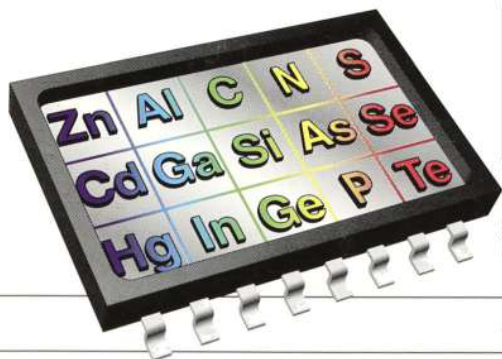




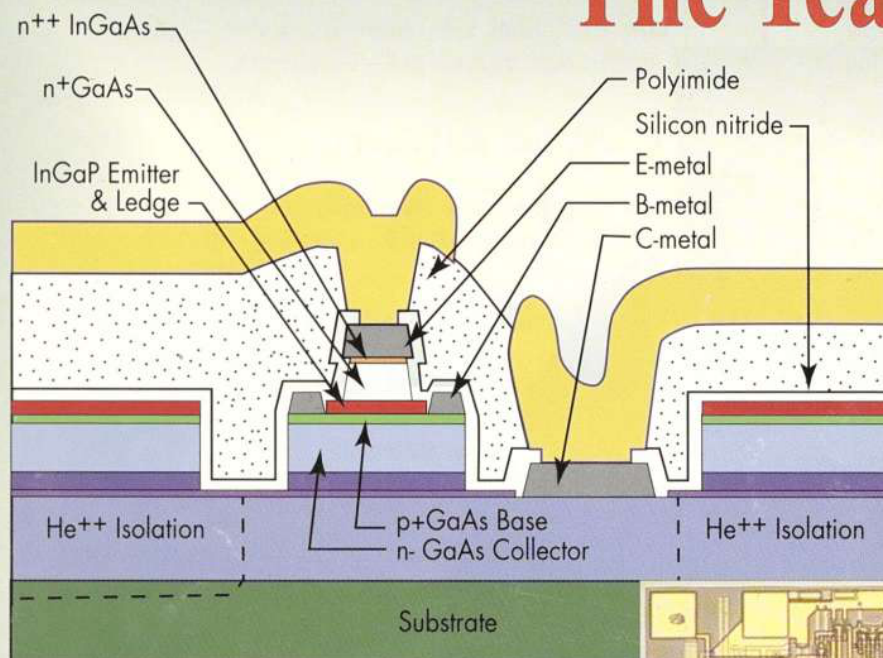
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December 1998

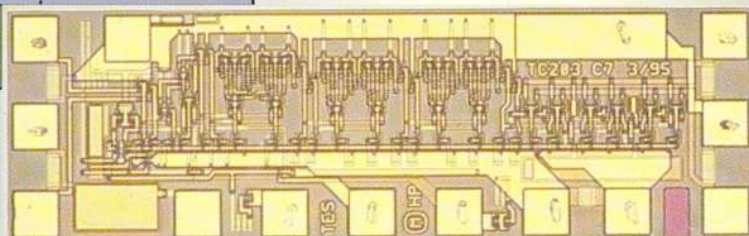
Volume 4 Number 9

The Year in Review

Leading Developments in 1998



- HP Introduces HBT Products



Also in this Issue

- European GaAs Report
- Several New Companies Appear
- Free-Space Optical Interconnects

Suppliers Directory Over 200 Companies Listed



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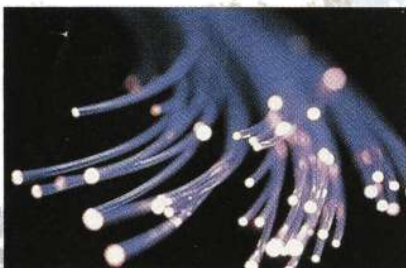
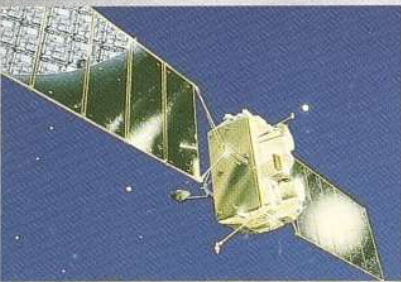
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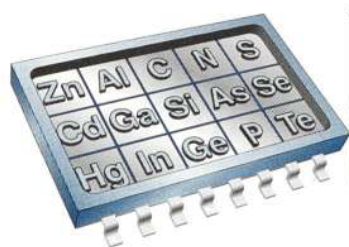
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SPECIAL FEATURE - THE YEAR IN REVIEW

19 How Good Can the Nitrides Get?

In terms of breakthroughs in the field of compound semiconductor materials, 1998 was the "year of the nitrides", according to Materials Editor Colombo Bolognesi.

22 Top Developments in Microelectronics in 1998

Recent breakthroughs in wide bandgap and InP-based devices could lead to the next generation of commercial devices. Microelectronics Editor Bob Metzger reviews developments in these and other more exotic areas.

26 Top Developments in Laser Diode R&D in 1998

Some of this year's most exciting developments have featured new epitaxial structures such as quantum dots, cascaded active layers and type II quantum wells, says Optoelectronics Editor Gary Wicks.

OTHER FEATURES

11 Forum

Low Cost, Free-Space Optical Interconnects

Optical interconnects, implemented with integrated arrays of vertical cavity lasers and detectors, have the potential to provide very high data throughputs and high interconnect densities, according to this article from the University of California at Santa Barbara.

16 Conference Report

GAAS '98: Europe's GaAs Industry Communicates

The most exciting emerging markets for GaAs are high frequency applications such as radar, satellite payloads and broadband microwave communications. Judging by the recent GAAS '98 conference in Amsterdam, the European GaAs industry is ready.

30 Research Review

Compound Semiconductor Materials: 2DEG density in AlGaIn GaN HFETs...Improved quality of MBE-grown GaN using In.

Microelectronic Devices and Circuits: High performance p-type SiGe MODFETs...40 Gbit/s decision and modulator driver ICs...InGaAs single electron transistor.

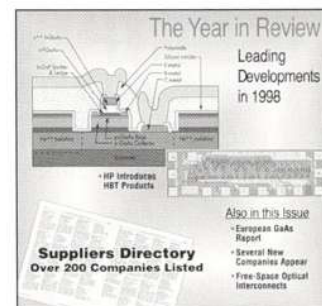
Optoelectronic Devices: Sb-based Mid-IR type II quantum well lasers...220K type II laser operation...high response photodiodes based on Be-chalcogenides.

35 Editor's Picks

A year-end look at the lighter side of the industry.

36 Compound Semiconductor Suppliers Directory

A comprehensive directory of the top two hundred companies supplying equipment, materials and services to the compound semiconductor industry, including a full index by product type.



Hewlett-Packard recently announced their first GaAs HBT products - see page 4 for the full story. (Diagram and photo courtesy of Hewlett-Packard Company). This issue also features our comprehensive Suppliers Directory - see page 36.

NEWS

4 Headline News

Hewlett-Packard Chooses InGaP Emitters For First HBT Products

5 New Compound Semiconductor Companies

Emcore, Optek Join Forces to Manufacture MR Sensors...Earth-bound Applications for ViaSpace Technologies...Tampere University Spawns Second Start-Up

6 Other News

Siemens Plans Semiconductor Sell-Off...Ericsson Orders GSM Power Amplifiers from TriQuint...Iridium Service Launched At Last...Nortel Networks' 10 Gbit/s System Earns US\$1 Billion...25 Terabit/s Bandwidth Demand by 2002...WinStar and Lucent Sign Broadband Network Agreement

10 Nitride News

Researchers from the University of Florida, Blue Lotus Micro Devices, Bell Labs and Sandia report AlGaIn GaN HBTs with improved performance above 250°C.

DEPARTMENTS

2 Index

52 Calendar

54 Employment

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Organization Index

Company/Organization	Page
A, B, C	
A.E. Ioffe Inst.	26
Alcatel-Telettra	16
Alenia	16
APA Optics	22
Bell Labs	10, 22
Blue Lotus	10
CalTech	6
CEA	30
Coherent	7
Cornell Univ.	22
Cree Research	22

D, E, F, G

Daimler-Benz	16, 30
EIC	4
Emcore	6
Ericsson	8
Fraunhofer IAF	31
Fujitsu	4, 26
GEC	4, 16
General Motors	6
Gore Photonics	26

H, I, J, K

Hewlett-Packard	4
Hokkaido Res. Inst.	32
HRL	4, 22
IEMN (France)	22
Iridium	8
JPL	6

L, M, N, O

Lucent	8, 22
MIT Lincoln Labs	26
NASA	6
Nat'l Cheng Kung Univ.	19
NCSU	22
NEC	4
Nichia Chemical	19, 26
Nordic Epitaxy	7
Nortel	4, 8
Northrup Grumman	4
NTT	22, 30, 31
Optek Technology	6

P, Q, R

Philips	16
Purdue Univ.	22
Raytheon	4
Rockwell	4, 22

S, T

Sandia Nat'l Lab	10, 22
Sarnoff Corp.	26, 32
SDL	26
Sensors Unlimited	32
Siemens	4, 7, 16
Sony	26
Stanford University	26
SVTA	22
Tampere Univ.	26
Texas Instruments	4
Thomson-CSF	16
TriQuint	4, 8
TRW	4, 22
Tutcore	7

U, V, W, X, Y, Z

U.S. Naval Res. Labs	19, 22, 26, 32
UMS	4, 16
Univ. of Ca Santa Barbara	11, 19, 22, 26
Univ. of Erlangen	19
Univ. of Florida	10, 22
Univ. of Houston	26
Univ. of Illinois	19
Univ. du Langudoc	26
Univ. de Montpellier	32
Univ. of Texas	26
Univ. of Uim	26, 30
Univ. of Utah	19
Univ. of Wisc.	26
Univ. of Wurzburg	34
ViaSpace	6

Advertiser Index

Aixtron	3
American Xtal Technology	IFC
Bio-Rad	IBC
Compound Semiconductor '99	51
Crystar	7
Emcore	25
EPI MBE Products	33
Epigress	17, 19
Epitaxial Products Int'l	OBC
Epitaxial Technologies	5
Logitech	5
M/A-COM	29
MTI	21
Oxford Applied Research	27
Performance Materials	31
SVT Associates	11
VG Semicon	14
Wafer Technology	9

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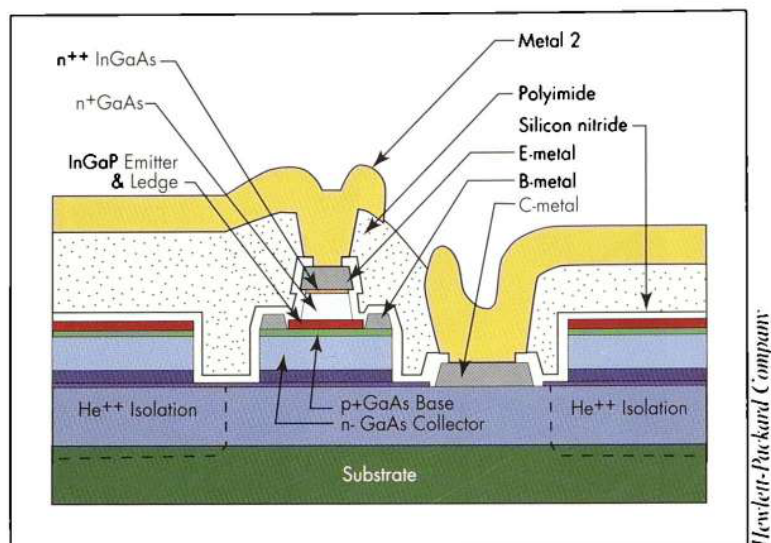
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HP Chooses InGaP Emitters For First HBT Products

Hewlett-Packard has launched a series of microwave ICs which are the company's first HBT-based products. The new products, which are prescalers and Darlington-feed-back amplifiers, are designed for use in microwave and communications test equipment, such as network and spectrum analyzers.



Cross-section of HP's InGaP emitter HBT device. Relevant features for reliability include a non-alloyed n+ InGaAs emitter contact, a non-alloyed base contact, alloyed collector contacts, a depleted InGaP passivation ledge, low damage PECVD Si₃N₄ passivation, and He implant for device isolation.

	Emitter	Base Dopant	Growth Method	Product Market
TRW	AlGaAs	Be	MBE	Fiber-optic, Satellite and Broadband Wireless Communications
Rockwell	AlGaAs	C	MOCVD	Wireless Handsets and Fiber-optic Communications
RFMD	AlGaAs	Be	MBE	Wireless Handsets
Nortel	InGaP	C	MOCVD MOMBE	Fiber-optic Communications
EiC	AlGaAs	C	MOCVD	Wireless Handsets
GEC	InGaP	C	MOCVD	Fiber-optic and Broadband Wireless Communications
HP	InGaP	C	MOCVD	Instrumentation

Major suppliers of III-V HBTs. This table covers commercial product lines only. Several other manufacturers, such as Northrop-Grumman and HRL, have well-established processes which are used for internal purposes or foundry services. In addition, several other companies including Fujitsu, NEC, Raytheon, TriQuint, Siemens and UMS are known to be evaluating or developing HBT processes.

ers, and RF sources. These systems, built around frequency translation and phase-locked loop technology, require that the frequency generation and conversion components have very low phase noise, which avoids destroying information content. HBT ICs are an attractive technology for these applications due to their high RF power, high gain per unit area, excellent uniformity of gain and turn-on voltage, large g_m and low $1/f$ noise. The large minimum feature size ($>1 \mu\text{m}$) allows the high-yield fabrication of highly complex circuits containing more than 3000 HBTs, and enables delivery of high functionality per chip for instrument applications.

AlGaAs or InGaP Emitters?

For these new HBT products, HP has chosen to use InGaP emitter structures. The first HBTs to reach the market were fabricated with AlGaAs emitters. While TRW developed a high reliability process (subsequently licensed to RFMD) using MBE growth, with Be as the base dopant, Rockwell used MOCVD-grown material, mainly to take advantage of the availability of high carbon doping levels in the base.

More recently, new entrants to the HBT market such as Nortel, GEC and HP have gone with InGaP as the emitter material (see Table). Nortel uses high speed GaInP GaAs HBTs for the production of OC-192 (10 Gbit/s) optical fiber communication components, and has been delivering production circuits containing up to 3,000 HBTs for over two years, with no evidence of field reliability problems.

Advocates of GaInP emitter technology cite several advantages, relating mainly to yield and device reliability. GaInP has a very high etch selectivity, which enhances device uniformity, and has several other material parameters which should increase reliability compared to AlGaAs GaAs HBTs. These include the large valence band discontinuity with GaAs ($\sim 0.3 \text{ eV}$), a large room temperature energy gap and a low surface recombination.

The Choice is Clear

TriQuint has a well-developed InGaP GaAs HBT process, acquired from Texas Instruments along with the Dallas fab, and is currently evaluating commercial applications for these devices. According to TriQuint's Tim Henderson, the switch from AlGaAs to InGaP emitters was made about a year ago. "The InGaP emitter technology gave significantly higher yields than the AlGaAs variant, largely due to better selectivity in etching," says Henderson. "A secondary reason was the reported higher reliability of HBTs with InGaP emitters."

HP selected the InGaP emitter technology after a 10x improvement in reliability was demonstrated compared to both commercially available and in-house AlGaAs HBTs. The devices (see schematic) have f_T and f_{max} values of 65 GHz and 75 GHz

respectively, and are fabricated from MOCVD-grown material supplied by Kopin. In a paper presented at the 1998 GaAs IC Symposium in Atlanta, HP's Tom Low described the evaluation of different HBT technologies. Reliability measurements of discrete AlGaAs HBTs and broadband amplifiers, from various sources, showed low and variable mean-time-to-failure (MTTF)

A 10x improvement in reliability was demonstrated, compared to AlGaAs HBTs.

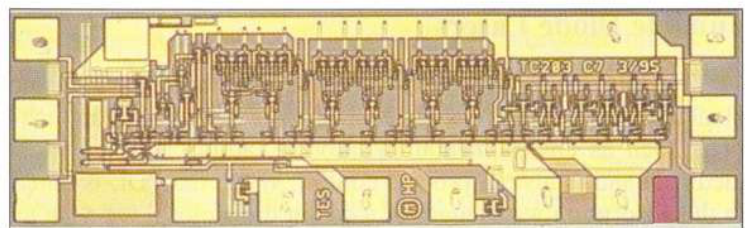
values between 3×10^4 and 8×10^4 hours, at the maximum allowed current density of $0.6 \text{ mA } \mu\text{m}^{-2}$ and junction temperature T_j of 150°C . In contrast, InGaP emitter HBTs showed a projected MTTF of $>5 \times 10^5$ hours at $T_j = 150^\circ\text{C}$, which is

acceptable for instrument applications. HP also reported very high yields for their process, which were typically above 70% for circuits containing 1300 HBTs.

Although HP clearly found in favor of InGaP emitters, other manufacturers such as TRW remain fully confident of the reliability of their GaAs AlGaAs HBTs. "We've had an exceptionally reliable HBT process for over 7 years," says TRW's Dwight Streit. "It is, to my knowledge, the only flight-qualified HBT process in the world."

HP's New Products

Three of HP's new HBT-based MMICs are 200 MHz to 16 GHz divide-by-two, divide-by-four, and divide-by-eight prescalers which feature very low phase noise of -153 dBc/Hz at 100 kHz offset and operation from a single positive or negative supply of 4.5 to 6.5 V. They also incorporate on-chip pre- and post-amplifiers for high input power sensitivity (-20 dBm to -10 dBm from 1 GHz to 10 GHz) and excellent reverse isolation. The post-amplifiers also allow selection of either high ($+5.5 \text{ dBm}$) or low (0 dBm) output power modes. Three other new products are 12 GHz prescalers operating at about half the current of the previously described devices (30 mA vs. 60 mA in low output power mode). The other new devices are DC-12 GHz and DC-15 GHz Darlington-feedback amplifiers, providing 50Ω input and output match, and operating from a single supply voltage. A typical device draws 44 mA and dissipates 190 mW, while providing $9.5 \pm 1 \text{ dB}$ gain across the band and $\pm 12 \text{ dBm}$ output power (at 1 dB gain compression) at 1 GHz. Both amplifiers have a low 1 f noise corner of less than 20 kHz.



HP's new HMMC-3008 DC-16 GHz prescaler, manufactured using an InGaP emitter HBT technology.

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Emcore, Optek Join Forces to Manufacture MR Sensors

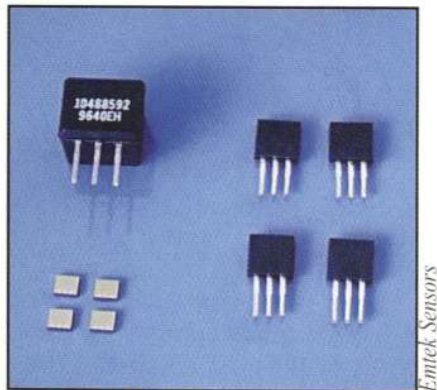
Optek Technology Inc., a vertically integrated manufacturer of application specific sensors, has linked up with Emcore to form a new company, Emtex Sensors LLC. Emtex will market discrete InSb magnetoresistive (MR) sensors manufactured as package-ready die by Emcore, and packaged by Optek. Emtex has already announced the availability of several InSb MR sensors, in a variety of configurations and packages, offering high sensitivity and signal-to-noise ratio, and consistent performance across a wide range of temperatures (-40°C to -165°C) and operating conditions. They will be targeted at existing automotive markets and emerging consumer and industrial applications.

