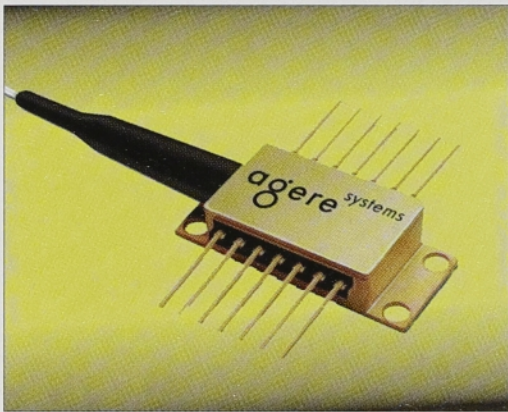
Tegal has received orders for 901e and 903e plasma etch systems from Opto Tech, a manufacturer of MOSFETs, LEDs and other optoelectronic devices. The 901e system will be used to etch polysilicon devices, and the 903e used for oxide etching in silicon and compound semiconductors. The etchers are scheduled for installation in May at Opto Tech's fab in Taiwan.

FIBER PRODUCTS

Agere unveils new L-band Raman pump

Breinigsville, PA. Agere Systems (formerly Lucent Microelectronics Group) has introduced an L-band Raman pump module designed for use with EDFAs to improve signal performance and lengthen transmission distances between repeaters.

At the heart of the module are InP-based 14xx nm pump lasers, which provide the high optical power needed to achieve signal amplification within the transmission fiber.

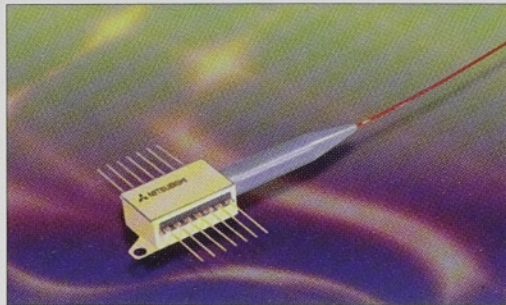


Samples in both C- and L-band format will be available in the second quarter of 2001, with production quantities in the third quarter. www.agere.com

Mitsubishi releases DFBs, transponder

Sunnyvale, CA. Mitsubishi Electric has rolled out three new DFB laser diode modules and a discrete component for 2.5 Gbit/s operation in long-haul and MAN applications. The FU-672PDF and FU-675PDF offer CW output power of 15 mW for single-channel and 24 mW for dual-channel versions.

The FU-645SDF is an uncooled, pulsed 1550 nm DFB-LD module that supplies 6 mW output power. Its mini dual in-line package reduces size requirements by 75% compared with the standard butterfly package. Finally, the ML7XX16 is an uncooled DFB-LD



discrete component for up to 11 GHz operation with a sidemode suppression ratio of 45 dB.

10 Gbit/s transponders

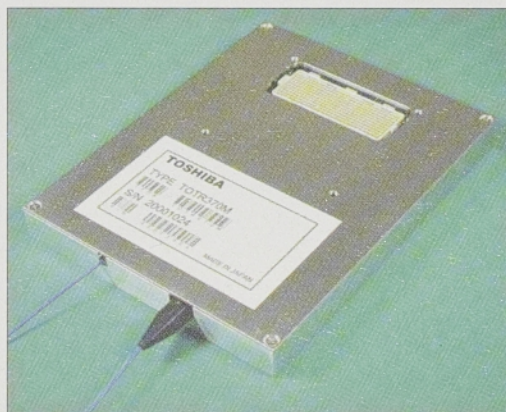
Designed for transmission distances between 0.6 and 12 km, Mitsubishi's MF-10KMXF uncooled transponder family offers a maximum of 0 dBm power output and -12 dBm sensitivity at 1310 nm. The MF-10KMXA and MF-10KMXG cooled transponders target 40 km spans and feature +2 dBm power output and -14 dBm sensitivity at the 1550 nm wavelength.

For distances up to 80 km, the MF-10KMXH offers +2 dBm power output and -26 dBm sensitivity at 1550 nm. All transponders are scheduled for volume production in the second quarter of the year.

www.mitsubishichips.com

10 Gbit/s transponder suits SDH/SONET

Irvine, CA. Toshiba's TOTR370M is a 10 Gbit/s transponder module designed for intermediate SONET and SDH applications. The transponder features a 1550 nm electroabsorption modulated laser (EML) transmitter and PIN



photodiode receiver, and 16-channel mux and demux (622 Mbit/s clock rate) interfaces are also included.

The transponder module operates at case temperatures between -5 °C and 70 °C in a thin profile package measuring 4.5 × 3.5 × 0.53 inches (114 × 88.7 × 13.4 mm). Mass production is slated for the third quarter of the year. www.chips.toshiba.com

Vitesse launches new cross-point switches

Camarillo, CA. Vitesse has expanded its cross-point switch family with two new switches operating at 3.2 Gbit/s suited to SONET/SDH, DWDM, SAN switches, HDTV/SDTV serial routing and ATE.

The VSC837 and VSC838 are 68 × 68 and 36 × 37 cross-point switches, featuring typical power dissipation of 6 W and 11 W respectively.



Scheduled for production later this year, the company has also introduced a 16-bit mux/demux chipset for operation at 11.5–12.5 Gbit/s. Integrating the clock recovery and generation functions, the VSC8185 (mux) and VSC8184 (demux) operate from a +3.3 V supply and consume 3.5 W of power.

www.vitesse.com

Anadigics expands its OC-192 portfolio

Warren, NJ. Anadigics' new ATA7602 transimpedance amplifier is the second in a planned series of five HBTs designed to service SONET OC-192 (10 Gbit/s) and DWDM fiber networks.

Nature tolerates poor survival rates.



A female marine turtle will typically lay 100 eggs.

Of these, approximately 50 will hatch, 2 will survive and only 1 will live longer than a year.

A photograph of two sea turtles resting on a sandy beach. The turtles are in the lower-left quadrant of the frame, facing right. The background shows a calm ocean and a distant shoreline under a clear sky. The overall tone is serene but carries a message of competition and survival.

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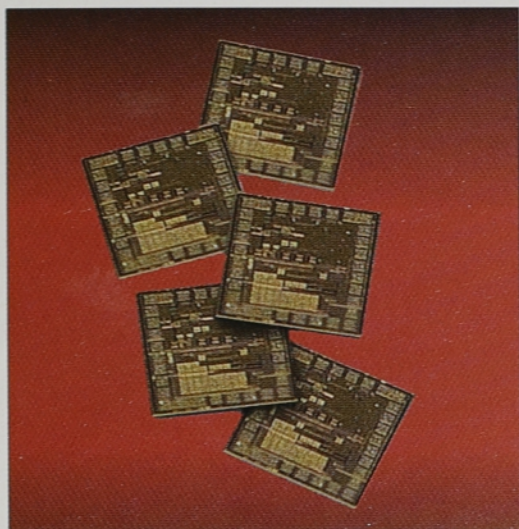
Operating from a 5.2 V DC supply, the device delivers a group delay of less than 50 ps and features -19 dBm sensitivity.

The ATA7602 is manufactured using the company's InGaP HBT technology on 6 inch wafers, and samples will be available in May.

www.anadigics.com

Physical-layer chips shake up the market

Ottawa, Canada. Quake Technologies, a new fabless semiconductor start-up, is sampling two optical networking physical-layer chips which are expected



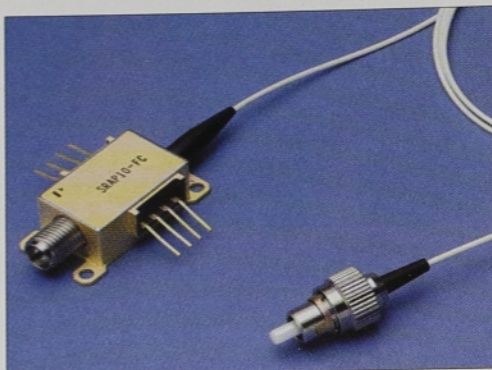
to be in production by the end of the year. The QT2010 is a 10 Gbit/s serializer-deserializer transceiver designed to deliver 9.953–10.3 Gbit/s for Ethernet and SONET/SDH applications. The device consumes 2.2 W of power from a single 3.3 V supply, and is available in a compact plastic ball grid array package.

Quake has also introduced the QT1090, an integrated transimpedance-limiting amplifier designed for fiber-optic LAN, MAN and WAN applications at data rates of 9.953–10.7 Gbit/s.

www.quaketech.com

PerkinElmer adds to its range of receivers

Sunnyvale, CA. PerkinElmer has introduced new 2.5 Gbit/s (SRNBA2.5 and SRNBP2.5) and 10 Gbit/s (SRAA10 and SRAP10) receiver modules for long,



intermediate or short-range networking applications. The 10 Gbit/s photodiode receiver includes a low-noise GaAs HBT TIA and is available with a single polarity power supply and eight-pin butterfly connector output.

The company's 1300 and 1550 nm InGaAs photodiode (PIN or APD) receiver is also available in a smaller mini-DIL package. This device offers a bandwidth of 2 GHz and sensitivity of -34 dBm (APD-based receiver). A 3.3 V power supply is required for the integrated TIA.

www.perkinelmer.com

NEC releases DFB lasers for DWDM

Santa Clara, CA. NEC's new offerings include a series of DFB lasers with integrated modulators for DWDM applications. Developed for C- and L-band operation, the NZ8560LJ is a 10 Gbit/s source for 40 km transmission, while the NX8564LE and NX8565LE are designed for 360 and 600 km spans. In addition, three new InGaAsP MQW DFB lasers with wavelength monitors are available for use under CW operation at 1550 nm. The NX8563LB and NX8562LB are 10 mW and 20 mW versions operating at 2.5 Gbit/s, while the NX8570SA offers 20 mW and features an on-board cooler, isolator and thermistor, in addition to an integrated wavelength locker.

In addition, a new 2.5 Gbit/s APD detector (NR4500) for operation at 1310 and 1550 nm is augmented by two new 1480 nm pumps. The 120 mW NX7461 and 150 mW NX7462LE pump lasers consume just 25 and 50 mA respectively, and are housed in 14-pin butterfly packages.

www.cel.com

New optical receivers have all bases covered

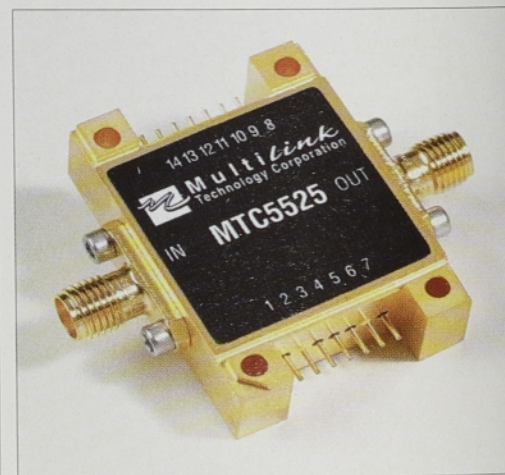
Ericsson Microelectronics' new optical receiver modules are designed for DWDM and single-channel metro and long-haul applications. Operating across the 1300–1600 nm range, the company's butterfly-packed modules consist of a PIN photodetector and low-noise TIA, and offer a sensitivity of -20 dBm for a 8 GHz bandwidth.

Ericsson's new OC-48 (2.5 Gbit/s) mini-DIL packaged receiver module is designed to reduce board space for applications up to 3 Gbit/s in the 1300–1600 nm range. The eight-pin package connects to singlemode fiber and offers a sensitivity of -33 dBm for APD versions and -23 dBm for PIN types. Low power consumption (0.2 W) is obtained by using SiGe TIAs, which are integrated into a module that operates from either 3.3 or 5 V power supplies. Samples of all modules are expected by the third quarter.

www.ericsson.com/microelectronics

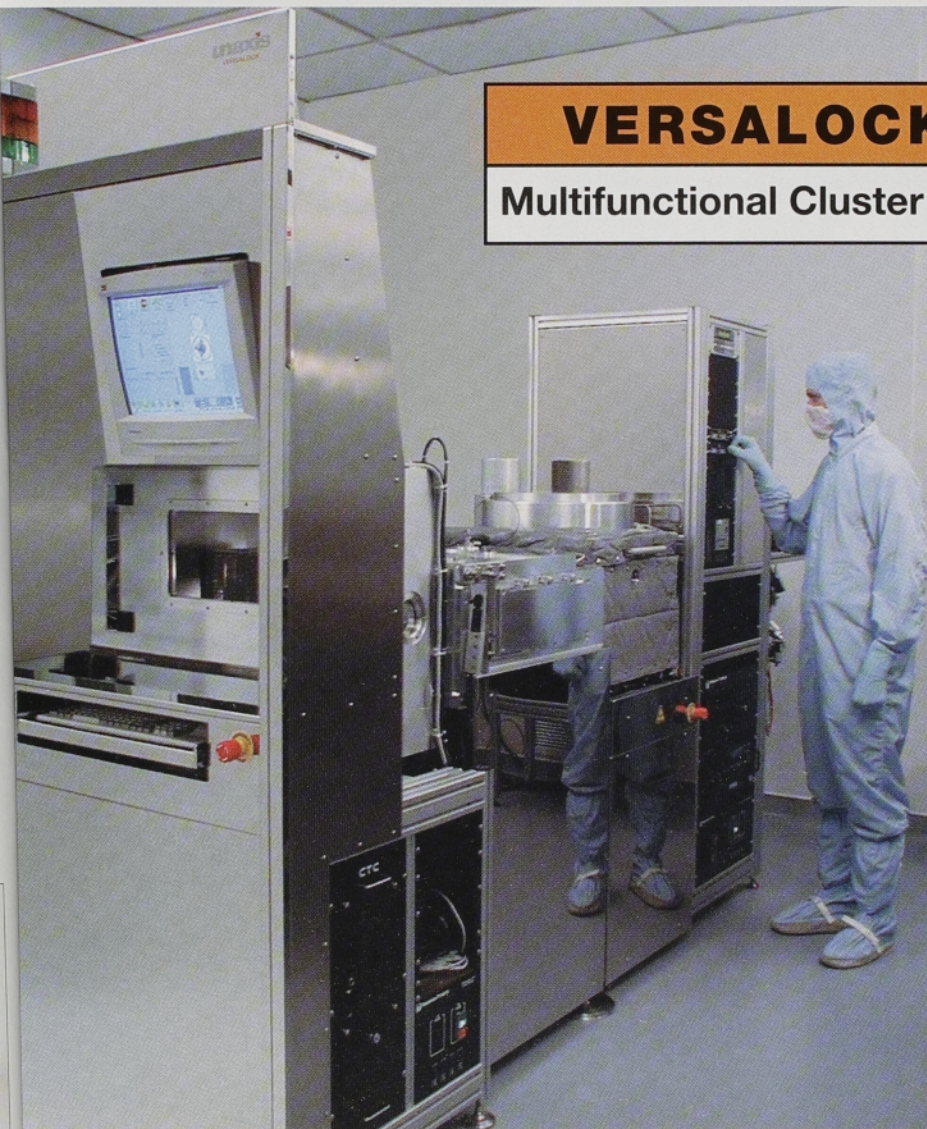
Multilink ships MCM modulator driver

Somerset, NJ. Multilink Technology's MTC5525 limiting modulator driver is a GaAs multi-chip module designed to connect to LiNbO₃ modulators in long-



haul SONET/SDH and DWDM transmission systems. The MTC5525 features a high-sensitivity input limiter that operates at up to 11 Gbit/s with low jitter. The MTC5525 is designed to match the company's MTC1233 SiGe

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Corning ships fiber component suite

Corning, NY. Corning Lasertron has introduced a range of fiber-optic components. The QLM915 is a 10 Gbit/s electro-absorption modulator (EAM) which provides a lower dispersion than directly modulated DFB lasers – over 80 km, the dispersion penalty is limited to 2 dB in singlemode fiber.

Corning now also offers the PureGain 5000R 750 mW and 1 W Raman modules for 10 Gbit/s transmission, in both C- and L-band formats. These are driven by the company's newly released Optilock VR pump lasers, which offer 250 mW for 1400–1500 nm wavelengths.

Raman amplifiers provide optical pumping in a window across the C- and L-bands, which means that standard optical channel monitors at 1480 or 1510 nm cannot be used. Corning's QLM6S891 is a DFB-based transceiver that supervises channels out to 1630 nm.

Corning has also released a telecom receiver (QR192) that features 18 GHz of bandwidth and a 50% improvement in frequency response flatness (± 1.5 dB) over its previous product.

www.lasertroninc.com

WIRELESS PRODUCTS

Conexant offers new base-station PAs

Newport Beach, CA. Conexant's new CX42053 and CX42054 downconverter and receiver front-ends and CX6500x series of three linear PA drivers are designed for cellular/PCS base-station receivers and other wireless transceivers operating at up to 2.5 GHz.

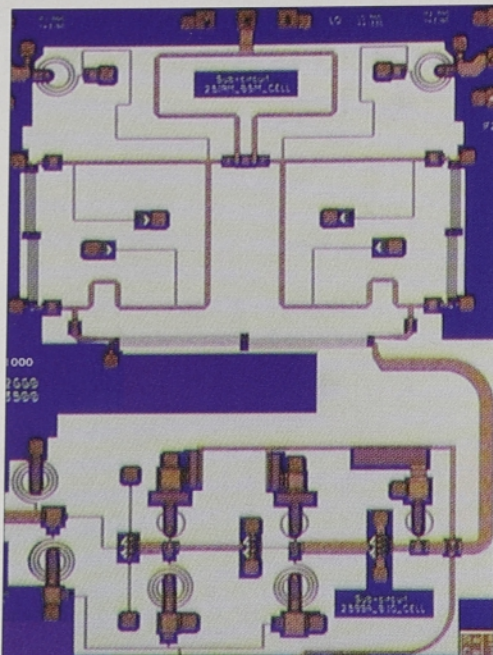
Operating in the 700–1000 MHz and 1700–2500 MHz ranges respectively, the CX42053 and CX42054 GaAs MESFET downconverter/receiver ICs may be used in single- or dual-channel configuration, with each channel featuring an LNA, double-balanced mixer and a local oscillator buffer amplifier.

The new PAs employ Conexant's GaAs HBT technology, and feature 1 dB performances of 23–25 dBm at a range of frequencies covering 200–2500 MHz.

www.conexant.com

Mimix Broadband unveils two-stage PA

Webster, TX. Mimix Broadband now supplies a two-stage PA for mm-wave point-to-point, LMDS, VSAT and



SATCOM applications. Leveraging an externally supplied 0.15 μ m GaAs PHEMT process, the XP1000 features an IP3 output of +36 dBm across the 17–24 GHz band. The small signal gain figure is 18 dB.

www.mimixbroadband.com

RFMD LNA/mixer reduces board space

Greensboro, NC. RF Micro Devices' new dual-band LNA/mixer is designed to reduce component count in the receive function of TDMA handsets. The new RF2475 reduces the number of VCOs, while the LO output buffers eliminate the need for external drivers for the LO signal feeding the transmit path.

The company's GaAs HBT device includes two LNAs and associated down-converting mixers, a frequency doubler and dual transmit LO output buffers. The

RF2475 maintains 25 dB cascaded gain and 2.2 dB cascaded noise figure for the cellular band (26 dB cascaded gain and 2.8 dB noise figure for the PCS band).

www.rfmd.com

Alpha integrates wireless switch/filter

Woburn, MA. Alpha Industries has introduced an integrated switch and filter for wireless handsets. The switch/filter combines multiple functions in a single module, and is based on the company's Alpha Integration Platform (aiIPTM), a technique for the design, simulation, packaging and testing of RF modules.

"By integrating passive and filter functions into a single module, Alpha is providing simplified, 'black box' functionality that enables enhanced performance from a smaller footprint," said Alpha's Dave Fryklund.

Alpha has also introduced a family of four GaAs HBT amplifiers that exhibit low noise and high linearity over a wide range of frequencies. The GBH1XX series is designed for cellular devices and PCS base stations, cable systems and direct-to-home satellite systems. The family supports wireless LAN systems – including Bluetooth, WI-FI, 802.11b, HomeRF, HiperLAN2 and 802.11a.

Each amplifier can be cascaded at 50 Ω , and four bandwidths are available, the widest being 8 GHz from the GBH112 device, which features a P1dB value of



12.5 dBm and IP3 of 25 dBm at 2 GHz. The other three devices offer bandwidths covering the DC–6 GHz (GBH114), DC–4 GHz (GBH120) and DC–3 GHz (GBH121) ranges. The GBH114 device supplies 15 dB of gain, while the GBH120 and GBH 121 offer 18 and 22 dB of small signal gain, respectively.

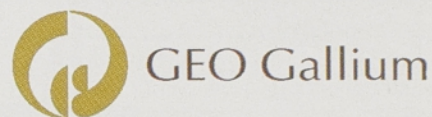
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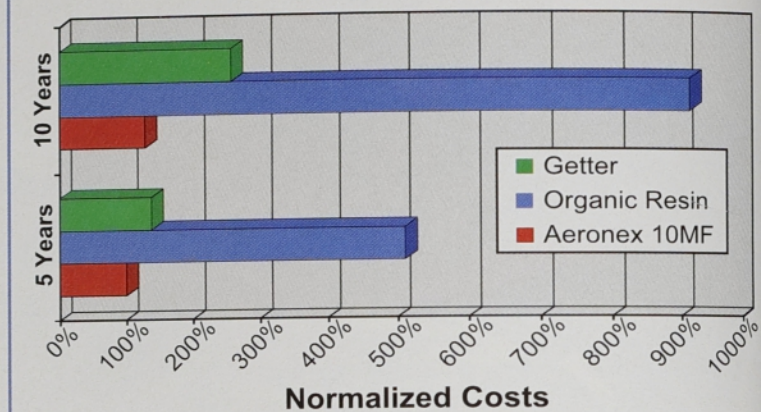
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The revolutionary design delivers the lowest cost of ownership. Starting with a lower ASP, GateKeeper purifiers provide continuous savings. Competitive purifiers become a hazardous waste once spent, generating high costs in time, money, and liability. GateKeeper purifiers are factory regenerable while Infinity Gas

Purification Systems are in-situ regenerable. All related disposal costs are eliminated. Regenerating Aeronex purifiers is simple and a fraction of the cost of a new replacement product.

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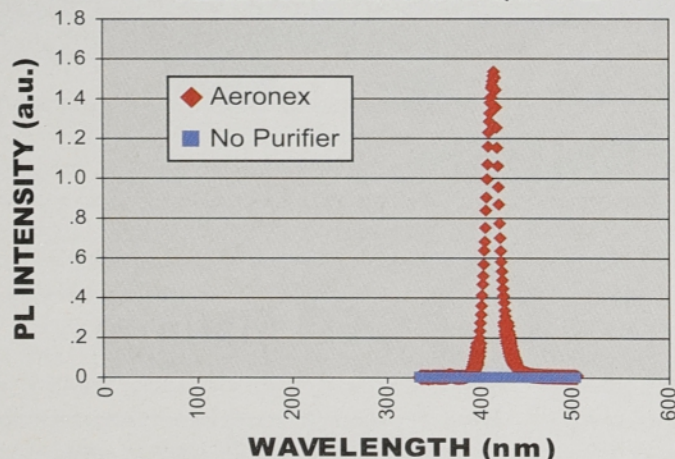
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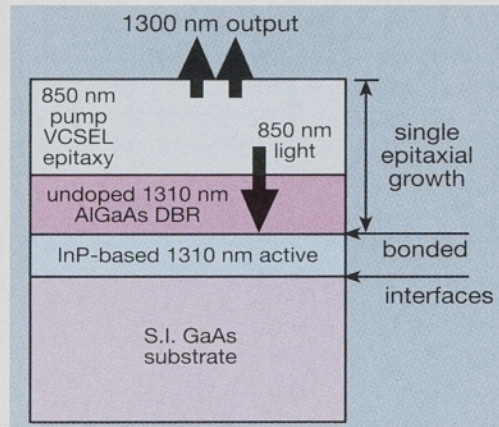


From report *Purification of MOCVD Sources with Aeronex Purifiers* by Prof. Steven Denbaars and Prof. Jim Speck, Materials Dept., UCSB

High temperature 1300 nm VCSELs arrive

Long wavelength VCSELs have yet to provide substantial CW output power above 70°C, which limits their commercial use in uncooled packages. This problem is addressed in two papers appearing in *Photonics Technology Letters* (2000, **12**(12), p1595 and p1707). The first paper by V Jayaraman and co-workers ("Gore Photonics") describes 1310 nm VCSELs that provide 0.5 mW CW operation up to the commercially important 85°C operating temperature, and continue in CW mode up to 115°C.

The device combines three epitaxial growth structures and a double wafer bonding diffusion process. The top 850 nm VCSEL is processed with two top contacts and emits downward into



A double bonded diffusion process and three epitaxial growths are used to integrate an 850 nm VCSEL pump with a quaternary InP 1310 nm active region.

the 1310 nm VCSEL through a 1310 nm undoped AlGaAs DBR (see figure). The InP-based 1310 nm active device re-emits back through the 850 nm VCSEL.

In the second paper, J Geske from UCSB and co-authors from Gore demonstrate transmission measurements from 1300 nm VCSELs using the structure described above. Error-free operation of 2.5 Gbit/s is achieved for a distance of 50 km. The device operated in CW single transverse mode at 1332 nm and featured a side mode suppression ratio of 55 dB. BER measurements showed that the transmission distance was attenuation-limited and that it suffered a 0.1 dB per penalty for reflection feedback of -25 dB at 5 m and -27 dB at 5.5 km.

Hole etching forms single mode devices

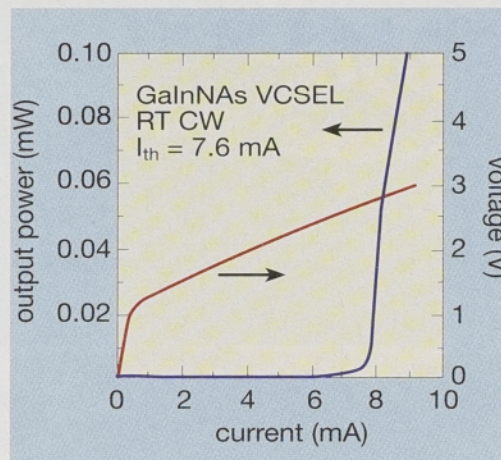
There are currently several different methods being investigated for reducing the cost of data communication lasers. Among these is the etching of DBR lasers to form single mode devices, which is achieved without the need for expensive regrowth techniques.

The approach taken by L Sargent and colleagues (Bristol University, UK) has been to etch a two-dimensional lattice of holes, around 50 µm long, on either side of a laser waveguide towards the back facet. This relatively simple process improves wave-guiding and produces a mode-hop-free, single longitudinal mode device capable of room temperature operation at 10 Gbit/s.

The holes are etched by post-processing with focused ion beams into a 1300 nm InGaAsP/InP ridge-waveguide laser. The pitch is tuned to the device wavelength and uses a diameter-to-pitch ratio of 0.33. No expensive regrowth is required.

Typically, an SMSR greater than 25 dB is observed, and open eyes are obtained at 10 Gbit/s with an extinction ratio of 6.5 dB, making the device suitable as a high-speed communications source. The work was first described in *Electronics Letters* 2000, **36**(24) on page 2014.

Growth on GaAs boosts 1300 nm VCSELs



The CW light output-current and voltage-current characteristics of Ricoh's GaAs-based 1300 nm VCSEL.

VCSELs operating at 1300 nm are key to high capacity optical communication

systems. Although GaAs-based 850 nm VCSELs have already been employed for these applications, longer wavelength devices have not been commercialized on a large scale. Current InP-based long wavelength lasers suffer from poor electron confinement and difficulty in forming highly reflective distributed Bragg reflectors. The GaInNaS/GaAs material system offers a potential solution to these problems.

This paper, from S Sato *et al.* of Ricoh and the Tokyo Institute of Technology (*Electronics Letters* 2000, **36**(24), p2018), reports on the electrically-pumped CW operation of GaInNaS/GaAs VCSELs at 1262 nm. For this device, the threshold current and voltage under CW operation were 7.6 mA and 2.8 V, respectively (see figure). The output power exceeds 0.1 mW and the slope efficiency is 0.1 W/A.

Blue emitter provides alternative to InGaN

The nitride semiconductor group at Nottingham University in the UK has recently demonstrated strong blue luminescence at room temperature from arsenic doped GaN films. The films, which may constitute a viable alternative to InGaN

as the basis for light-emitting nitride devices, were found to produce a strong blue luminescence at ~2.6 eV (462 nm).

The films were grown on sapphire at 800°C by plasma-assisted MBE, and the resulting intensity and wavelength of emission depended on the As₂ flux. The authors, A J Winsor *et al.*, described their work on page 2506 of *Applied Physics Letters* 2000, **77**.



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Graded base doping aids InGaAsN HBTs

Improvements in the material quality of InGaAsN has motivated the development of HBTs for low power electronic applications. InGaAsN is a low band-gap material ($E_G = 1.2$ eV) that can be used as the base layer to achieve greater efficiency at lower bias conditions.

In work first discussed this year in

Electronic Letters 37 on p198, C Monier *et al.* from Sandia National Laboratories (Albuquerque, NM) demonstrate the enhanced performance of *pnp* AlGaAs/InGaAsN single HBTs by employing a graded base doping to aid hole transport across the base.

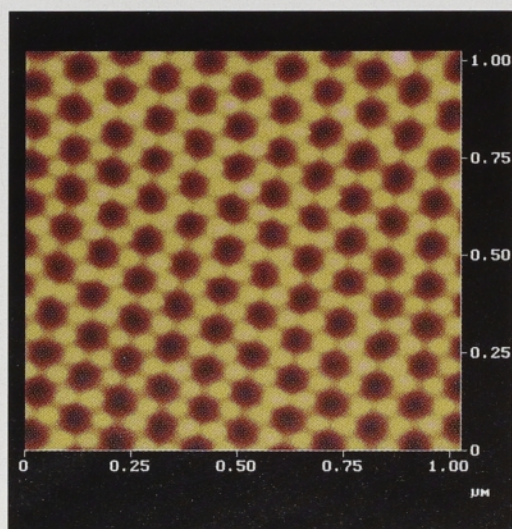
The band alignment is especially suitable for *pnp* HBTs with a change in conduction band energy (ΔE_C) of 0.5 eV that suppresses electron back injection, while an $\Delta E_V \sim 0.15$ eV facilitates hole injection

into the base. The introduction of the quasi-electric field in the base not only improves the base transport factor to produce a better current gain ($\beta > 60$) compared to a device with a uniform base doping, but reduces the base transit time to allow a cut-off frequency of $f_T > 15$ GHz.

The turn-on voltage is 0.29 V lower than that of *pnp* AlGaAs/GaAs HBTs, which indicates the potential of InGaAsN HBTs for reducing power dissipation in GaAs-based transistors.

Quantum dots with near-infrared output

Describing work undertaken at the University of Nebraska, S Bandyopadhyay and co-workers (*Applied Physics Letters* 2000, 76, p137) depict self-assembled quan-



An AFM image of a self-assembled nanoporous alumina film used as a template to produce quantum dots with output in the near-infrared.

tum dots made using an electrochemically-manufactured nanoporous template.

PL and Raman studies indicate that these dots confine electrons and holes in a volume with a radius of 3.5 nm, and have shown inter-subband absorption at room temperature at 3.3 μm . This holds promise for room-temperature quantum dot infrared photodetectors.

A number of potential applications are envisaged, including quantum dot static memory with unprecedented density ($> \$1$ terabit/sq. inch) and ultra-fast, low-threshold non-linear optical switches, mixers, frequency converters and couplers.

Monolithic arrays enable multi-wavelengths

The monolithic integration of DWDM sources is highly desirable for fabricating multi-wavelength transmitters. In work described at the International Semiconductor Laser Conference (ISLC 2000, p79), San-Liang Lee *et al.* from the National Taiwan University of Science and Technology demonstrated a novel technique for fabricating monolithic laser arrays of InGaAsP/InP materials which can be used to obtain multiple wavelengths from a single wafer.

The arrays dispense with grating fabri-

cation techniques such as e-beam writing or selective area growth, and are formed from sampled grating DBR (SGDBR) lasers whose sampling periods vary from laser to laser. Uniformly-spaced DWDM wavelengths can then be generated without tuning if the two sides of the SGDBR mirrors are fabricated on waveguides of slightly different thickness. Laser arrays with channel spacings of 100 and 50 GHz were demonstrated with better than 40 dB SMSR and no mode hopping.

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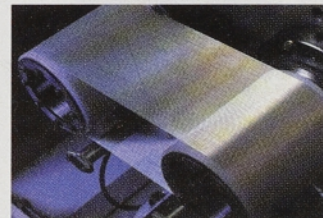
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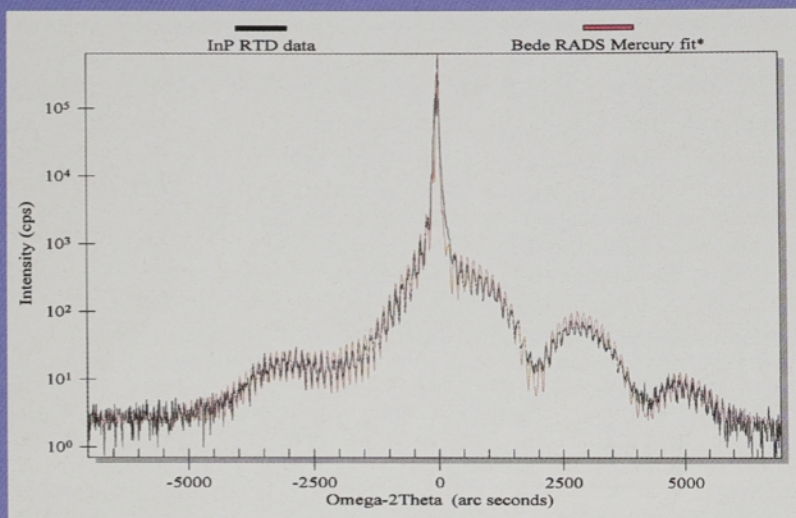
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Integration enables phone on a chip

Research in several camps suggests that the integration of front-end and baseband components in silicon technology may not be far off, writes **Bob Metzger**.

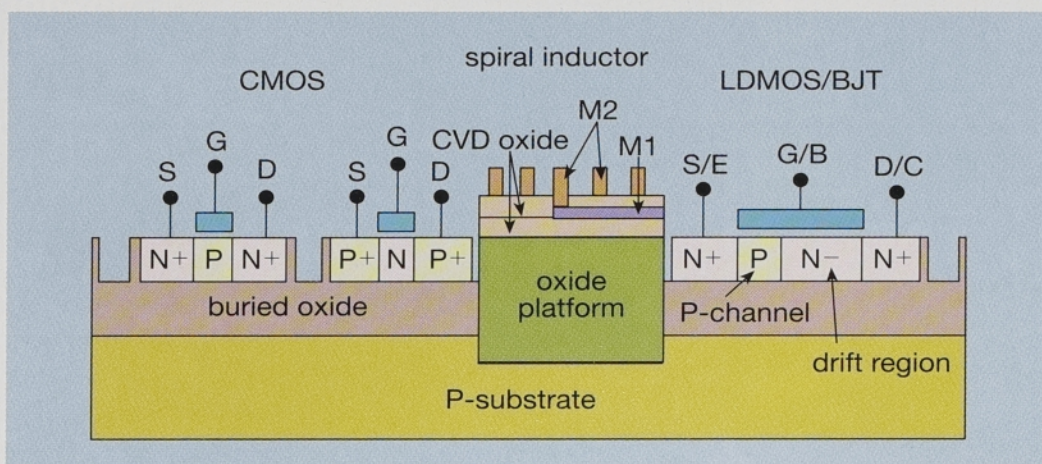


Fig. 1. Diagram showing the integration of devices into a BiCMOS process to allow the complete integration of the front-end (i.e. LDMOS/BJT power devices) with baseband circuits (BiCMOS ICs). This could lead to single chip transceivers that combine low power consumption and cost with high-volume manufacture in commercially important wireless communication bands up to 2.5 GHz.

As has been pointed out several times in this column, the power-generating capabilities of LDMOS (lateral doubled diffused MOS) transistors make them suitable for cell phone power sources. When used as a power source, these MOS-based devices are typically packaged in a module that is then inserted into the RF front-end, and interfaced to the other front-end RF chips with the liberal use of filters.

However, if the LDMOS structure could be integrated with a BiCMOS process, then it would be possible to fabricate an entire phone on a chip, including everything from the RF front-end to the baseband.

Merging technologies

It has been argued by many that while a phone on a chip would certainly result in a system with an incredibly small footprint, the restrictions imposed by the chosen fabrication technology will inevitably lead to design compromises and performance degradation. However, if a merged LDMOS/CMOS/BJT process were available, this might offer sufficient design latitude to optimize the

If the LDMOS structure could be integrated with a BiCMOS process, then it would be possible to fabricate an entire phone on a chip, including everything from the RF front-end to the baseband.

individual performance of the various RF and digital portions of the phone.

Researchers at the Hong Kong University of Science and Technology and from the Singapore Institute of Microelectronics have reported on just such a merged process, fabricating an LDMOS integrated power amplifier (IPA), including on-chip inductors, to demonstrate the technology's capabilities (Kumar *et al.*).

Figure 1 shows a cross-section of the device. Centered around a 1.5 μm CMOS process, the devices were fabricated on a SIMOX substrate with a 190 nm thick silicon layer over a 360 nm buried oxide. Prior to the transistor fabrication, a thick oxide platform for placing the on-chip inductors was formed using a modified LOCOS process. This involves etching a 1.5 μm trench on the silicon/buried oxide/silicon substrate and then grow-

ing a 3.0 μm SiO_2 layer. The gate oxide thickness used was 20 nm.

After lateral diffusion of the source/drain implants (these regions also serve as the emitter and sub-collector, respectively, of the lateral BJT), the effective channel length of the LDMOS is 350 nm (this layer also acts as the base of the lateral BJT). Two layers of aluminum are used for metallization and they are separated by an 800 nm layer of low temperature oxide. The top metal layer is 3.0 μm thick and is used in the fabrication of the inductor spiral.

Performance

The resulting LDMOS devices exhibit a breakdown voltage of 21 V, and an f_t and f_{max} of 4.5 and 4.1 GHz, respectively. The NMOS and PMOS transistors with channel length/width ratios of 1.5 μm /5.0 μm generate I_{Dsat} values of 1.3 mA and 0.8 mA, respectively, and threshold voltages of +0.8 V and -1.2 V, respectively.

The lateral BJT exhibits a small signal current gain of 20, and a BV_{CEO} of 6.4 V. For 900 MHz operation, the Q factor of the 7 nH inductors that were fabricated was 5.7.

Based on this LDMOS, a two-stage Class E common source IPA was fabricated. All matching components, including the output matching network, were also integrated on chip. Operating with a V_{dd} of 5 V and a quiescent bias voltage of 3 V, the IPA delivered 200 mW with a gain of 16 dB and a PAE of 49%.

Not alone

The Hong Kong/Singapore researchers are not the only group pursuing this technology. Researchers at MIT have also recently fabricated an LDMOSFET on SOI, in which an under-source body contact is implemented. This both increases the breakdown voltage and enhances the RF performance (Fiorenza).

Using a very similar SOI structure to that of the Hong Kong/Singapore researchers, with 20 nm of silicon on top of

a 40 nm buried oxide, the under-source body contact is implemented by inserting a p-layer beneath the n^+ source and above the buried oxide.

This p-layer is then shorted to the n^+ source contact by a shunting metal layer which forms an ohmic contact between the source and the p-layer. This body contact suppresses the kink effect typically seen the I-V characteristics of floating body devices, which often leads to excessive device leakage and premature breakdown.

When the body contact is turned on, the breakdown voltage of the LDMOS in the off-state is 25 V. After lateral diffusion, the effective gate-length is reduced to 200 nm and the device exhibits an f_t and f_{max} of 14 and 18 GHz, respectively.

Because this process is fully compatible with a CMOS process, this small gate-length LDMOS with its novel body contact could easily be merged with the approach used by the Hong Kong/Singapore group. This could result in an SOI LDMOS/CMOS/BJT process with

RF characteristics sufficient to meet the needs of RF applications over the commercially important 0.9 to 2.5 GHz band, opening up the possibility of not only a fully integrated RF front-end, but the potential for the entire radio to be implemented in a single chip.

Further reading

M Kumar *et al.* March 2001 *IEEE Electron Device Letters* **22(3)** 136.

J G Fiorenza March 2001 *IEEE Electron Device Letters* **22(3)** 136.

Designing GaAs HBTs based on silicon

Bob Metzger describes a patent for a GaP/GaAs HBT emitter and Si base/collector structure.

A team of researchers at the National Scientific Corporation (NSC) in Phoenix, Arizona has received a patent (#6 171 920) on the design of a novel HBT that combines a silicon base and collector structure with a GaP/GaAs emitter (see figure 1).

One of the major advantages of using a heterojunction at the emitter-base junction of a transistor, in which the emitter bandgap is larger than that of the base bandgap, is the formation of an energy band discontinuity at the valence band (ΔE_v). This effect inhibits hole transport from the base to the emitter, which in turn increases the device's emitter injection efficiency and therefore its DC current gain (β).

However, for those applications where no further increase in β is needed, the improvement in emitter injection efficiency can be traded off against an increase in base doping (which will decrease base resistance), and a decrease in emitter doping (which will decrease emitter-base capacitance).

The effect of both these modifications is to improve the RF performance of the device. NSC hopes to combine this enhanced performance with the cost savings gained by implementing the base-collector structure using a conventional silicon bipolar process to create a high performance, cost effective RF device.

Problems with interdiffusion

From a bandgap engineering perspective, GaP would be an excellent candidate for

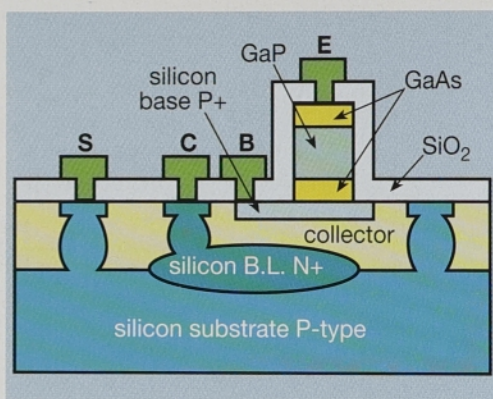


Fig. 1. The first patent on the design of a silicon-based HBT using a GaP/GaAs emitter structure.

Having obtained such an HBT we will have RF power amplifiers operating at frequencies much higher than silicon homojunctions.

the emitter as it has a bandgap of 2.24 eV. This is twice that of silicon, with the majority of the bandgap difference observed at ΔE_v . While the lattice mismatch between GaP and silicon is relatively small at 0.34% – an important consideration in inhibiting the formation of defects at the emitter-base junction – extensive interdiffusion of gallium and phosphorus out of the emitter and into the silicon base, along with silicon diffusion from the base and into the GaP emitter, is observed. Such an effect displaces the

electrical junction from the heterojunction and severely degrades device performance. NSC proposes to eliminate this diffusion by inserting a thin GaAs layer between the GaP emitter and silicon emitter. This undoped GaAs layer, which has a lattice mismatch of 3.7%, must be kept thin so it does not exceed critical strain limits and generate defects at the heterointerface. NSC estimates that this layer should be between 5.0 and 20.0 nm.

Graham Clark, director of Sales and Marketing at NSC commented on the intended applications for such a device: "Having obtained such an HBT we will have RF power amplifiers operating at frequencies much higher than silicon homojunctions."

"Since you can use a very thin highly-doped base region and still maintain extremely good emitter efficiency, in addition to having a highly doped base, you could achieve a transistor with much higher f_t and f_{max} ," he explained. "Therefore, this HBT will not compete with conventional homojunction devices, since the operating frequency will be very different."

"However, if the HBT device is used at the same frequency as a silicon homojunction, the advantages would be lower noise (due to low base resistance), higher gain (due to higher emitter injection efficiency), and better linearity (due to higher Early voltage and lower output conductance), while operating at the same power."



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The Technology of Choice for Compound Semiconductors

CS-MAX Expo takes center stage in July

CS-MAX is the first conference to cover the high-volume manufacturing of all types of commercially significant compound semiconductor devices. Marie Meyer provides a preview.

The Compound Semiconductor Manufacturing Expo – CS-MAX for short – is a unique new event for the compound semiconductor industry. To be held at the Hynes Convention Center in Boston, MA on 9–11 July 2001, this is the first conference to bring together the three major device types that are currently in high-volume production – transistors/integrated circuits, laser diodes and fiber-optic components, and LEDs – as well as all of today's most commercially important materials systems: GaAs, InP, GaN and SiC.

The mission statement for CS-MAX is to encourage productive interchanges among engineers and managers engaged in high-volume manufacturing of compound semiconductor devices and to provide a showcase for new ideas from semiconductor equipment and materials companies that can increase the productivity of compound semiconductor fabs.

The technical program

The technical program at CS-MAX will include approximately 100 presentations, organized into the following five tracks:

- Microelectronics
- Laser Diodes and Fiber Optic Components
- LEDs
- Characterization
- Epitaxy

All of the papers will focus on high-volume manufacturing issues.

Microelectronics In the plenary session Patrick Jenkins will analyse the wealth of experience that Vitesse has generated at its Colorado Springs facility, the first and largest 6 inch GaAs fab in the world. In that same session Bob Van Buskirk, president and CEO of Stanford Microdevices, will discuss the application of the fabless semiconductor model to the RF components industry.

Other presentations in this track include:



Boston, Massachusetts, the site for the inaugural Compound Semiconductor Manufacturing Expo to be held in July.

- Enhancement-mode PHEMT Processing Technology for High-Efficiency Power Amplifiers for Wireless Communications, presented by Gene Tkachenko, Alpha Industries;
- Back-side Processing of GaAs Wafers, presented by Henry Hendriks, M/A-COM;
- Application of X-Ray Lithography to GaAs ICs, presented by Donald Bailey, SAL;
- Increasing Capacity Together With Reducing Cycle Time – A Look at Productivity Improvement Process at Nortel's GaAs Wafer Fab, presented by Wladyslaw Danielak, Nortel Networks.

Laser Diodes and Fiber Optic Components

The plenary session will feature a paper entitled "The PCAD Program: Advances in Photonic Computer Aided Design" from Matthew Goodman, chief scientist at Telcordia Technologies. Jim Tatum, VCSEL technology manager at Honeywell will discuss the commercialization of VCSEL technology.

Other presentations in this track will include:

- Challenges and Solutions for VCSEL Manufacturing, presented by Geoffrey Rosenthal, AXT;
- Indium Phosphide Photonic Integration for DWDM Applications, presented by Charles Huang, Anadigics;
- On the Fast Track: Tapping into the Power of SPC and Demand-Flow Tools to Jump Start Production, presented by Tom Dearmin, Lasertel;
- Successful Implementation of Manufacturing Execution Systems in Fiber Optic Component Manufacturing, presented by Greg Sowle, Camstar Systems.

LEDs The explosion in LED manufacturing in Taiwan will be discussed in the plenary session by Jim Chi, deputy director of the Industrial Technology Research Institute in Taiwan. There will also be a presentation on high-volume production of InGaN-based LEDs by Kiyoshi Komatsu of Nichia. Attendees will also

get a preview of what could be a major change in business practices in the LED industry. Cameron Miller and colleagues from the National Institute of Standards and Technology (NIST) will make a presentation on NIST's efforts to develop standards for luminous intensity and luminous flux for LEDs. The purpose of this work is to establish much-needed standards whereby the performance of LEDs can be objectively measured – at present LED comparisons are often done on an “apples to oranges” basis.

Characterization It seems that every compound semiconductor fab is looking for the right combination of characterization techniques to increase yields without causing bottlenecks. Numerous techniques will be discussed at CS-MAX. Presentations will include:

- Quantitative X-ray analysis of GaAs- and InP-based HBTs for Rapid In-Production-Line Material Qualification, presented by Peter Velling, Innovative Processing AG;
- Contactless Electromodulation And Surface Photovoltage Spectroscopy For The Room Temperature, presented by Fred Pollak, Brooklyn College, CUNY;
- Topographic Assessment of EL2 and Implantation Dose Homogeneity in Semi-Insulating GaAs Wafers, presented by Peter Hiesinger, Fraunhofer IAF;
- Characterization of Multi-Carrier Heterostructure Devices with Quantitative Mobility Spectrum Analysis and Variable Field Hall Measurements, presented by Gang Du, Lake Shore Cryotronics;
- FTIR Characterization and Control of Compound Semiconductor Epi Layers, presented by Peter Solomon, On-Line Products.

Epitaxy The vast majority of compound semiconductor devices are based on epitaxial structures, and sophisticated techniques such as MBE and MOCVD are vital to the future progress of the industry. With this in mind, CS-MAX will include a lively track on epitaxy, focusing on the needs of high-volume producers. Presentations will include:

- High Volume and Flexibility in an MOVPE Foundry, presented by Jim Ermer, Spectrolab;
- Integrated MOCVD System Engineering and Fab Management, presented by Koh Matsumoto, Nippon Sanso;
- Productivity for Epi Manufacturing-

CS-MAX organizing committee

Marie Meyer, founder & managing editor, *Compound Semiconductor* magazine, Beverly, MA

Alan Swanson, director, Microwave Electronics Group, BAE Systems, Information & Electronic Warfare Systems, Nashua, NH

Mark Itzler, VP & chief technical officer, JDS Uniphase Epitaxx, West Trenton, NJ

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Equipment and Support, presented by Bernd Schulte, Aixtron;

- Epi Layer Temperature Measurement and Control in Large Scale MOCVD Manufacturing, presented by Jeff Bodycomb, Emcore;
- Automated Bulk Distribution System For Liquid Organometallics in MOCVD Production, presented by Ravi Kanjolia, Epichem;
- Control of Moisture in Arsine and Phosphine Delivery Systems for MOCVD Processes, presented by Virginia Houlding, Matheson Tri-Gas;
- Metalorganics Safety and Handling, presented by Gregory M Smith, Akzo Nobel.

The exhibit

The silicon industry is famous for its massive annual equipment exhibitions, such as Semicon West. The popularity of these events is due to their effectiveness as showcases for new ideas and commercially available solutions to important problems.

In the past five years the compound semiconductor industry has seen a rapid maturation of its infrastructure. The CS-MAX exhibition will include every major manufacturer of compound semiconductor-related equipment and materials. It is, therefore, an outstanding opportunity for fab managers and process engineers to bring themselves up to date on what's new – a “one-stop shop” for everything needed for a compound semiconductor fab.

The courses

Educational opportunities at CS-MAX will include two major multi-presenter workshops:

- Manufacturing InP Integrated Circuits will be chaired by Owen Wu, president of GCS. InP-based ICs are becoming increasingly important for the future prospects of the compound semiconductor industry. However, while there is a substantial body of knowledge about fabricating discrete optoelectronic devices such as laser diodes from InP, there is a critical shortage of experience in fabricating ICs from this material. This workshop will provide an overview of practical issues that must be addressed by any company that is interested in producing InP circuits.
- OIDA Roadmap on Solid State Lighting will be chaired by Arpad Bergh, president of the Optoelectronics Industry Development Association. It is widely recognized that solid-state lighting represents an exciting opportunity for the LED industry. But there are numerous issues that must be dealt with, such as the timing for the emergence of high-volume applications, and the types of LEDs that will be required. The OIDA, whose mission is to promote the global expansion of the optoelectronics industry, is spearheading the effort to stimulate discussion of these issues.

CS-MAX will also include several single-presenter tutorials, including:

- Plasma Processing of III-V Materials, presented by Stella Pang, University of Michigan;
- Fabricating and Packaging Diode Lasers and VCSELs, presented by Kurt Linden, Axcel Photonics;
- CAD for III-V MMICs, presented by Wolfgang Bosch, Filtronic.

For more information about CS-MAX, visit the conference Web site at “<http://www.cs-max.com>”.

CS-MAX

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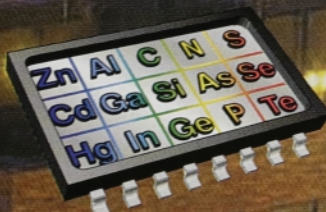
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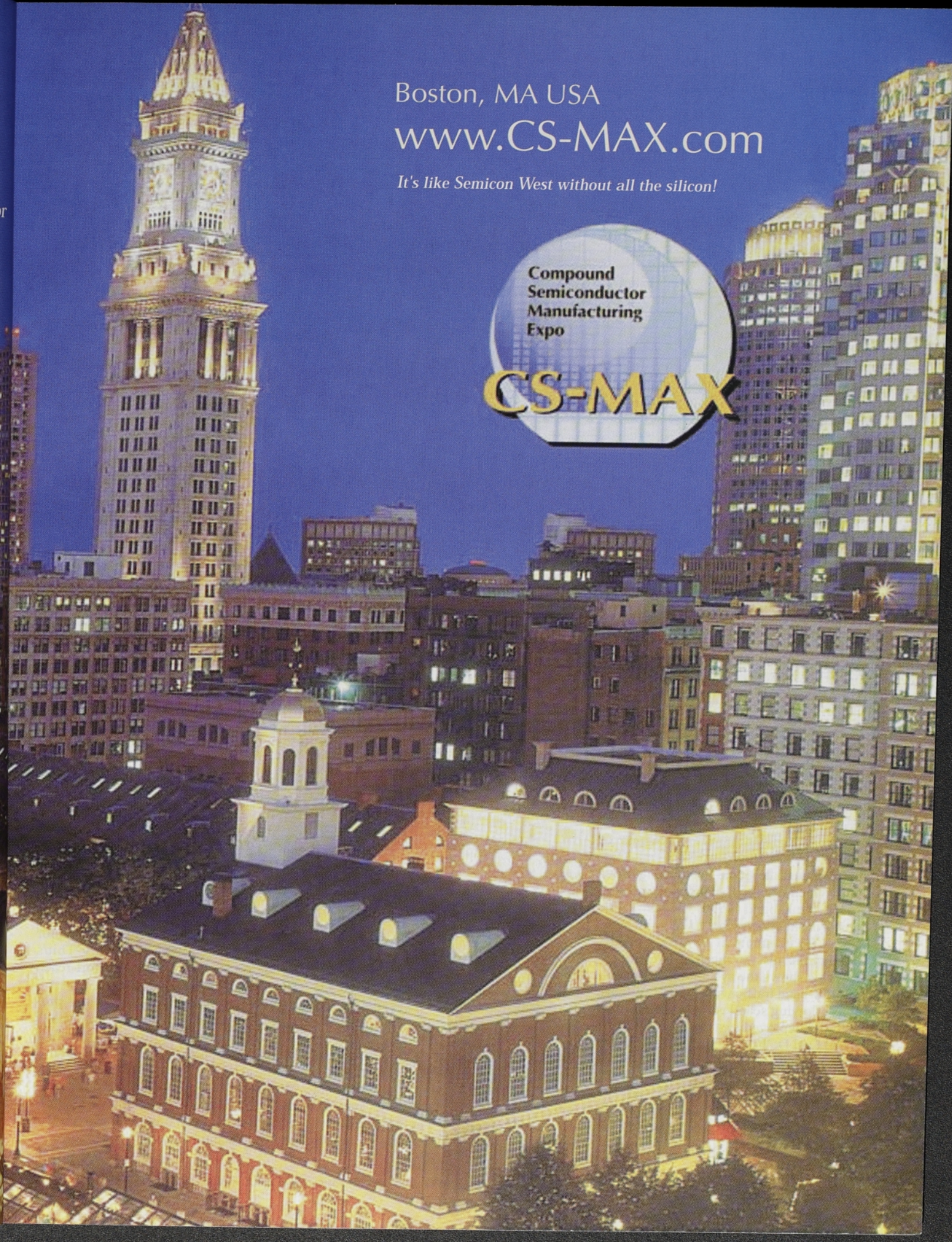
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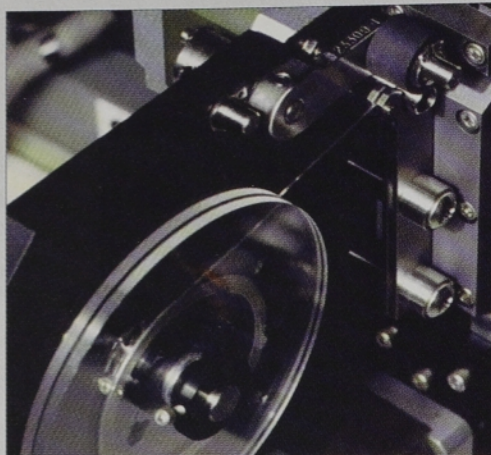


measurement of the front and back photodiode detector outputs needed to characterize edge-emitting lasers. The 2520 determines threshold current, light-intensity (L-I) efficiency, and current-voltage (I-V) linearity.

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MRSI introduces a new bonding system

The new MRSI 505 High Frequency Assembly Work Cell is a system designed for eutectic bonding of RF and microwave components. It can be configured for several component-attach technologies including *in situ* eutectic bonding, conductive and non-conductive epoxy attach, integrated eutectic bonding



in reflow chamber and flip-chip bonding.

The MRSI 505 is thermally and mechanically stable and supports multiple eutectic processes such as gold silicon, gold tin and gold germanium. Capabilities include a heated assembly station with fast closed-loop temperature ramping. For example, the MRSI 505 High Frequency automates the placement of GaAs die with air bridges and vias with controlled programmable contact force.

MRSI also offers an automated eutectic preform feeder based on its MRSI-505 platform. Called the Photonics Optical Assembly Work Cell, eutectic bonding is simplified by using a feeder that handles reels of solder and cuts a variety of preform sizes for immediate pick and place during the assembly process. The system can be configured for several component-attach technologies for epoxy die attach, eutectic and flip-chip bonding. Applications include filters, switches and amplifiers, transmitters and receivers, and other laser-based devices.

Contact Dan Crowley, MRSI, 101 Billerica Avenue, Building 3, North Billerica, MA 01862-1256, USA
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Fax +1 978 667 6109
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Pulse generator fits a range of applications

Directed Energy Inc. (DEI) has introduced the PVX-2110, a high-power pulse generator designed for pulsing low impedance loads (from 1–25 Ω) at up to

200 V and 50 A. The PVX-2110 delivers up to 10 kW of peak output power and 5 kW of average output power, making it suited to materials testing and processing, semiconductor testing and characterization, and other test and measurement and R&D applications.

The company's pulse generator can also be configured to generate positive or negative output pulses of up to 200 V with typical pulse rise and fall times of less than 100 ns. Pulse widths are continuously adjustable from less than 200 ns to 2 ms, at frequencies from single-shot to 50 KHz.

Contact Geoff Smith, Alrad Imaging, Alder House, Turnpike Road Industrial Estate, Newbury, Berks RG14 2NS, UK
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Fax +44 1635 32630
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New X-ray diffraction system from Bruker

The D4 Endeavor is a new X-ray diffraction system from Bruker-AXS designed for qualitative and phase analysis, micro-strain and crystallite size determination, residual stress analysis



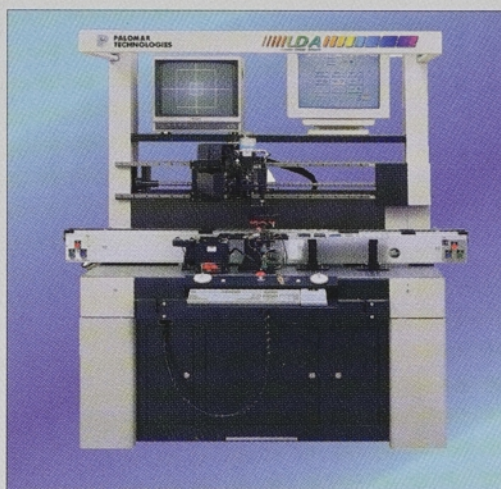
and crystal structure solution. The D4 has large magazines for 66, 72 or up to 120 samples, and features a gripper with automatic sample height detection, a large variety of sample holders including front and back loading, foil-covered,

spring-loaded cases and zero background. Also included are an integrated video camera and TCP/IP compatible software architecture to allow remote access of the two-circle goniometer using the Internet. The system footprint is 0.95 m².

Contact Hamid Ghanadan for Bruker-AXS, 5465 East Cheryl Parkway, Madison, WI 53711, USA
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Fax +1 608 276 3006
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Assembly cell gives laser soldering a boost

Palomar Technologies' new laser diode attach (LDA) system – an assembly cell that automates the packaging of InP laser diodes onto carriers prior to assembly into optoelectronic packages – includes a void-free eutectic solder interface that controls thermal and electrical connections needed to generate a stable



transmission of laser light.

The LDA assembly cell integrates a pulse-heat system that drives a patented eutectic hot bar heater to generate the eutectic solder interface. The programmable closed loop system gives tightly coupled control and repeatability of eutectic reflow processes while maintaining a final placement accuracy

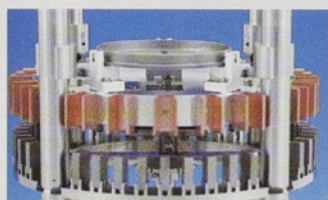
of 5 µm. A preheated blanket gas eliminates material oxidation during eutectic processing.

For InP diode assembly, the assembly cell positions the substrate, carrier or sub-mount in the pulse-heat unit, places a eutectic preform, heat spreader/spacer and a second preform, places the laser diode and pulse-heats the entire stack. This sub-mount is then placed onto a thermal electric cooler in the butterfly or transistor outline (TO) optoelectronic package typically used to package transmitters, receivers, transceivers and amplifiers. The LDA accommodates photodetector assemblies, and is able to handle various formats of presentation including expanded wafer, 2 inch and 4 inch wafer and gel paks.