Emcore's Pegasus division already manufactures MR sensors, using InSb epitaxial structures grown by MOCVD on GaAs substrates. The sensors were developed in conjunction with General Motors for a number of automotive position-sensing applications, including cam and crankshaft sensing for ignition timing and engine misfire detection. [See CS 4(4), p. 29]. The harsh operating environments of these applications required the development of a solid-state technology with high sensitivity over a wide temperature range. Several million InSb MR sensors are already deployed in GM vehicles, and the Emtex product line is based on the same technology, which is licensed from GM. According to a spokesman, the sensors could be used in a variety of industrial and aerospace applications, and also in consumer goods.

Optek, headquartered in Carrollton, Texas, manufactures custom optoelectronic, magnetic, and fiber optic sensors, for a wide variety of industrial, aerospace and defense applications. Among Optek's many existing custom sensor products are IR LEDs, fabricated from LPE-grown material, and Hall effect sensors.

"Optek brings strong capabilities in the design, manufacture, packaging and test of sensor products that make it an excellent partner for this new extension of our business," said Reuben F. Richards, President and CEO of Emcore. "In addition to our

work through this new venture, we will continue to market our current package ready die for MR applications to existing Emcore customers." According to Sensor Business Digest of Foster City, CA, the worldwide market for magnetic sensors used in industrial, commercial, and automotive applications is estimated at \$1.5 billion.



New MR sensor products available from Emtex Sensors LLC.

Earth-bound Applications for ViaSpace Technologies

Several technologies developed for space applications by Caltech's Jet Propulsion Laboratory (JPL), including quantum well infrared photodetectors (QWIPs) and tunable IR diode lasers, are to be commercialized by a new start-up company, ViaSpace Technologies, LLC (Altadena, CA). Founded by Dr. Carl Kukkonen, former Director of JPL's Center for Space Microelectronics Technology, the new company has obtained options for exclusive licenses from Caltech for five technologies that JPL developed for NASA space exploration missions. "These technologies are coming to the marketplace via the US space program, hence the company's name," says Kukkonen. "NASA and the Department of Defense have invested millions of dollars in developing these technologies for the needs of specific missions. ViaSpace plans to transform this government technology for the commercial marketplace."

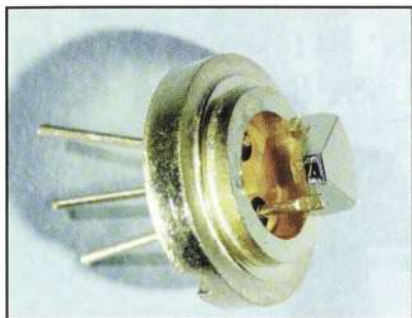
Quantum Well Infrared Photodetectors

QWIPs are emerging as an alternative to HgCdTe for IR imaging applications [see CS 4(4), p. 24]. The QWIP structure typically consists of many periods of GaAs QWs separated by AlGaAs barriers, and is sensitive to radiation in the 6-25 μm range. The photodetector is divided up into individual pixels and bonded to a silicon readout circuit to form an imaging system at the heart of an IR camera. Although QWIPs have to be cooled to cryogenic temperatures, arrays can be fabricated with very high uniformity due to the availability of well-understood MBE growth and fabrication processes in the GaAs material system.

Kukkonen sees several possible near-term applications for QWIPs, including: night vision optical devices; unobtrusive security/surveillance systems; agricultural sensors (diseased or blighted crops have a different IR signature than regular plants); medical sensors (breast tumors give off more heat than healthy tissue); and national defense systems. "The Defense Department is happy to have ViaSpace as a commercial source of QWIPs," said Dwight Duston of the Ballistic Missile Defense Organization. "We need QWIPs for missile detection and tracking, and we intend to demonstrate them on one of our space missions next year."

Tunable Diode Lasers

Tunable diode lasers (TDLs) were developed by JPL for planetary gas-sensing. ViaSpace will pursue commercial applications such as environmental monitoring, atmospheric science, medicine and industrial process control. When the TDL is tuned to the absorption wavelength of a gas in the atmosphere such as water (H_2O), carbon dioxide (CO_2) or hydrofluoric acid (HF), the presence of these gases can be measured at extremely low levels (parts per billion). TDL gas sensors are currently being used by



An IR laser diode developed at JPL for planetary gas-sensing; this technology is now being commercialized by ViaSpace.

Via Space Technologies

NASA to measure the distribution of water vapor in Atlantic Ocean hurricanes, and six of these sensors will be sent to Mars in January 1999, and will measure water and CO₂ in the Martian atmosphere. This type of laser is also appropriate for use in fiber-optic communications.

The TDL devices that will be produced by ViaSpace are DFB lasers containing strained layer InGaAs quantum well structures grown by MOCVD on InP substrates. Wavelength tuning is achieved by varying the pitch of the sub-micron grating, which is defined by e-beam lithography. In this way, it is possible to make single mode tunable diode lasers with wavelengths up to 2.1 μm .

Tampere University Spawns Second Start-Up

A new company, Nordic Epitaxy Inc., has been formed to capitalize on the red laser technology developed at the Tampere [Finland] University of Technology. The company is owned jointly by researchers from the University and Coherent, Inc., a major manufacturer of lasers and related equipment.

This is not the first tie-up between Coherent and Finnish research. In 1996, Coherent bought the majority interest in Tutcore, another company formed to capitalize on laser diode technology developed at Tampere University. Tutcore's area of expertise is the design and growth of IR laser diodes with Al-free active regions. Many of the founders of that venture are also involved in the new company, and both can trace their roots back to the Tampere University research group headed by Marcus Pessa. In addition, both companies are concentrating on the MBE growth technique to produce their epitaxial structures.

Seppo Orsila, Chairman of the Board of Nordic Epitaxy, says that the new company will first concentrate on the production of AlGaInAsP epiwafers for 600nm band laser diodes. The company's long-term plans call for a broader product range, including wafers for vertical cavity devices, such as RCLDs (Resonant Cavity LEDs) and VCSELs. Most of the company's products will be based on proprietary structures developed in collaboration with Tampere University. High power, low power, and single-mode structures with wavelengths between 690 to 650nm are already available, and shorter wavelength products will follow shortly. The company will also provide custom epiwafer growth services upon request.

Siemens Plans Semiconductor Sell-Off

Following severe losses in the DRAM business, Siemens AG has announced plans to spin off their Semiconductor Group into a private company. The move will allow Siemens to concentrate on its core businesses - which no longer includes the semiconductor sector. "However, the semiconductor business is marked by high, yet unsteady growth with huge fluctuations in earnings," said Heinrich Pierer, President and CEO of Siemens AG, at a press conference on November 4. "This has a major impact on our company's overall results." By listing the Semiconductor Group separately on the stock market, or by taking it public, Pierer explained that the company hopes to make the Group "suitable for partnerships or mergers able to further expand its activities into leading market positions."

Siemens was hit very hard by the sharp erosion of memory prices on the world market, and the Semiconductor Group posted a loss of DM 1.2 billion for the current fiscal year, compared to a profit of DM 109 million last year. Siemens' total semiconductor sales were \$3.48 billion in 1997, of which \$987 million was in DRAM, while compound semiconductors sales totaled \$388 million [see CS 4(2), p. 8]. Siemens' operations include one of the largest GaAs fabs in the world (see page 16), and they are also a major producer of III-V opto-electronics. There is no word yet on how the reorganization will affect these activities.



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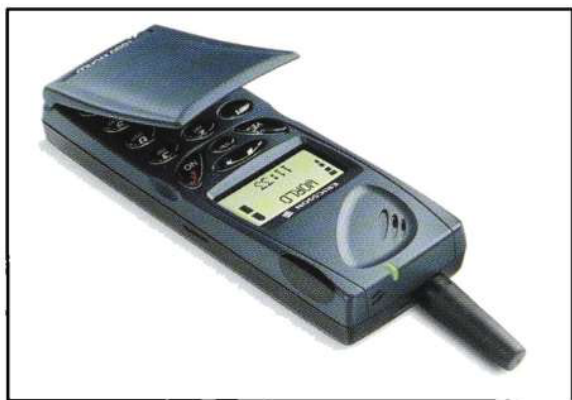
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Ericsson Orders GSM Power Amplifiers from TriQuint

TriQuint Semiconductor's Foundry Services division recently announced receipt of its first production order from Ericsson Components AB, under the terms of their joint development agreement signed last year. The product, a power amplifier for dual band GSM cellular phones, will be manufactured at TriQuint's Hillsboro, Oregon fabrication facility. Volume production of the new dual band PA is planned for early 1999. "We are pleased that Ericsson has chosen our proven GaAs technology for their family of GSM power amplifiers," says Bruce Fournier, VP of the Foundry Services division. "Our partnership with Ericsson has provided a major step into the GSM cellular phone market."

The device is the first of several planned under the agreement between the companies, under which TriQuint fabricates GaAs MESFET wafers according to Ericsson's proprietary designs. According to an Ericsson spokesperson, the prime focus of this activity is to establish an Ericsson internal strategic resource of GaAs RFICs to complement Ericsson's in-house silicon Bipolar and LDMOS process capability. The company believes that the high efficiency of GaAs makes it the optimal choice for power amplifiers, and that Ericsson will benefit from having a combination of processes that will enable them to offer a full range of RF ASIC components for future wireless and cellular requirements.



Ericsson's 1888 World dual band mobile phone for GSM 900/1900 frequencies.

Iridium Service Launched At Last

Iridium, the world's first hand-held, global satellite phone and paging system, became commercially available to customers on November 1, 1998. The Iridium system has a constellation of 66 low earth orbit (LEO) satellites, providing users with communication services from virtually any point on the globe. The first official phone call was placed by US Vice President Al Gore to Gilbert Grosvenor, Chairman of the National Geographic Society and a great-grandson of Alexander Graham Bell.

Nortel Networks' 10 Gbit/s System Earns US\$1 Billion

Revenues derived from Nortel Networks' 10 Gbit/s Optical Networking platform have now exceeded US\$1 Billion after two years in the marketplace, attaining more than 90% market share in its category worldwide. "Nortel Networks correctly predicted the bandwidth explosion that would take place and drive up the need for increased fiber optic capabilities," said Mike Unger, president, Optical Networks, Nortel Networks. "The market response to our 10 Gbit/s platform has been phenomenal, and more than 20 major network operators have now deployed this solution across tens of thousands of fiber miles." Nortel Networks currently markets a D-WDM system capable of delivering 320 Gbit/s down a single fiber, and is planning to introduce terabit networking by the year 2000.

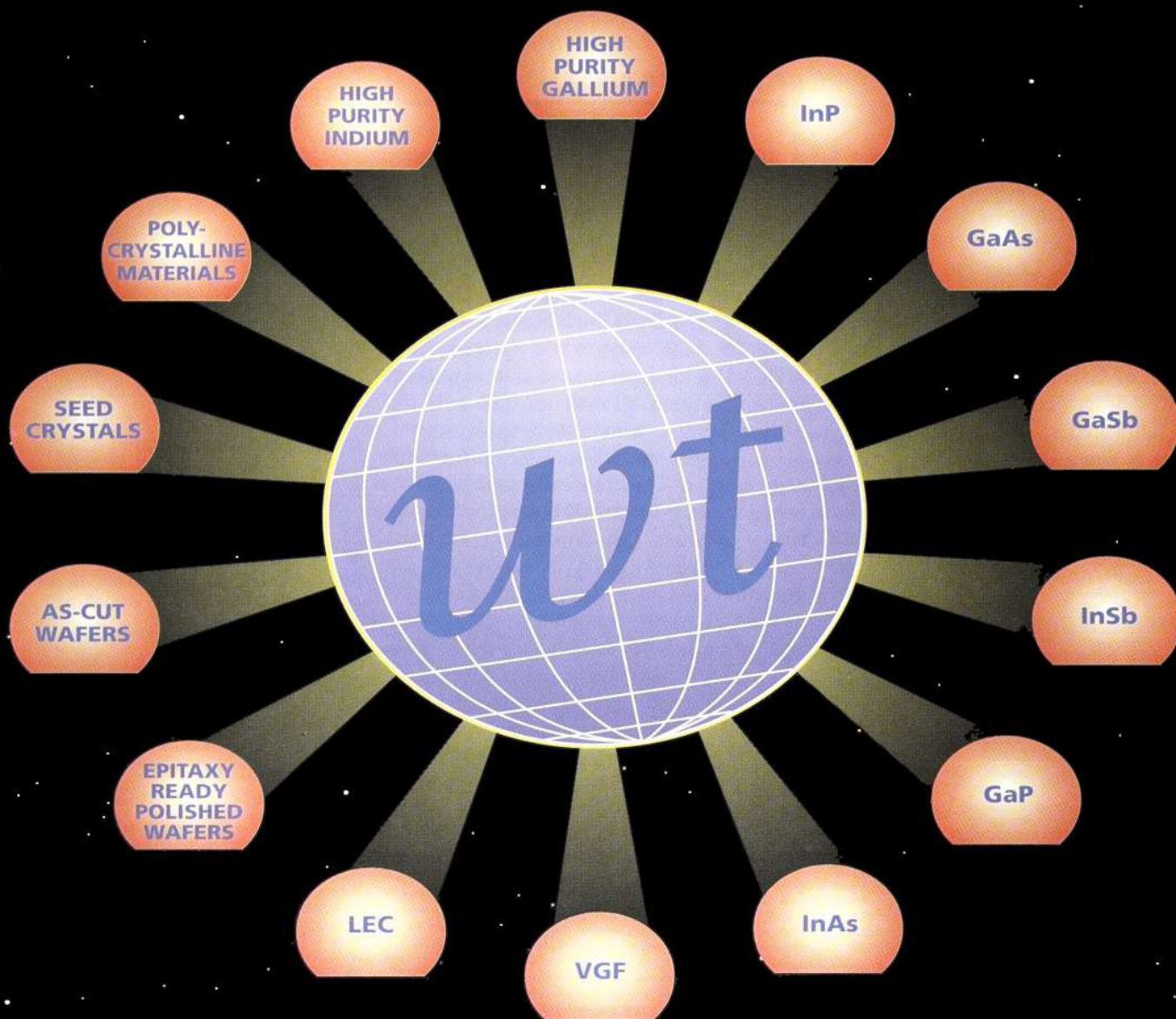
25 Terabit/s Bandwidth Demand by 2002

According to a new report by Insight Research, the global data traffic demand is expected to grow to a staggering 25 Terabits/s by 2002. Fiber optic SDH SONET-layered ring networks will continue to be the backbone for high-speed carrier networks, but they will increasingly use WDM technology to create the capacity to carry the expected data bandwidth demand. "WDM will be the most cost-effective option carriers have to provide the necessary bandwidth without installing additional fiber," explained Robert Rosenberg, president of Insight. "We expect WDM revenue to top \$4 billion in 2002." The report also shows that a "Photonic Moore Curve" is making it possible to double transmission bandwidth capability every 18 months while cutting the cost per bit per second in half every two years.

WinStar and Lucent Sign Broadband Network Agreement

WinStar Communications and Lucent Technologies recently announced plans to build the world's first global end-to-end broadband network. WinStar's Wireless FiberSM networks, which use wireless point-to-multipoint links at 28 GHz or 38 GHz to provide broadband voice, data and Internet services, will be implemented in up to 100 cities around the world. As we discussed in our last issue, broadband wireless communications are emerging as the first high volume commercial market for high frequency GaAs MMICs [see CS 4(8), p. 22]. Under the agreement, Lucent will provide network design, integration and build-out services, along with the vast majority of the communications hardware and software. To form the global network, the local wireless networks will be integrated with an optical network that will use Lucent's 80-channel DWDM optical networking equipment.

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High Temperature GaN/AlGaIn HBTs

A joint research effort by the University of Florida, Blue Lotus Micro Devices, Bell Labs and Sandia National Laboratories has demonstrated HBTs with improved performance above 250°C.

The field of GaN-based electronics continues to move forward rapidly. The wide bandgap of GaN and its alloys, which makes possible the remarkable success of blue LEDs and lasers, is also advantageous for high power and high temperature electronic applications. Two recent reports have described the fabrication of GaN/AlGaIn HBTs; previously we described MOCVD-grown devices fabricated by the University of California at Santa Barbara [see CS 4(8),

p. 16]. More recently, a second research effort has fabricated HBTs using a hybrid growth method.

The HBT epilayers were grown on a sapphire substrate (see schematic). Following growth of a low temperature GaN buffer, a 2 μm thick highly resistive undoped GaN layer was grown by MOCVD. This layer provided a template for subsequent growth of the active device layers, which were grown by MBE, using an RF atomic nitrogen source. An n⁺-GaN sub-collector was followed by an n-type GaN collector, a p-type GaN base (Mg-doped at $1 \times 10^{18} \text{ cm}^{-3}$), a p-type $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ emitter and a graded region to a p-type GaN contact layer.

An inductively coupled plasma (ICP) etch, using Cl_2/Ar , was used to fabricate large area ($\sim 90 \mu\text{m}$ diameter) devices, exposing both the base and sub-collector regions. Dry etch processes on GaN tend to produce N_2 -rich surfaces which are strongly n-type; in the case of the n⁺ sub-collector this improves the ohmic contact resistance and is therefore advantageous. For the p-type base layer, it was necessary to terminate the etch $\sim 100 \text{ \AA}$ above the base-emitter junction, oxide the surface using ozone, and strip away this layer in acid solution. The structure was completed with e-beam evaporation of p-type (Ni/Pt/Au) and n-type (Ti/Al/Pt/Au) contacts.

One of the major challenges in producing HBTs in the GaN material system is to get sufficiently high p-

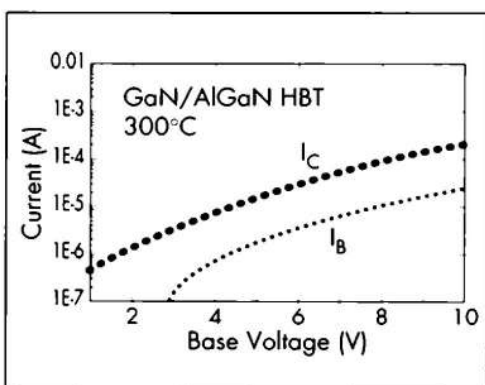
type doping in the base. In these devices, the hole concentration in the base at room temperature is relatively low, resulting in an I-V characteristic which is strongly influenced by the series resistance. The low bias current at 300°C is about an order of magnitude higher than at 25°C, due to enhanced activation of the Mg acceptors at elevated temperatures. The HBT also shows improved gain above 250°C as the hole density in the base increases. The dc current gain is around 10 at 300°C (see graph) because of the improvement in base resistance compared to room temperature.

Improving the Base Resistance

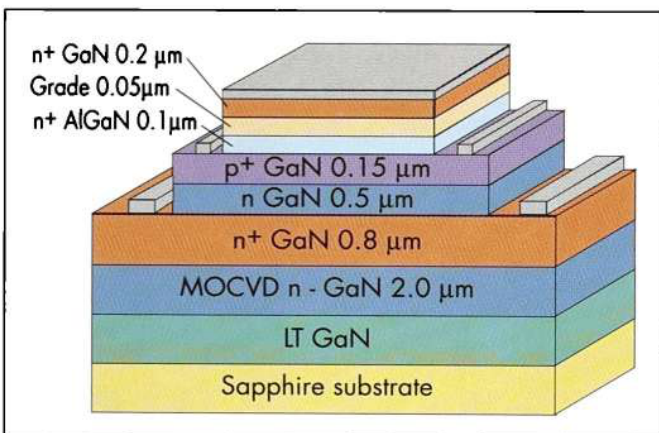
The authors suggested several approaches to improve the performance of their GaN HBTs. A number of recent studies have demonstrated that piezoelectric stress is effective in increasing the channel conductivity of AlGaIn GaN HFETs [see, for example, p.30]. An appropriate stress layer, placed between the collector and the base in the HBT, could possibly increase the hole concentration in the base. A second choice would be to decrease the base resistance using a lower bandgap material such as InGaIn or SiC, although achieving high p-type doping in these materials is also difficult.

The third alternative is selective regrowth of the extrinsic base region, which would allow optimization of both the base contact resistance and the gain. By keeping the doping level in the intrinsic base material relatively low, the minority carrier lifetime and hence the gain can be kept high, and the base thickness can be reduced to decrease base transit time, and increase device speed. Selective regrowth of a heavily doped extrinsic base contact layer could then significantly reduce the parasitic losses associated with the base contact resistance. Suitable materials would be heavily carbon-doped GaAs or GaP, although this would introduce the problem of hole transport across the hetero-interface.

See Fan Ren et al. MRS Internet J. Nitride Semi. Res. 1998, 3(41).



Gummel plot for the 90 μm diameter GaN/AlGaIn HBT at 300°C.



Schematic of the GaN/AlGaIn HBT. Following MOCVD growth of a 2 μm buffer, the subsequent device layers were grown by RF-MBE.

Low Cost, Free-Space Optical Interconnects

DUANE A. LOUDERBACK, OLA SJÖLUND, ERIC R. HEGBLUM,
SHIGERU NAKAGAWA, JACK KO, and LARRY A. COLDREN
ECE Department, University of California at Santa Barbara

Although computer clock speeds continue to increase, the bandwidths of board-to-board and chip-to-chip interconnects have not kept pace. Unless this interconnect bottleneck is addressed, the current growth of system performance will not continue. Free-space optical interconnects have received considerable interest for their potential to relieve such bottlenecks. Besides the potential for achieving large data throughput and high interconnect densities, optical interconnects also have the advantage of alleviating problems caused by electromagnetic crosstalk, capacitive loading, and signal distortion. In addition, optical chip-to-chip interconnects can be distributed across a chip and therefore have the advantage of scaling with chip size. Electrical interconnects are typically made to the periphery of the die and therefore scale with the perimeter of the chip. Figure 1 shows a schematic of a simple bi-directional free-space optical interconnect, implemented using integrated arrays of vertical cavity lasers (VCLs) and detectors

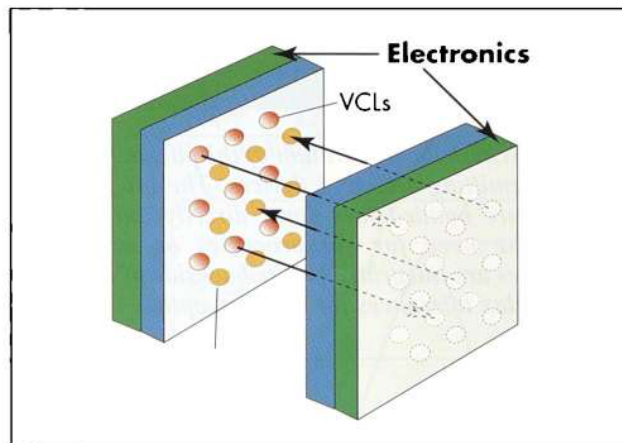


Figure 1. Schematic of a free-space optical interconnect consisting of dense two-dimensional arrays of integrated vertical cavity lasers and photodetectors. The optoelectronics are shown bonded directly to electronics. Optics, preferably integrated microlenses, are needed to maintain low crosstalk and coupling losses.



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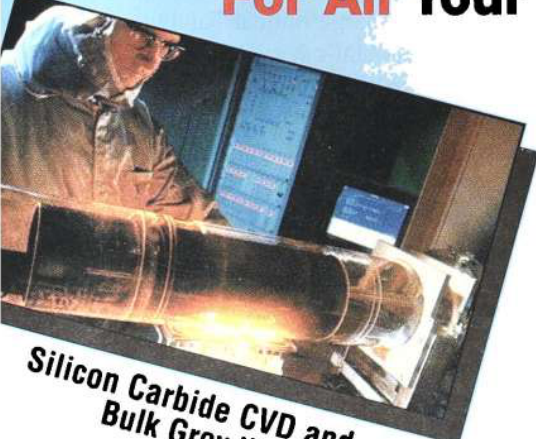


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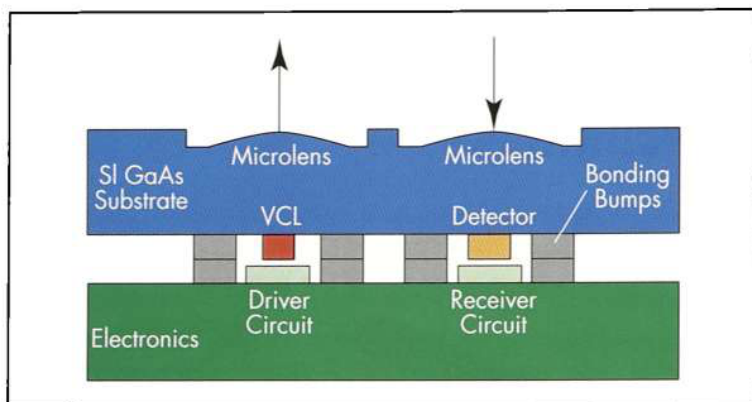


Figure 2. Schematic illustration of the packaging advantages of substrate emitting/detecting devices. The integrated VCLs and detectors are bonded face-down directly onto the electronics without the need for via processes or substrate removal. Microlenses are integrated on the backside of the wafer to eliminate or relax tolerances for external optics.

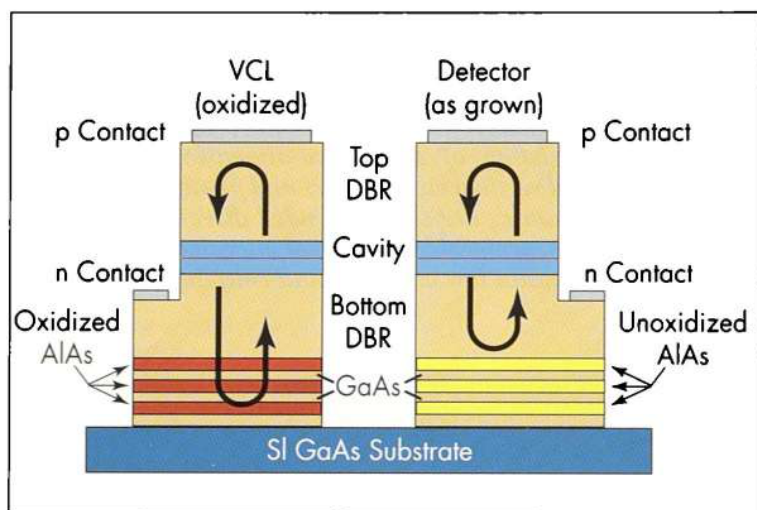


Figure 3. Schematic of the integrated device structure showing the VCL (left) and the detector (right). The active region consists of three 80 Å InGaAs quantum wells (~20% In) with 80 Å GaAs barriers. The "normal" DBRs consist of alternating quarter wave layers of GaAs and $\text{Al}_{0.90}\text{Ga}_{0.10}\text{As}$.

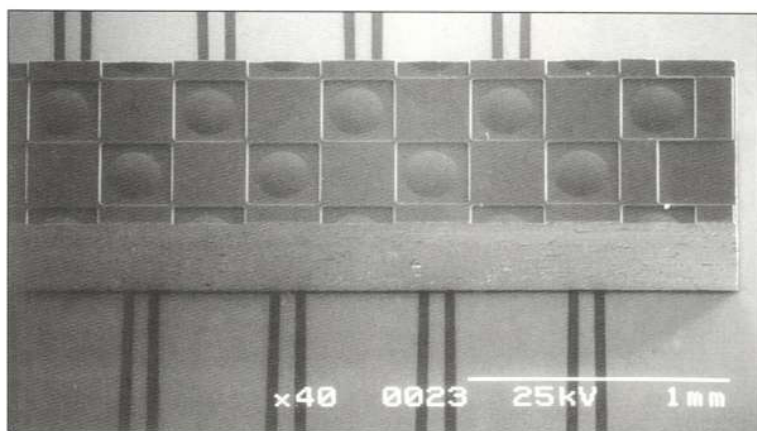


Figure 4. SEM image of an array of integrated VCLs and detectors with microlenses, flip-chip bonded to a submount with coplanar transmission lines. The microlenses visible on the top of the array are 200 μm in diameter.

Despite the many advantages of free-space optical interconnects, to become reality, they need to be manufactured in volume at low cost. To achieve this, not only must the optoelectronic devices be fabricated inexpensively, but they need to be packaged using simple, cost-effective techniques. This includes the incorporation of optics, preferably an array of microlenses, to maintain low crosstalk and insertion loss. Although satisfactory VCLs and detectors have been integrated onto the same chip, the packaging has been prohibitively complex and costly.

Packaging Problems

The problem with previously integrated VCL* and detector arrays was their top emitting/detecting geometry. To bond these arrays to electronics, complex via processes are needed to bring electrical contacts to the backside of the array substrate [1]. In addition, because the microlenses have to be fabricated on a different substrate than the optoelectronic devices, alignment of the optics with the VCL/detector arrays becomes a critical feature of the assembly process.

Bump-bonding the optoelectronic array face-down onto the electronics (commonly known as flip-chip bonding), which eliminates complex via processes, is the first key to low cost packaging. However, this demands the use of devices that emit and detect through the substrate, otherwise the substrate has to be removed. The other key to low cost packaging is the use of integrated microlenses, fabricated on the same substrate as the optoelectronics, that either eliminate external optics or relax the tolerances considerably allowing passive optical alignment of the arrays. The integration of microlenses is most easily accomplished with substrate emitting and detecting devices. In this case, the microlenses can be fabricated directly on the substrate side of the device wafer. Figure 2 shows a schematic that illustrates the inherent packaging advantages of devices that have through-the-substrate emission and detection.

Device Structure

Although integrated VCLs and resonant-cavity detectors can share the same epitaxial structure, they have very different requirements for the mirror on the substrate side (input/output mirror). VCLs require a very high reflectivity in the bottom mirror, typically greater than 99%. To simultaneously achieve a reasonably large optical bandwidth and adequate absorption, the resonant-cavity detector must have a much lower reflectivity in the bottom mirror (~80-85%). A large optical bandwidth is needed because of variations across a wafer and between epitaxial growths and differences in device operating temperatures.

Previous integration techniques were unable to achieve

* In this article, the generic term VCL is used, rather than the more commonly encountered VCSEL (vertical cavity surface emitting laser), since the lasers here are fabricated to emit through the substrate rather than from the top surface.

this reflectivity difference in the bottom mirror and were therefore limited to top emitting/detecting architectures. Using a new structure [2] requiring no regrowth, VCLs and resonant-cavity detectors are fabricated on a single epitaxial growth structure that is compatible with flip-chip bonding and integrated microlenses. The structure enables high performance VCLs and detectors with through-the-substrate emission and detection to be integrated without compromising the performance of either device.

To achieve the required difference in mirror reflectivities, three special GaAs/AlAs mirror periods are added to the bottom mirror. The AlAs layers are later oxidized for the VCLs, but not for the detectors. When oxidized, the special mirror periods are in phase and therefore add to the reflectivity of the VCL's output mirror, but for the detector, the unoxidized mirror periods remain out of phase and don't contribute to the detector's input mirror reflectivity. In this way, the VCLs and resonant-cavity photodetectors have their bottom (input/output) mirror reflectivities individually designed and implemented by post growth selective oxidation of some of the mirror periods to convert the detector structure into a VCL structure. Figure 3 shows a schematic of the integrated device structure when used as a detector (right) and converted to a VCL (left).

Array Fabrication

The integrated devices were fabricated using standard VCL processing techniques. After device processing, microlenses were integrated onto the substrate side of the arrays. The photolithographically aligned microlenses were fabricated by transferring the shape of a reflowed polymer mask into the substrate using chlorine reactive ion etching. The microlenses are recessed into the substrate and are designed to collimate the VCL output or focus a collimated beam onto the detector. After dicing the processed chip, the arrays of integrated, microlensed VCLs and detectors were flip-chip bonded directly to submounts with coplanar transmission lines. The submounts allow high-speed testing and

imitate the packaging necessary for integration with CMOS electronics. Figure 4 shows an SEM image of a flip-chip bonded array of VCLs and detectors. The recessed microlenses are facing up in the picture and the optoelectronic devices are on the bottom of the array next to the submount.

Device Characteristics

Flip-chip bonded VCLs with microlenses exhibited threshold currents as low as 135 μ A, which is the lowest reported for 3 quantum well VCL, while maintaining high differential efficiencies of over 50 %. VCLs such as these with low threshold currents and high efficiencies are critical for dense free-space optical interconnects due to thermal considerations. The detectors have responsivities of 0.48 A/W, corresponding to 60 % absorption, with fairly broad 7 nm optical bandwidths. The VCLs and detectors also have the same operating wavelengths. The light-current characteristics of an integrated VCL are shown in Figure 5, while Figure 6 shows the responsivity spectrum for the adjacent detector. The VCLs have bandwidths of about 9 GHz, while the detectors have bandwidths of 2.5 GHz for 50 μ m diameter detectors and 9 GHz for 25 μ m detectors. These characteristics are more than adequate for dense, massively parallel, high-speed free-space optical interconnects.

Free-Space Optical Links

A free-space optical link at 1.25 Gbits/s was demonstrated with the integrated devices. The link was tested with both the VCL and detector at 20°C, with both devices at 90°C, and also with the VCL and detector $\pm$ 75°C from each other. The free-space optical link demonstrated error free operation (bit error rate $<10^{-12}$) for all temperatures tested. The wide range of temperature operation is critical since the optoelectronics will set directly on integrated circuits that may have their temperature vary considerably.

Although work still needs to be done, arrays of integrated VCLs and detectors hold great promise for providing dense,

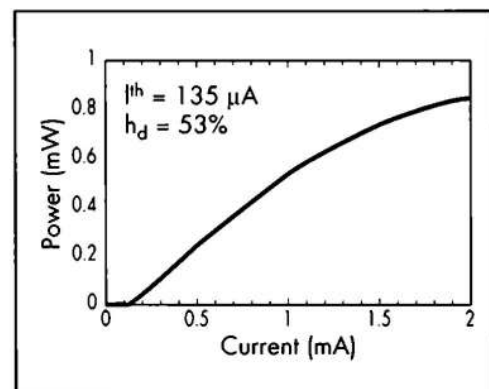


Figure 5. Light-current characteristics of a flip-chip bonded, microlensed VCL.

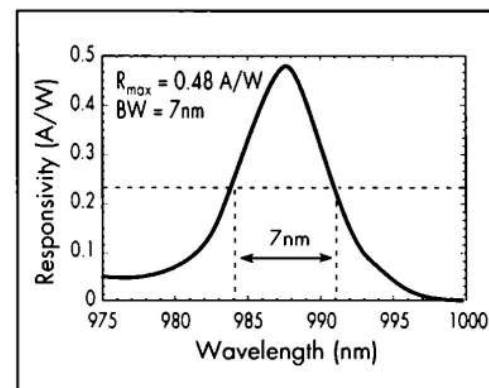


Figure 6. Responsivity spectrum of a flip-chip bonded, microlensed detector.

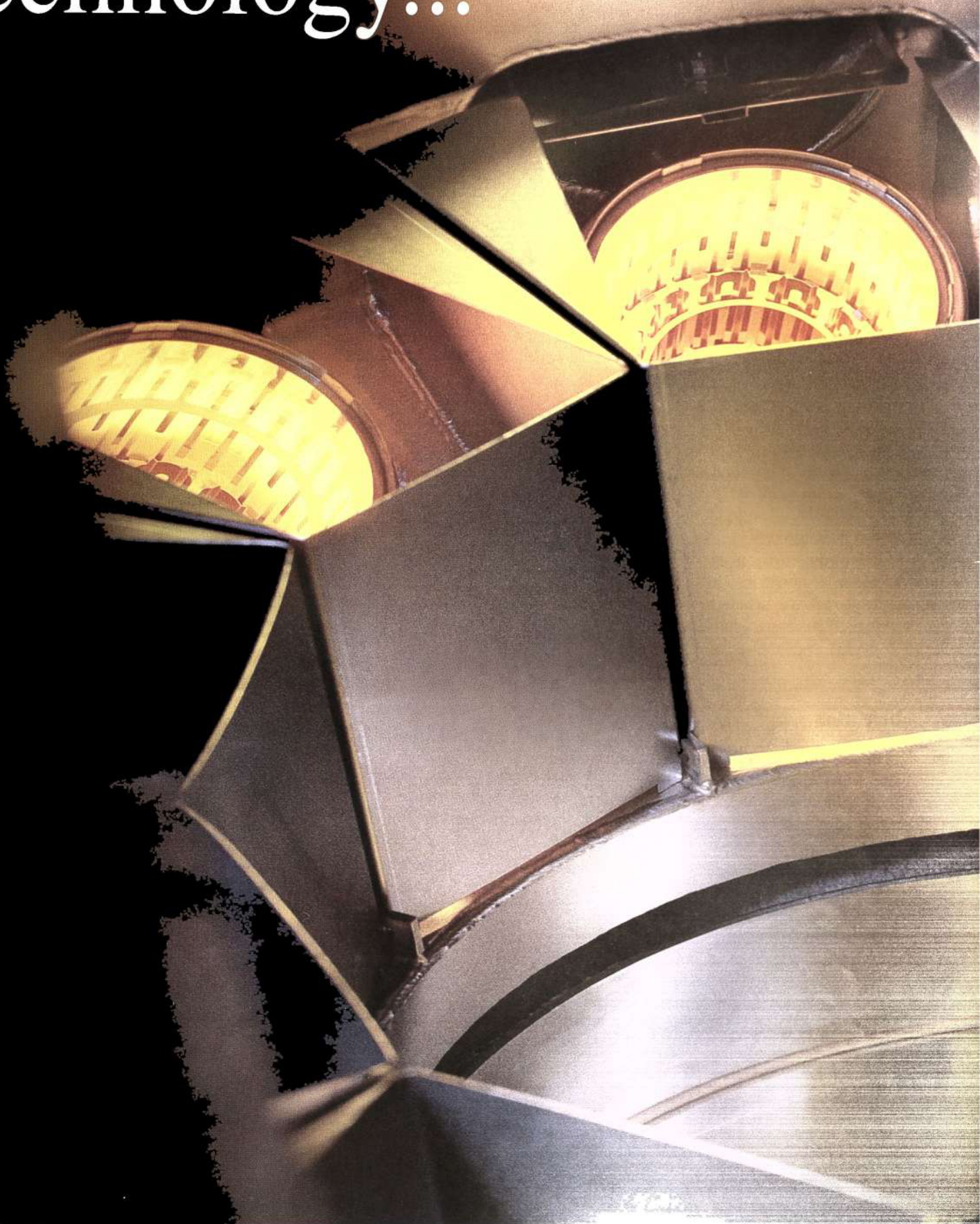
massively parallel, bi-directional free-space optical interconnects. The additional cost of the free-space optical interconnects, compared to electrical board-to-board and chip-to-chip interconnects, will likely determine when or if these systems will make their appearance in actual products. Integrated devices with substrate emission and detection that are easy to fabricate and package may hold the key to achieving the low cost production that will be necessary.