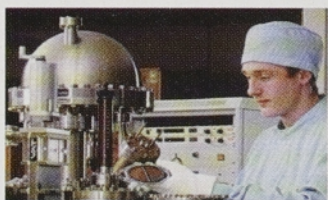
Contact Bruce Hueners, Palomar Technologies, 2230 Oak Ridge Way, Vista, CA 92083, USA
Tel. +1 760 931-3600
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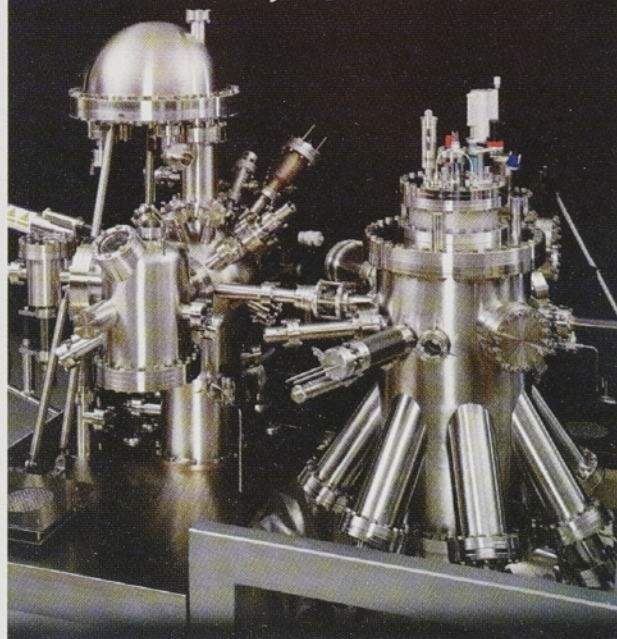
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New players make a big splash at OFC

Among the 970+ exhibitors at this year's Optical Fiber Communication conference were a number of companies seeking to revolutionize the fiber-optic components industry.

Tim Whitaker and Richard Dixon report from Anaheim, California.

Although their booths were dwarfed by the likes of companies such as Corning and JDS Uniphase, several much smaller optical component vendors were showing demos of some very exciting technologies at this year's Optical Fiber Communication conference (OFC, held 19–21 March in Anaheim, CA). Here is our selection of the most interesting, in no particular order.

Genoa

Among the major components of optical networks, the optical amplifier is the only one that has not been widely adopted in chip form. Instead, the commonly used EDFA is a box containing pump lasers, Er-doped fiber, gain-flattening filters and various other parts. Chip-based amplification is very attractive since it potentially offers smaller size, lower cost and power consumption, and high levels of integration. Also, especially in the metro environment, amplifiers need to offer linear gain and to be able to accommodate any data rate, handle multiple wavelengths without crosstalk, and work in switched networks.

Chip-based amplifiers already exist in the form of semiconductor optical amplifiers (SOAs), but these devices suffer from crosstalk when more than one wavelength channel is amplified. A solution introduced at OFC by Genoa, a company based in Fremont, CA, is the single-chip linear optical amplifier (LOA). This InP-based device can simultaneously amplify all wavelengths across the C-band (35 nm bandwidth) with 13 dB gain. Figure 1 shows a size comparison of an EDFA and the LOA in a 14-pin butterfly package.

The LOA has a deceptively simple structure; essentially it is a monolithic, 1550 nm InP-based VCSEL. Of course, this type of device is still very much a commercial rarity. The active region of the VCSEL acts as a waveguide for the

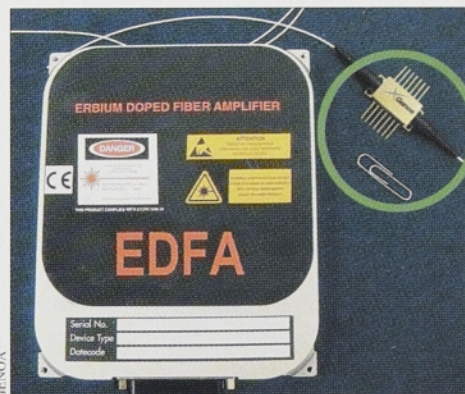


Fig. 1. Genoa's single-chip linear optical amplifier, housed in a 14-pin butterfly package, is significantly smaller than a typical EDFA.

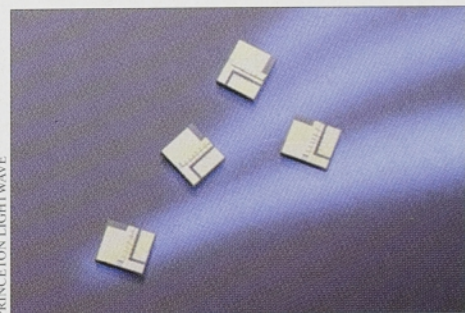


Fig. 2. Princeton Lightwave's new broadband gain chip is an InP chip-on-carrier that is used as the gain element within an external cavity laser.

signal as it passes through the device. The VCSEL pumps an excess of photons into the gain medium, amplifying all wavelengths at the same time. "We can observe the light coming out of the LOA," says Jim Witham, Genoa's vice-president of sales and marketing. "When the power of the input optical signal is increased, the light output dims as more photons are used for amplification."

Genoa operates a 45 000 sq. ft InP wafer fab in Fremont, CA which contains two MOCVD machines as well as capabilities for wafer fabrication, packaging

and testing. A second facility is being built in Eindhoven, the Netherlands, that will eventually also have InP fab capabilities. The company has recently completed a \$75 million funding round.

"We're concentrating on the C-band LOA at the moment," explains Witham. "Initial customer testing is under way, and we will offer commercial samples by fall of this year." By slightly changing the structure and materials of the device, the LOA can be made to work anywhere in the transmission band in the fiber. "As well as looking at other bands, we will also build amplet arrays, in addition to increasing the available output power," says Witham. "Looking further ahead, we will be introducing higher levels of integration on InP, building lossless switches and then moving into multifunctional optoelectronic ICs."

Princeton Lightwave

To use the company's own words, Princeton Lightwave Inc. (PLI) "emerged from stealth mode" shortly before OFC and announced its plans to deliver a clutch of advanced optoelectronic components. These include high-power 1480 and 14xx nm pump modules and sub-assemblies, broadband gain chips and high-power DFB source lasers. PLI is privately held, and backed by \$28.5 million in venture funding. The company was spun out from Sarnoff, and has an exclusive license to a broad patent portfolio. PLI carries out vertically integrated manufacturing of InP-based devices, from epitaxy to packaging, in its 90 000 sq. ft facility in Cranbury, NJ.

PLI's broadband gain chip (BCG – see figure 2) is an InP chip-on-carrier that is used as the gain element within an external-cavity laser (ECL). Tunable ECLs have recently been announced by several companies, namely New Focus, Blue Sky Research and Iolon. The new BCG allows

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customers to build ECLs with output powers of 40 mW while enabling tuning over an entire (S, C or L) band.

PLI has also developed high-power 14xx nm pump lasers for Raman amplifiers and 1480 nm devices for pumping EDFAs. Output powers have hit 500 mW in modules, while PLI announced in April that it has demonstrated 1 W of output power from 1480 and 14xx nm chips.

Novalux

After a long wait Novalux finally revealed details of its surface-emitting laser, and announced two 980 nm products. The first, a singlemode module for pumping EDFAs, is available with output powers of 200 mW and 360 mW, while the second is a multimode pump in the 750 mW power range for the emerging dual-clad fiber market. Novalux planned to begin sampling these devices in April.

Novalux says that the EDFA pump-laser market is driving its current business strategy. "The NECSEL is really a very flexible platform," explains chief technology officer Aram Mooradian. "This is the first of what will be a long line of affordable, high-performance and highly scalable NECSEL laser products for a wide range of telecom applications."

The NECSEL (for "Novalux extended-cavity surface-emitting laser") employs a three-mirror, coupled-cavity design (see figure 3). Two of these mirrors are epitaxial DBR layers surrounding the InGaAs/GaAsP gain region. The third mirror is external to the device, forming an extended cavity. The epitaxial structure is grown by MOCVD on 4 inch GaAs wafers, and contains several 8 nm wide, strain-compensated InGaAs quantum wells within the active region.

The device is mounted p-side down onto a heat sink, and emission occurs through the substrate. Current is injected through a circular aperture defined by a silicon nitride layer. The n-contact has a larger circular aperture with an anti-reflection coating to allow the beam through to the external mirror. The large aperture serves to keep the optical intensity well below the catastrophic damage level, and also results in a circular beam with low divergence.

The extended passive cavity controls both the longitudinal and transverse modes of operation. CW output power levels of 500 mW have been demonstrated in a TEM₀₀ mode with a single

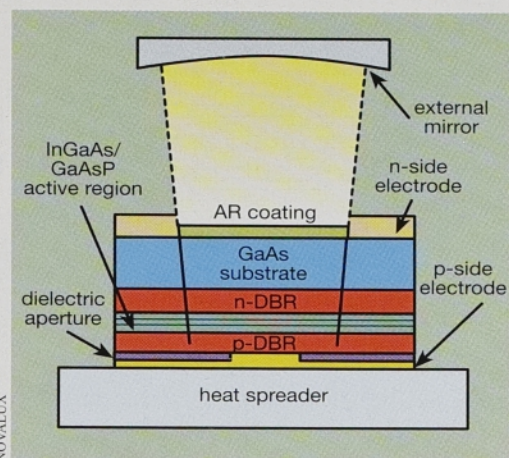


Fig. 3. Novalux's NECSEL device consists of two epitaxial mirrors surrounding the QW active region, and a curved external mirror forming an extended cavity that controls the optical mode and the wavelength.

frequency stabilized by the short-cavity Fabry-Perot. The circular output beam results in coupling efficiencies of 90%, with 420 mW CW of coupled power demonstrated from 150 μ m diameter lasers and uncoated singlemode fibers. In multimode devices more than 1 W of output power has been demonstrated, along with coupling efficiency of greater than 85%. The devices have the advantage of maintaining fundamental mode operation even as device diameter increases, allowing scaling to still higher power levels.

Reliability is a key concern for manufacturers of pump lasers for EDFAs. Preliminary accelerated lifetime tests with more than 2000 hours of operation show that NECSELs exhibit reliability characteristics similar to those of low-power VCSELs. Novalux says that this is not surprising given the similarity in materials, current densities and operating temperatures. As a surface-emitting laser technology the NECSEL has other features in common with regular VCSELs, not least the ability to test devices on the wafer prior to dicing and packaging. Novalux is focusing on wafer-scale manufacturing processes, and sees the use of 4 inch GaAs wafers as a major advantage for high-volume production. Based in Sunnyvale, CA, the firm has a 16 000 sq. ft building with class-10 cleanroom space for wafer processing, together with a second 22 000 sq. ft building for packaging and assembly. Last fall Novalux leased a 100 000 sq. ft facility that will house its highly automated packaging processes.

Princeton Optronics

The name is new, but Princeton Optronics has been around since 1993, and last year generated several million dollars in revenues from its RF-microwave products. The company began life as another spin-off from Sarnoff, and changed its name from Princeton Electronic Systems in 2000 to reflect its contributions to the optical components market.

Princeton Optronics is developing several interesting products, one of which is a tunable laser combining a high-power VCSEL with MEMS and an integrated wavelength locker. The company claims that its PowerSweep device delivers 20 mW of power over a broad tuning range of 40 nm, while at the same time providing stability of ± 1 GHz. Princeton Optronics' specifications significantly exceed the performance levels of most of today's commercially available tunable lasers. Sample products (with as-yet-unspecified performance characteristics) will be available this June. The high-power VCSEL technology behind the company's tunable laser will later be applied to solving other high-power requirements within the optical network. In the meantime the firm continues to scale production of its 10.7 Gbit/s modulator driver and 12.5 Gbit/s receiver products.

MetroPhotonics

Huge efforts are being focused on the need to reduce the cost of components in fiber-optic networks, and planar monolithic integration is one route being followed by a number of companies. MetroPhotonics, a year-old company based in Ottawa, Canada, is focusing on developing photonic ICs using planar waveguides fabricated in silica-on-silicon and InP. Initial products are being built around multiplexer and demultiplexer components, which use echelle gratings rather than the more common arrayed-waveguide (AWG) technology. Echelle gratings and AWG demultiplexers separate wavelengths by introducing phase shifts that result in light of different wavelengths being focused on different spatial locations on an output arc. An AWG achieves this with a fan of waveguides, each of a different length. But in an echelle grating, a vertically etched mirror with a large number of facets has the same function. Light travels through the input waveguide and expands from the end of the guide until it reaches the grat-

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ing, where it is reflected back to a series of output waveguides, each of which collects a single wavelength.

Echelle grating technology has been around for a long time, but MetroPhotonics has only recently established the necessary advanced fabrication techniques, in particular the ability to perform smooth, deep, vertical etches all the way through the waveguide material. Echelle gratings are typically four or five times smaller than AWGs and more easily scaled, since more wavelengths can be added by increasing the number of facets in the echelle grating rather than by adding more waveguides to the array.

Like other companies such as Intense Photonics, MetroPhotonics' ultimate goal is to use InP to integrate active optoelectronic components such as lasers, modulators and detectors with passive multiplexers and demultiplexers.

Teem Photonics

Targeting metro applications, Teem Photonics introduced at OFC an ultra-compact erbium-doped waveguide amplifier (EDWA). This gain block is essentially the same as an EDFA, except that amplification takes place inside a waveguide fabricated on glass, rather than within a 20 m spool of specialty fiber. The waveguide is only a few millimeters in length, so the EDWA package – which also contains a pump laser, pump multiplexer, pump kill filter and tap coupler – measures only $130 \times 27 \times 13$ mm, significantly less than a standard EDFA.

The waveguide amplifier offers 10 dB gain over the entire C-band, which is much lower than the gain from an EDFA. However, Teem believes that eliminating the Er-doped fiber from its amplifiers makes assembly more straightforward, and results in significant savings in time and labor costs.

Axon Photonics

Unusually for a small company, Axon Photonics has both passive and active technology platforms; it is manufacturing silica-on-silicon planar lightwave circuits including such components as arrayed waveguides (AWGs), as well as InP-based semiconductor optical amplifiers (SOAs – see figure 4). At present the company designs and packages the SOAs; it is in the process of installing chip-fabrication capabilities and will take delivery of an MOCVD system later this

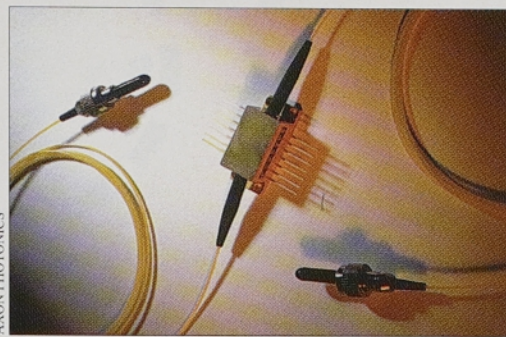


Fig. 4. Axon Photonics sells 1310 and 1550 nm InP-based SOA modules.

year. Axon operates a 25 000 sq. ft facility in Fremont, CA, and a 120 000 sq. ft building in Livermore, CA.

The company's SOAs operate at 1310 or 1550 nm and have a strain-compensated structure resulting in low polarization dependence. The modules feature high-gain (15 dB) and a wide 3 dB passband from 1280 to 1610 nm, as well as switch times of less than 1 ns. Axon is also developing hybrid optical subsystems combining active and passive devices. The simplest configuration combines an AWG with an SOA as a pre- or post-amplifier, resulting in a near-lossless AWG module (i.e. the SOA compensates for loss in the AWG).

At OFC, Axon showed a simulation of a reconfigurable optical add-drop multiplexer (OADM) consisting of AWGs with hybrid integrated SOAs, which can dynamically add or drop any wavelength from the fiber to the add-drop port. The AWGs ensure low crosstalk and wide passbands; the SOAs act as switches and also ensure a very low insertion loss.

Gemfire

As WDM systems move to the metro access space, networks will require low cost and flexible amplification. One firm addressing these demands is Gemfire, which recently announced a multi-port 980 nm source array for pumping multiple EDFAs. The compact, board-mountable module has eight independently controlled fiber outputs, providing pump power to eight separate amplifiers. Inside the module is a laser bar with eight emitters, which is integrated with a planar lithium niobate PhotonIC containing tapers, gratings and waveguides. This platform is mounted as a hybrid onto silicon v-grooves for fiber alignment.

Based in Palo Alto, CA, Gemfire was formed to develop integrated photonic

components for a range of applications, and is now focusing on the telecom market. "We have a great deal of expertise in laser arrays, as well as in planar, wafer-scalable photonic platforms using materials such as glass, polymers and lithium niobate," says Rick Tompane, Gemfire's chief executive officer. Gemfire does not make its own lasers, however.

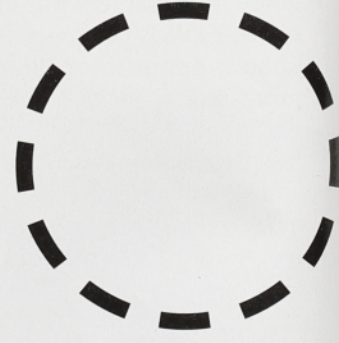
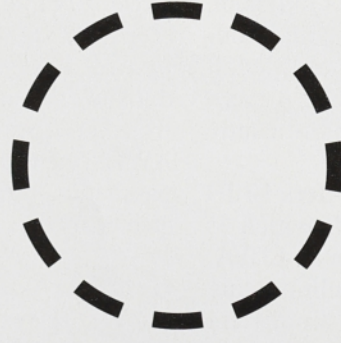
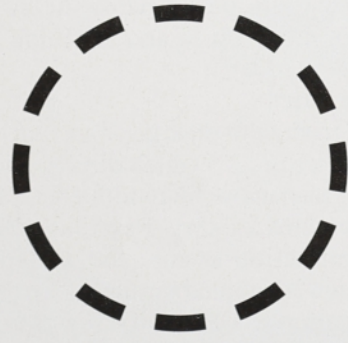
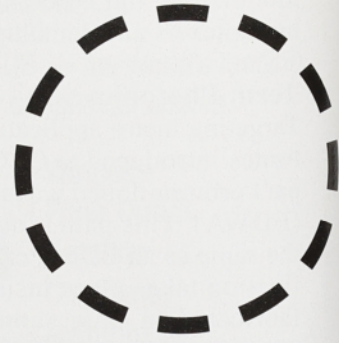
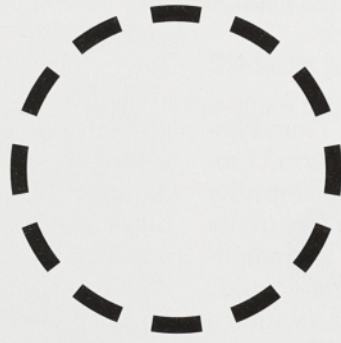
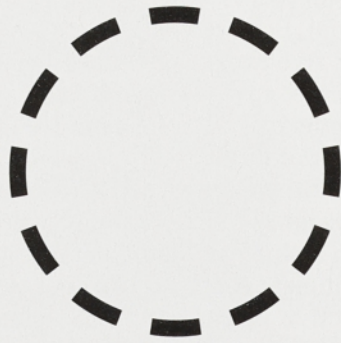
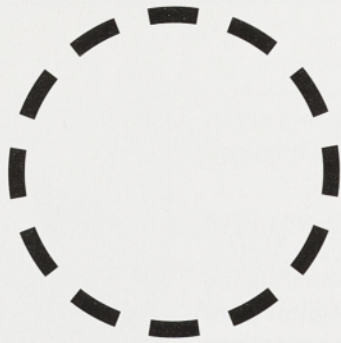
According to Tompane, one challenge is to make the laser bars with a high yield. "We also need to do the coupling, alignment and fiber-attach in an automated, repeatable process across all eight ports." Using hybrid integration onto a planar platform helps; building tapers into the ends of the planar waveguides ensures efficient coupling, and automated assembly is more straightforward as it becomes a 2-D problem on the planar surface.

"The new multi-port pump is targeted at low-cost applications like metro," says Tompane, "and high-channel-count systems like cross-connects, where requirements are a little bit of gain together with independent control over every channel, all in the same location." The product can provide 80 mW of kink-free power out of all eight ports; in Gemfire's demo at OFC, 50 mW provided 23 dB gain on a single channel. At the beginning of March Gemfire completed a \$63 million round of funding, with participants including Cisco, Corning, Finisar and TriQuint.

K2 Optronics

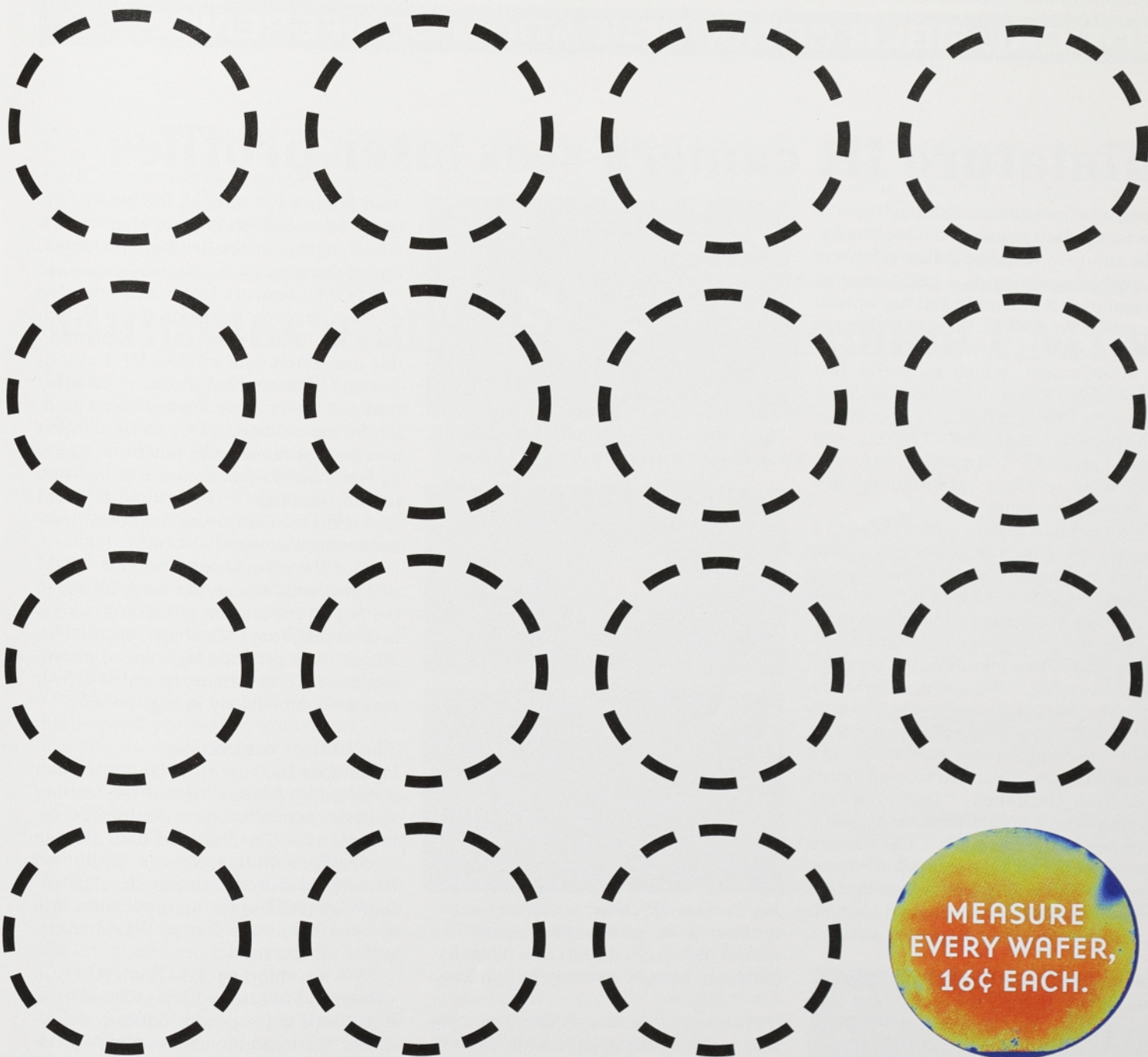
The first product to emerge from year-old K2 Optronics is a 2.5 Gbit/s directly modulated, ultra-narrow linewidth ECL. The device contains a Fabry-Perot laser with an anti-reflection coating on the front facet, which is coupled through a lens to a fiber section containing a Bragg grating. The laser cavity is formed between the grating and the back facet of the FP laser. Compared with directly modulated DFB lasers, these fiber-grating ECLs offer lower chirp and low dispersion over long distances. As the cavity is not entirely within the semiconductor chip, the lasers also exhibit lower temperature-induced variations of properties such as wavelength. Based in Sunnyvale, CA, K2 Optronics recently received \$30 million in its second round of financing, but does not intend to install its own laser-chip fabrication facilities.

Next year's OFC conference will be held on 17–22 March in Anaheim, CA.



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Miniature IR camera sees laser profiles

Almost all communication through optical fiber takes place at infrared wavelengths, so the ability to visualize radiation beyond the visible spectrum is a great asset to companies that assemble and test optical networking equipment. Sensors Unlimited has developed a lightweight IR imager, the MiniCamera, which measures just $5 \times 6 \times 9.5$ cm and weighs less than 350 g without its lens (see figure 1). It operates in the near-IR band at 900–1700 nm, and is based around a 320×240 InGaAs detector array, which is bump-bonded to a silicon readout circuit.

There are two keys to achieving such a compact unit. One is to incorporate a large amount of functionality into the readout IC of the imager, which in turn reduces the amount of separate support electronics. The other is to manufacture high-quality arrays that minimize the need for post processing. "We use a proprietary material structure for our imagers which is very different from the device structure used for our high-speed detectors," says Marshall Cohen, executive vice-president of Sensors Unlimited. "This gives the imaging arrays higher uniformity and a much lower dark current." The camera runs off batteries or a small wall transformer. It can easily be hooked up to a TV or a computer, and is compatible with microscopes and laser alignment stations.

A wide spectrum of applications

A major application for the camera is in the assembly of large optical switches; here, the ability to "see" in the infrared facilitates the active alignment of, for example, multi-channel arrayed waveguides (AWGs) with multiple fibers. Such cameras are also used to align and monitor large MEMS-based crosspoint switches.



Fig. 1. Sensors Unlimited's new near-IR camera measures just $5 \times 6 \times 9.5$ cm.

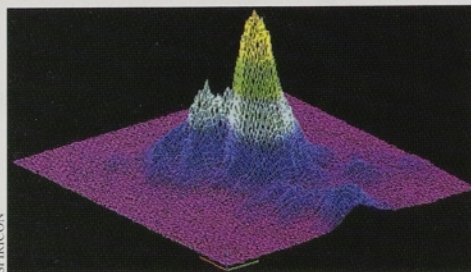
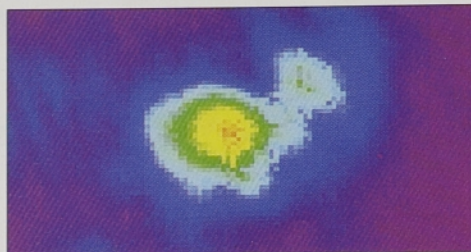


Fig. 2. Near-IR cameras can be used for laser beam profiling to measure spatial distribution (top) and intensity (bottom). Images courtesy of Spiricon.

Another application is laser beam profiling; the cameras have high dynamic range and can handle a high intensity of light without being damaged, so they can be used to measure features such as beam shape and spatial modes (see figure 2). In the silicon industry, IR cameras can be

used to view ICs through the back of the wafer (since silicon is transparent at NIR wavelengths) to see damage, hot spots, broken lines etc.

At OFC, Sensors Unlimited unveiled its first receiver product for telecom, namely a 10 Gbit/s InGaAs PIN photodiode integrated with a GaAs HBT amplifier in a fiber-coupled, Bellcore-certified package. This is the company's first product for the network itself; its IR cameras are used for monitoring functions, as are its linear arrays that are used to measure the performance of individual DWDM channels (see *Compound Semiconductor* September/October 2000, p41).

"Our detector array work for WDM monitors and cameras has made us one of the largest processors of InGaAs wafers in the world," says Marshall Cohen. "This allows us to produce high-speed photodiodes very cost-efficiently, and to deliver products immediately in high volume."

The Finisar connection

In October 2000, Sensors Unlimited was acquired by Finisar, one of the leading volume manufacturers of transceiver modules for datacom and data storage applications. In fact, Sensors Unlimited has already started to ship avalanche photodiodes (APDs) for incorporation into some of Finisar's coarse WDM transceiver products.

"We are shipping 2.5 Gbit/s APDs in volume to Finisar," explains Chris Dries, director of high-speed product development. "We expect to ship 10 Gbit/s products later this year. APDs are ideal for coarse WDM applications in the metro environment, where there are lots of passive components; the APD provides a simple way to make up for passive losses."

Finisar offers coarse solutions for WDM

Finisar, located in Sunnyvale, CA, is an established supplier of modules for gigabit-speed connectivity, serving applications such as Gigabit Ethernet and Fibre Channel. Recently, Finisar announced a full range of modules, including

transceivers for coarse WDM, which target metro access networks requiring multiple wavelengths.

Coarse WDM uses four or eight widely spaced wavelength channels. Finisar's Gigabit CWDM transceiver has eight channels, and incorporates uncooled DFB lasers with wavelengths separated by 20 nm in the 1470–1610 nm range. Eight identical PIN-based receivers are

used, providing a link budget of 21 dBm.

"Since the lasers are uncooled, their wavelengths drift with temperature, but only by 0.09 nm/°C over the operating range," says Mike Farley. "The 20 nm wavelength separation easily accommodates this drift. It's not possible to have tight spacing as in DWDM, but in the metro/access area, where a high density of wavelengths is not typically a criterion,

this approach is much more cost-effective." Finisar has also introduced a GBIC transceiver operating at rates from 100 Mbit/s to 2.5 Gbit/s; the module incorporates avalanche photodiodes to increase the link budget to 28 dBm.

In addition to Sensors Unlimited, which manufactures photoreceivers, Finisar has another subsidiary that makes active devices. Demeter Technologies, based in El Monte, California, was acquired in November 2000. The com-

pany is a vertically integrated laser manufacturer, with in-house epitaxy and wafer fabrication facilities. Demeter will continue to provide lasers to its external customers as well as beginning to serve Finisar's internal needs.

Multiplex and Agere demo tunable EMLs

Multiplex and Agere Systems (formerly Lucent Microelectronics) have introduced 10 Gbit/s tunable transmitters containing lasers with monolithically integrated electroabsorption modulators. Single chip tunable lasers and integrated electroabsorption modulated lasers (EMLs) are available from a number of suppliers, but increasing on-chip functionality represents the next step towards reducing the package size and power consumption of tunable transmitters. These devices will play an increasingly important role in DWDM systems, optical routers and OADM's used in short- and long-haul high-speed optical networks, not least because network operators will need to keep fewer lasers in stock as backups.