This research was supported by AFOSR and DARPA, via HOTC and the Free-Space Optical Interconnect Initiative.

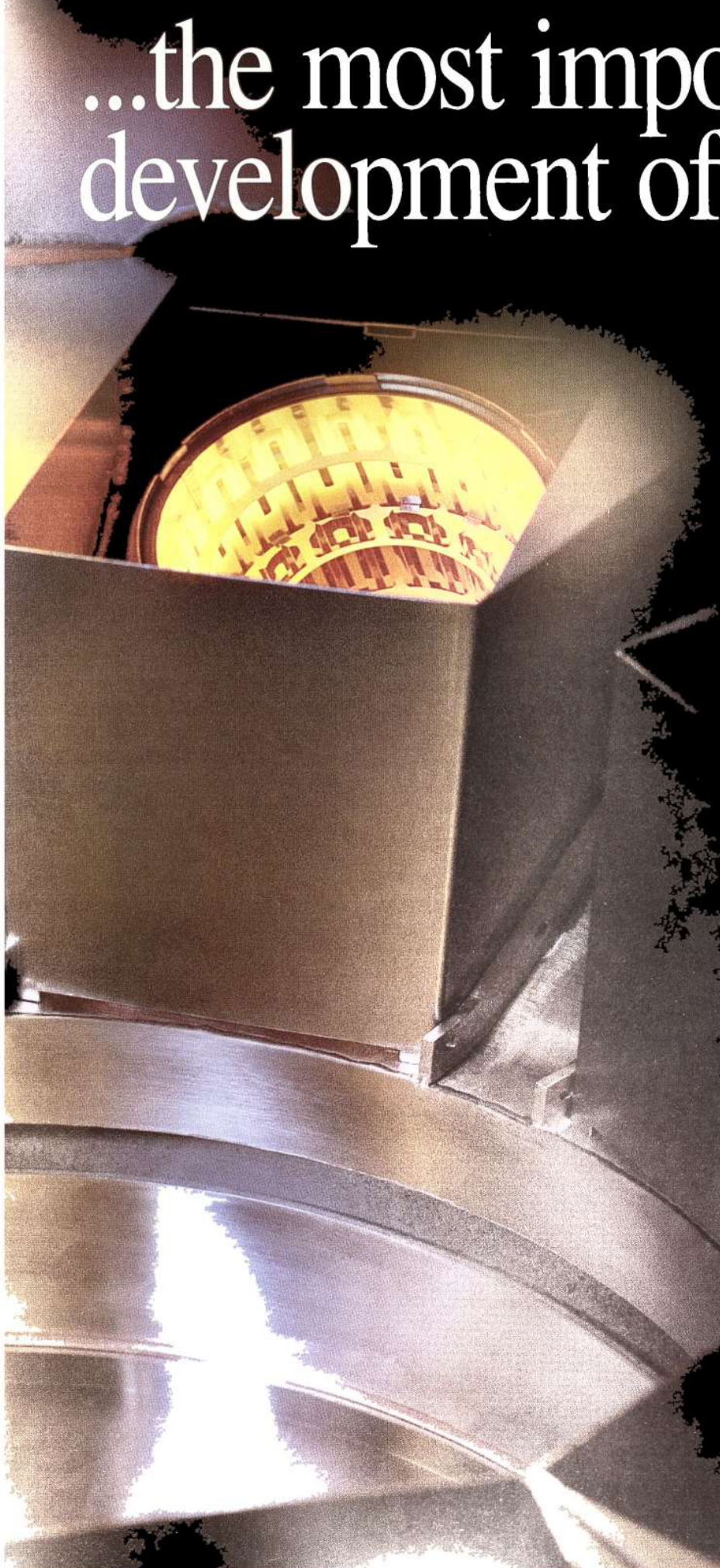
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GAAS '98: Europe's GaAs Industry Communicates

Much discussion of applications for microwave GaAs, and the first announcement of a 6" fab for analog applications

MARIE MEYER

While wireless handsets remain the biggest application for GaAs, the most exciting emerging markets are in high frequency applications such as radar, satellite payloads, and, above all, broadband microwave communications. That was the message from the Gallium Arsenide Applications Symposium (GAAS '98), held October 5-7 in Amsterdam.

The GAAS series of conferences were started in Europe in 1990, but the event was transformed this year by holding it in conjunction with the new "European Microwave Week" event. GAAS '98 alone drew over 350 attendees.

Europe has several companies with GaAs capabilities that are suited to commercial microwave applications, according to Heinrich Daembkes, president of United Monolithic Semiconductors. UMS was formed by the merger of the Thomson-CSF and Daimler Benz GaAs operations in 1996. Other European notables include Siemens, Philips Microwave Limeil, and GEC Marconi. In addition, Alenia and Alcatel-Telettra have GaAs technology for in-house use.

Daembkes' own company is probably most well known for developments in automotive radar technology. But in his opening-day talk, Daembkes warned that this application is evolving much more slowly than originally forecast. He also pointed out defense applications are not showing any growth. But at the same time the proliferation of new communications technologies is generating, for the first time, demand for commercial GaAs ICs operating at microwave frequencies. Daembkes presented a thorough discus-

sion of the opportunities for GaAs in systems operating between 5 - 100 GHz. See Table 1.

The most exciting area is broadband microwave applications. It includes LMDS and MVDS, which are essentially schemes to deliver entertainment to the home wherein the core of the system will be fiber or cable, but the "last mile" - the connection to the subscriber - will be implemented using microwave radio. It also includes point-to-point communications, which are used primarily to link the "cells" of a cellular wireless network together.

While none of these applications will generate the huge unit volumes seen in wireless handsets, they all represent significant commercial opportunities for GaAs fabs. And, unlike wireless, they seem nearly impervious to encroachments from silicon, because of their high operating frequencies. "GaAs has hardly any competition beyond 10 GHz," Daembkes said, "and its competitiveness has been proven in several markets, in terms of both price and performance." He concluded with his personal opinion that the GaAs industry was poised for solid growth over the next decade.

GaAs Opportunities from 5 - 100 GHz

System Type or Application	Operating Frequency	GaAs Chips Required	Status & Comments
WLAN	5.2 GHz	T/R MMICs	Emerging now, used for data communication
Short Distance Communications	5.8 GHz	Transceiver MMICs	Emerging, potentially large market for remote ID
DBS (Direct Broadcast Satellite)	10.5 - 11.5 GHz	LN converter MMICs & discrete HEMTs	Existing/mature; requires large volumes & lowest cost
Point-to-Point Communications	13 - 60 GHz	T/R MMICs	Emerging, fast growth, 1st volume application for MMICs >12 GHz
Video Distribution Systems	28 GHz* & 42 GHz**	LN converter & transceiver MMICs	LMDS started in 1997, MVDS will start in 2000. Consumer driven, requires low cost
Optical links	up to 60 GHz	digital drivers, MUX/DMUX	Existing, rapidly growing, today limited to commercial systems
Satellite Networks	12 - 40 GHz	T/R MMICs	Emerging, will serve commercial and consumer markets
Automotive Radar	76 GHz	Transceiver MMICs	Emerging in '98 but slow growth until after 2004

*LMDS = Local Multipoint Distribution System = North America

**MVDS = Microwave Video Distribution System = Europe

Table 1. Systems which will require key GaAs components. Based on material presented at GAAS '98 by Heinrich Daembkes, United Monolithic Semiconductors.

HEMTs All Around

Daimler-Benz, Thomson-CSF, Philips and Bosch Telecom all made presentations on GaAs MMIC modules for broadband communications. Daimler and Thomson use MMICs from UMS; Bosch uses TriQuint's newly acquired microwave operation (formerly part of Texas Instruments), and Philips has their own GaAs fab at Philips Microwave Limeil. All three fabs use 0.25 μm PHEMT processes, and there seemed to be unanimous agreement that this is the preferred semiconductor technology for both the power and low noise functions in this application.

The most detailed presentation was from J.P. Viaud of Thomson-CSF, who presented a Ka-band (24-26 GHz) transceiver module that will be used in a point-to-multipoint distribution system developed by P.COM in the UK. Thomson is manufacturing the modules at Thomson-CSF Microelectronics in Massy, France.

A block diagram of the module is shown in Figure 1. Eight MMICs are used - a high power amplifier (HPA), a variable gain amplifier (VGA), a low noise amplifier (LNA), two mixers, two buffers, and a frequency multiplier.

The frequency multiplier, the two identical buffer amplifiers, the 3-stage

LNA, and the VGA are all executed using the PH25 low noise PHEMT process. It utilizes 0.25 μm Al gates and is applied to very low noise and small/medium signal circuits up to 40 GHz. Typical noise figure is 1.5 dB with 8 dB of associated gain at 40 GHz.

The 3-stage HPA is fabricated using UMS' PPH25 process, which is a power variant of PH25, with a double heterojunction/delta doping epitaxial sequence and a double gate recess for increase linear power amplification. Typical breakdown voltage is >10V, and the PPH25 transistors exhibit about 600mW/mm of power density at the 1 dB gain compression point. The up- and down-converters are executed using a 1 μm Schottky diode MMIC process.

The assembled module exhibited an average conversion gain of 21 dB, with a ripple of ± 0.5 dB, in room temperature operation at 24 - 26 GHz. The noise figure was below 3.0 dB.

Other Applications & Devices

While the focus of the conferences was clearly on applications, there were some interesting papers relating to devices. Researchers from Alenia Difesa discussed their power HFET process, especially in comparison with MESFETs. Alenia grows a large-bandgap n-AlGaAs layer on top of a relatively highly-doped



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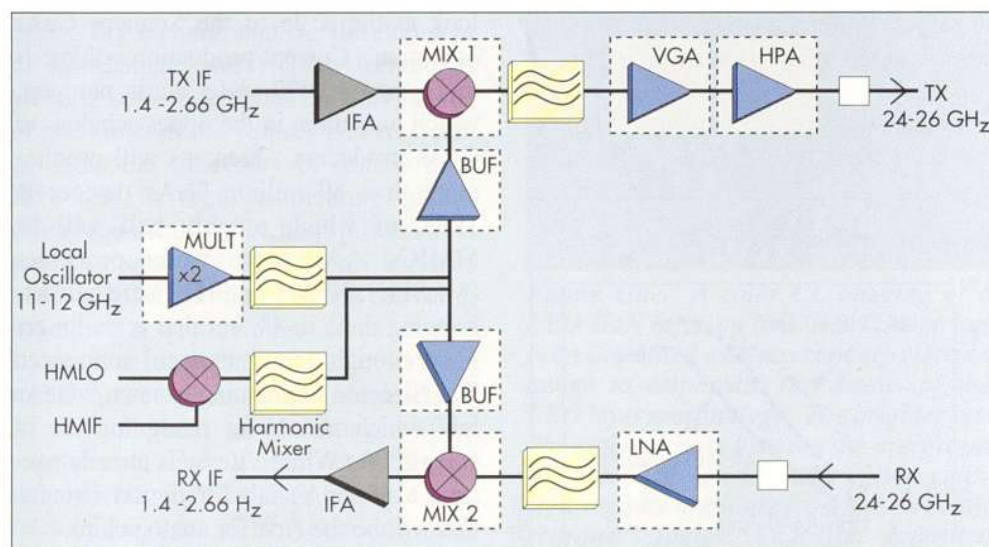


Figure 1. Block diagram of a point-to-multipoint Ka-band transceiver module developed by Thomson-CSF. Eight MMICs from UMS are used - a high power amplifier (HPA), a variable gain amplifier (VGA), a low noise amplifier (LNA), two mixers (MIX), two buffers (BUF), and a frequency multiplier (MULT).

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n-GaAs channel. After recess formation by wet etching, 1 μm Ti-Al gates are deposited, and then their length is reduced by selective lateral dry-etching of the Ti layer to form a T-shaped gate with the desired footprint length. It was reported that this non-lithographic gate scaling technique can be routinely applied down to 0.3 μm .

Compared to MESFETs, the Alenia HFETs offer better performance in terms of device gain and bandwidth capability per output power. And in comparison to PHEMTs, they are easier to grow, and they have a larger current capability, since the channel thickness is not limited by the critical value for pseudomorphic growth. Alenia is developing HFET-based circuits especially for microwave power applications, wherein the device design is aimed mainly at achieving large channel conductance, high breakdown voltage, good linearity over a wide gate bias range, and reduced hot electron effects.

Siemens Goes for Six

Of course, it is impossible to have a conference on GaAs applications and not discuss the wireless market. Marc Rocchi of Philips Microwave Limeil explained where GaAs has its strengths: digital cellular phones in North America and Japan (e.g. those using the DAMPS, CDMA, and PDC standards). He reported that almost all of these devices now use GaAs MESFET, HEMT or HBT PAs. But the

situation is different in the European standards (GSM, DCS), because their modulation schemes require less linearity. Most 900 MHz GSM handsets use silicon bipolar PAs. GaAs is more competitive in the 1800 MHz models, but silicon is not far behind in terms of performance.

Rocchi pointed out that this is an important "battleground", as many forecasters believe that GSM will eventually become the global standard. He also suggested that

1999 will be the year when multimode, multiband phones really begin to takeoff. This could increase the competitiveness of GaAs, because of its higher integration capability.

Both Rocchi and Ewald Pettenpaul of Siemens expressed some skepticism about SiGe's ability to compete in the PA market. Pettenpaul told the audience that he does not expect any major shifts in the nature of the RF semiconductor market. Currently, approximately 20% of all RF applications are covered by GaAs, and Pettenpaul believes that this ratio will hold. He said no fundamental change can be expected in wireless applications up to 3.5 GHz, meaning cellular and cordless phones, WLANs, & GPS. As he put it, "in simple words, Si dominates the receiver market up to 2 GHz, whereas GaAs is the preferred material for PAs above 0.5 W output power due to better power added efficiency at low supply voltages".

He also addressed the likely competitiveness of hetero devices - meaning

HEMTs, HBTs and SiGe. In his opinion, SiGe will result in only minor improvements for the known cellular and cordless phone systems, and therefore it is unlikely to substitute Si bipolar circuits, due to its higher cost. He sees its main potential for receivers at higher frequencies (2 - 20 GHz). GaAs HBTs provide good PAE and the advantage of a single supply, but, compared with MESFETs, provide reduced linearity because they are bipolar. GaAs HEMT technology, he said, "is the best millimeter wave material up to 100 GHz, because it combines the advantages of unipolar transistors with outstanding performance down to 1.5 V supply". Its major drawback is a 2x higher wafer cost compared to GaAs MESFETs.

The Siemens roadmap for wireless handset PAs is still clearly predicated on MESFET devices. Pettenpaul showed MESFET-based PAs for 3V GSM phones with typical PAE of 55%, as well as a dual-band PA for GSM handsets with PAE of 60%. It uses the super-small SCT 595 package, a factor of 4 smaller than the conventional TSSOP 16 package. But he also showed a new HEMT based version of the same chip that is now available for higher performance handsets; it has a 65% PAE. And he also discussed engineering samples of an HBT-based PA that has demonstrated 62% PAE in the PCN band.

Pettenpaul closed with an interesting look at the scale of the Siemens GaAs operation. Current production volume is more than 40,000 wafer starts per year, which puts them in the upper echelon of GaAs producers. Siemens will produce more than 80 million GaAs devices in 1998, of which roughly half will be MMICs. All three wafer processes (MESFET, HEMT and HBT) are currently being done in 4", but that is no longer good enough. So Pettenpaul announced that Siemens is planning a new 6" GaAs fab, which should be ready for use in early 2000. While Vitesse is already running a 6" GaAs fab for digital circuits, this will be the first for analog chips.

It is fitting, then, that the next GAAS conference will be in Siemens' back yard, as European Microwave Week is moving to Munich in 1999.

Siemens is planning a new 6" GaAs fab, which should be ready for use in early 2000 - the first for analog chips.

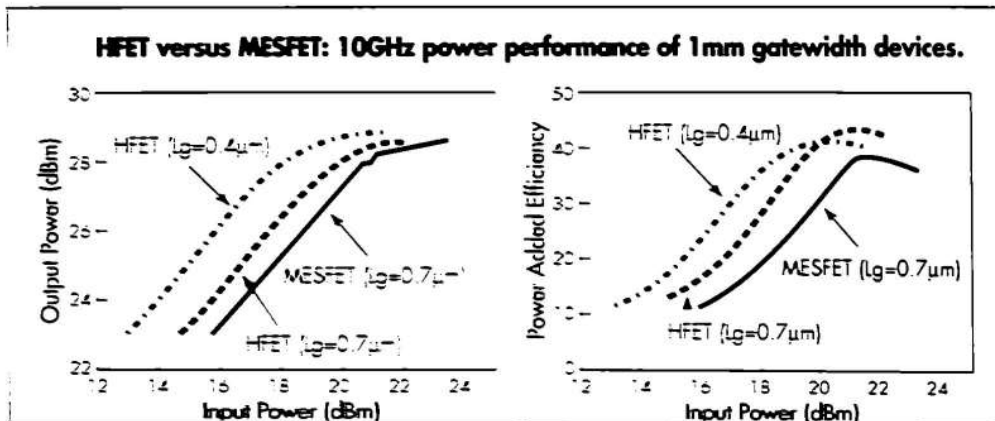


Figure 2. A comparison of 1mm gate-width HFET and MESFET power devices from Alenia Difesa.

How Good Can the Group-III Nitrides Get?

C. R. BOLOGNESI

Nineteen ninety eight indubitably was the "year of the nitrides" as far as semiconductor material breakthroughs are concerned. Only recently, the group-III nitrides were heralded as the "last frontier" in semiconductor science and technology - today, the question to ask seems to be "how good can they get?" Elements of the answer to this question can be inferred from some of the following contributions to the field.

Photoenhanced Wet Etching of GaN

The exceptional chemical stability of the nitrides makes them very difficult to etch when using conventional wet etch solutions, and a wide body of literature has developed describing the use of dry etching methods to successfully etch GaN. However, certain device applications such as the gate recessing in HFETs, are sensitive to ion damage introduced during dry etching, and the development of low-damage wet etching techniques yielding smooth surfaces on GaN is thus of great interest. C. Youtsey and co-workers from the University of Illinois have introduced a room-temperature photo-electrochemical wet etching process that produces smoothly etched GaN surfaces using a KOH solution and Hg arc lamp illumination [1]. Atomic force microscope measurements indicate a root-mean-square etched surface roughness of 15 Å, compared to a starting surface roughness of ~3 Å. Whereas conventional wet etchants used on GaN produce etch rates of the order of 10 Å/min only, etch rates of 500 Å/min were obtained with a 0.02M KOH solution and an illumination intensity of 40 mW/cm² measured at $\lambda = 365$ nm.