Both companies use electronic tuning of DBR lasers to select wavelengths across the C-band. Multiplex's device integrates a gain section with phase and Bragg sections to achieve quasi-continuous wavelength tuning. The data signal is then applied to the laser emission by the integrated modulator situated close to the front facet (see figure 1). As well as the gain, Bragg and modulator sections, Agere's single chip features a semiconductor optical amplifier (SOA) section to boost the output power, as well as a detector to monitor the power prior to modulation.

Agere's C92 tunable transmitter is housed in a small-form factor package that also contains a wavelength stabilizer in addition to the requisite physical layer processing ICs. Inside the chip, the Fabry Perot mode can be tuned to up to 20 channels by applying a current to the Bragg mirror. The wavelength is stabilized using Agere's on-board LambdaLock device, which is a patented system that locks the laser emission to 50 GHz channel spacings with a wavelength stability of 20 pm. Agere says the transmitter is suited to terminal equipment in DWDM appli-

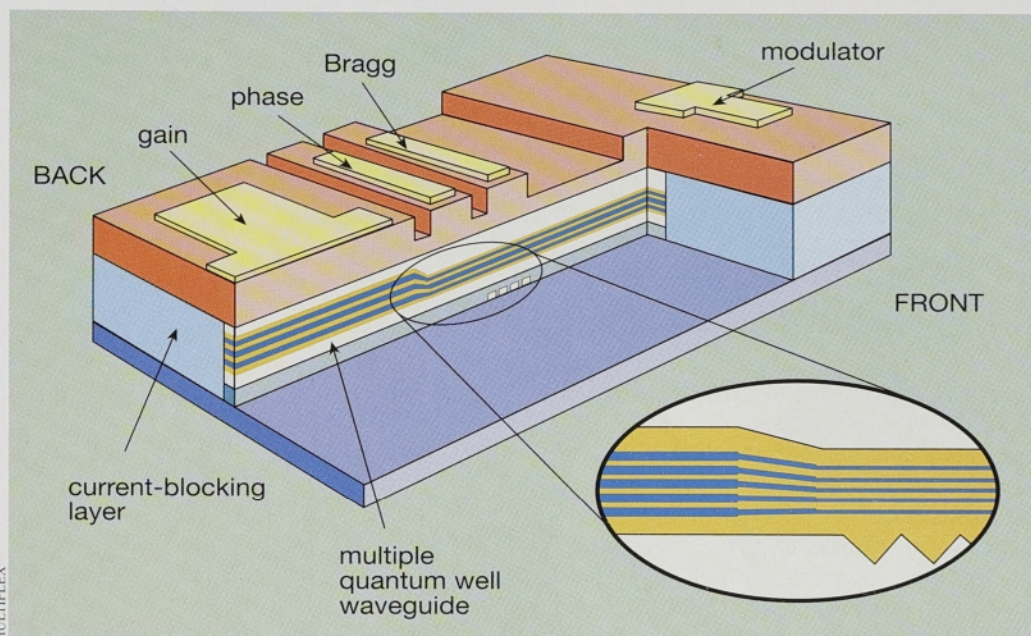


Fig. 1. Multiplex's tunable transmitter contains a three-section tunable laser with a monolithically integrated electroabsorption modulator. The InP-based chip is grown by MOCVD. Agere's monolithic chip also contains an SOA and a photodetector to monitor the power.

cations from metro to extended-reach systems up to 40 km. The company introduced a 2.5 Gbit/s tunable transmitter and 20-channel tunable laser module last year. The C92 will be sampled in the second quarter of 2001, with production expected by the fourth quarter.

Transponder sends and receives

Multiplex's MTX-TEML transmitter is a 10 Gbit/s variant of its earlier 2.5 Gbit/s transmitter that can be tuned to any one of 16 channels in under 10 ms.

Multiplex also introduced a packaged transponder (see figure 2) which contains the new tunable EML together with a 10 Gbit/s receiver. The MTRX192L receiver features an integrated limiting amplifier and achieves a sensitivity of -19 dBm at a bit rate error of 1E-10. Eye patterns from the transponder typically

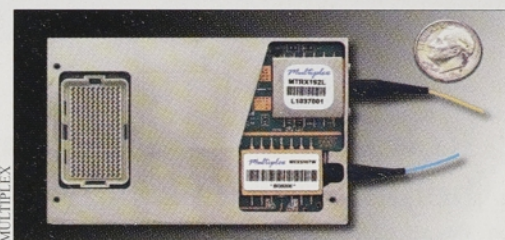
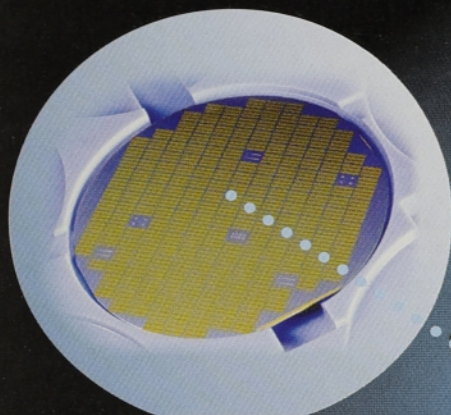


Fig. 2. Multiplex's tunable transponder is based on its transmitter and a 10 Gbit/s receiver and integrated driver amplifier.

indicate rise and fall times of 30 ps. Also built into the module as separate components are current sources, a temperature controller and a modulator driver. The package measures only 2 x 3 x 0.59 inches. Multiplex will begin shipping samples of the transponder in the second half of the year, with production expected three to six months later.

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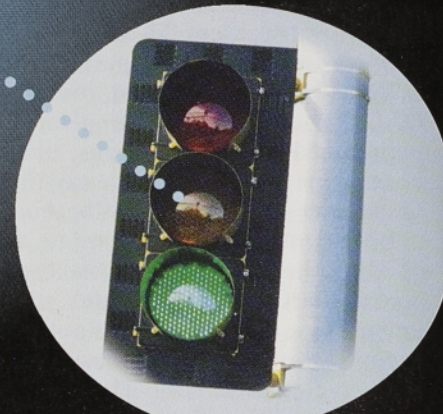
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Surface texturing boosts light emission in new-generation AlInGaP LED chips

*Controlling how light reflects at the surfaces of an LED chip has led to a doubling of the extraction efficiency of high-power red and yellow AS-AlInGaP LEDs, say **Norbert Linder** and co-workers from Osram Opto Semiconductors.*

LEDs have begun to penetrate the lighting component market, replacing both light bulbs and fluorescent lamps and at the same time opening up a whole range of new applications. Currently LEDs are principally used where monochromatic light sources are needed or in situations where the available space is restricted in some way. Examples include the interior and exterior lighting fixtures of automobiles, traffic signals and display applications.

To increase the market penetration of high-brightness LEDs, highly efficient emitters must be made available at low cost. With this in mind Osram Opto Semiconductors has developed a new generation of MOVPE-grown AlInGaP-LEDs for the red (620 nm) to yellowish-green (560 nm) wavelength range.

Getting the light out

The most severe constraint on the performance of LEDs is poor light extraction from the chip. This is a result of the small critical angles of total internal reflection, which are due to the large differences in refractive index between the semiconductor and the epoxy resin used in encapsulation. In the new device design an etched surface structure enhances the light emission through the window layer of the chip (see figure 1).

The basic elements of the surface texture of the chip are triangular-shaped structures which have tilted sidewalls. Within these structures closed reflection loops, such as are also present in rectangular-shaped chips, are broken by the non-rectangular geometry. Photons which are generated in the active layer can then be extracted more efficiently, either directly through the various surfaces or after multiple reflections with changing

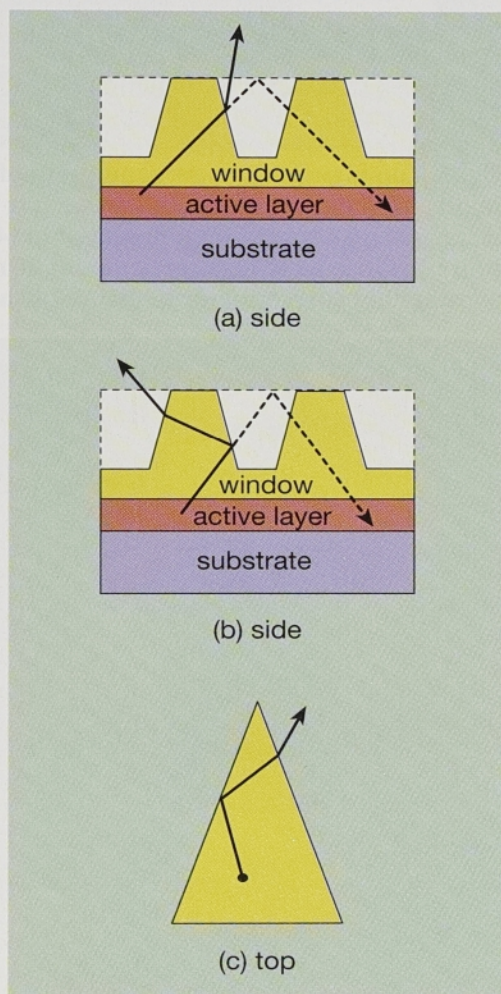


Fig. 1. Light extraction modes resulting from surface texturing. The full lines show the LED with surface structure incorporated, while the dotted lines show the LED with a plain window layer overgrowth: a) direct emission through sidewall of surface structure, b) emission through the sidewall after a reflection, changing the angle of incidence on the opposite surface, and c) emission in the lateral direction after reflection (top view).

angles of incidence.

Furthermore the contact geometry is chosen such that current is injected primarily under the light extraction structures. Using this design, an improvement in the external efficiency of more than 50% is obtained depending on the thickness of the window layer.

Absorbing substrates

The devices are grown on 4 inch absorbing GaAs substrates and the epitaxial structure is optimized for maximum electro-optical conversion efficiency using an appropriate choice of the layer composition and widths. For longer wavelengths such as 620 nm (red), the internal quantum efficiency is estimated to be close to 100%, and drops to about 60% at 590 nm for yellow devices.

Different layer structures are used for red and yellow LEDs, leading to similar values for the luminous flux for both colors with a maximum for reddish-orange (~610 nm). A specially designed wide-angle Bragg reflector is employed to recover a large part of the backward radiation of the chip.

Scalability

The wall-plug efficiencies obtained for surface-textured packaged chips exceed 30 lm/W. This is about twice as high as that obtained for conventional absorbing-substrate LEDs based on GaAs, and comparable to transparent substrate (TS) LEDs. TS-LEDs contain a device that has the original substrate removed and is typically wafer-bonded to a GaP substrate. This technique is currently limited to 3 inch wafers. Absorbing substrate (AS) LEDs omit this process.

The angular radiation characteristic of the chip is almost unaffected by the sur-

face structure and deviates little from the Lambertian shape. This particular feature allows standard square chips to be replaced without changing the package, even in applications where the radiation pattern is critical. A major attraction of the concept is the easy scaling to larger chip sizes.

At present there are three versions of the new-generation LED chip available for different types of applications: a high-current version, a standard chip and a low-cost design (see figure 2). For all chip types the typical operation voltage remains below 2.2 V. The LEDs are fabricated using standard chip processes, leading to high production yields and low manufacturing costs. The new chip is compatible with conventional mounting techniques and is available in a variety of SMT packages.

N Linder, S Kugler, P Stauss, R Wirth, H Zull and K P Streubel are with Osram Opto Semiconductors, Regensburg, Germany. Contact: "norbert.linder@osram-os.com".

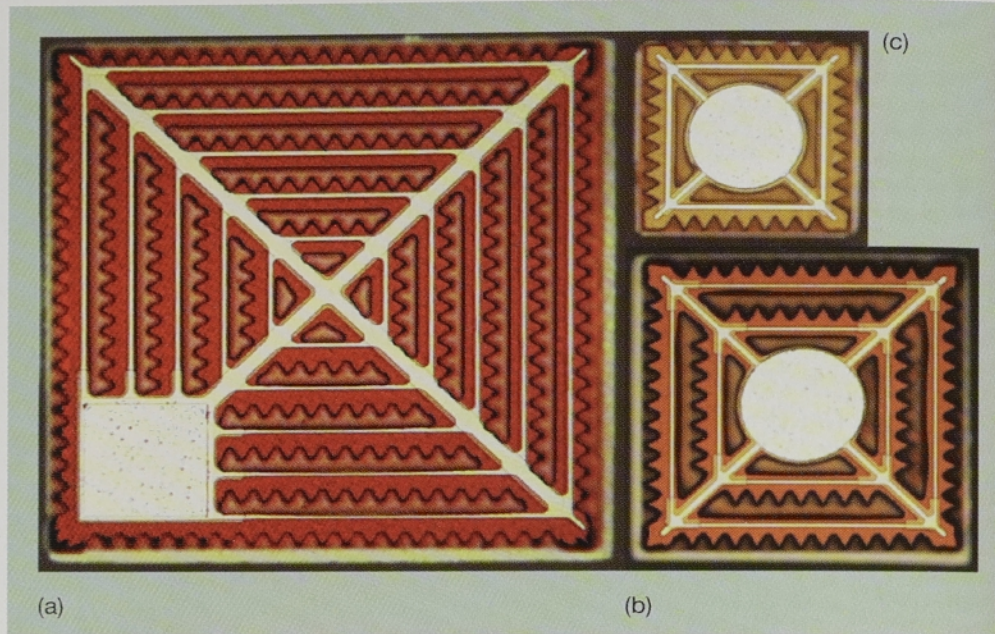


Fig. 2. Top view of the new generation of surface-textured chip from Osram Opto Semiconductors, showing the geometric patterning and several kinds of contact arrangement for: a) high-current chip (400 mA drive current, 500 $\mu\text{m} \times 500 \mu\text{m}$ die); b) standard chip (drive current 70 mA, 300 $\mu\text{m} \times 300 \mu\text{m}$ die); and c) low-current chip (drive current 30 mA, 200 $\mu\text{m} \times 200 \mu\text{m}$ die).

**She didn't know
the temperature either**

LEDEX flies under Nichia's radar

*As well as collaborating with an Australian university to develop blue lasers, Taiwanese firm LEDEX is mass-producing nitride LED chips and epiwafers. **Bob Johnstone** reports.*

Taiwan's LED makers are putting blue and green LEDs into mass production. But they are also cranking out patents, which they hope will protect them when Nichia's lawyers come knocking on their door.

LEDEX is perhaps the largest of the island's 14 or so nitride wannabes. The company began selling wafers and chips last December. According to LEDEX president Tony Wu, annual production capacity has reached 15 000 wafers.

"We're a similar size to Uniroyal already," Wu claims. The company operates three MOCVD reactors at its newly built \$35 million plant in the southwestern

Taiwanese port of Kaohsiung.

Though blue and green devices account for 90% or more of LEDEX's production, the firm is also fabricating ultraviolet LEDs. "We can make devices operating from 390 to 550 nm," Wu says.

LEDEX is co-operating with mainland Chinese companies in order to develop applications for UV LEDs. The firm has a head start in this area thanks to good relationships between the mainland government and its parent company, Yuh Chen. This group, whose chairman is Wu's father, has extensive interests including construction, hotels and real estate. "We're talking about letting some-

one do the OEM work [i.e. the LED packaging], then we buy back the finished products and sell them to the government," Wu explains.

UV LEDs can be used to excite phosphor materials, thereby creating white light. Among the possible applications are roadside lighting and the illumination of signs. The Chinese government recently approved the building of a very long highway that will run from the north of the country to the south. LEDEX has already sent samples for what could turn out to be a very big market.

Meanwhile the company is keeping its profile as low as possible. "Our focus is

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niche applications," Wu says. "We're not trying to compete in dominant markets with Toyoda Gosei or Agilent."

In particular, LEDEX is keen to avoid attracting Nichia's attention, which has stated publicly that it will defend its patents at all costs. But, anticipating an encounter with the Japanese company, LEDEX is accumulating a portfolio of its own intellectual property.

In December, soon after starting its marketing activities, the company applied for three patents in Taiwan and the US. Two of these concern wafer fabrication; the other relates to chip processing. LEDEX plans to file applications for four more patents this year.

"We're using a different LED structure [than Nichia] and different growth conditions," Wu says. Concerning the chip-processing patent he comments: "We're trying to reduce the chip-processing time and also the number of steps – the procedure cannot be completely different, but we can eliminate some of the steps and also use our own methods."

Wu is reluctant to divulge further details. But he believes the patents should

afford LEDEX some protection in case Nichia sues. "We cannot stop them suing us," he says, "but patents are useful when you go to patent court; at least we will have a very positive position."

LEDEX's precious intellectual property springs mostly from the brain of the company's star researcher and vice-president, Alan Li. A native of mainland China, Li did his PhD and postgraduate research at the Australian National University (ANU) in Canberra. Li moved to the National University of Singapore in 1998. Starting from scratch, Li demonstrated within a year that he could make blue LEDs. Word of this achievement reached Wu who had identified optoelectronics as a high-tech area with good prospects. He immediately recruited Li, who single-handedly designed and equipped the LEDEX plant in Kaohsiung.

Since Wu is also an Australian citizen, LEDEX leveraged its connection with the southern hemisphere. Thus far the company has sent two production engineers to ANU for training in ohmic contact and various processing issues. In the second quarter of this year the company plans to

establish an advanced R&D facility in Canberra. "BlueLab" will eventually employ about 15 scientists plus another 15 support staff. Investment in the lab will be around \$10 million.

BlueLab will focus on two projects. One will involve co-operation with the optoelectronics group at ANU to develop long wavelength components. But far more important is the development of a commercial blue laser, a feat that only Nichia has achieved so far.

There are two reasons why establishing an R&D facility so far from home makes sense. One is that Taiwanese universities do not produce the right kind of graduates. The other is the danger of poaching. Wu explains that in Taiwan, as in Silicon Valley, "engineers and scientists might be working for Company A in the morning, then they talk to someone at lunch, and in the afternoon they go to work for Company B." Locating your most advanced technology offshore makes such a scenario much less likely.

Bob Johnstone is a freelance writer based in Australia.

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Lasertel powers into the market

Despite being less than a year old, Lasertel has already established itself as a volume producer of high-power laser diodes for a wide range of applications.

A new Tucson-based laser manufacturer has opened its doors, built its first 10 000 square feet of clean-room, installed molecular beam epitaxy reactors, established processes to qualify for ISO 9001, and shipped products – all within its first six months of operation.

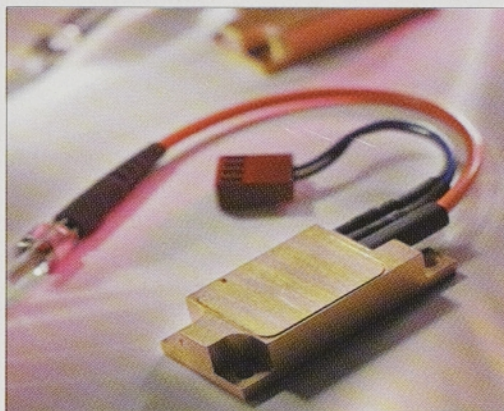
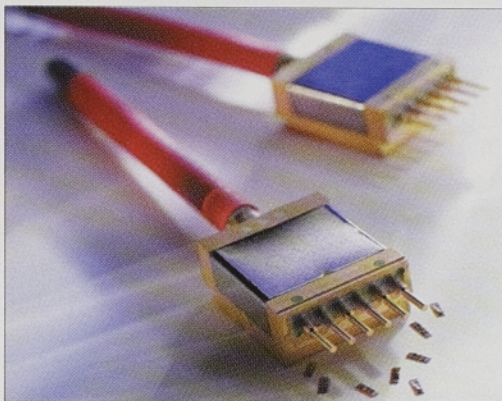
Lasertel, which was founded in May 2000, manufactures high-power semiconductor lasers. Initial products include 1 cm long unmounted bars with output powers of 20, 40 and 60 W. Also in Lasertel's portfolio is its unique Quad Blaster LT-Series, a fiber-coupled package containing four channels of individually addressable diodes at 830 nm. These high-power lasers incorporate packaging innovations that significantly reduce size. In comparison, four single-emitter packages require more than three times the space of a single Quad Blaster (see right).

The Quad Blaster was initially developed for Lasertel's parent company Presstek, based in Hudson, NH, which uses the Quad package as a component in its ProFire line. Presstek, the world's largest user of high-power, fiber-coupled diode lasers, manufactures digital imaging and thermal plate products.

Space savings

A large number of high-power lasers are required to achieve an acceptable plate write time in digital imaging applications. However, space is also at a premium, giving the four-emitter Quad Blaster a distinct advantage. Each of the four lasers is coupled to a 60 μm core fiber that emits up to 1 W of optical power. The four fiber outputs are sent through a single lens assembly, resulting in adjustable spot sizes of between 18 and 24 μm on the plate material. Presstek manufactures integrated optical assemblies with 32 optical outputs which contain 8 Quad Blaster packages.

In fact, says Lasertel CEO Tom Dearmin, Presstek created its newest sub-



The Quad Blaster package (top) contains four channels of individually addressable diodes at 830 nm and occupies less than one-third of the space of four single-emitter packages (bottom).

sidiary specifically to ensure that the company had a supply of lasers to maintain its cutting-edge position in digital technologies. "The high demand for semiconductor lasers, especially for the fast-growing telecommunications market, puts pressure on companies [such as Presstek] that need diodes for other applications," says Dearmin. "By starting Lasertel, Presstek guaranteed itself a reliable source of high-power, cost-effective lasers."

Just as important, Dearmin says, is that Lasertel was designed from the ground up to be a high-volume, state-of-the-art manufacturer for a broad range of industries.

It intends to use its design capabilities and excess capacity to serve other markets, including telecommunications, industrial, materials processing, illumination, medical, and government/defense industries. The company's quick start-up has already allowed it to offer unmounted bars and other semiconductor laser products to outside customers.

By the end of the year, Lasertel's 80 000 sq. ft facility will include clean-room space of 30 000 sq. ft, four molecular beam epitaxy reactors, additional production lines and a new manufacturing area devoted entirely to telecommunications products. "As a semiconductor laser company, Lasertel is focused on meeting specifications, high production volumes and on-time delivery," explains Dearmin. "Only a handful of companies can do high volume, and in the markets for semiconductor lasers, volume is crucial to sustained success."

An atypical start-up

With prior experience in starting and running a semiconductor laser operation, Lasertel's management team knew the importance of having a solid business plan at the outset. "Our plan was designed to capitalize on the successful operations of other companies, but also to correct for their weaknesses," notes Steve McComb, director of business development.

To fast-track its operation, Lasertel hired engineers, scientists and managers known for their work in photonics and their experience in volume manufacturing. The company also created an extensive employee development program, cross-training all workers in processing, assembly and fiber coupling. Once Lasertel operators and technicians have been certified on one process, they work in that area while simultaneously training on the next procedure.

With highly trained staff maintaining standardized quality processes, Lasertel



Lasertel technicians participate in an extensive employee development program, becoming certified on one procedure while cross-training for the next. This process leaves the company's engineers free to develop next-generation technology.

engineers are free to develop next-generation technology. "Our goal was to create a system that would retain key staff in a high-growth environment, while building flexibility into the very heart of the manufacturing process," explains Bernard Walik, vice-president of operations.

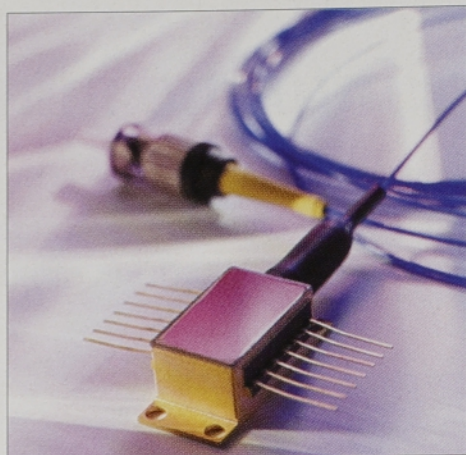
A second goal of Lasertel's business plan was to set up a paperless factory. Operator stations have flip charts that graphically demonstrate the manufacturing and assembly steps for each product, and touch-screen monitors are located at each station for more detailed instructions. "Both steps help streamline and standardize processes and increase throughput," says Walik.

Lasertel has also taken a different approach to materials management. Traditionally, a product is built in anticipation of what will be sold. By contrast, Lasertel's "lean manufacturing" strategy encourages production, engineering and marketing to work together to cut production time and fill orders quickly.

"The goal is to have a batch size of one, and a lead time of zero," says Linda Moore, materials manager. "This results in less inventory, less reworking, less wasted manufacture and less wasted material." Combined with cross-trained operators, this approach allows Lasertel to optimize resources, particularly for meeting customer-specific orders.

A powerful product range

At present, Lasertel manufactures multi-mode diode lasers and has plans to expand into single-mode products at the end of 2001. The primary LT Series includes



Lasertel manufactures 915 nm and 980 nm pump lasers for telecom applications and is also developing a 14xx nm variant.

single- and multi-emitter options. Standard wavelengths include 808, 830, 915, 940 and 980 nm, with a 14xx nm pump source in development. Seven standard product lines offer a variety of high-performance options, including small footprints for easy OEM integration, thermoelectrically cooled pump lasers, void-free bonding and robust packaging with TE and TM polarization.

In addition to its standard lines, Lasertel has devoted considerable resources to customer specific products. The company plans to integrate custom product packaging to meet customer specifications at market-enabling prices. "Our goal is to develop long-term partnerships," says Dearmin. "Some market segments in graphics, medical, industrial and other areas have been closed because of the high price of semiconductor lasers. Lasertel's volume operation, with optimized production and controlled costs, allows customers to efficiently integrate our products, and to innovate and expand into new markets."

Optics Valley

All the manufacturing steps at Lasertel are based at its Tucson facility, a distinct advantage in a high-tech industry in which companies routinely conduct assembly in other countries. According to Dearmin, 100% on-site production of semiconductor lasers results in quicker order-to-shipment times and greater control over R&D.

In-house development has also allowed Lasertel to make significant product advancements, starting with the initial epitaxial material and extending through the final polishing techniques for optical

fibers. Laser design has been optimized to improve electrical and optical performance. Epitaxial structures, laser cavities and emitter-to-emitter spacings have also been arranged to eliminate electrical and optical cross talk, allowing the emitters to be closely spaced and improving overall system performance.

Simplifying the internal characteristics of the package reduces the number of soldering steps, tolerance build-up and overall manufacturing time. Other improvements include aluminum-free platforms, the use of metallized ceramics, custom pre-deposited solder configurations, and automated pick-and-place equipment.

Lasertel uses state-of-the-art MBE reactors to grow its crystal wafers. These reactors and Lasertel's proprietary epitaxial processes significantly improve yield over that possible with other wafer technologies. As with all semiconductor devices, improved yield reduces the company's pass-along costs.

Lasertel is one of nearly 200 optics companies that, along with the highly regarded optical sciences and semiconductor programs at the University of Arizona, make up the Optics Valley in Tucson. This confluence of optics experts, supported by the Arizona Optics Industry Association, creates a unique synergy.

The future of semiconductor lasers

Industry experts agree that semiconductor lasers are in great demand, fueled by the growth in telecommunications. In positioning itself as a volume manufacturer, Lasertel expects to compete for its share of the pump laser market, making it one of a handful of independent suppliers.

Within two years of start-up, Lasertel plans to have the capacity to ship 1500–2000 diode packages a day, and increase its staff (now 100 plus) to more than 250 employees. Lasertel anticipates ISO qualification by the end of this year, and is also in the process of attaining Bellcore qualification for its telecommunications products in 2001.

"Our patents in semiconductor laser design and production, customer-specific product capabilities, and progress towards attaining ISO 9001 and Bellcore certification are attracting considerable attention," says Dearmin. "We're on track to produce hundreds of thousands of units per year. It's been a great first year, and I believe the next five years will show the same rate of growth."

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European start-ups take components further

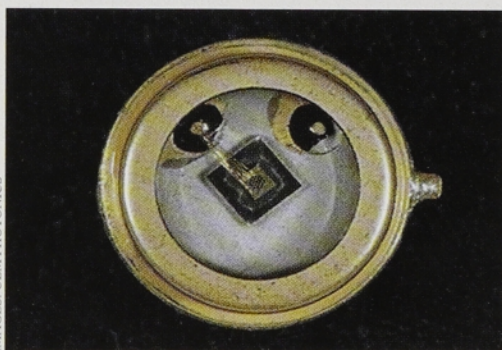
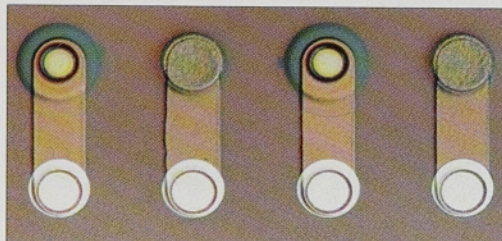
The demand for advanced fiber-optic components has resulted in the formation of a number of European companies that are manufacturing products such as VCSELs, 40 Gbit/s devices and hybrid assemblies. Bridget Adams reports.

Sales of active elements for telecommunications systems, primarily laser diodes, more than doubled last year, and strong growth is predicted for the next few years. The thirst for bandwidth caused by the Internet revolution and the recent interest in installing short-haul "metro" systems have helped fuel this situation. The spiraling growth of this sector has led to the expansion of existing optical components suppliers, and also to the setting up of new specialist component suppliers to the industry.

Many of these have spun out of universities, or are closely linked to them, as academic research finds real applications. The next-generation optical networks are likely to be based on functions executed directly in the optical domain, reducing the number of conversions between the electronic and optical domains. Integration of active and passive elements on the same optical chip is also attracting a great deal of interest. Here we take a look at some European start-up companies that are supplying active components based on compound semiconductor materials.

Ulm Photonics

Schott Communications Technologies of Sturbridge, MA, is the lead investor in a German start-up. Ulm Photonics GmbH is based in Ulm and was established last year. The new company specializes in oxide-confined VCSELs and has its own production facility. Ulm Photonics was founded by researchers from the optoelectronics department of the University of Ulm. The group was the first in Europe to develop oxide-confined VCSELs, which are associated with low threshold currents and high modulation bandwidths. Ulm Photonics has an MBE system to grow epiwafers for VCSELs in the 710–980 nm range; other material is purchased externally. The company says that challenges in production are to get an outstanding and



VCSEL devices fabricated by Ulm Photonics of Germany. The company is a spin-off from Ulm university.

homogeneous wafer material and to perform reproducible lithographic processing.

Ulm Photonics is already supplying products: these include 850 nm multimode VCSELs operating at up to 3.125 Gbit/s, 1-D and 2-D multimode arrays at 850 and 980 nm, and 1 mW singlemode VCSELs operating between 780 and 1020 nm. The next generation of products will include both single- and multimode VCSELs at 850 and 980 nm operating at up to 10 Gbit/s, and a multimode device producing more than 1 W output power.

u²t

An older German start-up is u²t Innovative Optoelectronic Components, based in Berlin and founded in 1998 by three researchers from the Heinrich-Hertz-Institut für Nachrichtentechnik (HHI). The institute houses the "Center of Excellence for InP Technology in Germany" and technology developed in this center

forms the base for the company. Its current products include ultrafast waveguide-integrated photodetector modules and chips. u²t also manufactures InP-based modulators that are designed using ultrafast travelling waves from a single RF supply, and provide a bandwidth of up to 50 GHz.

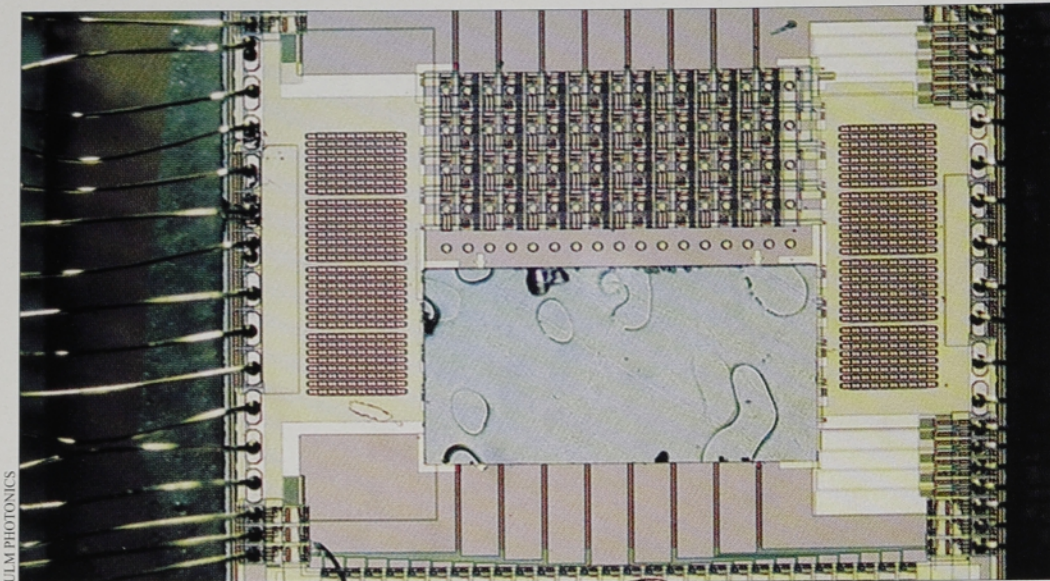
Nanoplus

A third German start-up, also founded in 1998, is Nanoplus Nanosystems and Technologies GmbH, based in Würzburg. The company's main products are DFB lasers, although it also produces a range of Fabry–Perot (FP), MQW and quantum-dot lasers, using a variety of materials including InGaAs, InGaAsP, GaInNAs, InGaAs/AlGaAs and Ga(In,Al)SbAs.

Using technology developed at the University of Würzburg, the company produces DFB lasers at customer-specific wavelengths in the 700–2300 nm range with high spectral purity (typical side-mode suppression ratio of > 35 dB). In this novel design, lasers are fabricated with metal gratings patterned laterally to the laser ridge: unlike conventional DFB lasers this structure does not require epitaxial regrowth. In the InGaAs/AlGaAs system monomode emission of up to 64 mW and sidemode suppression ratios of more than 45 dB have been obtained in laboratory trials in the university.

AIFotec AG

AIFotec AG, based in Martinsried near Munich, was also launched in 1998 as a profit center within the AMS Electronic Group. The company supplies a range of DFB and FP lasers and PIN photodiodes, although it does not manufacture the semiconductor chips. At the Optical Fiber Communication exhibition held in Anaheim, CA in March (OFC), AIFotec introduced a fiber grating laser (FGL) consisting of an FP laser and a grating



A multi-VCSEL array for applications such as parallel optical interconnects.

contained within the fiber (in contrast with DFB lasers, where the grating is part of the laser chip). The company claims the FGL approach provides higher flexibility and yield as well as longer transmission distances due to reduced chirp. The laser source for the FGL has an integrated spot-size converter, which improves coupling into the fiber.

AIFOTec plans to build a facility in Berlin to manufacture these and other types of advanced laser chips. The company is also focusing on the development of hybrids, using silica-on-silicon as a platform technology, as well as manufacturing automation. One example is the use of a high-precision laser-welding technology, utilizing a special process to avoid post-weld shift of components.

Marconi Optical Components

While not a new company, Marconi Optical Components represents a new business venture in the UK. The unit, formed in December 2000, combines Marconi Caswell laboratories' skills in optical design, material science, semiconductor technology and module optical design with the optical amplifier design and manufacturing expertise of Marconi Applied Technologies, based in Chelmsford. The unit also combines experience in InP and GaAs components with silicon expertise from Applied Technologies.

The new company will add a purpose-built, automated volume manufacturing facility. Caswell announced last year that it was converting its existing GaAs wafer fabrication facility to process wafers

6 inches in diameter. The first products from the new company include a tunable laser with wide tuning range and high-power and high-data-rate (10–40 Gbit/s) optical modulators. There will also be a strong emphasis on R&D programs to provide fully integrated solutions combining active and passive functions for high-value sub-system applications.

CST

Scotland's optoelectronics industrial base has expanded dramatically over the past few years. One key player is Compound Semiconductor Technologies (CST), a III-V optoelectronics foundry and technology-transfer company (see *Compound Semiconductor* Sept/Oct 2000, p27). CST has already acted as an incubator for two start-ups, Intense Photonics (see box) and Kamelian, and also undertakes foundry work at its facility in Glasgow.

Kamelian

One of two companies to emerge from the CST incubator, Kamelian is developing InP-based semiconductor optical amplifiers (SOAs). These will be integrated with externally fabricated passive components, such as arrayed waveguide gratings (AWGs), on a silicon micro-bench to form highly functional hybrids (see *Compound Semiconductor* April 2001, p41). Kamelian is currently using CST for prototype manufacturing and is building its own facility in Oxford, England. At OFC the company demonstrated an eight-channel reconfigurable optical add-drop multiplexer (OADM) based on an array of

SOA gates. Samples of the reconfigurable OADM and discrete SOAs will be available in the next few months.

Salento Innovation Technology

In Italy a commercial spin-off from the Nanotechnology Research Group at the University of Lecce is in the process of being established. Salento Innovation Technology aims to develop new quaternary (InGaAsN-based) heterostructures for active devices operating at 1310 and 1550 nm. According to Lecce group leader Roberto Cingolani, for the first three years Salento IT will focus on R&D work, although it has been set up as a profit-making company. Purpose-built laboratories will be ready in a few months, at which point the company will start its research program.

Cingolani aims to capitalize on the experience and production capability within his group to sell R&D to outside companies. The Lecce group already works with InGaAs- and InGaN-based materials, and has extensive MOCVD reactor and cleanroom facilities. The nanotechnology division is based on a complete facility, consisting of a class-10 000/1000 cleanroom, various kinds of lithography, reactive ion etching, plasma-enhanced CVD, mask aligner and device packaging and fabrication facilities. It has produced novel quantum-wire as well as quantum-dot lasers.

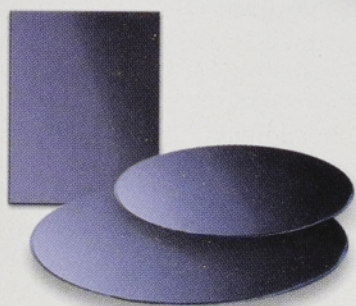
Optillion

New in Scandinavia is Swedish start-up Optillion, currently based in Kista. Optillion plans to develop and manufacture highly integrated, ultrahigh-bandwidth Ethernet transceivers for next-generation networks. The company recently received second-round funding of \$53 million to help finance its new high-volume manufacturing facility. Products will include InGaAsP-based lasers, as well as modulators and detectors, which will be integrated onto silicon platforms to produce transceiver modules (see *Compound Semiconductor* March 2001, p9).

Modulight

Based in Tampere, Finland, Modulight is another Scandinavian start-up. The company is currently in the product development stage, but hopes to be in production by summer this year in a new purpose-built facility. Its range includes lasers, amplifiers and receivers, shipped

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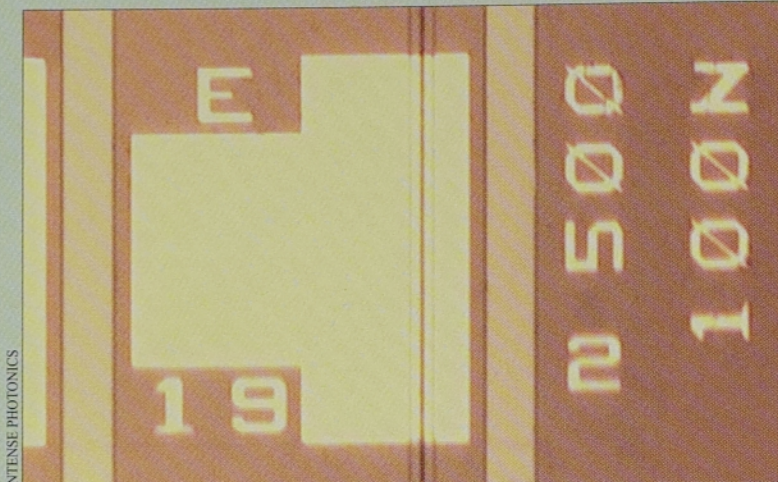
Quantum-well intermixing leads to Intense products

Several recently formed start-up companies are addressing the monolithic integration of multifunctional devices and waveguides on indium phosphide. One of these is Intense Photonics, based at the West of Scotland Science Park in Glasgow, Scotland. The company has licensed a technology, quantum-well intermixing, which was developed at the University of Glasgow over a period of some 12 years by the optoelectronics group led by John Marsh.

Quantum-well intermixing (QWI) uses rapid thermal annealing to alter the shape of a quantum well from its regular square profile. Elements inside the quantum well diffuse out while elements in the barrier layers diffuse in, creating a more Gaussian shape.

"The effect is to increase the quantum-well bandgap, forming a transparent waveguide," explains Craig Hamilton, Intense Photonics' technical director. "The QW-intermixed regions do not absorb light created in the regions where intermixing has not been applied." QWI is applied to selected regions of an epitaxial wafer, after which devices are defined by more conventional processing techniques such as dry etching.

One application of the QWI process is the



A 980 nm laser chip fabricated by Intense Photonics. Quantum-well intermixing (QWI) is used to fabricate non-absorbing mirror structures on the facets.

incorporation of non-absorbing mirror structures onto the device facets of 980 nm pump lasers. Since QWI is a wafer-scale process, it offers manufacturing advantages over other techniques that use regrowth onto cleaved facets of individual devices.

There are other benefits too, explains Hamilton. "As well as generating low-loss regions we can manipulate the light, for example by incorporating spatial mode filters to maintain a single-mode output," he says. "We can also incorporate mode stabilizers to prevent the beam from moving around as the output power is increased." Intense Photonics has already demonstrated 980 nm pump lasers in the

laboratory that provide output powers of up to 500 mW. Commercial products are expected to be available towards the end of the year.

Monolithic integration

A key focus now for Intense Photonics is to apply QWI technology to monolithic integration on InP. The research team which generated the IP behind the QWI approach have fabricated laboratory demonstrators such as all-optical packet switches and crosspoint switches that have nanosecond switching speeds. The latter example integrates active devices such as amplifiers and modulators with waveguides and multi-mode interference couplers for splitting and combining.

In the short term Intense Photonics is developing discrete components such as 980 nm pump lasers, using QWI to add functionality to these devices. "We're also engaging with companies doing hybrid integration, with a view to providing them with components that make integration easier," says Hamilton. "In the longer term we will move towards true monolithic integration."

Intense Photonics began life as the first company to use the services of Compound Semiconductor Technology (CST), an independent foundry and technology-transfer company. Intense Photonics was initially housed with CST, but now occupies its own facilities on the same campus.

The company uses CST's foundry processing services, although the critical QWI procedure is performed at Intense Photonics' laboratories. The company has not yet committed to a plan to build its own manufacturing facilities, given the uncertain state of the market.

Intense Photonics was incorporated in May 2000 with seed capital from 3i and ACT Venture Capital; the University of Glasgow also took an equity stake in return for an exclusive license to its QWI patent portfolio and technology. Its first round of funding should close soon.

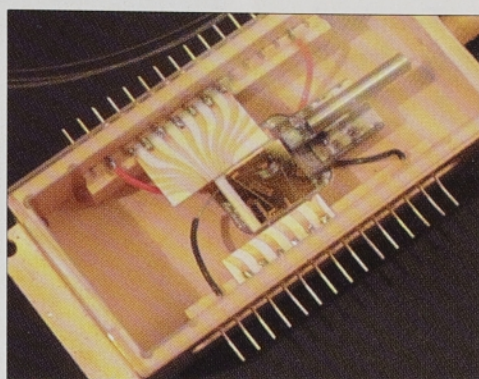
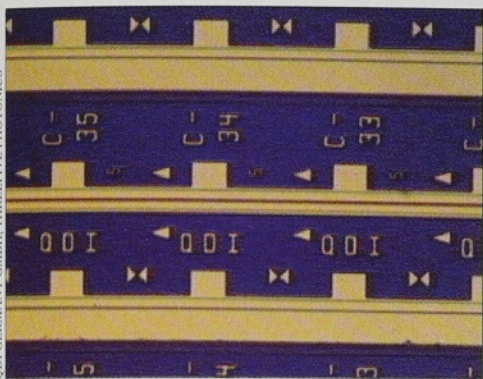
as chips and processed wafers and based on InP and GaAs-based materials. Modulight was founded in May 2000 by a group of researchers from the Optoelectronics Research Center at the Technical University of Tampere (TUT), with funding provided by the French company Picogiga, a producer of compound semiconductor epiwafers for microwave applications. The company currently has 14 employees, and is developing transmit-

ters, receivers and higher-power lasers.

The focus of Modulight's 1310 nm and 1550 nm transmitter products is on short- and intermediate-reach medium-speed networks. The lasers are Fabry-Perot in design and operate at up to 2.5 Gbit/s. Receiver products are based on high-speed, high-sensitivity avalanche photodetectors (APDs). The company is also developing aluminum-free higher-power pump lasers for EDFAs.

Avalon Photonics

New Swiss company Avalon Photonics, based in Zurich, spun out of the Swiss Center for Electronics & Microtechnology SA (CSEM) in June 2000. Avalon also has links with the Paul Scherrer Institute in Zurich, where CEO Karlheinz Gulden was previously responsible for VCSEL development. The new company was set up to develop and manufacture optoelectronic products in general and



QDI Germany is manufacturing temperature-tunable DFB laser chips (left), while ThreeFive Photonics is developing monolithically integrated InP components.

VCSEL arrays in particular, targeting the short-reach, high-bandwidth data communications market.

In September 2000 the company raised \$14 million in venture capital. The funding is being used to extend production and optoelectronic engineering capabilities to allow the manufacturing of volume products. As part of CSEM Avalon was active in developing single- and multimode VCSELs (see *Compound Semiconductor* July/August 1999, p34), including the first 16×16 individually addressed VCSEL array for optical interconnects.

The company uses multiwafer MOVPE reactors and lithographic processing to produce AlGaAs wafers. Current products include 1×4 and 1×12 VCSEL array chips operating at 850 nm at up to 3.125 Gbit/s. Experimental 2-D VCSEL array chips are also available with an 8×8 configuration. Development is currently centered on 10 Gbit/s VCSELs, high-power bottom emitting arrays, integration of diffractive optics and customer-specific projects. Longer-term research is focusing on long-wavelength VCSELs.

QDI Germany GmbH

For the last three years Quantum Devices Inc. (QDI), an optical device manufacturer based in Yorba Linda, CA, has co-operated with the HHI to develop laser chips. At the start of 2001 QDI established a subsidiary, QDI Germany GmbH, to transfer the technology developed at HHI into a high-volume manufacturing source of tunable lasers. Chips are currently fabricated by QDI in facilities leased from HHI; production will be transferred to a purpose-built fab with a 750 m² cleanroom area. By the end of next year QDI will invest about €10 million (~\$9 million) in the new facility, which will increase its production level from 200 to 100 000 chips per month.

QDI uses DFB lasers for its tunable modules; the wavelength is selected by adjusting the temperature. Although these devices offer slower tuning and a narrower tuning range than electronically controlled DBR-type lasers, QDI feels that DFB lasers are a field-proven technology offering very high reliability and wavelength stability. QDI's first tunable product, λ -Light, is a 1 mW device with tuning over four wavelengths at 100 GHz spacing; the WSL device, due to be released in June, will cover between eight and 16 wavelengths.

ThreeFive Photonics BV

Finally the newest company around is ThreeFive Photonics BV, which is based in Delft, The Netherlands. ThreeFive spun out of the Photonic Integrated Circuits group of the Delft University of Technology earlier this year, with funding from the Gilde IT Fund. The company is planning to offer monolithically integrated InP systems, and believes that InP is the platform for next-generation optical networking. The material allows the construction of extremely compact devices because of the relatively high refractive indices of InP and its ternary and quaternary derivatives.

These high refractive indices allow for small curve radii, leading to components that are at least 10 times smaller than current state-of-the-art silicon technology. As an active material it is also ideally suited to monolithic integration, with active and passive components on the same platform. The company claims that incorporating SOAs in these devices can compensate for the higher insertion losses which are associated with InP.

Bridget Adams is a freelance writer based in the UK. Additional material provided by Tim Whitaker.

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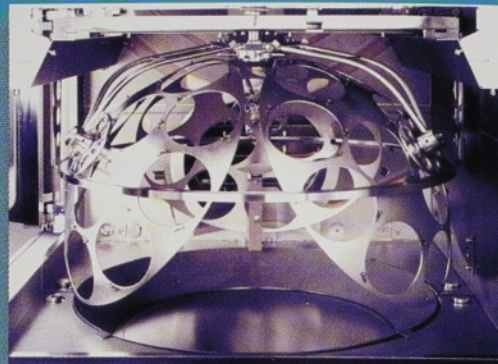
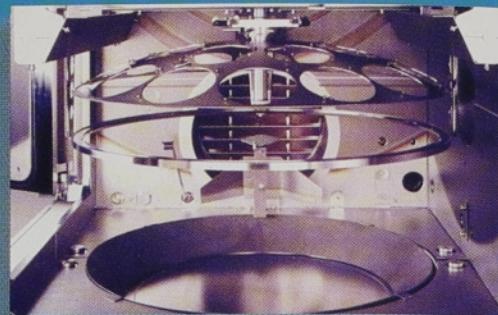
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Market slowdown deflates GaAs bubble

*Despite all the recent bad news surrounding the GaAs industry its medium-term prospects remain strong, according to **Stephen Entwistle** and **Asif Anwar** of Strategy Analytics.*

As major GaAs players such as RF Micro Devices, Vitesse, Anadigics and TriQuint announce slowdowns and revised quarterly and full-year revenue projections, is the GaAs industry's shining star about to fade into obscurity? Only four months ago GaAs companies were announcing record revenues and profits and making projections for continued strong growth. However, the major GaAs companies have recently announced revisions of their financial guidance for the coming quarter and in some cases for the full financial year. The slowdown is primarily in the two markets which have been the key areas of growth, namely cellular and fiber-optics, although it seems that even consumer markets such as cable and satellite infrastructure and set-top boxes are not immune.

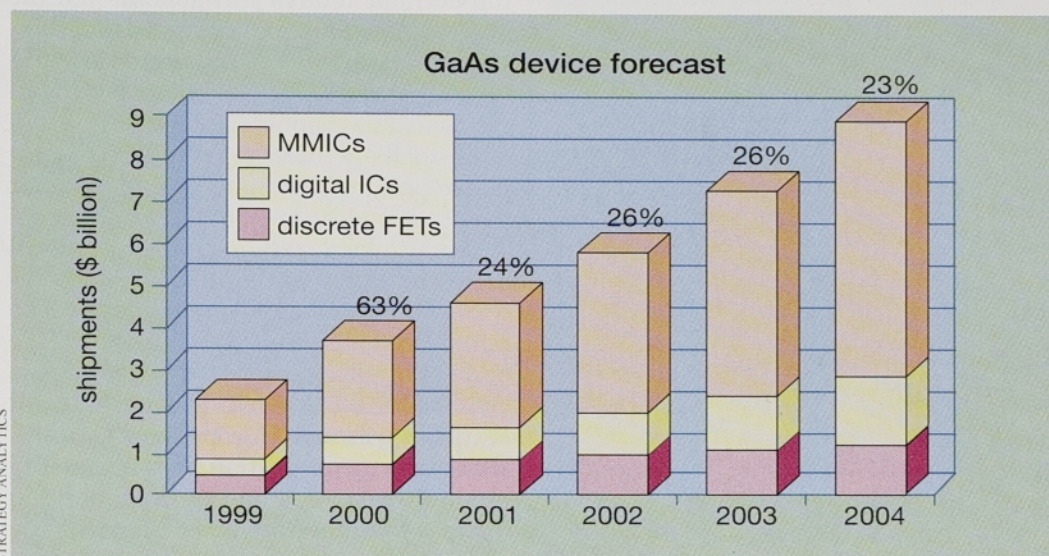
So what does the future hold for the GaAs industry? And how will its fortunes change in the medium and long terms? A few months ago the industry was full steam ahead: ever-expanding wireless markets and the demand for bandwidth generated high growth for firms involved in the infrastructure markets for both wireless and fiber-optic communications.

Europe shoulders the strain

Economic slowdown has resulted in the telecom sector suffering in particular. This situation has been triggered by the general malaise in the American economy and the continuing woes of the Japanese sector, leaving western Europe with the demanding task of counterbalancing the overall market.

This economic slowdown is filtering down into the GaAs market, with major players such as Vitesse, Anadigics, RF Micro Devices and TriQuint announcing revisions to their financial projections and cutting back on planned expansions. It would appear that the boom in the GaAs industry is over.

Currently most industry executives and



Strategy Analytics predicts continued growth for the GaAs market, although at lower rates than in recent years. Percentage figures represent year-on-year growth for the total GaAs market.

some observers are talking about inventory corrections, coupled with a falling back of growth from the recent dizzy heights. In the latter part of 2000 the top GaAs companies had book-to-bill ratios in the 1.1 to 1.2 range, meaning that the industry had a backlog in the order of hundreds of millions of dollars. Many are forecasting a return to strength in the fourth quarter of 2001, based on the push-out of orders resulting in shipments later in the year. Clearly a worsening situation would develop if these same customers later cancelled these delayed orders.

Based on the popular views of the moment, it is easy to assert that total demand will continue to grow. Last year saw a glut of inventory in the handset market, and the recent slowdown there is a consequence of companies attempting to balance this inventory, rather than as a result of slowing demand. The demand for bandwidth, driven by the growth of the Internet, will carry on and this will require the continued roll-out of 10 Gbit/s products. It will also drive the 2.5 Gbit/s

and 10 Gbit/s data-centric markets.

Therefore perhaps the first question that should be addressed is whether slow demand is truly due to inventory corrections or a sign of something much worse. Strategy Analytics closely tracks the key markets for GaAs devices and our view of the key issues is outlined below, starting with the real factors which are affecting market growth in the key sectors of fiber-optic and cellular communications.

A change from voice to data

With fiber-optic telecoms, there is an issue with the market demanding that the operators' business models change from voice to data. Adjustments have been made, but the current slowdown is forcing the pace for further structural changes, with the addition of value-added services and flexible data provisioning becoming key parameters for future success. The operators are not quite on a "spending strike" but are looking closely at every dollar of capital investment. Currently this focus is not having too significant an effect on the key

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FORUM - GaAs DEVICE MARKET

GaAs application of 10 Gbit/s markets (see our report "Analog IC demand from fiber-optic communications viewpoint"). In the short term the supply chain is taking the opportunity to ease up and enjoy a well-earned breathing space. This is only a positive thing if the current slowdown is short lived or not too pronounced.

Handsets still in demand

This year will definitely be interesting for the cellular industry in general and the handset market in particular. Annual shipment growth rates in the region of 65% (1999) or even 46% (2000) are a thing of the past, and vendors (and operators) will need to work hard to give users compelling enough reasons to replace their handsets, and so drive on demand.

It may appear extreme to put the recent dramatic downturn in market expectations down to a one-time adjustment in inventory levels, but we believe that the underlying metrics of the wireless market remain firm. Subscriber growth will slow in western Europe and the US. However, growth remains promising in south-east Asia and in the emerging markets in Latin America, eastern Europe and Africa.

Apart from subscriber growth, one of the key drivers for the handset market is the rate of replacement. In 1999, 43% of global handset shipments were replacement sales, with the average handset life-cycle standing at 31.7 months. This figure fell to 27.5 months in 2000. Our forecasts of 500 million shipments for 2001 are based on a rather modest downward shift in replacement rates to 25.6 months. (This topic is discussed in more detail in an Insight from Strategy Analytics' Wireless Device Strategies service - "Handset market fundamentals remain sound".)

Implications for the future

We do not believe that there is any danger of a collapse in the medium-term prospects of the GaAs market for the following reasons:

- Shipments across the industry will grow during 2001, or at worst remain flat;
- GaAs device penetration will increase in most applications;
- ASPs can be held from deep declines by the general single-sourcing nature of the GaAs industry.

But, as some in the industry already appreciate, the issues are more complex than the prospects for growth in the

medium term. For example, would a decrease in confidence make the industry adopt short-termist tactics, which could damage longer-term prospects?

Given that inherent demand is still strong and will produce unit shipment growth for GaAs devices, the final outcome for GaAs revenues for 2001 and beyond would seem to rest in the hands of the OEMs of GaAs device themselves. If they can withstand any excessive price pressure and keep their nerve then revenues will continue to grow.

The leading GaAs device OEMs are certainly strong enough to weather twelve months or more of difficult times, with many having extremely strong balance sheets including good amounts of cash reserves. In addition, we still observe pos-

It is a perverse testimony to the recent success of the GaAs industry that it has reached a level of maturity which makes it vulnerable to fluctuations in the global market.

itive signs of health outside the high-profile, US publicly listed GaAs device companies with, in particular, strong growth in Japan and Asia-Pacific.

No reason to panic

The GaAs market is clearly suffering the effects of a general deceleration in the world economy. However, we believe that while this may lead to a temporary six to twelve-month slowdown in the expansion of the GaAs market, it will not cause a collapse or contraction. Indeed, in some respects it is a perverse testimony to the recent success of the GaAs industry that it has reached a level of maturity which makes it vulnerable to such fluctuations in the global market.

We aim to work with companies to keep them focused on the "sweet spots" of market growth. Perhaps we should be saying that the GaAs bubble has not burst, it has merely had some air (or should that be GaAs) knocked out of it.

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Taiwan's foundry race will have few winners

Taiwan's GaAs foundry companies have ambitious plans to capture large slices of the device wafer market, but most of these will not come to fruition, writes Tim Whitaker.

The last two years have seen the emergence of a number of companies intent on establishing GaAs foundries in Taiwan. Buoyed by the strong growth in demand for GaAs ICs, these companies sought to emulate the success of the giant Taiwanese silicon foundries, notably TSMC and UMC. There has been impressive progress; Taiwan can already boast the world's first "pure play" 6 inch GaAs foundry company, WIN Semiconductors. However, prospects are much less rosy than they were as recently as six months ago. The precise level of demand within the GaAs market is unclear at present, but it is apparent that the GaAs industry as a whole has plenty of capacity to sustain itself for at least one or two years. Coupled with the inherent problems in establishing a foundry company in the GaAs industry, no-one expects that all the GaAs foundry projects in Taiwan will survive.

Several plans have already gone up in smoke. Last summer, a company named G-Advanced Semiconductor held a groundbreaking ceremony for a 6 inch GaAs fab, then promptly vanished without trace. More recently, Arima, a major OEM supplier of notebook PCs and wireless handsets, reportedly shelved its plans for Arima Broadband, a subsidiary company which was to have built a GaAs fab and offered foundry services.

Even so, there are already four GaAs fabs in Taiwan (Hexawave, Transcom, Advanced Wireless Semiconductor Company (AWSC), and WIN Semiconductors), with three more under construction (Compound Semiconductor Manufacturing Corporation (CSMC), Global Communication Technology (GCT), and Suntek Compound Semiconductor Company). In addition, most of these companies already have plans to expand or to build second fabs. These projects will now be described in more detail,



First of many: GaAs foundry companies in Taiwan intend to produce tens of thousands of 6 inch wafers per month.

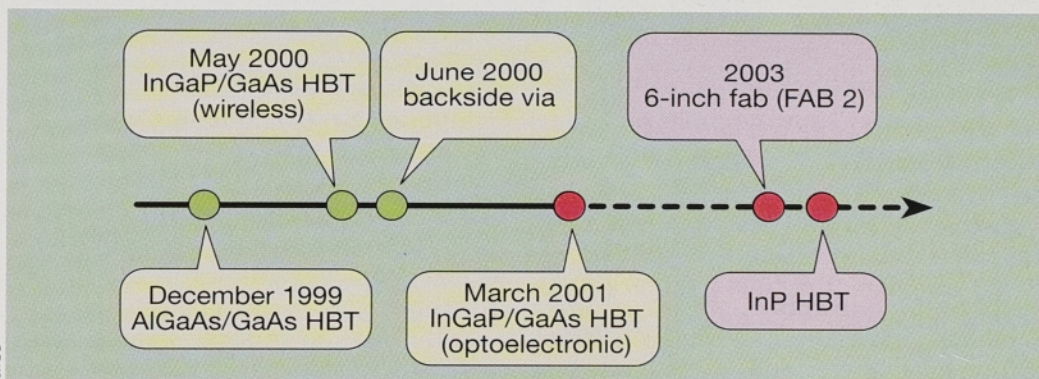


Fig. 1. Technology roadmap for Advanced Wireless Semiconductor Company, who recently delayed plans to install a 6 inch fabrication line until 2003.

based on the information supplied by the companies themselves.

AWSC

Dating back to April 1998, AWSC is the oldest of Taiwan's GaAs foundry companies. The company operates a 4 inch HBT fab in Tainan, with a current capacity of 600 wafers per week. The facility is being expanded to double its capacity for 4 inch wafers. When *Compound Semiconductor* spoke to AWSC one year ago, the company was about to start the installation of a 6 inch manufacturing line, but these plans were subsequently put on hold. "Originally, we planned to do 6 inch for phase 2 of our FAB 1," says AWSC's

Charles Wang. "However, it now seems that this is not a good time to jump into 6 inch GaAs. Therefore, phase 2 of FAB 1 will be 4 inch."