LEO GaN Substrates - is the Search Over?

Last year's biggest news story was undoubtedly the achievement by Shuji Nakamura and co-workers from Nichia Chemical Industries Ltd. of a 10,000 hour blue laser. Those devices were grown on GaN material deposited on sapphire substrates using what Nakamura calls epitaxial lateral overgrowth (ELOG), but what many others call lateral epitaxial overgrowth (LEO).

This year Nakamura demonstrated InGaN multi-quantum well laser diodes grown on pure GaN substrates that were produced by first performing lateral epi-

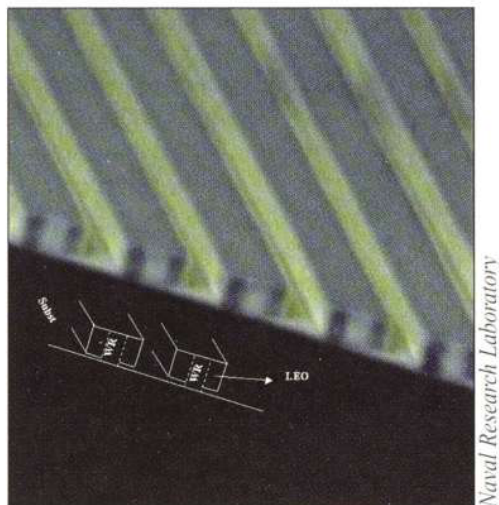


Figure One. A color CL imaging of a LEO GaN layer on SiC. This image has been combined with a secondary electron image to emphasize the details of the LEO layer morphology. The brighter yellow region occurs between the overgrown regions. The low-intensity yellow emission regions originate from the "window regrown" region, i.e., film deposited directly over the mask aperture. The dark region is the LEO region, which is characterized by low defect concentration. From Ref. [3].



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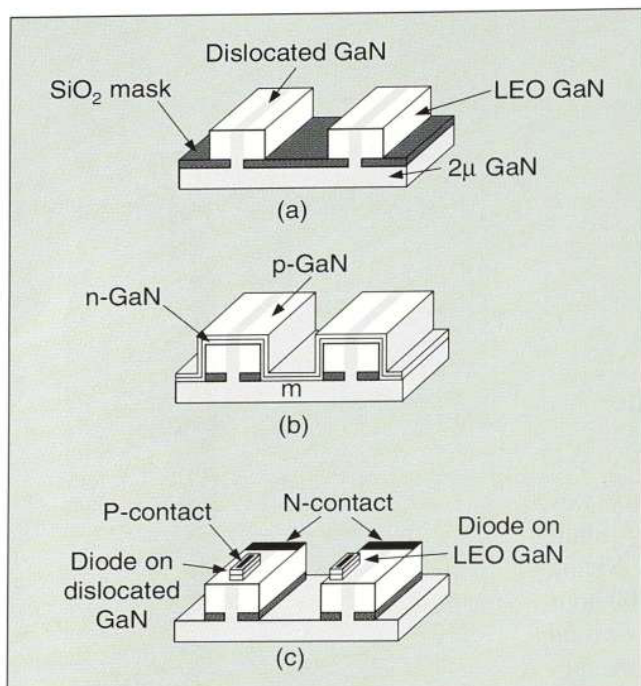


Figure 3. Process flow for LEO growth and device formation. (a) LEO growth: an SiO₂ mask is deposited on a GaN film and window stripes are opened to the GaN beneath. During regrowth dislocations propagate vertically - GaN above the window region remains dislocated while laterally grown material has reduced dislocation density. (b) SiO₂ mask is removed and the p-n junction layers are grown. (c) Mesa is etched and metal contacts are deposited to form diode structures. Adjacent diodes lie on LEO GaN and on the window regions. From Ref. 4.

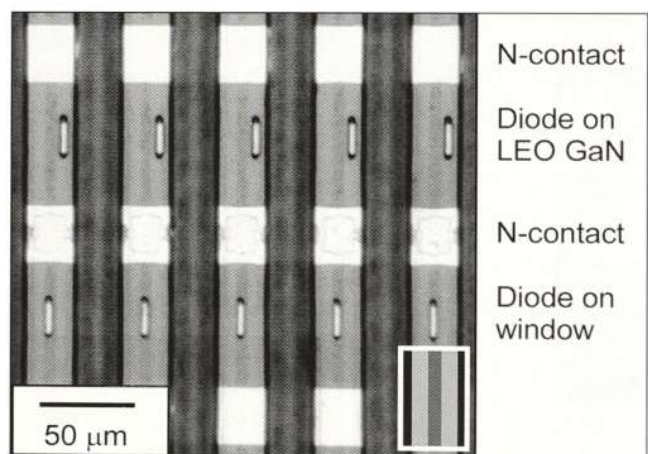


Figure 4. Photograph of diodes grown using the process described in Figure 3. The top row of diodes are on LEO GaN; those in the bottom row are on the window region (dislocated GaN). The inset (lower right) shows the position of the overgrown GaN and the window region. This setup was used to compare diodes grown on areas of low dislocation density ($\sim 10^6 \text{ cm}^{-2}$) to diodes grown on areas of high dislocation density ($4 \times 10^8 \text{ cm}^{-2}$), showing that reverse-bias leakage current is reduced by 3 orders of magnitude in the LEO material. From Ref. 4.

taxial overgrowth of GaN on a (0001) C-plane sapphire substrate and then removing the sapphire substrate by polishing. The result was a $\sim 80 \mu\text{m}$ thick free-standing GaN-only substrate. Lasers fabricated on it showed a threshold current density of 5 kA cm^{-2} and an estimated lifetime of more than 10,000 hours [2].

Which raises the question: is this technique possibly the best way to produce a substrate for GaN devices? Given the importance of this question, it is not surprising that some of the other highlights of material research in 1998 involved characterization of LEO GaN material.

J. A. Freitas Jr. of the Naval Research Laboratory and co-workers from North Carolina and Moscow State Universities reported the optical characterization of homoepitaxial GaN layers deposited by OMVPE on stripe-patterned 1.5-2.0 μm thick GaN films on 6H-SiC substrates. Spatially resolved Raman scattering spectra indicate an improvement in the material quality in the LEO grown regions that is consistent with the reduction of biaxial strain and structural defects in the overgrown regions. Low-temperature photoluminescence spectra revealed an additional emission band with a zero phonon line at 3.263 eV which was assigned to a recombination process involving shallow donor and acceptor defect levels, and the temperature dependence of the PL signal suggests that the new luminescence band is due to the Si donor incorporated from the SiO₂ stripes. Full color cathodoluminescence (CCL) imaging was used to investigate the spatial distribution of radiative defects. Blue light emission was clearly observed in the LEO layers, whereas yellow radiation was detected in the more defective GaN epilayers between the SiO₂ mask ing stripes [3].

Along similar lines, the effect of dislocations on the electrical characteristics of GaN p-n junctions was examined by P. Kozodoy and colleague from UCSB in an experiment in which LEO was used to produce areas of low dislocation density ($\sim 10^6 \text{ cm}^{-2}$) in proximity to areas of high dislocation density ($4 \times 10^8 \text{ cm}^{-2}$) typical of GaN material grown on sapphire [4]. P-n diodes fabricated in the LEO material were sufficiently small to contain no threading dislocations whereas devices fabricated in the window region were expected to contain ~ 200 threading dislocations. The junction current voltage characteristics revealed that the reverse-bias leakage current is reduced by 3 orders of magnitude in the LEO material. The remaining leakage current in LEO GaN was found to be related to a deep trap level.

- InGaN MQW lasers grown on "pure" GaN substrates produced by LEO - Nichia Chemical
- CL imaging of radiative defects in LEO GaN layers - NRL/Moscow State University
- Electrical characterization of GaN p-n junctions in LEO structures - UCSB
- Room-temperature photoelectrochemical wet etching process for GaN - Univ. Illinois
- Micropipe-free 6H-SiC single crystals - Universität Erlangen-Nürnberg
- Improved breakdown characteristics of InP HFETs fabricated with a lattice-matched InAlAsSb Schottky layer - National Cheng Kung University (Taiwan)
- Growth of DyP/GaAs and DyAs/GaAs heterostructures - Univ. of Utah

Micropipe-Free 6H-SiC

In another interesting widebandgap development, N. Schulze and co-workers from the Universität Erlangen-Nürnberg reported the growth of 6H-SiC single crystals that were free of micropipe defects through the modified Lely method, a physical vapor transport technique. The authors met with success by reducing the temperature gradient to $5^{\circ}\text{C}/\text{cm}$ in order to avoid mechanical stresses in the crystal and therefore reduce the number of dislocations which are thought to be involved in the formation of micropipes. Increasing thermal gradients to $7.5^{\circ}\text{C}/\text{cm}$ was found to be enough to result in the formation of a high density of micropipes ($> 200\text{ cm}^{-2}$). Micropipe-free material was grown under near equilibrium conditions with a source temperature of $2150\text{--}2180^{\circ}\text{C}$ in an argon pressure of $30\text{--}820\text{ mbar}$, resulting in a maximum growth rate of 0.27 mm/h . Hall effect measurements carried out between 70 and 700 K on micropipe-free and conventional 6H-SiC wafers revealed no significant difference in low-field mobility between the two wafers [5].

High-Breakdown InP-Based HEMTs

Interest in growing in the use of antimony-containing layers in III-V transistor structures. Su and co-workers from the National Cheng Kung University (Taiwan, R.O.C.) reported improved breakdown characteristics of InP HFETs fabricated with a lattice-matched $\text{In}_{0.34}\text{Al}_{0.66}\text{As}_{0.85}\text{Sb}_{0.15}$ Schottky layer grown by low-pressure metalorganic chemical vapor deposition. The devices exhibited a two-terminal gate-to-drain breakdown voltage of 40 V and a three-terminal ON-state breakdown voltage of 18 V at 300 K with a composite $\text{Ga}_{0.4}\text{In}_{0.5}\text{As}/\text{Ga}_{0.2}\text{In}_{0.8}\text{As}$ channel structure. The high breakdown values were attributed to the large Schottky barrier height of $\sim 0.73\text{ eV}$ on $\text{In}_{0.34}\text{Al}_{0.66}\text{As}_{0.85}\text{Sb}_{0.15}$. A maximum extrinsic transconductance of 216 mS/mm was achieved in a $1.5\text{ }\mu\text{m}$ gate transistor [6].

MBE Growth of DyP/GaAs and DyAs/GaAs Heterostructures

And finally, 1998 saw a report on one of the more unusual material systems. P.P. Lee and colleagues from the University of Utah, Lucent, AMD, and the U.S. Army Research Laboratories (Adelphi, MD) reported the solid source MBE growth of DyP/GaAs and DyAs/GaAs heterostructures. DyP and DyAs have only one stable phase with a sodium chloride crystal structure and lattice constants of 5.6534 and $5.7894\text{ }\text{\AA}$ respectively. X-ray diffraction, transmission electron microscopy, and atomic force microscopy measurements revealed good quality epitaxy for DyP and DyAs layers on GaAs. AFM measurements showed an RMS surface roughness of $4\text{--}8\text{ }\text{\AA}$ for DyP/GaAs, and $10\text{--}15\text{ }\text{\AA}$ for DyAs/GaAs. Hall effect measurements indicated that the DyP films were n-type with electron concentrations of the order of $3.5 \times 10^{20}\text{ cm}^{-3}$ and mobilities between 250 and $300\text{ cm}^2/\text{Vs}$. The effective Schottky barrier height for DyP on GaAs was estimated to be equal to 0.81 eV from I-V measurements. On the other hand, DyAs was found to be a poor Schottky contact on GaAs, but Hall data revealed electron concentrations of the order of $1.5 \times 10^{21}\text{ cm}^{-3}$ and mobilities in the range of $25\text{--}40\text{ cm}^2/\text{Vs}$. DyP films were found to be stable in air and showed no sign of oxidation after several months of exposure [7].

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Top Developments in Microelectronics in 1998

ROBERT A. METZGER

Today's exotic materials and devices quickly become tomorrow's manufacturable mainstays. We are already witnessing this transformation in the area of GaAs, in which the workhorse of the GaAs IC industry, the MESFET, is starting to give way to more sophisticated devices such as the HEMT and the HBT. Graphic evidence of this shift is evidenced by the new fabrication facility started this year at RFMD that is devoted solely to GaAs HBTs.

However, this move to more complex GaAs-based device structures in the manufacturing arena is just the tip of the iceberg. To get an accurate assessment of where the III-V industry may evolve in the coming years, you need to look beyond the manufacturing facilities and into the research labs and universities where the next generation of devices are currently being fabricated.

Wide Bandgap Devices

This year, as last, the wide bandgap semiconductors continued to make rapid progress in the microelectronics arena. Nowhere was this more apparent than in the area of GaN, in which two groups reported for the first time this year the successful fabrication of GaN-based HBTs [1,2]. The challenge of producing an HBT in the AlGaIn GaN system is to obtain sufficiently high p-type doping in the base, a task which is very difficult due to the deep acceptor level of Mg. A team from UCSB reported on an MOCVD grown AlGaIn GaN HBT with a 10% Al content in the emitter which showed a DC current gain of 2-3. They reported that this low gain was probably due to a combination of high recombination rates in the base, and to the high resistivity of the p-type layer in the base. The second group to report on the successful implementation of an HBT was from the University of Florida, SVT Associates,

Wide Bandgap Devices

- 1st Reports of AlGaIn/GaN HBTs - UCSB; Univ. Florida/SVTA/Lucent/Sandia
- GaN HEMT with extremely high breakdown voltage - UCSB
- GaN-on-SiC HFET with 2.3 W output power at 10 GHz - APA Optics/Rockwell
- GaN HFETs with $f_t = 67$ GHz & $f_{max} = 140$ GHz - Cornell
- SiC MESFET with 80 W output power at 3.0 GHz - Cree
- GaN-on-SiC HEMT with 6.8 W/mm at 10 GHz - Cree
- 1st 4H-SiC n-channel MOSFET - NCSU
- 1st SiC-based transistors and circuits operating at 5V - Purdue

GaAs & InP Devices

- InAlAs/InGaAs HEMT on InP with $f_t = 350$ GHz - NTT
- InAlAs/InGaAs HEMT on GaAs with $f_t = 195$ GHz - IEMN (France)
- D-Band InP HEMT monolithic amplifier with gain of 30 dB at 140 GHz - HRL
- E/D InP HEMT ring oscillator with record low power delay product - Univ. Illinois
- Transferred Substrate AlInAs/GaInAs HBTs with $f_{max} = 500$ GHz - UCSB
- Manufacturable high speed AlGaInAs HBT for 100 Gbps circuits - HRL
- InP-based HBTs with 2x higher IP_3/P_{DC} - TRW

Further Afield

- AlSb/InAs HEMTs with $f_t = 180$ GHz with a V_{DS} of 0.6 V - NRL
- $Ga_2O_3(Gd_2O_3)/InGaAs$ MOSFETs with transconductance of 190 mS/mm - Bell Labs
- First implementation of a THz detector utilizing a 2D electronic fluid in a HEMT - RPI/Univ. Florida

Lucent Technologies and Sandia National Laboratories [see page 10]. They reported on the operating of their GaN AlGaIn HBT at an elevated temperature of 300°C in order to enhance the ionization of the Mg acceptors. At this elevated temperature the device exhibited a current gain of 10, using a base doping of $1 \times 10^{18} \text{ cm}^{-3}$. Both these initial efforts demonstrate that GaN-based HBTs are possible, as well as demonstrating quite clearly that the continuing challenge for GaN-based HBTs will be to improve base conductivity.

In the area of GaN-based HEMTs, improvement in device performance continues at a rapid rate. At this year's IEDM, R. Ventury and coworkers from UCSB report on an extremely high breakdown device which utilizes a cap and Schottky layer of $Al_{0.5}Ga_{0.5}N$, and were able to obtain a maximum breakdown voltage of 405 V with a gate to drain separation of 7 μm , the highest value reported to date for a GaN FET. [3] In terms of speed and power capabilities, a whole host of record-breaking results were obtained this year. G.J. Sullivan and coworkers from APA Optics and Rockwell reported on obtaining a total output power of 2.3 W at 10 GHz operation for a HFET grown on SiC, with a 1.28 mm gate width, at a V_{DS} of 33 volts, along with obtaining a maximum power density of 2.8 W/mm [4]. UCSB GaN HEMT efforts resulted in 3 W/mm at 18 GHz with 0.25 μm gate length devices, and 2.57 W/mm with a 31% PAE and 5.1 dB gain at 10 GHz operation. Cornell reported HFETs with outstanding RF characteristics, of f_t of 67 GHz and f_{max} of 140 GHz, while Y-F Wu et al from UCSB reported on observing very little device degradation when using up to 50% Al content in the Schottky layer of the device, opening the possibility of these structures being designed to contain very high levels of charge in the 2DEG, as a

result of the large ΔE_c which would be produced at this high Al content in the Schottky layer. These GaN HEMTs, grown on sapphire were able to attain an output power of 2.84 W/mm at 8 GHz. [5]

While GaN continued to report impressive improvements, the other wide bandgap material, SiC, was also being used in the fabrication of devices with impressive performance improvements. At the European Silicon Carbide Conference in September, Cree reported on a SiC MESFET with a total output power of 80 W at 3.0 GHz operation. In addition, Cree GaN-on-SiC HEMTs achieved a power density of 6.8 W/mm at 10 GHz with a PAE of 52% and 10.7 dB gain - this power density more than twice what anyone else has achieved in SiC or GaN [6]. Cree also reported on a SiC power diode with a record breaking blocking voltage of 5900 V, with losses during switching only 5% of that typically experienced with Si-Based devices [7].

Other SiC highlights for this year include the first lateral n-channel MOSFET fabricated on 4H-SiC by researchers at North Carolina State University, which obtained inversion layer electron mobilities of 165 cm²/Vsec [8] and work from Purdue which produced a lateral double implanted MOSFET on 4H-SiC which exhibited a blocking voltage of 2.6 kV - nearly double the previous best value. Purdue efforts also resulted in a host of SiC-based transistors and simple circuits which were the first to operate with only a 5 volt power supply [9-10].

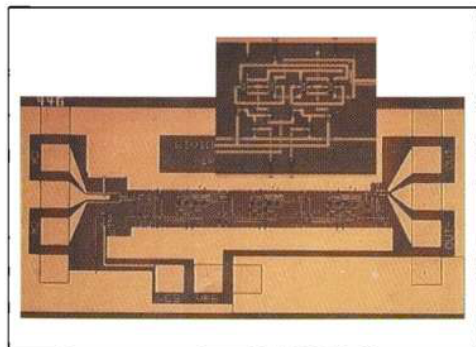


Figure 1. Photomicrograph of a divide by eight circuit recently developed by HRL Laboratories (formerly Hughes Research), showing a detail of the flip-flop in the inset. This AlInAs/InGaAs/InP HBT-based static divider operates at a record 52.9 GHz.