AWSC now offers two InGaP/GaAs HBT processes, one suited for wireless power amplifiers and the other targeted towards ICs for high data-rate OC-192 fiber-optic networks. AWSC has a 6 inch fab (FAB 2) on its technology roadmap (see figure 1), along with InP HBTs. According to Wang, the 6 inch fab is likely to be built in 2003, and will be expanded in two phases, each providing a capacity of 1500 wafers per week. AWSC has a foundry agreement in place to supply HBT wafers to Conexant, but

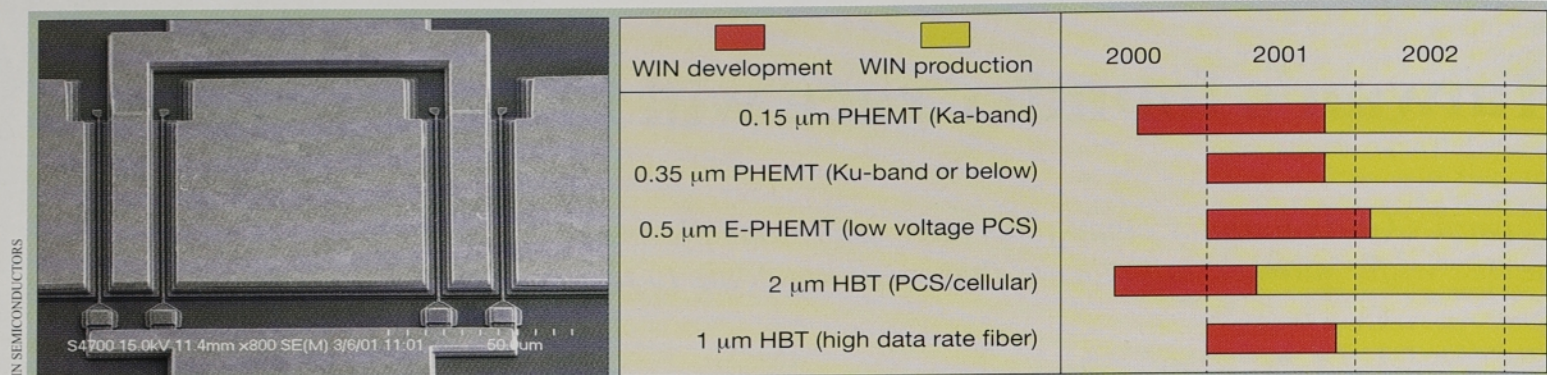


Fig. 2. Detail from an MMIC fabricated by WIN Semiconductors using a 0.15 μm gate length PHEMT process (left). WIN's technology roadmap (right) shows that full production of 2 μm HBTs is expected in April 2001.

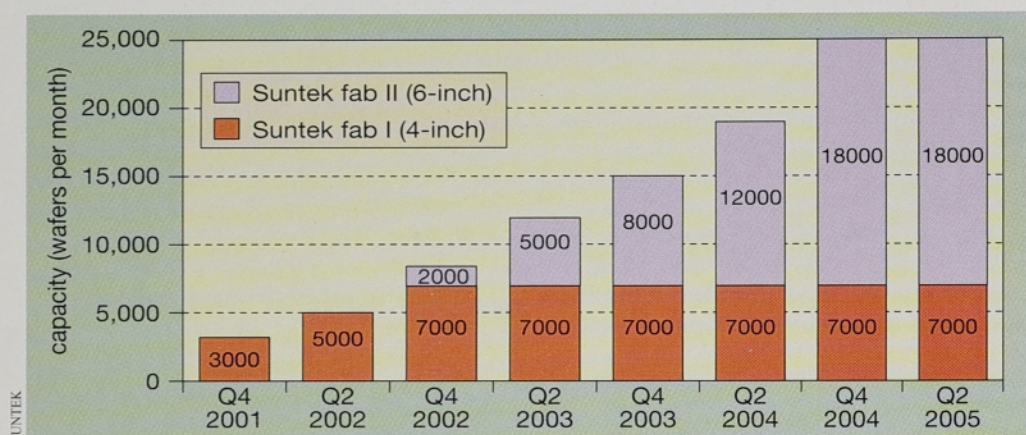


Fig. 3. Capacity ramp-up plan for Suntek Compound Semiconductor Company, a joint venture between Procomp Informatics and Acer.

reports suggest that the AWSC process has still to be qualified.

WIN Semiconductors

WIN (an abbreviation of Wireless, Information and Networking) was founded in October 1999, and completed construction of its fab, including a 20 000 sq. ft clean-room, in July 2000. The company rightly claims to be the world's first "pure play" 6 inch GaAs foundry. Following equipment installation in August, the company demonstrated 6 inch, 2 μm HBT wafers in November of last year, and 6 inch PHEMT wafers in December. In March, WIN demonstrated another milestone – the first 6 inch MMIC wafer fabricated using a 0.15 μm gate length PHEMT process (see figure 2), which has f_T and f_{max} values of 85 and 220 GHz, respectively.

As shown in the company's technology roadmap (figure 2), WIN plans to enter full production in April 2001, initially offering 2.0 μm HBTs for L-band PCS/cellular phones, WLAN and two-way pagers. PHEMT processes of 0.15 μm

and 0.35 μm, together with a 1 μm HBT process for high data-rate fiber-optic applications, will follow towards the end of this year.

WIN aims to process 10 000 6-inch wafers this year, rising to 30 000 wafers in 2002, and will reach its full annual capacity of 100 000 wafers in 2005. Annual revenues are expected to reach \$0.5 billion. WIN believes the current fiber-optic and broadband wireless markets require around 250 000 6-inch equivalent GaAs wafers every year, and that this figure will reach 1 million wafers by 2005. If these figures are correct, WIN's capacity will supply 10% of the world market in 2005.

CSMC

Founded in July 2000, CSMC plans to start mass production in June of this year, at a level of 2000 4-inch wafers per month. Products will include HBTs and PHEMTs for both wireless and fiber-optic applications. CSMC's current 800 m² clean room space will be expanded later this year to 2500 m², and the company expects to have

as many as 10 fabrication lines in place by 2003. Capacity is forecast to reach 16 000 wafers (4 and 6 inch) per month.

GCT

GCT is setting up a 6 inch GaAs fab in Hsinchu that will have a capacity of 5000 wafers per month. Mass production is expected to commence by the end of 2001. GCT also plans to construct a second, larger fab in 2002 (see *Compound Semiconductor* February 2001, p57).

Suntek

Suntek Compound Semiconductor Company was founded in August 2000 as a joint venture between Procomp Informatics, Taiwan's leading supplier of microwave epiwafers, and Acer Communication and Multimedia. Suntek is working closely with at least two established IDMs (integrated device manufacturers). According to Suntek's James Lin, the foundry has a technology transfer agreement with Mitsubishi, under which the Japanese company will transfer its 4 inch HBT processes to Suntek. "Mitsubishi also has a foundry service agreement to buy back HBT-based ICs from Suntek," says Lin. Furthermore, the US GaAs manufacturer Celeritek has invested \$2.4 million in Suntek, and also has a foundry service agreement in place.

Suntek's plan to implement its first fab, which will process 4 inch wafers, calls for construction to be completed by the end of April 2001. Following equipment installation and test runs, the production ramp-up phase is scheduled for the final quarter of 2001. Mass production is expected to commence by the end of this year. Suntek's initial products will be AlGaAs and InGaP HBTs. In 2002, the company expects to offer InP HBTs and 0.5 μm

GaAs foundry projects in Taiwan

Fab	Capacity	1st phase	2nd phase
AWSC	Fab 1: 1200 × 4 inch wafers/week Fab 2: 3000 × 6 inch wafers/week	2300	13 000
WIN	100 000 × 6 inch wafers/year	8330	
CSMC	Phase 1: 5000 wafers/month (4 & 6 inch) Phase 2: 11 000 wafers/month (4 & 6 inch)	3000*	9000*
GCT	Fab 1: 5000 × 6 inch wafers/month Fab 2: 15 000 × 6 inch wafers/month	5000	15 000
Suntek	Fab 1: 7000 × 4 inch wafers/month Fab 2: 18 000 × 6 inch wafers/month	3100	18 000
	Total (6 inch wafers/month)	21 730	55 000
	Combined total	76 730	

*Estimates.

Table 1. Production capacity for the major foundry projects in Taiwan, based on information supplied by the companies themselves. The two columns on the right give the monthly capacity of 6 inch equivalent wafers.

GaAs PHEMTs, as well as optical devices such as photodiodes, lasers and VCSELs.

Suntek also has plans to build a 6 inch line for the production of GaAs HBTs and PHEMTs. As shown in figure 3, 6 inch

production is expected to commence in the final quarter of 2002. According to its current plans, Suntek plans to ramp its capacity to a level of 21 100 6-inch equivalent wafers by the end of 2004.

Analysis

Even without the downturn being experienced by the GaAs industry at the moment, it will be impossible for all these companies to be successful to the full extent of their original plans. As shown in table 1, Taiwan's GaAs production would exceed 1 million 6 inch wafers per year by 2005 if all the projects went forward, and this would be almost entirely composed of foundry capacity. The likely scenario is that most, if not all, of the "fab 2" projects will be put on hold indefinitely, or simply cancelled. Many observers have predicted that only one or perhaps two of the Taiwanese foundries will be successful. Of the larger projects, WIN has achieved a "first-mover" advantage, GCT has strong but complicated links with an established US GaAs foundry, GCS, and Suntek already has two foundry partners, Mitsubishi and Celeritek. Picking a winner will certainly not be easy.

The challenges of founding a foundry

Taking a high-performance GaAs process from an R&D environment to a high-volume manufacturing facility offering commercial foundry services is fraught with problems. One person with first hand knowledge of this area is Ding Day, president of Network Device Incorporated (NDI), established in February 1997 as the GaAs industry's first "pure play" foundry. In February 2000, NDI was acquired by Alpha Industries.

Attracting investment

Taiwan's GaAs boom is based on the success of the foundry model in the silicon industry and the stellar performance of companies such as TSMC and UMC. By drawing parallels between TSMC and their own business plans, the technical teams behind Taiwan's GaAs foundry projects were able to attract plenty of investment. "The technical teams told their investors that the market would be big; that they had the best technology and would capture the whole of the GaAs foundry market; and that they would become the TSMC of the GaAs industry," says Day. "Many fab projects were funded on this basis alone."

From his experiences with NDI, Day understands that new foundry companies face several major challenges. The first is that the technical teams involved in setting up foundry companies tend to lack operational knowledge. "In most foundry companies, the technical teams have a background in R&D or in small-scale manufacturing," says Day. "They lack real exposure to high-volume manufacturing." He contends that wafer fab operation skills are equally as important as the basic technology. "Foundry is basically a service industry. You need to have the right infrastructure in place for high-volume production, such as establishing foundry manuals, setting up quality control and assurance, getting ISO qualification and installing manufacturing execution software for wafer tracking, data collecting and engineering, production control and customer interfaces. You also need a very strong management team that can deal with issues like quality, delivery and customer support. It's a huge task to try to emulate TSMC in the GaAs world." In fact, TSMC started life as a spin-off from Philips, so a lot of the manufacturing infrastructure was already in place.

The other problem, says Day, is that the financial backers for the Taiwanese GaAs foundries probably made their decisions based on insufficient information or overly optimistic data. "Investors have been told that the overall market demand for GaAs wafers and the foundry market are several times higher than they actually are."

According to reliable estimates, made prior to the current slowdown in demand, the entire worldwide market for wireless and broadband GaAs ICs and devices in 2002 could be supplied by the equivalent of a large silicon fab producing 30 000 to 40 000 6 inch wafers per month. "Consider the number of IDMs around the world" says Day. "Many of these have recently expanded to 6 inch operation. There's a huge amount of GaAs capacity available, and a good portion of it is standing idle right now."

Over-estimated markets

Unrealistic numbers are also used for the foundry market. "The new companies tend to assume they will capture a huge share of the foundry market," continues Day. "Also, they over-estimate the ratio of business that will go to the IDMs and

to the foundries." In the silicon industry, foundries have somewhere around 20% of the total wafer fabrication market. Reaching this level has taken well over 10 years, as well as a huge investment in capital and talented personnel.

Design houses

When dealing with IDMs, the foundries face the lengthy challenge of getting their process qualified to customers' various design specifications. There is also a problem with fabless design houses, which are very significant customers for silicon foundries. "Most of the fabless companies in the GaAs industry are very small, and there are not many of them," says Day. "It can be very difficult for small companies to gain a foothold with big OEMs such as handset manufacturers, which tend to form close working relationships or supply chains with their established IDM suppliers." Furthermore, like the wafer foundries, the design houses need to establish the necessary infrastructure to ship products at high volume. "They have to

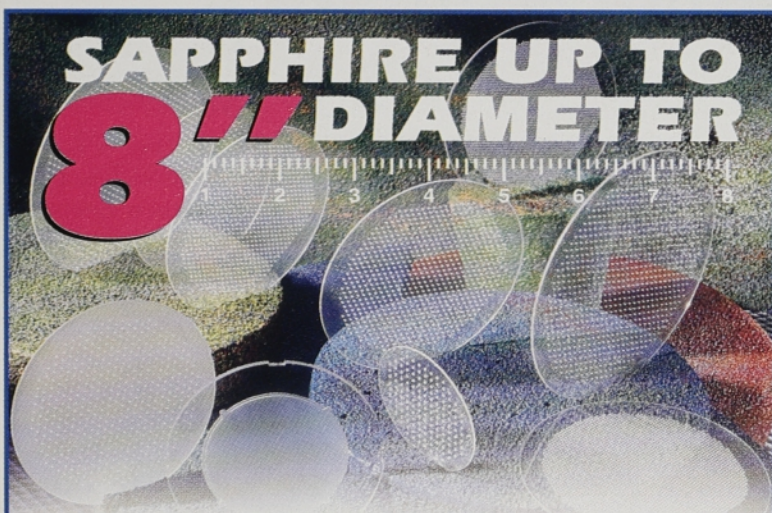
demonstrate their capabilities before the handset manufacturers will give them a chance," Day adds. One area that might prove successful is the second- and third-tier suppliers in the handset industry, the so-called "handset foundries" such as Arima and Acer that manufacture low-end phones initially. "These companies would need RF expertise from the design houses and could prove to be ideal customers for fabless design houses," says Day.

Limited success

Perhaps the best hope for the Taiwanese foundries comes from Japan. The major Japanese manufacturers have been slower to expand than their US counterparts; several, notably Fujitsu, have been assessing foundry partners (see *Compound Semiconductor* August 2000, p31). Also, as described above, Mitsubishi has established a foundry relationship with a Taiwanese company. "Taiwanese foundries will have a better chance of success if Japanese IDMs transfer a large portion of their manufacturing to Taiwan," says Day.

Even then, profit margins are likely to be very tight, since the IDMs understand all the cost structures involved. The foundries may not be able to demand a premium for highly advanced processes, since their technologies will probably trail behind those available internally to the IDMs. In contrast, TSMC or UMC are able to offer leading-edge processes that are not available elsewhere.

So what does the future hold? "In my opinion, probably only one or two GaAs foundry companies in Taiwan can prosper by working according to the pure foundry business model," says Day. "The successful companies will be the ones with strong management focused on establishing efficient, service-oriented manufacturing infrastructures to realize economies of scale." However, because the private sources of capital behind these companies will be reluctant to abandon their investment, they will almost certainly try new directions and move into other markets, such as optoelectronics, if their GaAs foundry business does not pan out.



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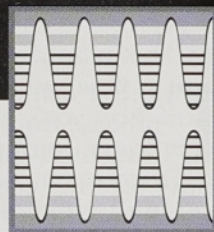
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Design is the key to optimal performance

Building a fab from scratch is a very risky and complicated business. Oded Tal of MAX International Engineering Group looks at the best way to create a complete design and construction process to ensure a better-performing fab at a reasonable cost.

Choosing to design and build a new fab is one of the most important and complex decisions a company will have to face. A working fab is more than a building, a set of tools and systems and human operators: it's the sum of all these parts working together. In today's uncertain trading environment, designing and building a facility that will only be fully operational a year and a half later could be seen as a real gamble. Nevertheless, if the process of fab design is done properly – from paper flow to finished layout – it will yield an agile facility that is geared toward changes in market behavior.

This article will discuss the best way to start the fab design process and create the right toolset from a paper flow, incorporating different market scenarios. The process also involves modeling the capacity requirements of the different scenarios to finalize the tools' quantity and selection, designing the right physical layout to support the manufacturing process and understanding the pros and cons of different layouts with respect to management goals. Following this complete fab design process will help organizations to make better choices.

Designing the process

There are four main objectives of a good design process. First, it is necessary to forecast performance demands as accurately as possible, and understand the resources needed to meet them. Then, we need to generate the best possible fab design within a budget. As an overall target, we need to get from the initial decision to capacity on line as fast as possible. As part of this, it is necessary to build, install and qualify all tools on time and on budget. Figure 1 gives an overview of the design process.

Designing any fab must start with a detailed process flow or flows. A good process flow is detailed down to the level

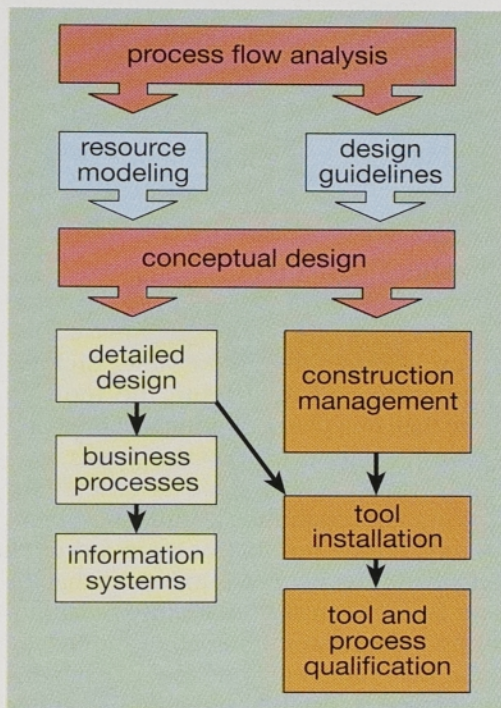


Fig. 1. An overview of MAX IEG's process for designing a better fab.

of individual steps and describes each step from both process and manufacturing standpoints. The fab's physical layout should be based on the predominant flows, and from these a composite flow is superimposed. This flow should capture 80% of the products or processes. The process flows dictate the tool list and the size and relationships of the functional areas.

Of course, since different sections of the process flow may have varying levels of confidence, your toolset confidence will mirror these variations. But even in a very uncertain flow, it is possible to identify problematic areas and look for the right tools to fix them. A thorough analysis of the steps allows the decision about tool choice to be delayed until the last moment when the flow is more mature.

Cleanroom space is not the most expensive resource in a fab, and fab design is

not simply a matter of layout and tool locations. To truly understand fab operations, all the available resources must be modeled. All the available tool types must be included and fully understood. The flow of materials and products must be analysed to create a flow model. Furthermore, the allocation of operators, technicians and support staff should be based on a detailed resource model.

Finding a balance

Obviously, management's role is to demand the best fab for the least money. But while budget constraints are easily determined, the best criteria for fab design are harder to define. Clearly, performance should be optimized, and people typically aim for either the best cycle time or the highest capacity. However, closer scrutiny shows that these are not mutually exclusive: both are important to optimize performance, and we suggest a composite of the two. (To help the actual design process, the criteria in figure 2 should be studied.)

The key performance indicators of any manufacturing environment are throughput, cycle time and inventory level. Throughput (TPT) is the number of units a toolset can process in a given time, typically measured in wafers per week. Cycle time (CT) is the time it takes to process a single wafer from start to finish, typically given in weeks or days. Inventory or work in process (WIP) is the average number of products in the line at any stage of production.

For any toolset it is desirable to maximize TPT, minimize CT and make sure that the WIP level is as small as possible. Figure 3 shows the relationship between the three values. Drawing from Little's law ($WIP = CT \times TPT$) there is an optimal WIP level for each toolset that allows for the best CT and TPT composite (a WIP level of 4000 wafers for the example in

Operational criteria	Business criteria
product/material flow	capacity
productivity/staffing impact	time to capacity on line
dispatch method (pull, push, etc)	cost/return on investment (investment return rate)
layout flexibility and ramp impact on existing production	quality/yield
maintenance practices	
ergonomics	Design alternative selection criteria
automation	TCO – total cost of operations vs performance
material handling	
modularity to future expansion	budget – project budget vs performance
installation and qualification complexity	

Fig. 2. Suggested list of performance criteria for the fab design process.

figure 2). The quality of the fab design can be measured by the ability to sustain manufacturing at that level. Our experience shows that understanding the capabilities of the toolset and building the fab and layout to support them – by providing efficient flow and a controlled WIP – will allow the manufacturer to achieve the best CT and TPT composite.

From concept to construction

Once the design guidelines are set and the resources are understood, the next stage is to create a conceptual layout by locating the different functional areas. In this stage, it is important to understand the weights of the different functional areas in the fab, and to analyse the transactions and the number of wafers going between the areas. At this point, we know how big the functional areas are, as well as the movements between them, so it is possible to start designing the shell, based on a block diagram of the type shown in figure 4.

By designing the building to accommodate the functional areas, it is possible to begin construction without knowing the final location of each tool. There is plenty of time to finalize tool location since some tools have lead times of longer than a year. But by starting the construction in parallel with the detailed design stage, it is possible to save two to six months.

Once the high-level design has been processed and construction has begun, the next steps are the detailed layout and the architectural and engineering design. Each tool's location is pinpointed, together with the support infrastructure that it needs. After the detailed layout is finalized, the execution process begins when it is time to take control of the actual pro-

ject management, i.e. construction and tool installation.

Phasing the project

The cost and complexity of building a new fab, coupled with the desire to have capacity on line as soon as possible, dictates populating and qualifying the tools in more than one phase. We suggest breaking the project into the following phases.

Early toolset This stage is crucial for proving fab capabilities. With a new technology, a new product or even a proven part, the fab owner needs to be sure that the new facility can sustain quality manufacturing before committing all resources.

To save time, only one tool of each different type is installed and qualified at this point. There are two typical milestones to execute the early toolset stage: tool qualification, which involves installation and qualification of each individual tool by both the vendor and the process engineers; and process qualification, where the process is certified by running short loop cycles for different blocks, and by running a full loop process and analysing yields.

Redundancy toolset Once the process is running, the second tool of each tool type is installed. If the second source is not physically installed in this location, a performance test is in order. This phase should achieve no single point of failure across the line.

Ramp steps Here the fab goes to full-blown capacity in steps, e.g. 100 wafers per week, then 200 wafers per week, etc. The available resources and complexity of the installation influence the ramp slope. Realistically, the average capability should not increase by more than 500 wafers per week, from month to month.

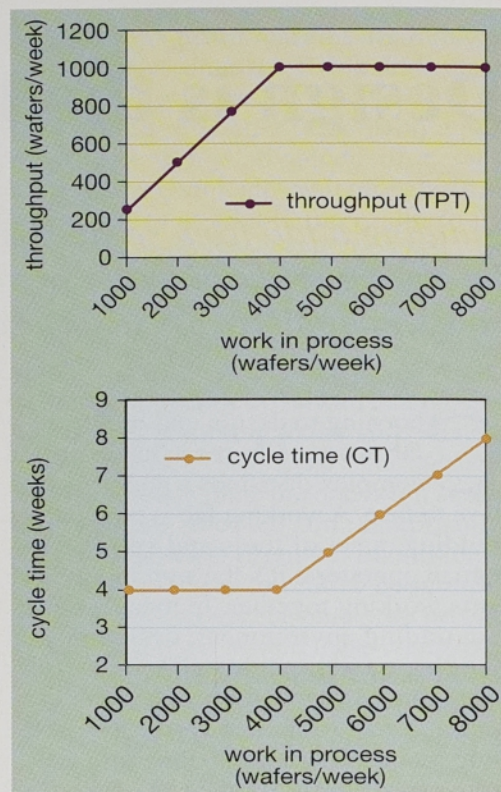


Fig. 3. The relationship between throughput (TPT), cycle time (CT) and work in process (WIP) is defined by Little's law ($WIP = CT \times TPT$). In this example, the optimal WIP level is 4000 wafers per week.

Reducing the fudge factor

To make sure that the gains achieved by aggressive design schedules are not wasted in the execution of the project, the building construction and tool install/qualification phases must be managed carefully. We recommend the "critical chain" philosophy of project management. To implement the critical chain you need to identify all the activities, get their real duration and reduce all the "fudge factors" across the schedule.

As can be seen in figure 5, this process is done in three stages. In stage 1, all activities and relationships are defined on a Gantt chart. In stage 2, the real duration of each activity is determined, and the excess time is compiled into a project buffer. In the third stage, the time saved is divided by three; a third goes to the activity owners, a third remains in the central project buffer, and a third is subtracted from the overall duration of the project.

It is important to keep in mind that once the building is ready and all the tools are hooked up, the facility still might not qualify as a "best of breed" fab. A



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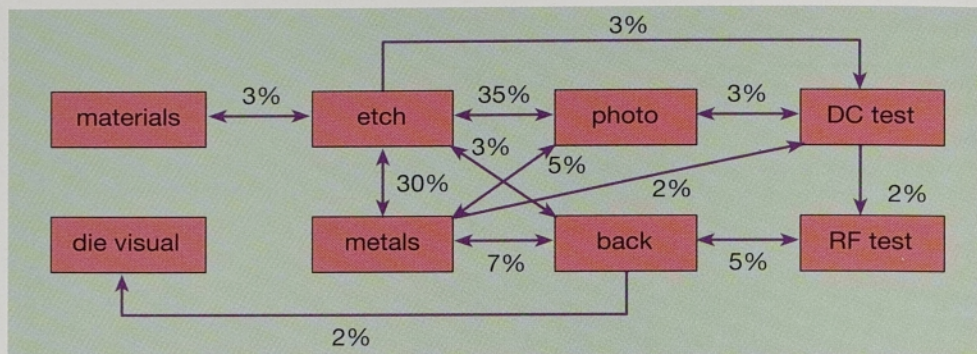


Fig. 4. Block diagram showing the main functional areas in a fab, together with the movements between them. By using this type of diagram, it is possible to begin construction without knowing the final location of each tool.

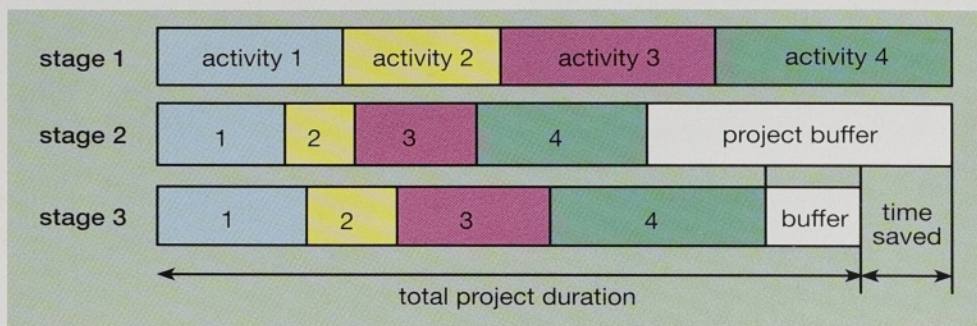


Fig. 5. A project management Gantt chart explaining the critical chain approach.

whole slew of business transactions still need to be defined and it is necessary to map out all these business processes ahead of time and create standard operating procedures (SOPs) to cover them. Typical processes include shift management, maintenance practices, tool and recipe SOPs, and WIP management.

Once all the business processes are defined, the right systems must be put in place to support them. Many organizations do not follow a defined process when selecting a system, which should consist of identifying all the relevant systems needed, analysing them and then looking for vendors who can fulfill most of those needs. Although it is best to stick to off-the-shelf systems, in many cases these are not available. The most common information systems found in a fab are manufacturing execution systems, computerized maintenance management systems, enterprise resource planning, facilities control systems and visual management, i.e. cleanroom personnel and management updates.

Future trends in GaAs fabs

The GaAs industry is experiencing high demand for commercial products, particularly for wireless applications, and this

is driving high-volume manufacturing. Market forces are dictating that processes need to become mature, and that product mixes need to be reduced. Yields and cycle time will be the focus of all the major players. Along with shorter times to market, these will force the modernization of fabs and raise operating efficiency towards that seen in the silicon industry. We expect the same trend to emerge in optoelectronics and lasers.

Designing and building a new facility in the semiconductor industry cost a great deal of money. The challenge for every design is to find a balance between the desire to build a facility with the best possible performance and the need to minimize costs. Going through the right fab design and project management process reduces overall time to capacity, brings down the total cost of operations and will ultimately result in a better-performing fab for less initial outlay.

Oded Tal is chief executive officer of MAX International Engineering Group, a global consultancy providing operational solutions to the semiconductor industry, specializing in facility design and operational quality. For further information see "www.maxieg.com".

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InGaP emitters make HBTs more reliable

Using InGaP emitters in GaAs heterojunction bipolar transistors not only offers advantages in terms of cost and performance – it makes for excellent reliability too. **Barry Lin** and **Larry Wang** summarize the findings of EiC's latest research studies.

Comparison of transistor technologies

Performance	GaAs HBT	GaAs FET	Si bipolar	Silicon on sapphire CMOS	SiGe bipolar
High breakdown voltage for RF power	•	•			
RF power efficiency	•	•			
Positive power supply only	•		•	•	•
Suitability for analog RFIC (frequency response, uniformity, linearity)	•		•		•
Low substrate signal cross-talk	•	•		•	
Mature technology	•	•	•		

GaAs HBTs are versatile devices suitable for RF applications requiring high linearity and a high breakdown voltage. The HBT is popular with device designers because it features a single positive power supply, which saves board space and battery power, and reduces the cost of cell phones.

In recent years InGaP has begun to replace AlGaAs as the material of choice for the emitter layer in GaAs HBTs, affording superior device performance and providing a highly suitable process for power and high-frequency ICs in wireless and optoelectronic applications. One of the main reasons stems from the reliability and processing issues that have plagued AlGaAs devices.

This article looks at the evolution of InGaP HBTs and discusses new reliability data obtained for EiC's new InGaP HBT broadband MMIC amplifiers.

The HBT advantage

HBTs offer a number of advantages compared with existing technologies (see table). HBT MMIC power amplifiers offer a combination of high frequency of operation, high linearity, excellent power-

added efficiency and a high breakdown voltage for power RF applications. The device also features a near-zero leakage current in the off-state, which has allowed handset manufacturers to simplify module design by eliminating the negative voltage supply.

The new generation of InGaP HBT emitter structures has also given design engineers further advantages, such as the combination of a highly reproducible manufacturing process, tighter DC and RF parameter distributions, and smaller die. These factors have led to cheaper MMIC power amplifiers and modules.