High Speed

The new reigning champions for speed are the researchers at NTT who reported at this year's IEDM on an InAlAs/InGaAs HEMT lattice matched to InP which used a 30 nm gate length to obtain a record setting f_t of 350 GHz. [11] And for those not yet willing to give up their GaAs substrates, researchers from the Institut D'Electronique Et De Microelectronique Du Nord in France reported on the fabrication of InAlAs/InGaAs HEMTs on GaAs using In contents which ranged from 30 to 60%. For In contents of 50% they were able to achieve drain to source currents of 500-650 mA/mm, and transconductances up to 1350 mS/mm. In terms of RF performance, they were able to obtain an f_t of 195 GHz with a 0.1 μ m T-gate structure [12].

Other speed records utilizing HEMTs were set by researchers at the Hughes Research Labs with a D-Band InP HEMT 3 stage monolithic amplifier using 0.1 μ m gate length AlInAs/GaInAs HEMTs, which gave an extremely high gain of 30 dB at 140 GHz. Measured gains exceeded 10 dB over 129-157 GHz, and up to 5 dB up to 184 GHz operation. [13]. Researchers at the University of Illinois continue to refine their E/D InP-based HEMT process, using direct coupled FET logic, having fabricated a 23-stage ring oscillator with a propagation delay time of 16.7 ps and a power delay product of only 0.322 fJ/stage which is the lowest reported to date in the InP material system [14].

The pace of work in InP-based HBTs continues to accelerate. Researchers at UCSB, using their transferred substrate approach, continue to set records. This process allows them to flip the HBT device and fabricate from both sides - see Figure 2. As a result, it permits smaller collector dimensions and therefore reduces parasitics and improves RF performance [15-16]. Using this approach, the UCSB group have fabricated AlInAs/GaInAs HBTs with f_{max} values to 500 GHz, which have been utilized in the fabrication of master-slave flip-flops operating up to 48 GHz, along with a differential amplifier with a gain of 11 dB

and a bandwidth of 50 GHz, which is the highest bandwidth reported for such an amplifier in any technology.

Researchers at the Hughes Research Laboratories have developed a manufacturable high speed AlGaInAs HBT process targeted for 100 Gbps circuit operation. This process supports f_t and f_{max} matched values of approximately 180 GHz, with f_{max} values as high as 257 GHz. Using these devices, they have demon-

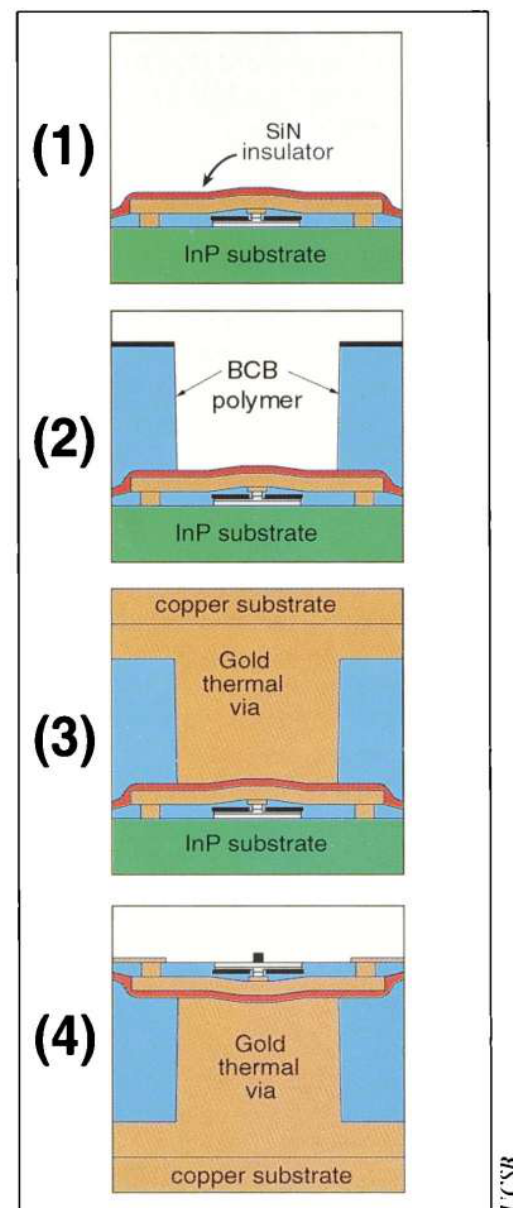


Figure 2. The UCSB transferred substrate HBT process. (1) HBT is grown on an InP substrate. SiN insulation is deposited. (2) Wafer is coated with BCB polymer, vias are etched. (3) Electroplate gold vias & copper substrate. (4) Wafer is inverted, InP is substrate removed, and collector is deposited.

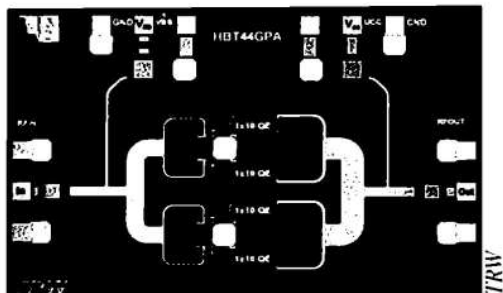


Figure 3. Photograph of an InP-based HBT amplifier recently reported by TRW which obtained a peak gain of 7.6 dB over a 44-50 GHz frequency band. The peak IP₃ figure of 34 dBm at 42 GHz corresponds to a record IP₃/PDC of 21:1, which is a record for MMICs in this frequency range.

strated a 52.9 GHz static 1/8 divider - this representing the fastest static divider reported in any semiconductor technology [17]. The circuit consumed 40 mW/flip flop when operating at maximum speed, while a second, lower power version, consumed only 8.6 mW/flip flop at 35 GHz operation.

For applications where high linearity is critical, researchers from TRW reported on an InP-based HBT utilizing devices with an f_t and f_{max} of 70 and 200 GHz, respectively. With these devices, they fabricated an amplifier which obtained a peak gain of 7.6 dB over a 44-50 GHz frequency band. At a bias current of 48 mA and a total dc power of 120 mW, the amplifier obtained a peak IP₃ of 34 dBm at 42 GHz which corresponds to a record IP₃/P_{DC} of 21:1, a factor of two better than state of the art MMICs in this frequency range. [18]

The Future

It is relatively easy to believe that wide bandgap and InP-based devices represent the future of compound semiconductor microelectronics. What is not so easy to see is what may come after them, what approaches or devices have the potential to open up new applications. Crystal-ball gazing can be risky, but several interesting technologies are beginning to appear on the horizon.

One such possibility is that of antimony containing alloys for HEMT structures. Groups at NRL, Hughes Research

Laboratories and Simon Fraser University are pursuing AlSb/InAs HEMTs due to the extremely high mobility of InAs and the potential for extremely low voltage applications. NRL researchers reported this year on HEMTs with an f_t of 180 GHz with a V_{DS} of only 0.6 V, and showed that the HEMT has a noise figure of 1 dB with 14 dB of gain at 4 GHz and V_{DS} of 0.4 V. [19] Other innovative work came from researchers at Bell Laboratories on the development of Ga₂O₃/(Ga₂O₃)₂/InGaAs enhancement mode n-channel MOSFETs. Using 0.75 μ m gate length devices which exhibited f_t and f_{max} of 7 and 10 GHz, respectively, they were able to obtain an extrinsic transconductance of 190 mS/mm, which is an order of magnitude better than that obtained with InGaAs MISFETs [20].

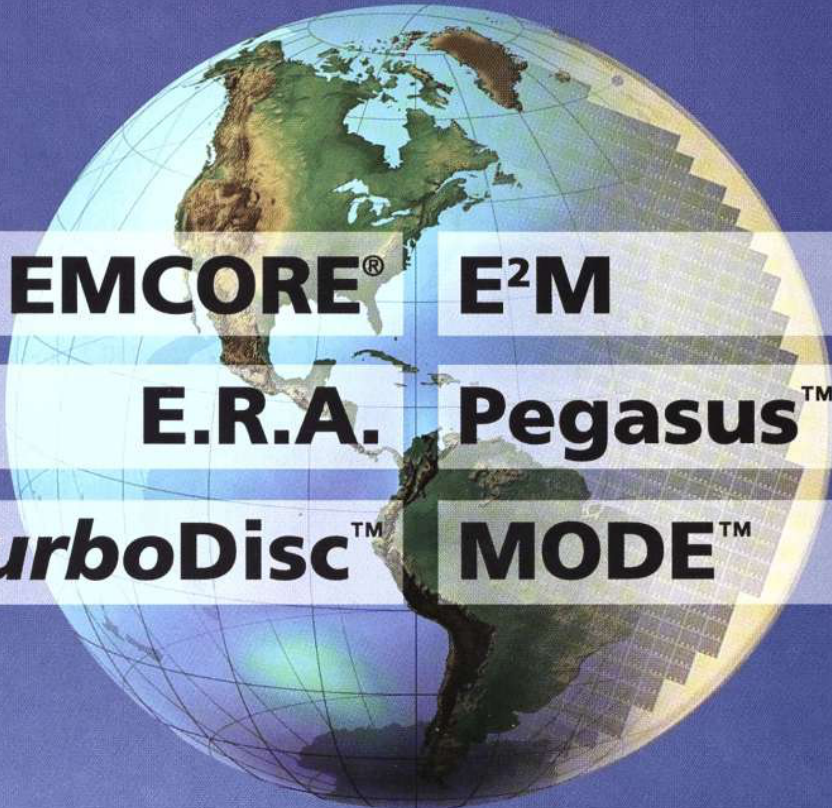
And lastly, researchers at Rensselaer Polytechnic Institute and the University of Virginia, have reported the first implementation of a terahertz detector utilizing a 2D electronic fluid in a HEMT which operated at 2.5 THz. Called plasma wave electronics, the terahertz radiation is detected by the HEMT as a result of an induced DC drain-to-source voltage proportional to the radiation intensity. [21]

Many - or maybe most? - of the readers of this magazine remember when GaAs seemed like a pretty exotic semiconductor - and now it is so common as to be almost a commodity in some applications. It is very likely that some of these rather exotic-sounding achievements will also eventually result in mainstream commercial products.

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Top Developments in Laser Diode R&D in 1998

GARY WICKS

Semiconductor laser research has continued to be very active in 1998. However, the flavor of the research has changed somewhat. In past years, semiconductor laser work has been led by epitaxial materials - perfecting the existing ones and developing new ones. This type of research still goes on, of course, but stealing many of this year's headlines are innovations in epitaxial structures and laser cavities. Epitaxial structures that have been productive in this year's crop of semiconductor lasers include quantum dots, cascaded active layers and type II quantum wells. And vertical cavity semiconductor lasers (VCSELs) continue to expand into new wavelengths and functionalities.

Quantum Dots - Intentional and Unintentional

Quantum dots for laser active regions offer many theoretical advantages, and some are actually achieved!

Among the potential benefits are modification of the density of states to enable lower thresholds, trapping of carriers for isolation from non-radiative recombination centers, and accessing new wavelengths. Nearly all of the recent work involving intentional quantum dots utilizes so-called Stranski-Krastanov dots, strained islands that can be spontaneously grown by either MBE or MOCVD. The most common material system for this approach, InAs dots on GaAs-based layers, has produced numbers that rival the much more mature quantum well lasers, namely room temperature thresholds and threshold densities [1] as low as 5 mA and 160 A cm⁻², respectively, and output powers [2] up to 1.5 W.

Many approaches have been tried over the years to make 1.3 μm wavelength lasers on GaAs substrates. The important communication wavelengths of 1.3 and 1.55 μm are conventionally made in InP-

based materials, which are expensive and don't lend themselves to VCSELs (more on this later). Attempts to move pseudomorphic GaInAs quantum wells on GaAs

substrates out to these longer wavelengths have run out of steam in the 1.1 - 1.2 μm range. But quantum dots grown by depositing partial monolayers of InAs and GaAs in a GaAs-based edge emitting laser structure have recently been measured to exhibit room temperature lasing [3] at 1.31 μm with a threshold density of 270 A cm⁻².

A discussion of quantum dot lasers wouldn't be complete without the mention of unintentional quantum dots which, at the moment at least, are more important than their intentional counterparts. Some ternary semiconductors, most notably GaInN, have growth instabilities that cause inhomogeneous compositions. Small, low bandgap regions develop, immersed in a larger bandgap matrix. These unintentional quantum dots are thought to play a key role in the surprisingly high efficiency blue nitride lasers and LEDs.

Cascade Lasers

In semiconductor lasers, "cascade" means that the active region consists of many gain layers stacked so that an electron flowing through the region has the opportunity to cause a photon emission in each layer. The electron is injected into the upper lasing level of one gain layer, drops down to the lower lasing level perhaps by the emission of a photon, and is subsequently injected into the upper lasing level of the next gain layer to repeat the process all over again. It is theoretically possible in these cascade lasers to have more photons coming out than electrons going in, i.e. quantum efficiencies greater than 100%.

Cascade active regions were first demonstrated several years ago [4] by Bell Labs researchers in unipolar lasers that operate on intersubband transitions in quantum wells. This work has continued to evolve, with this year's version operating above room temperature at wave-

InAs/GaAs Quantum Dot Lasers

- 5mA threshold density - Fujitsu
- 1.5 W output power - Ioffe Inst.
- RT operation at 1.31 μm - Univ. Texas

VCSELs

- Quantum cascade VCSEL with >100% quantum efficiency - Univ. Ulm
- RT operation of a 1.3 μm VCSEL pumped by a 850 nm VCSEL - Gore Photonics
- RT operation of a 2.2 μm VCSEL - Univ. du Languedoc
- Optically pumped 2.9 μm VCSEL - NRL
- Micromachined cantilever VCSEL - Stanford
- 2-D VCSEL Arrays with Integrated Detectors - UCSB
- 3 x 3 High Power 980 nm Array - Univ. of Ulm

Across the Spectrum

- LEO GaN blue lasers - Nichia Chemical
- 400 hour ZnSe laser - Sony
- 680 nm GaInP laser with 92% quantum efficiency - Tampere Univ.
- 870 nm AlGaAs lasers with 16.5 W output powers - SDL
- 980 nm Al-free lasers with 11 W output power - Univ. Wisc. & Sarnoff
- First RT operation of a 3-5 μm laser - NRL & Univ. Houston
- 3-5 μm laser with extremely low RT threshold density - Lincoln Labs

lengths as long as 11.5 μm .

Last year the cascade concept was extended to bipolar interband lasing transitions in type II quantum wells [5]. This year researchers at Sandia National Labs used cascaded interband transitions in type I quantum wells to make lasers that operate at wavelengths near 4 μm at temperatures below 200K. Another type I interband cascade laser was reported by researchers from the Ulm University (Germany) [6]. They employed an InGaAs VCSEL operated at a temperature of 175K, and observed a differential quantum efficiency greater than 100%.

VCSELs Everywhere

VCSELs have been in vogue for several years now, but their success had mainly been limited to GaAs-based materials, lasing in the 700 - 900 nm range. This year VCSELs have appeared in diverse of forms and materials, enabling operation in many wavelength bands. The InP-based materials, which lase at the 1.3 and 1.55 μm communication wavelengths, do not lend themselves well to VCSELs because of insufficient refractive index contrast to make good mirrors. Nonetheless, there has been a lot of activity in these types of VCSELs, with a variety of approaches to circumvent the mirror difficulty.

A common approach has been fusing one set of epitaxial layers to another set, for example fusing an InP-based active region between two sets of GaAs-based

mirror stacks. Gore Photonics recently reported a particularly novel approach along these lines, [7] consisting of a GaAs-based 850 nm VCSEL which is fused to and which optically pumps a 1.3 μm VCSEL.

VCSELs have now been extended to longer wavelengths using antimonide materials. French researchers [8] have reported a 2.2 μm VCSEL with a room temperature threshold density of 2 kA/cm². The Naval Research Lab has reported an optically pumped 2.9 μm VCSEL [9] that lases cw up to T=160K.

Meanwhile VCSELs in the GaAs-based materials have gone beyond simple low threshold, high efficiency devices. Stanford researchers have reported a micromachined cantilever VCSEL [10] with a continuously tunable wavelength range of 31.6 nm, centered on 935 nm. Two-dimensional arrays of VCSELs have been constructed. University of California at Santa Barbara researchers have integrated arrays of VCSELs and detectors with microlenses for optical interconnect applications [11]. University of Ulm (Germany) researchers have produced a 3 x 3 array for high power at 980 nm, achieving up to 650 mW [12].

Several groups are addressing the problem of polarization control of VCSELs. Simple VCSELs are posts that are circular, thus having no preferred direction to set the polarization. Asymmetric posts [13], growth on (311) B substrates [14] to produce gain asymmetry, and uniaxial stress [15] have all been used to control polarization.

Improved Epitaxial Materials and Structures

For three years running, and continuing into 1998, the star of this show continues to be Shuji Nakamura of Nichia Chemical for his pace setting work in the GaN-based blue laser materials. This year's results include epitaxially laterally overgrown GaN on sapphire [16] to reduce the dislocation density and enable an estimated lifetime of 10,000 hours. Still making quite progress is the other short wavelength material based on ZnSe in which Sony researchers [17] have reached 400 hour lifetimes at cw powers of 1mW.

Jumping to the other end of the visible spectrum, record quantum efficiency has been achieved in red lasers [18] by researchers at Tampere University

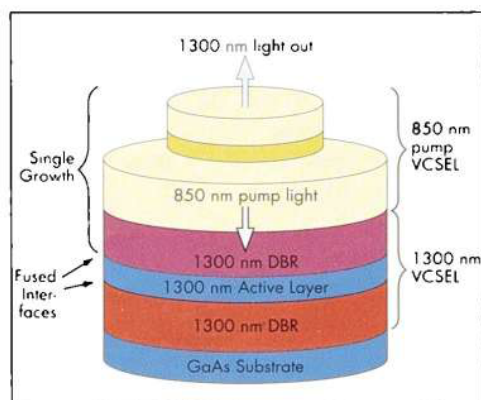


Figure 1. Schematic of a double-fused VCSEL structure developed by Gore Photonics. The output of the 850 nm VCSEL optically pumps the 1300 nm device.

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(Finland) using GaInP-based materials. Facet coated edge emitting lasers had quantum efficiencies as high as 92% at 680 nm.

In the near IR, the traditional AlGaAs-based materials and the newer "aluminum-free materials" (GaInP/GaAs/GaInAs), continue their battle for high power records. SDL [19] has now 870nm AlGaAs-based lasers with output powers of 1.3 W and 16.5 W cw using 100 and 200 μm wide stripes, respectively. Meanwhile, a collaboration of Univ. of Wisconsin-Madison and the David Sarnoff Research Center [20] has used a broad transverse waveguide (see Figure 2) in aluminum-free materials to obtain 11 W cw at a 10° C heatsink temperature in a 100 μm wide laser emitting at 980 nm. Certainly both of these high power results depend on very high quality epitaxial material, however the main new development in the broad waveguide work is the epitaxial structure. The broad waveguide design uses a waveguide core that is many times thicker than that used in conventional lasers. The result is that the optical mode is nearly completely confined to the nominally undoped core, producing very low loss and high quantum efficiency.