Early HBTs were based on the well-known AlGaAs structure. These devices employed MBE to achieve the beryllium doping required to form the p-doped base region. This technology met the enhanced performance and cost goals of the industry,

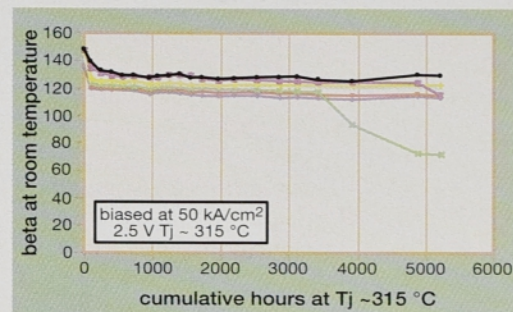


Fig. 1. Reliability results for EiC's InGaP HBT transistors tested at a junction temperature of 315 °C and current density of 50 kA/cm². In the majority of cases the device operation remains unaffected for up to 6000 hours (eight months), translating into millions of hours of lifetime under normal operating conditions.

but created two problems. The first is that the beryllium dopant, being a very small atom, is unstable and diffuses relatively rapidly. At elevated junction temperatures and higher operating current densities, this phenomenon is accelerated – resulting in DC current gain (beta) degradation.

The second issue is that the base access surface near the emitter-base junction of the AlGaAs HBT is relatively unstable. This requires a careful surface passivation technique (ledge passivation) to reduce surface recombination effects. This surface effect leads to further beta degradation due to the increase in base current.

Solving the problems

The former problem was overcome by substituting the base dopant, beryllium, with the larger and more stable carbon atom. The high effusion cell temperatures required meant a switch in growth technique to MOCVD. While MOCVD did help, a problem existed with beta degradation at the HBT base access region due to the surface effect at the AlGaAs HBT.

In addition, a higher current density

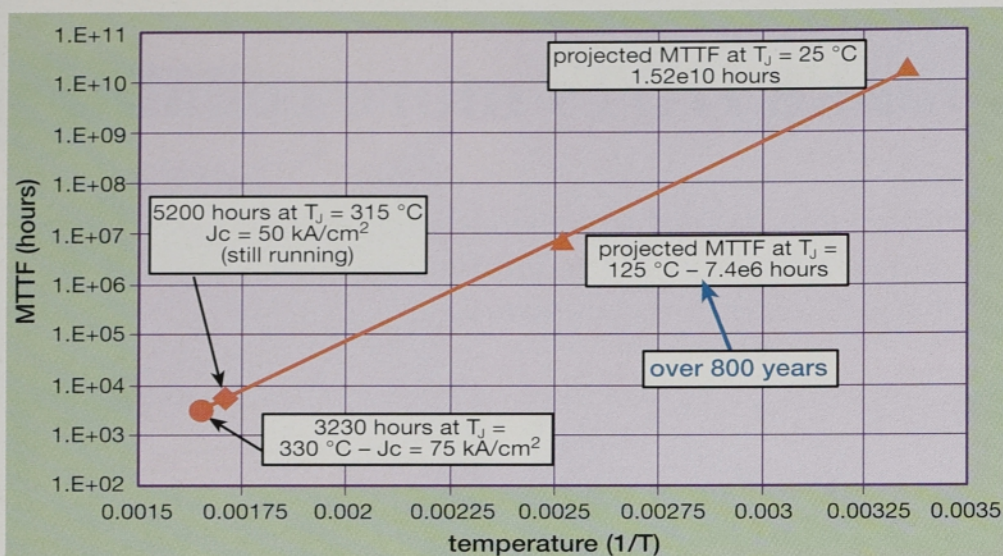


Fig.2. Degradation occurs only in devices driven at 75 kA/cm² with a junction temperature of 330 °C. Using a 20% degradation of current gain as the maxim for failure, the MTTF at this level of stress is 3200 hours. Projecting these data leads to a life of more than 7.4 million hours at a junction temperature of 125 °C.

across the emitter junction further aggravated the current-gain phenomenon. Applications requiring continuous current flow or high-temperature environments—including wireless and optical components and CATV infrastructure equipment—are particularly vulnerable.

Fortunately, replacing AlGaAs with InGaP to form the HBT emitter has solved these problems, and the InGaP emitter structure has been shown to offer a robust solution to the reliability issues of AlGaAs structures. Indeed, InGaP HBTs have been successfully used in the optical communications industry since the early 1990s.

MBE-grown AlGaAs HBTs gave a good indication of potential reliability problems that exist as a result of a high junction temperature in certain applications. As a result, a decision to manufacture InGaP HBT material by MOCVD—paying special attention to circuit design as it relates to the emitter finger junction temperature—has paid dividends.

Reliability data

Figure 1 shows an example of long-term reliability data (mean-time-to-failure or MTTF) collected for InGaP HBTs. The data are obtained from devices with a measured ambient temperature of 250 °C and a junction temperature of 315 °C. The devices operated at 2.5 V and a current density of 50 kA/cm². For testing, each chip was mounted on a ceramic package,

InGaP HBTs offer a highly reproducible manufacturing process, tighter DC and RF parameter distributions and smaller die.

and the current density and junction temperature conditions documented for accelerated life testing. Several different conditions were also chosen. These included higher (5 V) voltage operation at 25 kA/cm², and 75 kA/cm² at a higher junction temperature of 330 °C.

To date, those devices with bias at 25 kA/cm² and 50 kA/cm², with a junction temperature of 315 °C, have run under continuous operation for more than 6500 hours and most of them have not failed yet. Noticeable degradation has only occurred in the devices driven at the highest current density of 75 kA/cm² and with the higher junction temperature of 330 °C. Using a 20% degradation of current gain as the maxim for failure, the MTTF at this level of stress is approximately 3200 hours. The projected MTTF, which is shown in figure 2, is expected to be greater than 7.4 million hours for a junction temperature equal to 125 °C and current density of 75 kA/cm². This assumes a conservative value of activation energy of 0.8 eV.

Contributing further to the robust performance of InGaP HBTs is the relatively cool junction temperature of the transistors under normal bias conditions. EiC

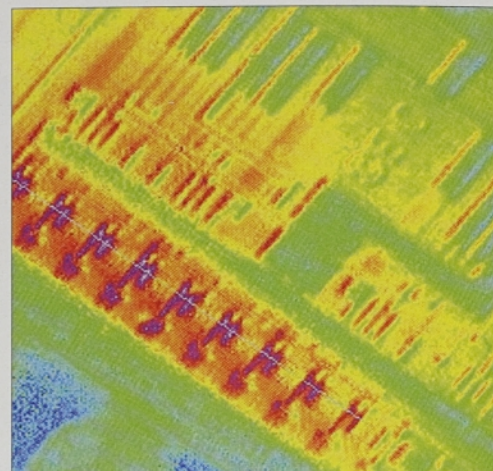


Fig. 3. An infrared image obtained from an EiC broadband amplifier reveals temperature gradients that are relatively evenly distributed across the surface; these gradients do not exceed the company's 125 °C design criteria for the junction.

has employed a careful thermal budget design in the device circuits that results in a relatively low temperature for the emitter finger junction.

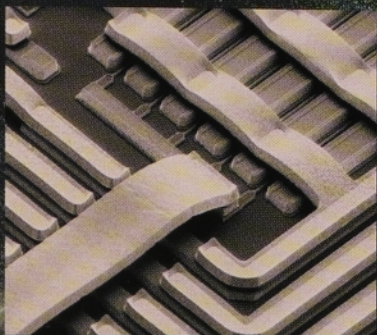
To demonstrate this, the company's EC-1019 broadband amplifier is shown in figure 3. This component supplies 18.5 dB gain from DC to 3 GHz and an IP3 of +34 dBm. The junction temperature profile of the surface of this device is measured with an infrared scanning microscope, and the temperature gradients are shown to be evenly distributed across the surface.

The data also confirm the thermal design target as lower than 125 °C. These results are highly encouraging and show the advantages of the combination of InGaP HBT technology and a careful thermal budget in MMIC circuit design.

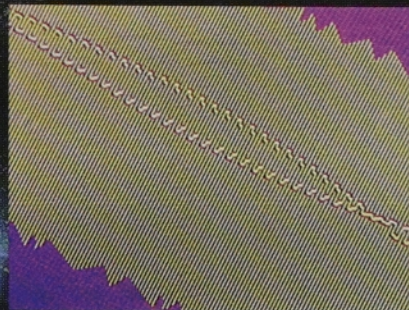
EiC's proprietary InGaP HBT design provides excellent reliability and is inherently superior to AlGaAs HBTs. Although handset PA applications do not require such stringent operating requirements as MMIC devices used for the infrastructure market, the high reliability of InGaP HBTs assures a high-quality MMIC suited to high-volume production.

Barry Lin is senior vice-president for manufacturing and Larry Wang is senior vice-president of engineering at EiC. The company operates a 44 000 sq. ft GaAs manufacturing plant in Fremont, CA. See also "www.eiccorp.com".

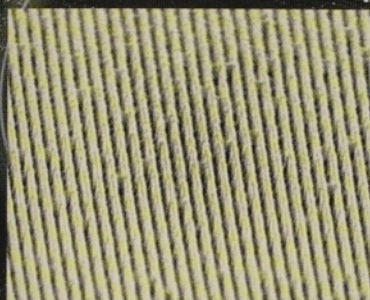
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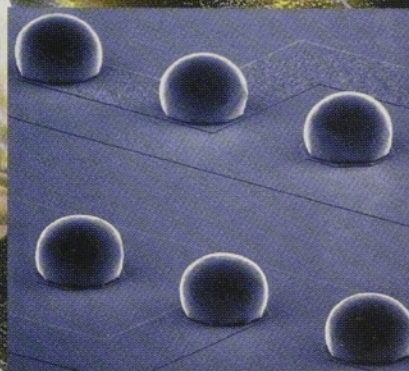
Air bridge on high speed GaAs device,
courtesy of M/A-COM



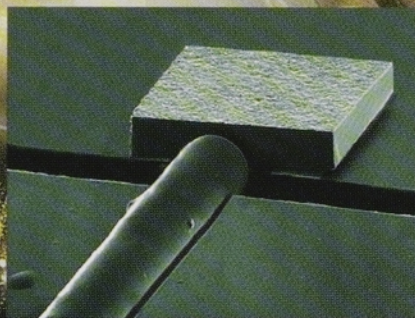
Saw filter, courtesy of AME Space



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Wafer bumping, courtesy of IZM/TU Berlin



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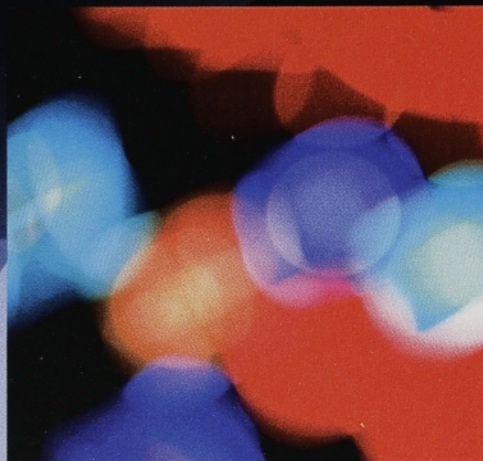
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In alliance with the future

Filtronic exploits the benefits of PHEMTs

Filtronic Compound Semiconductor Limited is manufacturing a range of PHEMT-based products using its 6 inch fab, writes Wolfgang Bösch.

Just 18 months ago, Filtronic, a UK-based RF and microwave systems supplier, acquired an empty wafer fabrication facility in County Durham in the north of England. With just over 100 000 square feet of high-quality class 100 clean-rooms available for use, the start-up team installed one of the world's first and largest operational 6 inch GaAs wafer facilities. The equipment was installed and the first processes established within a one-year period.

The equipment set was chosen to allow for 0.5 μm PHEMT processes to be established with high reliability, high volume and wherever possible complete automation. Batch processing of production lots allows for repeatability not only from substrate to substrate but also across each wafer. The toolset includes steppers, wet and dry etchers, backside processing capability, evaporators, sputtering systems, a host of in-line measurement systems and DC and RF testers, as well as the recently installed high-volume MBE system. This system completes the major first phase toolset purchases and allows for on-site control of the complete wafer processing cycle.

This first phase of investment has provided the capacity to process 30 000 wafers per year. Currently, Filtronic Compound Semiconductor Limited (FCSL) has close to 120 employees at the County Durham site, where all aspects of the business from R&D through design and manufacturing to sales, marketing and customer support have been installed.

PHEMT technologies

State-of-the-art PHEMT technologies are being developed to address the wireless and high-speed fiber-optic markets. Two depletion-mode (D-mode) processes are about to be released; a low noise, single recess process and a high power, double recess process. The low noise process is used for discrete PHEMT

D- and E-mode PHEMTs for handsets

Mode	Gate width (mm)	Output power (dBm)	PAE (%)
D	2.5	23.6	69
D	4	26.4	63
D	8	29.6	67
E	12	30.1	65

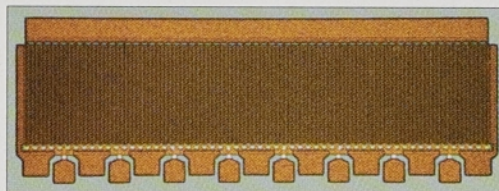


Fig. 1. A power PHEMT with a gate periphery of 60 mm.

product development and low noise amplifier (LNA) development for both handsets and base-stations. The use of the double recess D-mode process for switch products has shown both state-of-the-art performance and very high yield on 6 inch wafers. The D-mode process shows typical values for I_{max} , pinch-off and breakdown of 500 mA/mm, -1.0 V and 15 V, respectively.

A 0.5 μm enhancement-mode (E-mode) process is in an advanced state of development. The highly selective dry etch used for the gate recess was shown to be critical in controlling the recess depth and therefore threshold voltage of the device. Typical parameters are I_{max} of 240 mA/mm, breakdown voltage of greater than 20 V and pinch-off voltage of $+0.25$ V, ensuring a very low leakage current with zero volts on the gate. Single-supply handset power amplifier development is underway based on this process and shows excellent gain and PAE under 3.5 V operation (see table).

AWR's *Microwave Office* has been selected as the tool of choice for MMIC design; customization of the tool is complete, including automated layout and

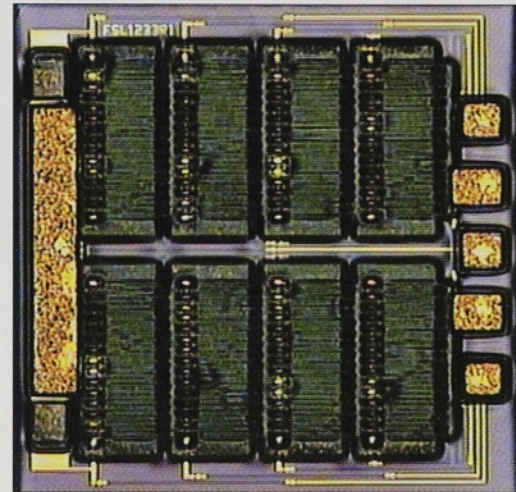


Fig. 2. A single-pole, double throw (SPDT) switch with optimized layout.

design rule checking. The first release of the design manual and circuit modeling tools for both active and passive components is due by the end of April 2001.

Roughly 60% of all GaAs semiconductor products are utilized in wireless applications (mainly handsets), with fiber optics being the second biggest market. These are the two major market segments being addressed by FCSL with its current product portfolio. A series of switch designs in various packages is available today. Discrete power transistors with overall gate peripheries ranging from less than 1 mm up to 60 mm are in the development phase (see figure 1), together with power amplifier modules. A wideband PA MMIC for optoelectronic applications will be released shortly.

Switches

In today's handsets, switches are used for a great variety of functions, such as mode selection, band selection, power control and transmit/receive switching functions. State-of-the-art handsets have become more complex, and switches have emerged as key elements which significantly determine the overall handset perfor-

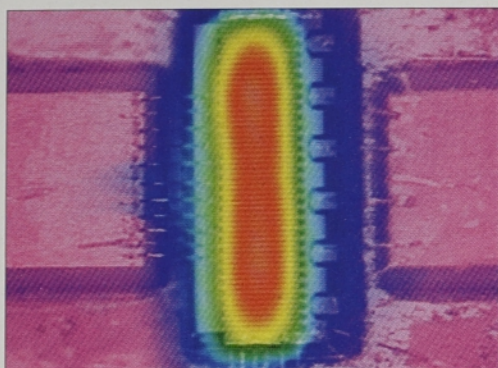


Fig. 3. Thermal image of a 20 mm periphery PHEMT MMIC. Junction temperature strongly affects the reliability of GaAs devices.

mance. There are typically three to five switching functions incorporated in a handset. Currently, GaAs-based MMIC switches are replacing PIN-diode-based components. The main reasons for this transition are better performance, wider bandwidth, lower power consumption, higher linearity and smaller size. More complex switching functions, such as those required in 3G phones (e.g. single pole five throw – SP5T – switches) are much easier to implement in GaAs MMIC technology compared to a traditional MIC–PIN diode technology.

There are several reasons why we believe that PHEMT technology is ideal for switching applications. Compared to traditional MESFET technology, PHEMT semiconductor devices have a lower channel resistance and hence yield lower insertion loss. Due to the very low output capacitance of the 0.5 μm PHEMT device, high isolation can be achieved in the switch. The very low knee voltage makes these devices ideal for low-voltage operation, however the power handling capability provides low harmonic generation when operating the switch under high RF input power.

Significant effort went into device modeling and circuit optimization to ensure excellent performance and high yield. In this way a first turn-around success was achieved, and within a very short period of time a comprehensive portfolio of switches, ranging from SPDT to DP5T switches, was in fabrication. These highly linear, low loss switches operate up to 38 dBm input RF power with supply voltages lower than 3 V and still meet the operating requirements for E-GSM, DCS, PCS and UMTS systems. A newly developed circuit topology and

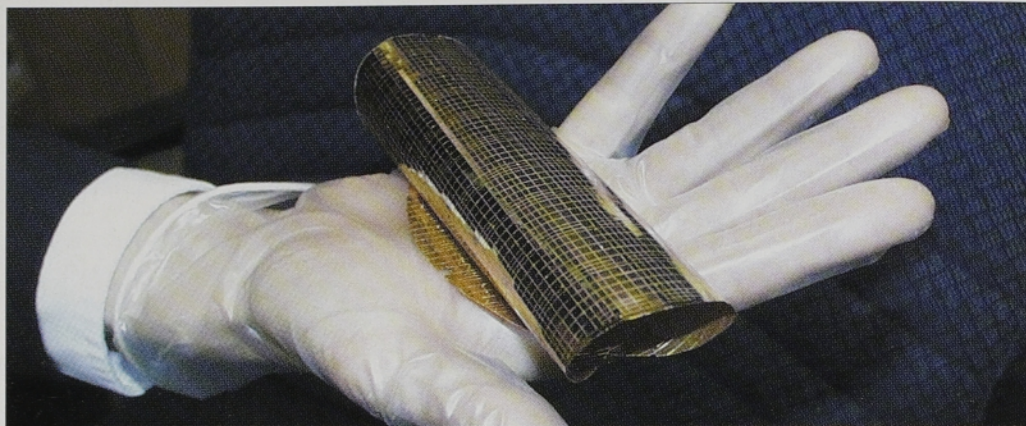


Fig. 4. Filtronic has demonstrated that 6 inch wafers (shown here with backside gold plating) can be thinned to 30 μm for more efficient heat removal.

an optimized switch device design (see figure 2) results in switches that achieve a very low second and third harmonic content of -70 dBc when operated at GSM RF power levels. The typical insertion loss is less than 0.5 dB and the isolation is 24 dB for wireless operating conditions.

For high-volume products in 3G handsets, performance and cost are the key factors in order to maintain competitiveness. In conjunction with novel circuit design, PHEMT technology offers superior switch performance compared to traditional MESFET or MIC–PIN diode technology. At present, a central feature of the R&D program at FCSL is the size reduction (and hence cost reduction) of the switch MMIC family. The newly optimized semiconductor devices will have an optimized gate layout, which enables a significant reduction in size.

FCSL is committed to this technology and its importance for next generation multimode handsets, which will simultaneously require highly linear operation for the W-CDMA/UMTS mode and high-power operation for EGSM and DCS/PCS operation. At the same time, handset OEMs are clearly moving toward using PHEMT switches and integrating these with filters in the future.

Power PHEMTs

As mentioned above, FCSL is developing discrete power transistors with overall gate peripheries in the 1 to 60 mm range. Currently these devices are electrically and thermally characterized. Because the junction temperature strongly affects the reliability of GaAs devices (see figure 3), the thermal management is very important. Wafer thinning improves the thermal conductivity and hence allows a more ef-

ficient heat removal (as shown in figure 4). FCSL has demonstrated that 6 inch GaAs wafers can be thinned down to 30 μm and that devices can successfully be demounted.

Integrated modules

The level of integration in wireless products is continuously increasing. In combination with the growing functionality of handheld products, there is a clear trend towards integrated modules. Considering that in the future OEMs will outsource a greater portion of their handset manufacturing business, a module approach represents a lower risk and more cost-effective solution. FCSL is currently evaluating the optimum integration technology for a combined switch/filter module. One step further towards a fully integrated front end is a GPS module that combines an integrated antenna, receive filters and an LNA MMIC in one unit. All these components are designed and manufactured within the Filtronic Group. Several customers have already received samples of the first prototypes.

On the power amplifier front, dual-band, multi-mode amplifiers with integrated matching networks, power control and monitoring are required for next-generation handsets. FCSL has characterized and measured initial PA MMICs, and the fully integrated PA module is in the development phase. Eventually the market will demand a fully integrated front-end module. Starting from the integrated antenna, to the switches, transmit and receive filters, power amplifiers and low noise amplifiers, and some level of control logic, all functions will be combined in a single module (see figure 5).

GaAs PHEMT technology is particu-

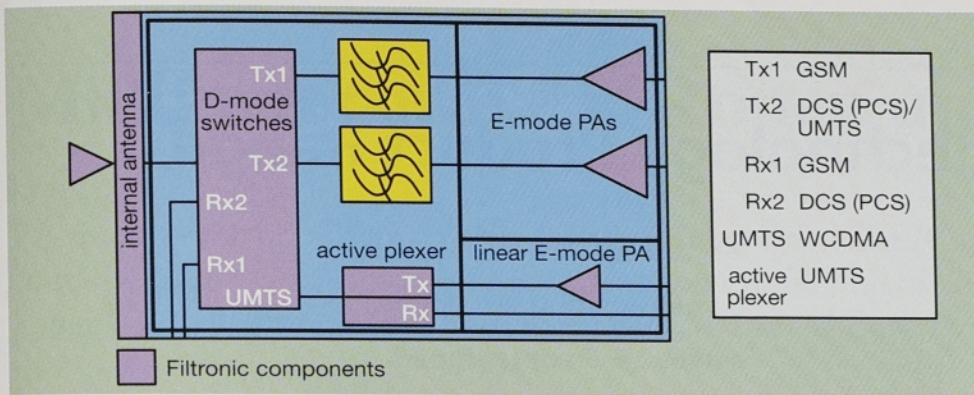


Fig. 5. Proposed layout of a fully integrated front-end module for handset applications. Many of the components, including the integrated antenna, will be designed and manufactured within the Filtronic Group.

larly attractive for the broadband market because of its high gain and excellent microwave frequency performance. D-mode PHEMTs with f_t values above 25 GHz are suitable for a number of applications up to the millimeter-wave frequency range. The process offers a low-cost, high-volume solution to the MMIC requirements for the OC-192 optoelectronic driver amplifier market, and a family of devices for this application is being developed.

FCSL plans to offer low and medium power distributed amplifiers based on the standard D-mode process. Distributed amplifiers offer ultra-broadband operation by integrating the input and output capacitances of a number of PHEMTs with short inductive microstrip lines into two terminated artificial transmission lines. An input signal propagates through the artificial gate transmission line, exciting the inputs to the PHEMTs and causing modulation of the current flowing between the drain and source terminals. The current from each of the devices adds in phase in the drain transmission line and flows into the load. The MMICs employ both cascode and single common source configured PHEMTs in five- and seven-stage designs depending on the electrical and size specifications. The cascode arrangement is particularly well suited to distributed amplifier design offering high gain, high output resistance, low intrinsic feedback and good gain control via the second gate connection. Typically the low power amplifiers offer small signal gains in the order of 9 dB, with low ripple and better than 10 dB return loss from DC to 20 GHz with DC power requirements of 4 V and 150 mA.

A seven-stage low-power design using

small gate width PHEMTs in a cascode configuration measures approximately 2.8×1 mm. The medium power amplifier offers a P_{sat} of 25 dBm, a small-signal gain of 7 dB and input and output return losses of greater than 10 dB with DC power requirements of 8 V and 300 mA. A number of custom chip solutions are available with a choice of on- or off-chip terminations, flexibility over pad configuration and chip dimensions. The first prototypes will be available shortly.

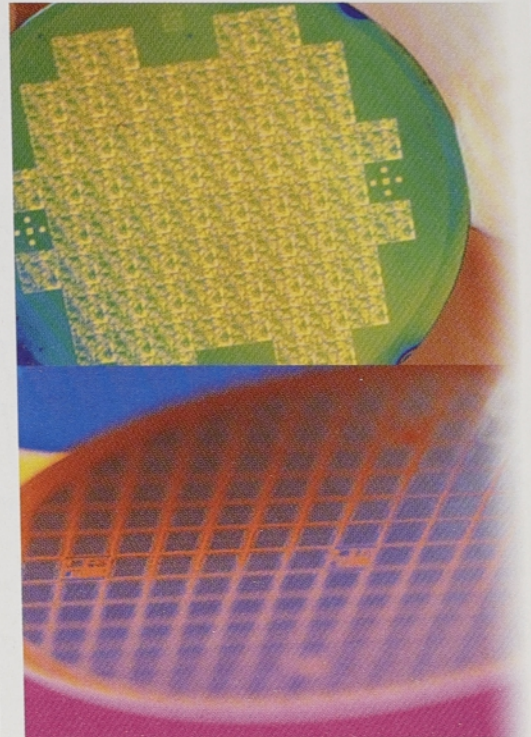
Summary

Through investment in technology and quality, we believe that FCSL is well positioned to become a leading force in GaAs wafer manufacturing specifically for the wireless and the optoelectronic market. The purchase of enabling technology such as MBE systems allows the company greater vertical integration, greater control over the fabrication of transistors, and overall added value offering a comprehensive fab at world-class standard. The current development of PHEMT D-mode and E-mode switches is the first step on a commercial road map that will lead to the introduction of discrete PHEMTs, PAs, LNAs and finally complete RF front-end solutions.

Using 6 inch wafer technology has allowed the fabrication of discrete GaAs PHEMT devices and MMICs in a very cost-effective way. FCSL is well positioned to take advantage of these developments which, when combined with other Filtronic group activities, will provide many innovative RF solutions to the wireless market.

Wolfgang Bösch is head of the Global Technology Group of Filtronic plc.

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Millimeter-wave ICs open up new spectrum

The market for applications that rely on millimeter-wave ICs has grown substantially in recent years. Increases in performance and reductions in cost will ensure that the range of applications continues to expand, writes Al Lawrence of TRW Ventures.

In the last decade there has been tremendous growth in applications that use the millimeter-wave region of the spectrum. Critical to this growth has been the development of low-cost, mass-producible compound semiconductor integrated circuits operating in the millimeter range (30–300 GHz). Millimeter-wave ICs are currently used in a diverse set of applications including terrestrial and space-based telecom systems, scientific instruments, passive imaging and transportation products. In the future there will continue to be many drivers in the marketplace motivating manufacturers to make use of this higher-frequency regime, including the demand for ever-higher bandwidth communication links, improved transportation safety systems and advanced scientific observation systems.

The millimeter-wave portion of the spectrum is of interest for a variety of reasons. First, it offers new operating regions ideal for high-bandwidth, high-capacity communications systems. In addition, the millimeter-wave spectrum contains frequency bands suited to both limited-range and long-range communication links. Figure 1 illustrates the wide signal attenuation range that can be obtained with a relatively small change in operating frequency. While atmospheric attenuation is 15 dB/km at 60 GHz (V-band), the corresponding figure at 94 GHz (W-band) is only 0.4 dB/km. This makes the V-band highly suitable for short-range transmissions where interference from other nearby V-band transmitters can be minimized since signals are quickly attenuated.

Conversely, the W-band is ideal for transmitting high-data-rate signals extremely long distances. For applications requiring narrow antenna beams or high spatial resolution in a compact size, millimeter-wave solutions work well thanks to their smaller wavelength (1–10 mm), which permits the use of small-diameter

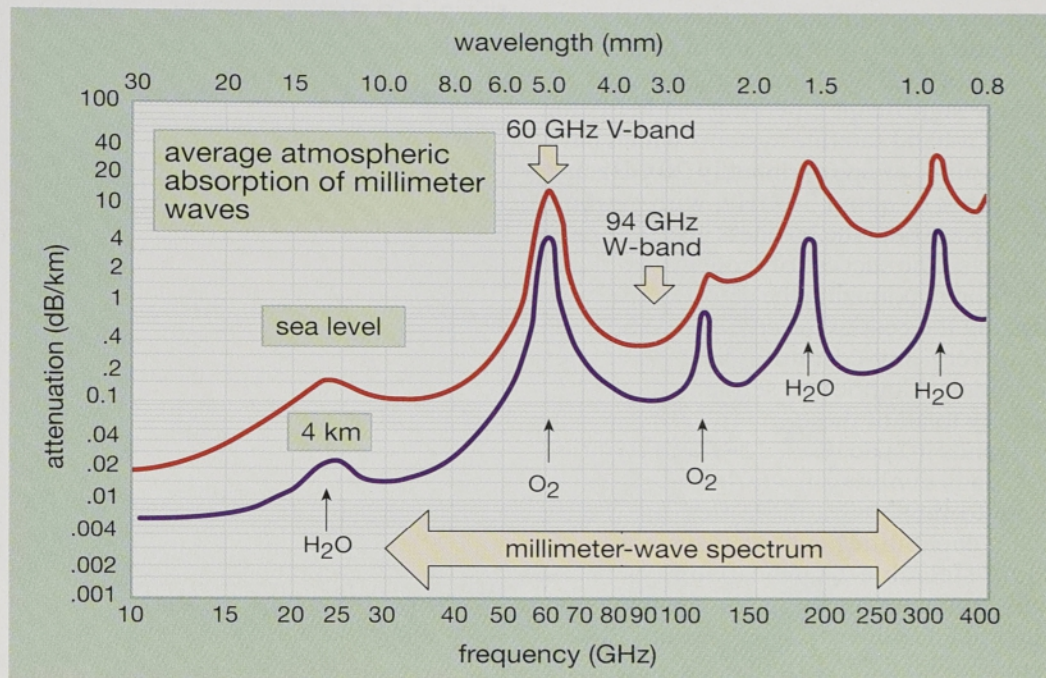


Fig. 1. Variations in atmospheric attenuation provide windows for long-range transmission (e.g. at 94 GHz) and frequencies that are more suited to short-range uses (e.g. 60 GHz). The millimeter-wave region covers the 1–10 mm wavelength range, which is equivalent to the 30–300 GHz frequency range.

receiver and transmitter elements. The millimeter-wave portion of the spectrum also contains regions which have reasonably good propagation characteristics in all types of weather, as well as absorption lines and other properties which can be exploited for a variety of scientific studies.

Performance up, costs down

Efforts throughout the compound semiconductor industry continue to advance millimeter-wave MMICs. Developments in materials, processing technologies and circuit-design techniques have pushed MMIC performance and reliability up while at the same time driving costs down. As an example, TRW has developed and supports a wide range of device types and processes in the pursuit of millimeter-wavelength applications. For

HEMT-based circuits, TRW has production MMIC processes using 0.15 μm gate-length HEMTs suitable for applications operating at up to 60 GHz, and a 0.10 μm process which can be used for MMICs operating through 94 GHz.

With InP, integrated circuits to 220 GHz have been produced with a 0.07 μm HEMT process. For reliable, flight-qualified, high-volume HBT-based circuits, a 2.0 μm GaAs MMIC and digital process suitable for applications up to 20 GHz can be used, while a 1.0 μm GaAs process can support applications up to 50 GHz. A 1.0 μm InP process suitable for high-speed digital and RF applications up to 200 GHz is in qualification. When they reach production GaN-based devices should play an important role in high-frequency, extremely high-power applications.

Space-based telecoms flying high

Space-based telecommunications was one of the first important uses of millimeter-wave ICs. GaAs and, more recently, InP have been used extensively in satellite payloads to meet size, weight, power, cost and reliability requirements. Microwave and millimeter-wave integrated circuits are used in payload hardware such as low-noise amplifiers (LNAs), receivers, frequency converters, frequency sources, transmitters, modulators, RF switches and beamforming networks. Strong growth is expected to continue in this market as numerous new systems are in production and additional ones are being planned.

One significant emerging market is for new Ka-band satellite systems which have a downlink of approximately 20 GHz and an uplink of about 30 GHz, with systems addressing both the business and consumer markets. The success of these new systems relies on maximizing the capacity and minimizing the cost of the spacecraft and realizing very-low-cost millimeter-wave user terminals. Compound semiconductor ICs are key to all of these.

Trends in space-based telecoms will see payloads evolving from fixed-beam systems to those with more flexible multi-beam capabilities and even systems with some steerable-beam capability. There will continue to be efforts to lower the cost and enhance the capacity of transponder-type payloads. All of these will push MMIC technology toward lower-power, higher-performance, lower-cost circuits.

High volumes, low costs

The potential volume for the user terminal portion is projected to be in the millions. MMICs will be used extensively to realize the millimeter-wave transceiver portion of the terminal. A key component of the transceiver is a multiwatt power amplifier, with power levels ranging from 1–2 W for commercial applications to more than 10 W for large enterprise terminals. Initial products for this application can be implemented in GaAs. These terminals will also require very-low-noise amplifiers (< 1.5 dB) that will be critical to achieving desired antenna size – GaAs and InP ICs are potential solutions for such LNAs. And in all cases, cost reduction is critical in order for them to be competitive, especially in the consumer market.

In terrestrial-based telecommunications, the market for microwave and millimeter-wave digital radios has grown

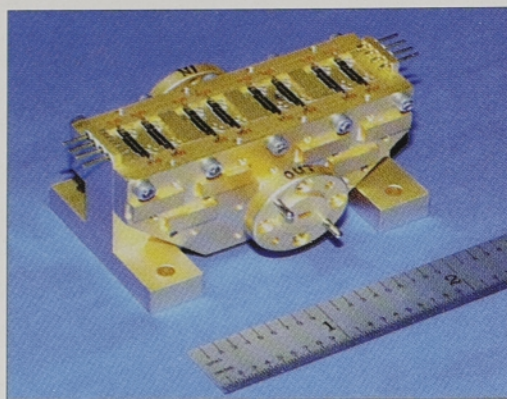


Fig. 2. InP HEMT-based ICs are used in this eight-way combiner providing a total output power of 2.2 W at 94 GHz.

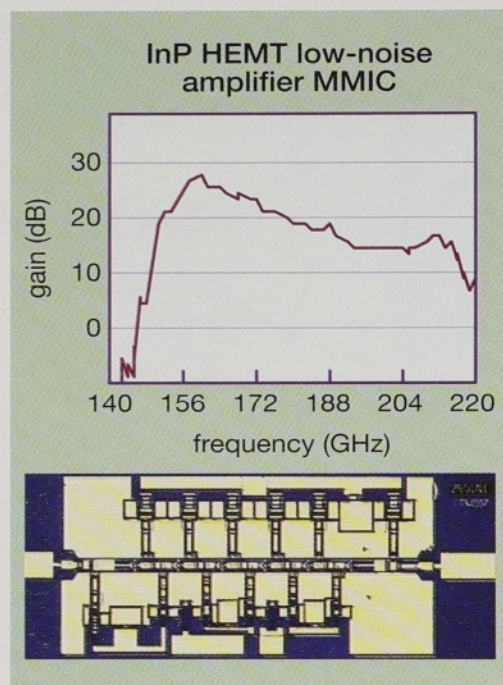


Fig. 3. This 150–215 GHz LNA MMIC, designed by JPL and fabricated by TRW, demonstrates 27 dB gain at 160 GHz and 16 dB gain at 215 GHz.

tremendously in the last several years. Volume production is already taking place at 40 GHz, and 60 GHz parts are ready for production. Demand is being driven by applications such as broadband wireless access, cellular backhaul, picocell mobile systems and wireless networking.

The growth of these markets depends not only on system capabilities, but also on reducing the cost of the devices. These objectives are being pursued through advances in processing equipment and techniques, while new processes are also being used to reduce die size, simplify overall transceiver architecture and increase yields. In addition, the need for

higher data rates will continue to drive not only the development of higher-linearity ICs, but also the use of more complex modulation schemes.

Higher data rates can also be achieved by increasing operational frequencies above 40 GHz, and GaAs is well suited for bands up to 94 GHz. Furthermore, the enhanced capability of InP parts can be used to realize even higher operating frequencies, or can be traded off against other system requirements.

The outstanding characteristics which InP-based HEMTs are able to deliver have been discussed previously (see *Compound Semiconductor* April 2000, p28), demonstrating their suitability for next-generation high-frequency systems. For example, power MMICs can deliver 200 mW with 40% PAE and 1000 mW with 25% PAE for 60 GHz operation, while 480 mW is obtained at 95 GHz with 20% PAE. When these InP HEMTs are inserted into an eight-way combiner (see figure 2), a total output power of 2.2 W at 94 GHz operation is achieved, with a PAE of 9.8% and associated gain of 19.5 dB.

The development of InP HBT technology has led to new options for designers of digital radios. InP HBTs show exceptional linearity and provide the best linearity performance for amplifiers operating at up to 44 GHz, achieving record IP3:DC power ratios. These HBTs are also well suited to the fabrication of very-low-noise VCOs operating over the 20–100 GHz range. InP HBT device characteristics also allow extremely high-efficiency power amplifiers. Operating at 28 GHz, these devices exhibit a PAE of 60%, and when operated at 2.4 GHz a PAE of 94% can be obtained. In addition, InP HBTs are capable of operating at higher current densities than either GaAs HEMTs or GaAs HBTs, which enables the fabrication of smaller die-size ICs for a given power requirement, thereby lowering the overall cost per die.

Instruments of observation

Millimeter-wave technologies are also widely used in scientific instrumentation. A good example is in the implementation of Earth observation systems, which use microwave and millimeter-wave sensor electronics in devices such as radiometers, where imaging is achieved by exploiting the differences in the reflectance and emission properties of different materials. As an example, TRW has

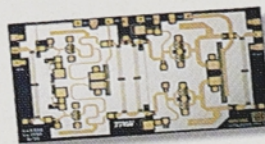
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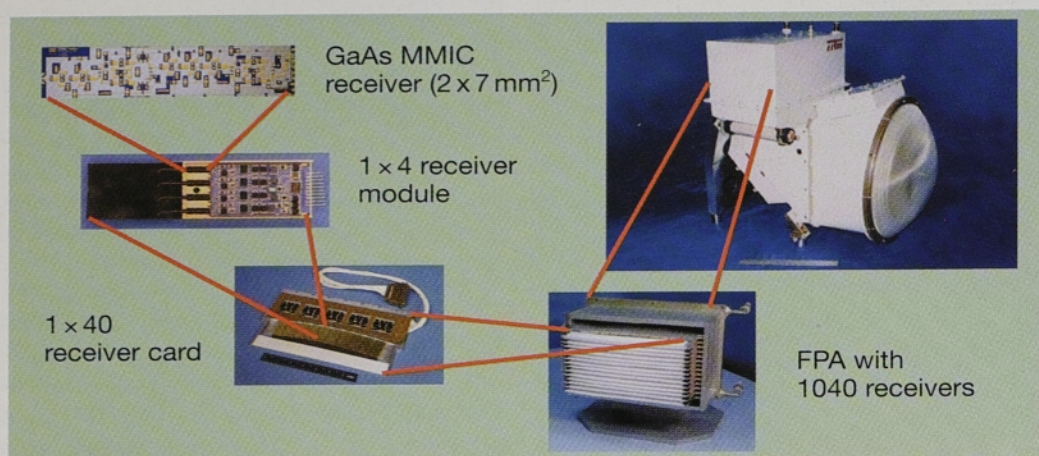


Fig. 4. A passive millimeter-wave camera that has been developed by TRW contains a focal plane array with 1040 GaAs low-noise amplifier MMICs.

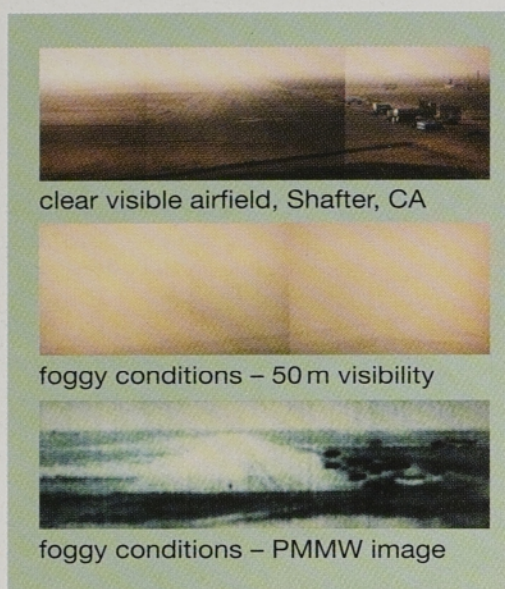


Fig. 5. Passive millimeter-wave imaging is able to see through fog, heavy rain and smoke, as illustrated by these scenes of Shafter airfield in California.

fabricated a cryogenic radiometer suitable for the range 77–106 GHz. When operated at 20 K, the InP HEMT MMIC module delivers 32 dB of gain with an exceptionally low noise figure of 0.4 dB. Figure 3 shows an LNA MMIC that was designed by the Jet Propulsion Laboratory (JPL) and manufactured in an InP HEMT technology at TRW. The six-stage coplanar waveguide MMIC has a bandwidth of 65 GHz, and is employed in applications such as space-based Earth observation systems.

Getting a clearer picture

Passive millimeter-wave imaging exploits the differences in absorption and reflection of different materials to construct an

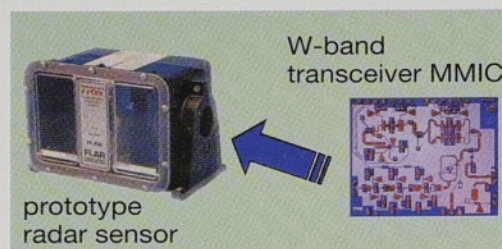


Fig. 6. TRW has developed prototype radar sensors for automotive cruise control and collision avoidance.

image. As shown in figure 1, there is a minimum in the atmospheric absorption curve at around 94 GHz, making this an optimum frequency for seeing through fog, heavy rain and smoke. One example of a passive millimeter-wave imaging system is an all-weather aircraft camera system built by TRW. This first-generation millimeter-wave camera consists of a focal-plane array with 1040 receiver cards (see figure 4), each containing 40 receiver modules which in turn hold four GaAs receiver MMICs. The seven-stage LNA MMICs were implemented in a GaAs PHEMT technology, providing 40 dB of gain with an 8 dB noise figure at 94 GHz. A second-generation camera is now being developed employing InP HEMTs to improve performance.

The effectiveness of a millimeter-wave camera is shown in figure 5, in which a view of an airfield on a clear day is compared with the visual image on a foggy day when the visibility has been reduced to 50 m. When viewed through the millimeter-wave camera, the fog-shrouded airfield is as clear as the fog-free image. As figure 6 suggests, take-off and landing systems in all-weather aircraft are a major application of this technology; others

include television imaging through fog, rain and smoke; enhanced vision for fire-fighters in smoky environments; and land, air and sea navigational aids.

Homing in on the transport market

Transportation is potentially a huge market for microwave and millimeter-wave devices. Applications for vehicle safety and convenience could include collision warning, obstacle-detection systems, intelligent cruise control and predictive crash sensing, which in turn would allow air-bag inflation to be tailored to better protect the passengers. These devices could also be used in infrastructure applications and intelligent vehicle highway systems, including vehicle-to-vehicle and vehicle-to-infrastructure communications, as well as roadway sensing and obstacle detection.

While the basic concept of automotive radar has been around since the 1960s, development did not begin until the 1990s when the costs of sensor technology and processing hardware began to drop substantially. MMIC-based millimeter-wave sensors offer a very effective solution for many of these applications; they are rugged, reliable and can be produced at low cost and in high volumes. In addition, the small wavelength at millimeter-wave frequencies minimizes antenna size and allows for an extremely compact sensor.

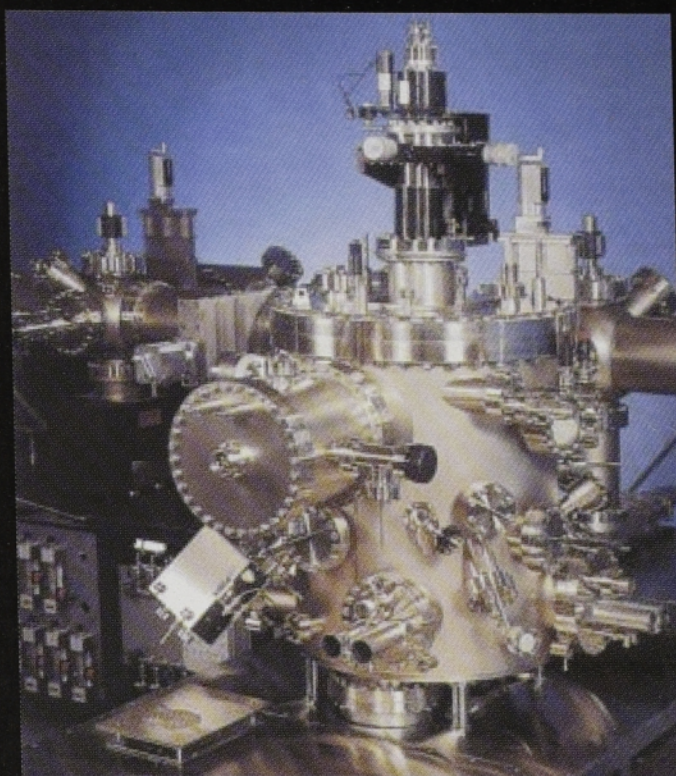
Systems operating at 60 and 77 GHz are now being produced, with 94 GHz and higher-frequency versions expected in the future to further reduce the sensor size. Typical forward-looking radar systems need to operate over a 100 m range, and need about 1° resolution, which translates into a single lane width at 100 m. In addition, they require about an 8° field of view to be able to view adjacent lanes. Figure 6 shows a prototype radar sensor developed at TRW, which employs W-band transceiver MMICs.

Clearly there exists a broad range of applications that can be satisfied through the use of millimeter-wave ICs. As the demand for these devices continues to grow, and costs are driven down, it is expected that even more potential applications will arise.

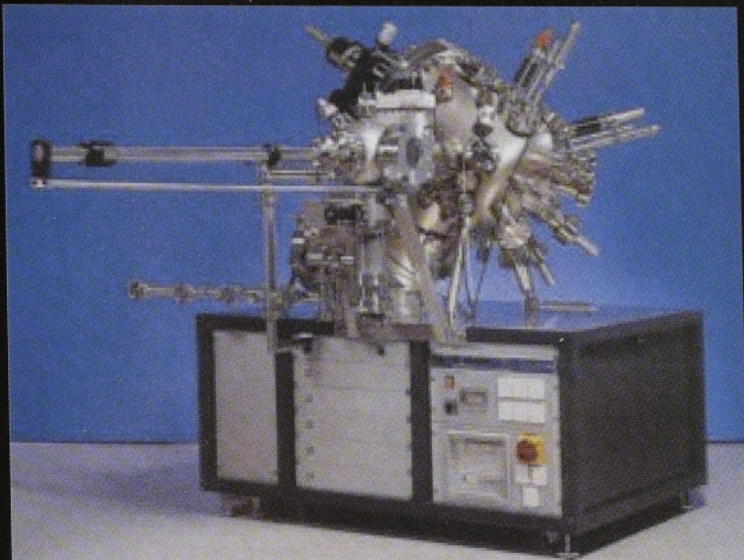
Al Lawrence is the director of wireless telecom products of TRW Ventures, Redondo Beach, California. This article is based on a presentation at the 2001 Key Conference, held 5–6 March in Key West, Florida.

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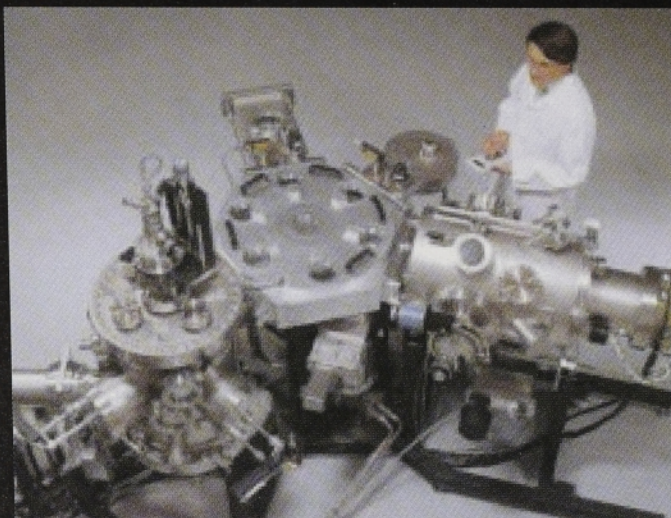
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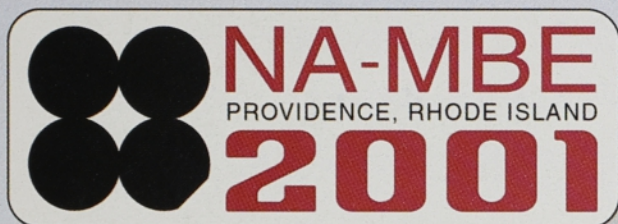
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Agere and Bede join the Compound Semiconductor Portfolio

IQE demonstrates growth in the merchant epiwafer market despite, or perhaps because of, unfavorable economic conditions, reports Marie Meyer

All eyes were on Agere in April, watching its share price performance after its spin-off from Lucent and subsequent IPO. Lucent was unlucky in the timing of the offering, because the sharp downturn in technology stocks meant that they raised just \$3.6 billion in the offering, whereas earlier estimates had been as high as \$10 billion (see *Compound Semiconductor* February, 2001, p87). Nevertheless, the deal still ranks as the largest IPO thus far in 2001, and the fifth largest in US history (it would have been the second largest if the original estimates had held up). Agere was valued at slightly less than \$10 billion, which is three to five times lower than earlier estimates. Several analysts noted that the original valuations for Agere could not be supported because of the drop in share prices for comparable companies, and because of uncertainties about whether the current conditions in the telecommunications equipment market might erode Agere's profits over the next few quarters. Indeed, Agere has already warned that its results for the June quarter are likely to be disappointing, because of canceled or rescheduled orders from its largest customers.

After several delays and three rounds of reductions in the offering price, Lucent was at last compelled to complete the deal on March 28, knowing that it would receive a less-than-favorable, and at times downright hostile, reception. Lucent desperately needed to raise what cash it could – so desperate that each time the deal was repriced Lucent increased the number of shares that would be offered, moving all the way from their original proposal of 100 million shares to the final tally of 600 million shares, roughly 37% of the company. The deal also allowed Lucent to remove around \$2.5 billion in short-term debt from its balance sheet. That

Company	Symbol	Closing price April 19	52 week low-high	Market cap*	P/E ratio**
GaAs IC companies					
Alpha	AHAA	27.35	13.0625–64.5000	1.188B	26.10
Anadigics	ANAD	17.15	10.5000–80.1250	516.0M	27.92
Celeritek	CLTK	14.43	9.8125–63.2500	172.0M	29.16
Conexant	CNXT	11.05	6.9000–62.7500	2.686B	N/A
Endwave	ENWV	2.30	2.0000–20.6250	78.5M	N/A
RF Microdevices	RFMD	27.50	8.7500–70.7500	4.485B	133.40
Standford Microdevices	SMDI	15.94	4.2188–60.2500	453.2M	N/A
TriQuint	TQNT	26.74	10.2500–66.6250	2.142B	26.64
Vitesse	VTSS	34.77	15.1250–95.1875	6.606B	163.18
Opto companies					
Agilent	A	40.40	25.0000–104.1250	18.454B	22.41
Agere	AGRA	7.57	4.1000–8.4000	12.378B	N/A
Alcatel Optronics	ALAO	29.42	20.0000–71.7500	485.4M	27.73
Coherent	COHR	43.25	25.0000–93.5000	1.182B	17.84
Cree	CREE	21.73	12.2100–87.5000	1.614B	52.42
JDS Uniphase	JDSU	28.53	13.0625–140.5000	37.213B	N/A
SDL	SDLI	146.75	125.0000–460.5000	N/A	N/A
Uniroyal Technology	UTCI	9.80	5.2500–23.2500	252.6M	N/A
Semiconductor materials & equipment companies					
ATMI	ATMI	26.45	14.3750–50.5000	800.1M	18.81
AXT	AXTI	28.26	13.2500–47.1875	622.5M	25.42
Emcore	EMKR	36.60	19.8750–62.5000	1.258B	N/A
Kopin	KOPN	7.46	4.0000–47.4375	484.3M	N/A
Tegal	TGAL	3.10	1.3125–8.0000	39.0M	13.26
Trikon	TRKN	10.00	7.1250–28.5625	118.7M	6.59
European shares (currency data in Euros)					
Aixtron	AIX	90.10	63.50–304.50	2.9B	90
Bede	BED	3.08	1.85–3.03	86.94M	N/A
Filtronic	FTC	4.44	2.16–7.84	323.24M	N/A
IQE	IQE	4.10	2.40–4.37	666.6M	185
Picogiga	PICO NM	18.99	13.00–35.60	122.7M	36
Riber	RIBER	11.36	8.26–36.50	219.21M	N/A

*Market capitalization = # shares × current share price.

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

line item, which Lucent attributed to funding Agere's operations, is now transferred to the new company.

If there is a bright spot in this story, it is the fact that Agere's shares have actually done OK since the offering. Although it

IQE's view of growth in the compound semiconductor epiwafer market

Year	CS device sales (US \$B)*	Total epiwafer market		Outsource epiwafer market		IQE sales forecast (US \$M)***
		% of CS device sales**	Value (US \$B)	% of total epi market	Value (US \$B)	
2000	13.5	20%	2.70	17%	0.46	42
2001	17.6	22%	3.86	19%	0.72	89
2002	22.8	24%	5.52	21%	1.14	130
2003	29.7	26%	7.71	23%	1.74	200
2004	38.6	28%	10.80	25%	2.69	300
2005	50.1	30%	15.04	27%	4.12	455

*Assumes 30% CAGR.

**Assumes the value of the epitaxy as a percentage of the value of the device increases by ~10% per year.

***At a fixed market share of ~11%.

did dip below the offering price for a brief time, shares are now up more than 25%.

Bede makes public debut

In addition to Agere, there is another new company in the Portfolio table this month: Bede plc, a manufacturer of characterization equipment. Two-thirds of the company's annual revenues of \$7 million came from the compound semiconductor industry. Products offered include both destructive and non-destructive X-ray characterization systems.

The company went public in November last year, raising \$42.6 million. Bede, which is based in Durham, England, is traded on the London Stock Exchange. The \$7 million in 2000 revenues was a 46% improvement over 1999 sales; the company reported profits of \$311 000 in 2000 (before one-time charges).

Bede's management indicates that while the pace of their growth may be slowing a bit, sales are continuing at a brisk pace and the company had a backlog of \$5 million at the end of the March quarter. The proceeds of the IPO are being invested in new facilities and inventories so as to bring down delivery times, which climbed from 11 weeks in 1999 to 16 weeks in 2000 due to the increase in bookings.

IQE moves against the cycle

In other interesting news from Europe, epiwafer vendor IQE reported record results for the December quarter and for the year 2000. The company appears to be performing in a "counter-cyclical" fashion – as times get tough for other companies in the compound semiconductor industry, IQE appears to be thriving.

Sales in the December quarter more than doubled to \$15.7 million, compared to \$7.6 million in the year-ago quarter,

and they were up 63% compared to the September quarter. For the full year, sales were \$45.1 million, up 58% compared to 1999.

Profits for the December quarter, excluding one-time charges, were a record \$2.4 million, a six fold increase compared to the year-ago period. Full year pre-tax profits, excluding one-time charges, were \$4.8 million, an increase of 168% over profits of \$1.79 million reported for the 1999 calendar year.

The company also reported record bookings in the December quarter of \$18.45 million, giving IQE a backlog at year-end of more than \$36.5 million, nearly four times the 1999 levels. The company now has a book-to-bill ratio (the comparison of new orders received vs orders completed and shipped) of 1.17.

IQE's results were boosted in part by their acquisition of Wafer Technology, a manufacturer of compound semiconductor substrates. That deal was concluded toward the end of the December quarter. An even bigger factor, according to Drew Nelson, IQE's chairman and CEO, was the bringing on line of several new epi reactors, which increased shipments and gave an added impetus to sales. Four new MOCVD reactors were commissioned at IQE's headquarters in Cardiff, Wales, and two new MBE reactors were brought on-line at IQE's operations in the US (the former QED). "We were successful in transferring a number of existing products to the large capacity platforms," Nelson said, "allowing much more flexibility in catering for customer's needs and allowing us to significantly enhance productivity." He went on to say that these development have also freed up more resources for new product development. Nelson reports that IQE currently has a number of "new and ex-

citing products" that are close to market, particularly in the area of VCSELs and in InP microelectronics.

IQE has also recently launched a new effort, IQE Silicon Compounds, aimed at providing epitaxy services for silicon and silicon germanium structures. This business is located at the company's plant in Pennsylvania. Nelson said that the facilities are finished and the first reactors have been installed, and the company has its first customer, is in the qualification process with two other customers, and has signed non-disclosure agreements with more than 15 other prospects.

At a meeting with analysts, Nelson also laid out an interesting view of the size of the epiwafer market, shown in the table above. IQE believes that the merchant epiwafers market has strong growth prospects, for three reasons: 1. consumption of compound semiconductor devices is growing at 25–40% per year; 2. the value of the epi as a percentage of the value of the device is growing at around 10% per year, as the epitaxial structures become more and more sophisticated; and 3. outsourcing of epiwafers production continues to grow, at the expense of in-house production, also at the rate of around 10% per year.

This latter factor also explains why IQE is moving against the general trend in the industry right now. "Our strategy, to be a pure-play outsource epiwafer house, works very well in times like these when capital is at a premium," Nelson told analysts. He also said that the proliferation of new start-up companies also works to IQE's favor, as the companies are attracted to the idea of buying their epiwafers instead of growing their own, freeing up resources to be dedicated to design or processing functions instead.

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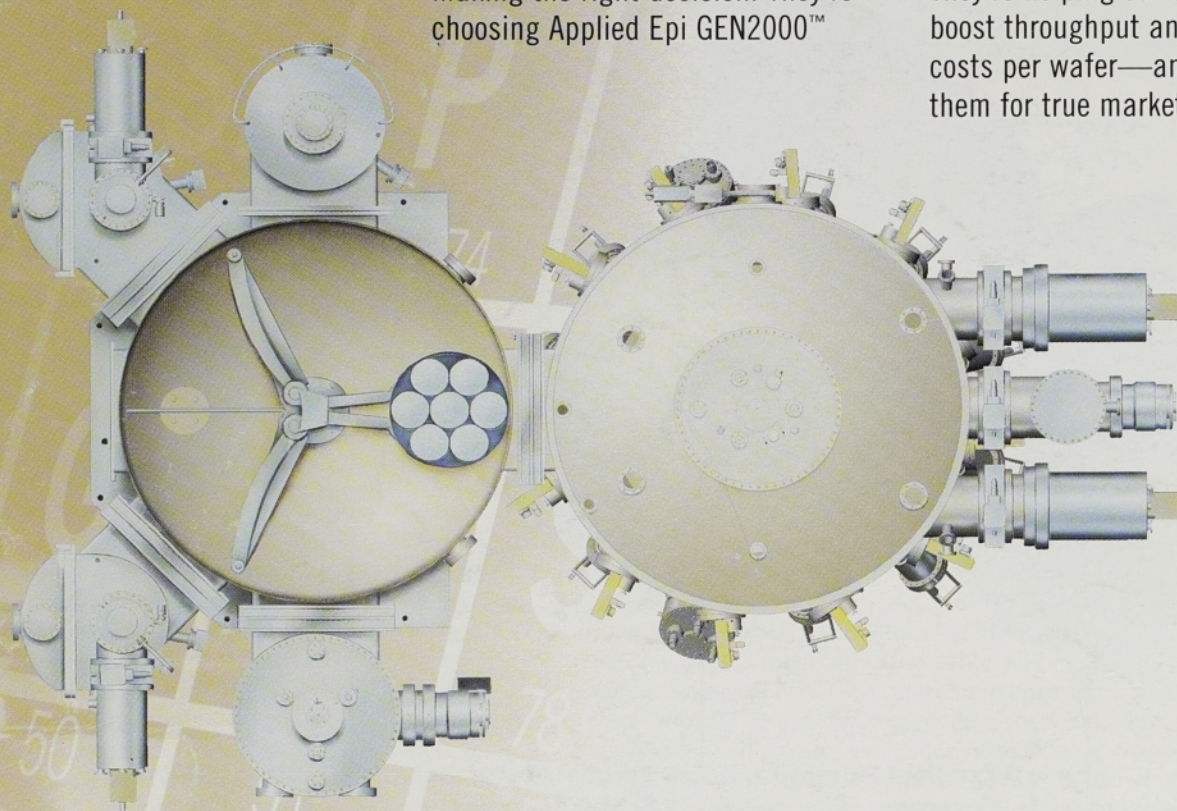
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