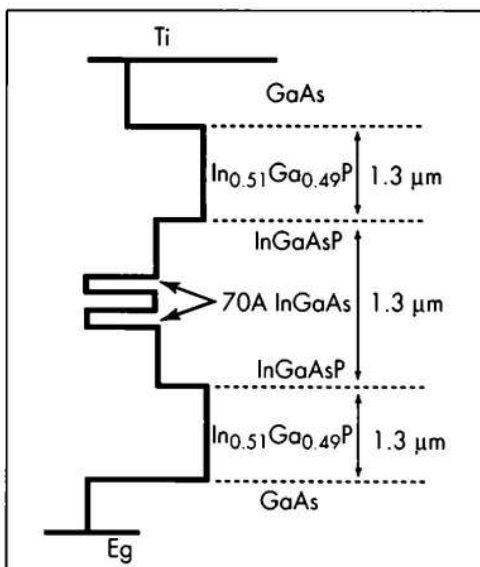


Figure 2. Schematic representation of Al-free, broad-waveguide 970nm emitting laser diode fabricated at the University of Wisconsin-Madison. The device demonstrated electrical-to-optical power conversion efficiencies in excess of 40% from 1 W up to 10.6 W cw output power.

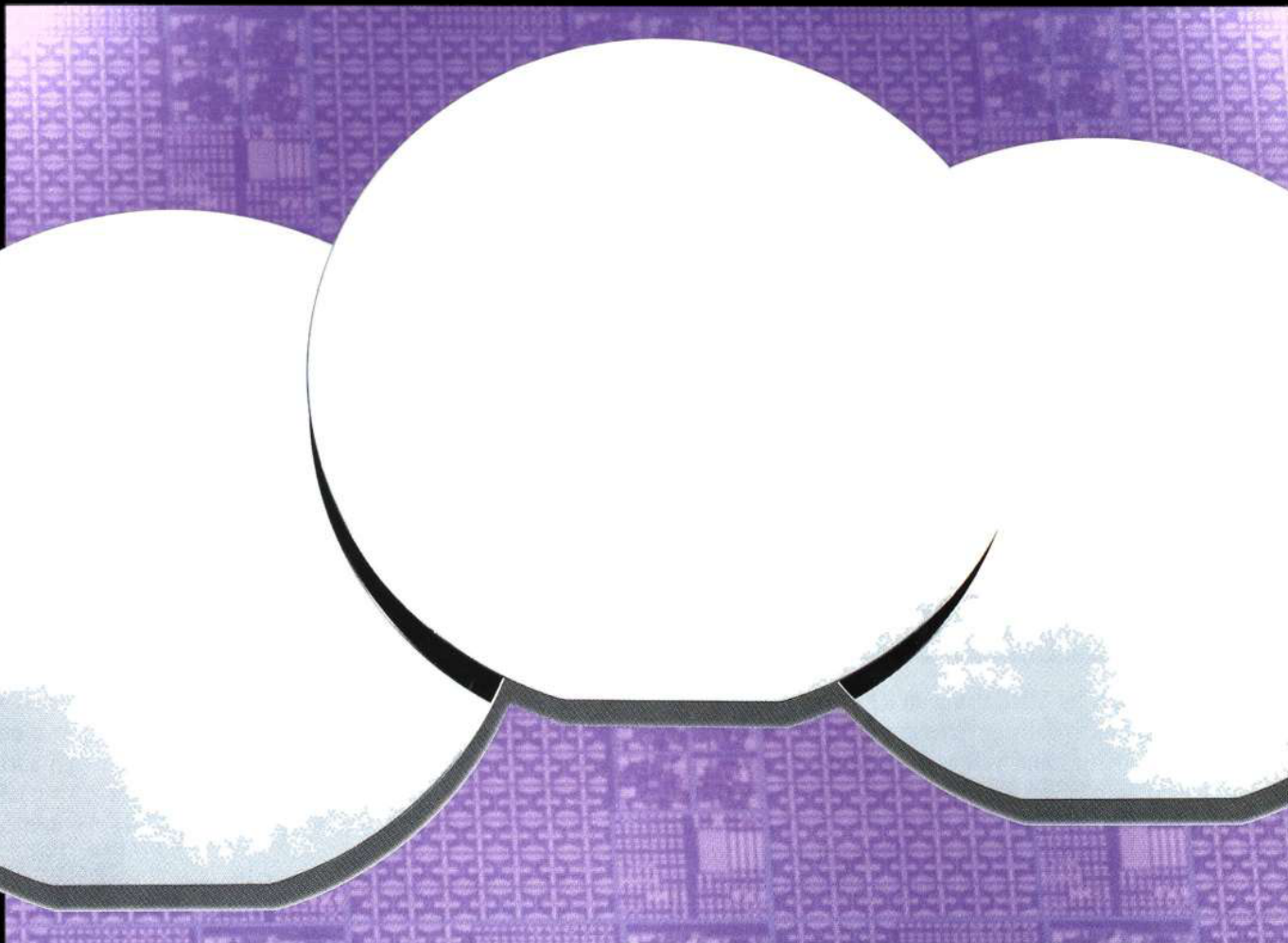
Finally, the 2 - 4 μm band has been very active in recent years using a variety of arsenide / antimonide materials and structures. The most impressive result in this area has used a so-called "W" active region, named for the shape of the conduction band profile in this cascaded type II quantum well structure. A collaboration of Naval Research Labs and University of Houston [21] has made the only 3-5 μm laser to operate at room temperature by using the W structure and optical pumping. Another impressive result, accomplished by Lincoln Labs [22], is the extremely low room temperature threshold density of 50 A/cm² achieved in a 2.05 μm edge emitter.

The semiconductor laser results of 1998 show no loss of momentum in a very active field. Some predictions for the near future seem fairly safe: practical implementations of optical interconnects, blue laser commercial products, 1.3 μm VCSELs and high performance room temperature diode lasers at longer wavelengths. Quantum dots and nitrides may continue to provide surprises, perhaps finally filling in the void in the middle of the visible spectrum.

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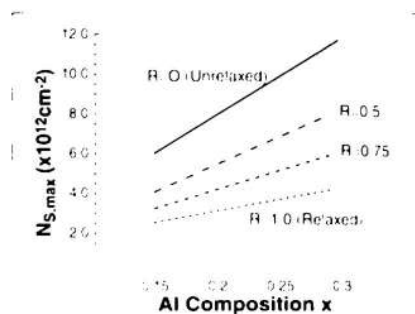
The following is a sampling of recent papers from a variety of international journals, compiled by the staff of Compound Semiconductor.

Compound Semiconductor Materials

2DEG Density in AlGa_xN/GaN HFETs

N. Maeda et al, Appl. Phys. Lett., 1998, 73(13), p. 1856

Increasing the 2DEG density in AlGa_xN/GaN HFETs is a fundamental way to improve the high power operation of these devices. This paper, from NTT, calculates maximum 2DEG densities ($N_{S,max}$) in HFETs with wurzite crystal structures in the (0001) orientation, and reports that the maximum electron density depends more strongly on the lattice relaxation than on the Al composition. AlGa_xN/GaN HFETs normally have a GaN channel with an Al_xGa_{1-x}N barrier; the Al composition x affects the conduction band discontinuity ΔE_c at the hetero-interface. The lattice relaxation parameter ratio R ($R=0$ for an unrelaxed structure, $R=1$ for complete relaxation) also affects the 2DEG density due to the piezoelectric charge at the hetero-interface, which arises from the strain caused by the lattice mismatch. As the accompanying graph shows, an unrelaxed heterojunction is essential for obtaining a high $N_{S,max}$ value. The graph also shows that although increasing x usually increases $N_{S,max}$, the 2DEG density could actually decrease if the consequential increase in lattice mismatch causes R to increase. Therefore, controlling the lattice relaxation is crucial to obtain high electron density in devices in this material system.



Dependence of the maximum 2DEG density $N_{S,max}$ on Al composition x , as a function of the relaxation ratio R . Values were calculated for a simple HFET with a 150 Å Al_xGa_{1-x}N barrier layer uniformly doped at $6 \times 10^{18} \text{ cm}^{-3}$.

Improved Quality of MBE-Grown GaN Using In as a Surfactant

F. Widmann et al, Appl. Phys. Lett., 1998, 73(18), p. 2642

In the growth of GaN by MBE using an RF plasma source, the metal-nitrogen ratio critically governs the structural defect density, electronic properties and yellow band emission of nitride films. This paper, from CEA/Grenoble, France, reports the use of In as a surfactant species to modify the surface growth kinetics, in particular to increase the Ga mean free path, allowing growth of GaN with improved electrical and optical properties under N-rich conditions.

GaN was grown on sapphire at 700°C, following nitridation and AlN buffer growth. After a growth pause during which In was deposited on the surface at 700°C, the RHEED pattern during GaN growth was different and much more intense RHEED oscillations were observed. GaN grown in the presence of In exhibited an intense band-edge luminescence free of the compo-

nent at 3.41 eV which is characteristic of defects associated with growth in N-rich conditions. TEM studies of GaN grown under N-rich conditions showed stacking faults and a rough surface morphology, which were not observed for material grown under Ga-rich conditions or under N-rich conditions in the presence of In.

When In is deposited on the GaN growth surface at 700°C during the growth pause, InN does not grow; instead, the In segregates and wets the surface. The role of In is to saturate the free bond of the N atoms, allowing Ga to diffuse freely on the surface, leading to a smooth surface and many fewer stacking faults. In contrast, N-rich growth conditions limit Ga surface mobility, leading to rough surface morphology.

High Performance 0.25 μm p-type Ge/SiGe MODFETs

G. Hock et al, Elec. Lett., 1998, 34(19), p. 1888

This paper, from the University of Ulm and Daimler Benz, reports the fabrication of a 0.25 μm gate length p-type Ge channel modulation-doped FET (MODFET), with a maximum operating frequency f_{max} of 85 GHz. The structure was grown by MBE on an n-type Si substrate with a 5 μm thick strain-relaxed SiGe buffer with compositional grading up to a Ge content of 60%. The 9 nm thick, p-type Ge channel was sandwiched between 5 nm thick, undoped Si_{0.4}Ge_{0.6} spacers and 5 nm thick,

p-type Si_{0.4}Ge_{0.6} supply layers. A 2D gas hole mobility of 1870 cm^2/Vs was measured for a sheet carrier density of $2.1 \times 10^{12} \text{ cm}^{-2}$. The devices exhibited DC transconductances of up to 160 mS/mm and saturation currents up to 300 mA/mm. The f_t value of 32 GHz is more than double that of the best p-type Si MOSFETs with the same gate length, while the f_{max} value (85 GHz) is comparable to n-type SiGe MODFETs.

Microelectronic Devices and Circuits

Decision and Modulator Driver ICs For 40 Gbit/s Optical Transmission

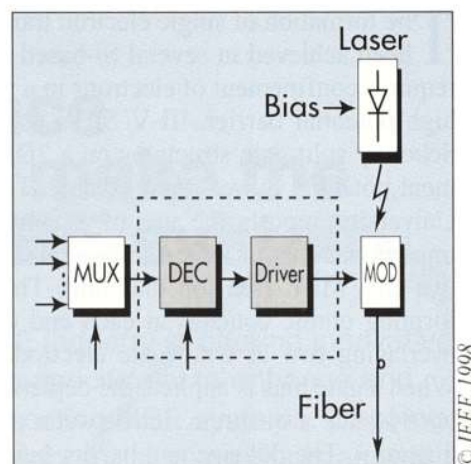
[1] Z. Lao et al, IEEE J. Solid-State Circuits, 1998, 33(10), p. 1520

[2] K. Murata et al, *ibid*, p. 1527

High speed, reliable electronic components are increasingly in demand for the development of cost-effective, optical transmission systems operating at speeds as high as 40 Gbit/s. The figure opposite shows a simplified block diagram of part of an optical fiber transmission system. After the incoming data is multiplexed up to the correct data rate for transmission, signal regeneration is performed by a data decision circuit (DEC), which also minimizes noise and jitter at the maximum system bit rate. The driver IC amplifies the signal and drives the Mach-Zehnder or electro-absorption modulator (MOD), which modifies the laser output to transmit the data down the optical fiber.

The Fraunhofer Institute in Freiburg reports [1] a **40 Gbit/s monolithically integrated data decision and modulator driver IC**, operating at 40 Gbit/s and fabricated using a 0.2 μm gate length **AlGaAs/InGaAs HEMT** technology with an f_t of 68 GHz. The 1x1 mm² IC's contain a data decision circuit monolithically integrated with a differential amplifier and an output driver. On-wafer measurements with 50 Ω coplanar probes showed an output voltage swing of 2.9 V_{pp} at each output, a slew rate of 200 mV/ps, and a measured clock phase margin of 210°. The IC had a moderate power dissipation of 1.6 W using a single supply voltage of -5 V. The 40 Gbit/s modulator driver performance matches results achieved with SiGe [see CS 4(6), p. 41].

Process maturity makes GaAs MESFET technology an attractive choice for implementing 40 Gbit/s data decision circuits. NTT Optical Network Systems reports [2] that while a conventional (static) master-slave D-type flip-flop (D-FF) can operate at around 25 % of the f_t of the device, a superdynamic D-FF is able to operate nearly twice as fast. Therefore, 40 Gbit/s operation was achieved using a superdynamic D-FF implemented with a **0.12 μm gate length GaAs MESFET**, with f_t of 98 GHz and f_{max} of 97 GHz.



Simplified block diagram of an optical fiber transmission system, showing the multiplexer (MUX), decision circuit (DEC), driver, modulator (MOD) and laser



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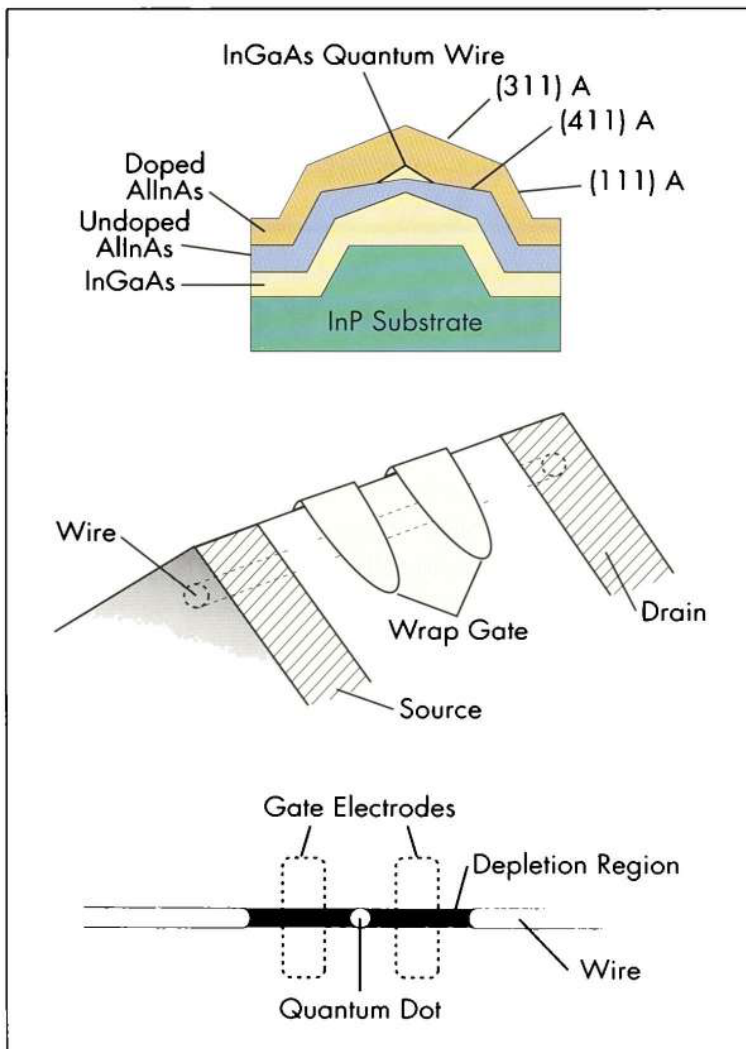
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InGaAs Single Electron Transistor

H. Okada et al, Solid-State Elec., 1998, 42(7-8), p. 1419

The formation of single electron transistors (SETs), which has been achieved in several Si-based and metal-based systems, requires confinement of electrons in a small area using an abrupt high potential barrier. III-V SETs have previously used planar Schottky split-gate structures on a 2DEG, however the confinement potential is weak and gradual. This paper, from Hokkaido University, reports the use of a Schottky wrap gate structure implemented in an InGaAs ridge quantum wire grown by selective-area MBE (see top diagram). The SET was fabricated by forming ohmic contacts at each end of the quantum wire, and overlaying two Pt wrap gate electrodes (see middle diagram). When a gate bias is applied, the depletion regions in the quantum wire isolate a quantum dot between the electrodes (see bottom diagram). The dot size and barrier height are determined by the gate bias. The SET showed clear and reproducible conductance oscillations up to 27 K, with an effective Coulomb gap of 10 meV.



(Top) Schematic cross-section of InGaAs quantum wire (Middle) Positioning of wrap gate electrodes (Bottom) View from above showing quantum dot formation.

Optoelectronic Devices

Sb-Based Mid-IR Type II Quantum Well Lasers

Y. Rouillard, presented at the 10th IC-MBE, Cannes, Sept. 1998

The 2-3 μm spectral range is very attractive for Tunable Diode Laser Absorption Spectroscopy (TDLAS) because absorption bands of many gases are much stronger at these wavelengths in comparison with shorter wavelengths. High performance diode lasers employing type I GaInSbAs/GaAlSbAs QWs and operating near 2.0 μm at room temperature have already been reported. To increase the emission wavelength, both the In and As content in the QW should be increased and the band alignment in the active zone becomes type II.

This paper, from University of Montpellier II, described low threshold current type II GaInSbAs/GaSb QW edge emitting lasers, grown by MBE. The undoped region consisted of five 6-8 nm thick compressively strained quantum wells with 30 nm thick GaSb barriers enclosed between GaSb spacers. The composition of the $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{Sb}_{1-y}$ QW was varied in the range $x = 0.26-0.5$, $y = 0.08-0.22$ to obtain different emission wavelengths. Low threshold Fabry-Perot edge emitting lasers were fabricated operating between 2.0 and 2.65 μm . The RT threshold current density was in the vicinity of 300 A cm^{-2} for devices emitting between 2.0 and 2.4 μm and increased up to 1.5 kA cm^{-2} for lasers operating at 2.6-2.65 μm . Narrow stripe ridge waveguide lasers designed to emit near 2.35 μm exhibited CW operation and threshold currents from 50-100 mA at RT. The lasers were successfully used for TDLAS of methane and carbon monoxide.

The same group has also fabricated VCSELs with AlSbAs/GaSb distributed Bragg reflectors and GaInSbAs/GaSb QWs in the active region. These devices operated between 2.2 and 2.35 μm at RT in the pulsed regime.

220 K Operation of 3.4 μm Type-II Laser

E. Aifer et al, Elec. Lett., 1998, 34(16), p. 1587

Applications such as IR-countermeasures and mid-IR chemical sensing require lasers with a practical operating temperature, at least within the range of thermoelectric coolers. This paper, from the Naval Research Lab, Sarnoff Corp., and Sensors Unlimited, reports an optically pumped type II laser operating at 3.4 μm with over 50 μW output power at 220 K. The structure, grown by MBE on an n-GaSb substrate, has a W-shaped conduction band profile, with Sb-based hole QWs sandwiched between InAs electron QWs. The active region has 80 periods of 16 Å InAs, 25 Å $\text{Ga}_{0.1}\text{In}_{0.9}\text{Sb}$, 16 Å InAs, 40 Å $\text{AlGa}_{0.05}\text{Sb}_{0.95}$ surrounded by AlGaAsSb optical cladding layers. For optically pumped CW operation, the maximum output power at 120 K was 27 mW (for 16-20 μm stripe widths). The threshold pump intensity was 600 W cm^{-2} at 78 K, and the characteristic temperature T_0 was 51 K over the range 78 - 220 K.

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Optoelectronic Devices [cont.]

High Response Photodiodes based on Be-Chalcogenides

J. Siess et al, presented at 10th IC-MBE, Cannes, Sept. 1998 (to be published in J. Crystal Growth)

Be-containing II-VI semiconductors are promising high bandgap materials for optoelectronic devices, largely because the incorporation of Be into the II-VI material increases the degree of covalent bonding in the lattice. The resulting "lattice hardening" effect in Be-chalcogenide materials such as BeMgZnSe is supposed to reduce defect generation and propagation, and therefore enhance the lifetime of green laser diodes. Both LEDs and laser diodes based on BeMgZnSe have already been realized, using epilayers grown by MBE. The high structural quality of Be-compounds and the possibility to tune the bandgap of quaternary BeMgZnSe lattice matched on GaAs from 2.8 eV to more than 4 eV also makes the material interesting for photodetector applications.

UV detection has a wide range of applications, particularly when the UV component can be detected in the presence of a large visible or infrared background. Possible applications are flame and heat sensors, plasma diagnostics, environmental control through biological or chemical reactant detection, ozone monitors, or engine controlling. This paper, from the University of Würzburg, Germany, reports the fabrication of efficient p-i-n photodiodes for the detection of UV-radiation that are insensitive to wavelengths longer than around 0.45 μm .

The p-i-n detector structures were grown by MBE on epitaxially p-doped GaAs wafers, using a 300 nm p-type GaAs epitaxial buffer to provide a flat surface for II-VI growth. The II-VI structure has a p-type BeTe layer, an undoped BeMgZnSe active layer with a bandgap of ~2.9 eV, and an upper n-type BeMgZnSe

layer. The BeTe layer serves two important purposes: firstly, it eliminates stacking faults which are often found in Se-containing II-VI structures grown on GaAs, due to the chemical reaction of Se with the GaAs surface. Also, the wide bandgap of BeTe is necessary to achieve a low responsivity at wavelengths above ~0.45 μm . The GaAs substrate absorbs photons with energies between 1.42 eV and 2.9 eV (the bandgaps of GaAs and the BeMgZnSe active layer respectively), forming electron-hole pairs; however, the BeTe barrier prevents electrons originating in this way from contributing to the photocurrent. (See figure 1).

Arrays of square cells were fabricated with different active areas. Photodiodes dark currents were limited by the noise of the measurement equipment, with an upper limit in the order of 10^{-12} A, at -1 V and room temperature. The breakdown in reverse direction occurred at -25 V. The quantum efficiency and responsivity as functions of wavelength are shown in figure 2. Below the bandgap of BeMgZnSe, the photodiode is transparent, while the sensitivity for wavelengths below 450 nm is a factor of 4×10^3 higher than in the transparent region.

The maximum responsivity of 225 mA/W was obtained at a photon energy of 2.86 eV, which corresponds to a wavelength of ~433 nm. The peak quantum efficiency is 65 %. In comparison, the responsivity of commercialized GaN-based Schottky diodes, in the range 300-365 nm, is around 130 mA/W [see CS 4(2), p.10]. In the current work, the reason for the relatively broad cut-off at 450 nm, and the sensitivity at wavelengths between 450 nm and 600 nm, is possibly due to the high carrier concentrations in the doped regions, or to a leakage current from the GaAs back to the photodiode. Future work will include increasing the BeMgZnSe bandgap up to 3.1 eV, to reduce the cut-off wavelength and increase the solar-blind properties of the photodiodes.

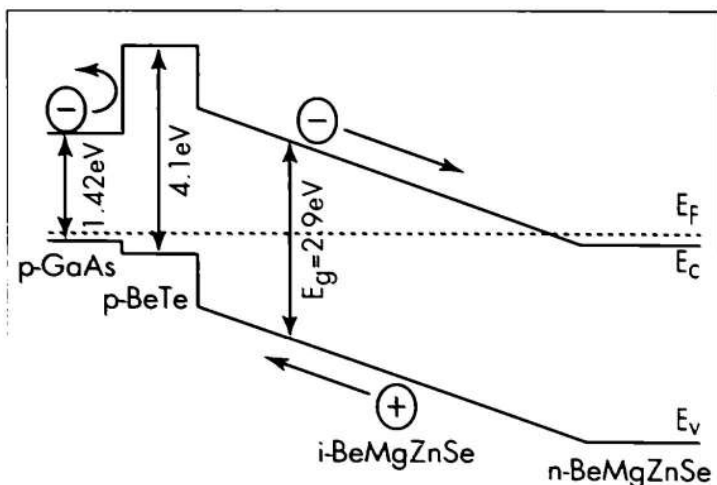


Figure 1. Band structure of the BeMgZnSe/BeTe p-i-n photodiode, grown by MBE. The BeTe buffer eliminates stacking faults, and blocks electrons originating in the GaAs substrate.

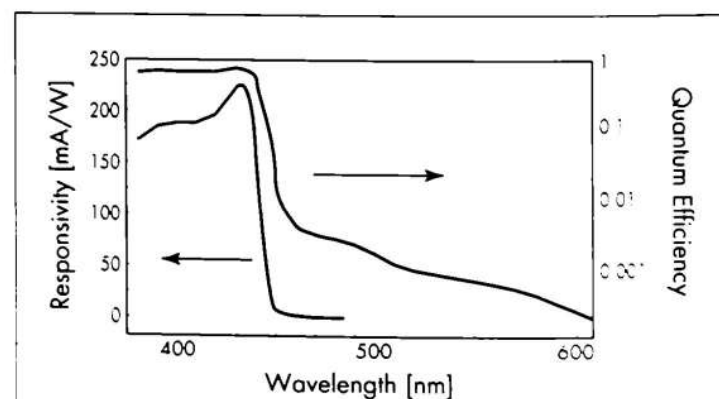


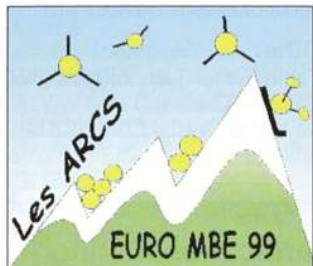
Figure 2. Quantum efficiency and responsivity of the BeMgZnSe/BeTe p-i-n photodiode.

Editors' Picks

Editing a magazine is serious business. Really, it is.

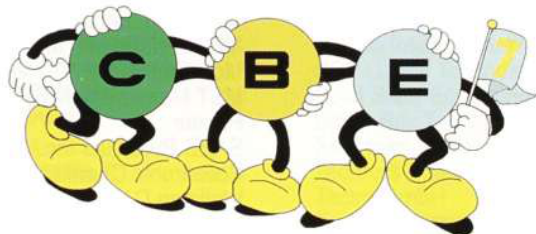
But, given that this is the last issue for the year, the editors would like to share a few non-serious items which have crossed their desks in the past 12 months...

Best Conference Logos



Euro MBE '99, which will be held March 28 - April 1, 1999 at Les Arcs (Savoie), France. The emphasis at this series of workshops is on "informal interaction" (read: skiing). But all the attendees are expected to attend early morning and evening technical sessions as well. Therefore in

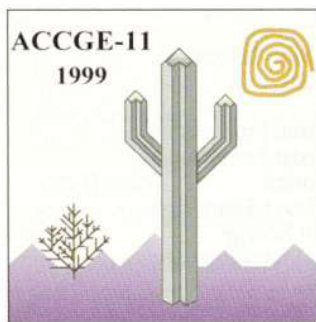
the conference logo the epitaxial growth process has been cleverly disguised as an alpine skiing excursion. Or is it vice versa??



The 7th International Conference on Chemical Beam Epitaxy and Related Growth Techniques, which will be held July 27-30, 1999 in Tsukuba, Japan. Are they molecules? Wafers? We're not sure, but we do think it is cute. Sign us up.

11th American Conference on Crystal Growth & Epitaxy, which will be held August 1-6, 1999 in Tucson, Arizona. Georgia O'Keefe has met her match in the ACCGE committee, who have come up with a very clever use of desert imagery - highly appropriate for a group brave enough to host a conference

in Tucson in early August. The cactus represents a faceted crystal; the sun is a spiral defect, the tumbleweed is either a dendritic structure or a nasty threading dislocation, and the mountains are growth hillocks.



Name Game, Part I:

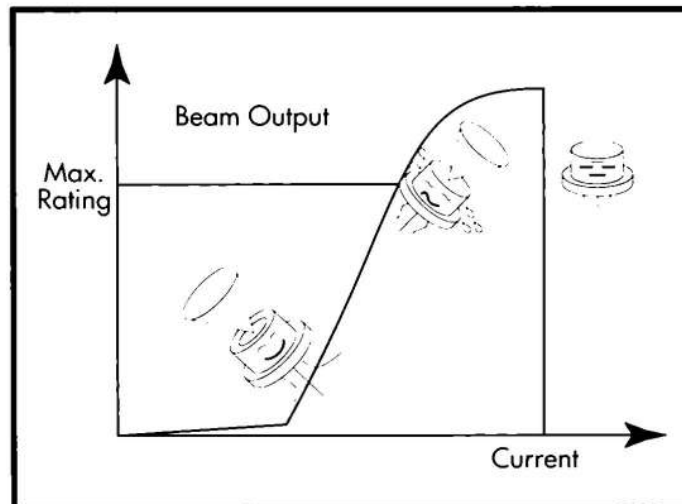
Coherent recently introduced a high speed laser called Vitesse. Should Vitesse retaliate with a high speed IC called Coherent?

Name Game, Part II:

Unfortunately, we have to single our friends at the ECE Department at UCSB for a little abuse. Through no fault of their own, they have been assigned a web server named "FETish". Apparently, someone on the systems administration side of things thought that would be a clever takeoff on Field Effect Transistor. The result is that their WWW address is "FETish.ece.ucsb.edu". Which is a shame, because their email server is named "Scully". Why not "Mulder" or even "CigaretteSmokingMan" for the web site?

Name Game, Part III:

The company called Vixel no longer makes VCSELs.



This graph of light output power vs. forward current characteristics for laser diodes appeared in the Mitsubishi Electric Optoelectronics catalog. Use it to explain to your new employees what happens if you turn the power up too high.

And our top picks are....

Marie: 1999 Super Bowl, Minnesota 28, Denver 21.

Tim: 1999 FA Cup Final, Huddersfield Town 3, Wolves 0.

Very best wishes for a Happy and Prosperous New Year from the entire staff of Compound Semiconductor.

The Compound Semiconductor Suppliers Directory

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INDEX

A. Bulk Crystal Growth Equipment

Amistar
Eagle-Picher Technologies
Epigress
Kayex Corp.
Leybold Systems
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B. Epitaxial Growth Reactors & Related Equipment

Addon
Aixtron
CTA Centrotherm
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Emcore
EMF
EPI MBE Products
Epigress
HanVac
J.I.P.ELEC
Leybold Systems
MBE - Komponenten
Oxford Applied Research
Raboulet
Riber
SVT Associates
tecta GmbH
Thomas Swan
VG Semicon
VTS-CreaTec
Wellman CJB

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Aixtron
CTA Centrotherm
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Addon
DCA Instruments
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SVT Associates
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VG Semicon
VTS-CreaTec

MOCVD/MOVPE

Aixtron
CVD Equipment
Emcore
EMF
Epigress
HanVac
J.I.P. ELEC
SVT Associates
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Aixtron
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Riber
SVT Associates

Other Epi Reactors

Aixtron (CVD,LPE)
CVD Equipment (CVD, VPE)
J.I.P. ELEC (CVD)
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SVT Associates (CVD)

C. Epiwafers/Epitaxial Growth Services

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Epichem
Indium Corporation
Intercrystal
Insaco
Japan Energy
Johnson Matthey Electronics
Marktech International
Mining & Chemical Products
Mochem
Morton International
Nimtec
PPM Pure Metals
Praxair
Prometec Electronics
Rhodia
Solkatronic Chemicals
Solmetex
Stratedge Corporation
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United Mineral & Chemical
Wafer Technology
Wellman CJB

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Eagle-Picher Technologies
Indium Corporation
Intercrystal
Japan Energy
Johnson Matthey Electronics
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Mining & Chemical Products
Nimtec
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Prometec Electronics
Rhodia
United Mineral & Chemical
Wafer Technology

Group V Hydrides [arsine, phosphine, ammonia]

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Praxair
Solkatronic Chemicals

Metalorganics

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Eagle-Picher Technologies
EMF
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Marktech International
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Morton International
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Other

Brush Wellman
(metal matrix composites)
Insaco (Al₂O₃ wafer carriers)
Solmetex
(GaAs wastewater treatment)
Stratedge Corporation
(ceramic packages)
Wellman CJB
(hydrogen generators)

J. Software**Design & Modeling**

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Gateway Modeling
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Implant Sciences Corporation
Integrated Systems Engineering
Silvaco International
Sonnet Software
Top-Vu Technology
UES Inc.

Growth Control

EPI MBE Products
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VTS-CreaTec

K. Substrates

Airtron
American Xtal Technology
Amistar
Atramet
CMK
Crystacomm
Crystal Specialties
Crystallod
Dowa Mining
Dora Texas
Eagle-Picher Technologies
Epitronics
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Sumitomo Electric
Sumitomo Metal Mining
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Union Carbide
Union Miniere
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CdTe, CdZnTe

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GaAs

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Epitronics
Marketech International
SiCrystal
Sterling Semiconductor
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Substrates, III-V, Other

Amistar (ternaries)
Atramet (InAs)
Crystallod (ternaries)
Intercrystal (InAs)
Marketech International (InAs)
MTI (InAs)
Promecome Electronics (InAs)
Sumitomo Electric (InAs)
Wafer Technology (InAs)

Substrates, Misc. Other

Atramet (ZnO)
Eagle-Picher (ZnSe, ZnO)
Intercrystal (II-VIs)
Johnson Matthey Electronics
(II-VIs)
Marketech International
(II-VIs, Oxides)
MTI Corp. (oxides)
Union Miniere (ZnSe and ZnS)
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L. Recycling**Wafers/Scrap Material**

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Leading manufacturer of deposition and process monitoring components and systems. These include Si, oxide, and III-V MBE; SiGe UHV/CVD; and oxide CVD for materials and device research. SVTA's new III-Nitride MBE system guarantees material specifications. Also offers epi-wafer research and service.

Technics Plasma GmbH
Dieselstrasse 22a
Kirchheim D-85551 Germany
Contact: Gerhard Liebel
TEL: [49] 89 905 03 126
FAX: [49] 89 904 903 23
tepla@compuserve.com

Technics Plasma GmbH (TePla) is a global supplier of advanced microwave batch plasma systems for the semiconductor industry and R&D. Microwave batch processing provides cost-attractive solutions for damage-free resist ashing and cleaning of small to large substrates in manufacturing of compound-semiconductor-, silicon-, and FPD devices as well as for plasma cleaning of PBGA and COB substrates prior to bonding and packaging.

Technologies and Devices International, Inc.
8660 Dakota Dr.
Gaithersburg, MD 20877 USA
Contact: Vladimir Dmitriev
TEL: [1] 301 208 8342
FAX: [1] 301 897 3229
welcome@tdii.com

TDI manufactures advanced substrate materials for silicon carbide and Nitride bulk and epitaxial growth including SiC epiwafers with reduced micropipe density and GaN/SiC epiwafers for GaN homoepitaxy. TDI provides characterization service for wide band gap semiconductor materials and device structures. Visit TDI's Web site at <http://www.tdii.com>

tectra GmbH
Phsikalische Instrument
Reuterweg 65
Frankfurt, Main D-60323
Germany
Contact: Andreas Gati
TEL: [49] 69 720 040
FAX: [49] 69 720 400
tectra@t-online.de

Offers vacuum coating systems, MBE systems, and electron beam evaporators, plasma ion sources, sputter guns, and more.

Tegal Corporation
2201 South McDowell Blvd
Petaluma, CA 94955 USA
Contact: Jim McKibben
TEL: [1] 707 763 5600
FAX: [1] 707 773 3015
jmckibben@tegal.com

Tegal Corporation, headquartered in Petaluma, California, is a leading designer and manufacturer of Plasma Etch Systems used in the production of compound semiconductors and related devices. These are production worthy automated systems designed for the rigors of full scale compound semiconductor manufacturing.

Temescal BOC Coating Technology
2700 Maxwell Way PO Box 2529
Fairfield, CA 94533 USA
Contact: Brian Kaemmer
TEL: [1] 707 423 2100
FAX: [1] 707 425 1706
brian.kaemmer@us.bocct.boc.com

Temescal thin-film deposition systems and components have been used since 1952. New systems for the compound semiconductor industry include Model FCE-3800, AL-3800 and CE-6150 for operator-free, cassette-to-cassette processing of 150 mm GaAs substrates. Temescal components include electron beam sources, power supplies, beam sweepers and deposition controllers.

Thermionics Vacuum Products
231-B Otto Street
Port Townsend, WA 98368 USA
Contact: Michael Ricks
TEL: [1] 360 385 7707
FAX: [1] 360 385 6617
mricks@thermionicscorp.com

Thermionics Vacuum Products manufactures vacuum systems and components: Hanks HM2 e-Gun™ evaporation sources; PyraFlat™ rectangular and other flanges, fittings; M.E.S.C./ M.E.S.A. compatible rectangular gate valves, poppet valves; DRS-1000™ in-situ, non-contact substrate temperature control systems; sample handling and transfer systems.

Thomas Swan
Scientific Equipment
Unit 1C Button End Harston,
Cambridge CB2 5NX UK
Contact: Sandra Holdsworth
TEL: [44] 1223 872 282
FAX: [44] 1223 871 714
sandra@thomasswan.co.uk

MOCVD systems for 1, 3 or 6 wafers. GaAs, InP, GaN and related compositions, with growth demonstration/guarantee. Support instrumentation includes scrubbing systems, alkyl concentration monitors and in-situ diagnostics.

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1261 Broadway
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FAX: [1] 212 213 6906
tgmca@aol.com

Offers GaAsP, GaP, AlGaAs and AlInGaP epi wafers, GaAs, InP and sapphire substrates to the optoelectronics industry. Products include high brightness and high power visible & Infrared LED die, SMD and discrete lamp, laser chip and diode, and Silicon PIN diode and other (InGaAs & Germanium) detectors.

TLC
Precision Wafer Technology
1411 West River Road North
Minneapolis, MN, 55411 USA
Contact: Anju Sohal
TEL: [1] 612 341 2795
FAX: [1] 612 341 2799
sales@tlcprecision.com

Offers high performance epitaxial wafers, including MESFETs, HEMTs, HBTs and photonic structures. Specialties include high In and Al mole fractions, OEIC structures, varactor diodes, SEU-hard HFETs and dielectric insulated MISFETs.

Top-Vu Technology, Inc
2650 14th Street N.W.
St. Paul, MN 55112-6348
Contact: Tho Vu
TEL: [1] 651 633 5925
FAX: [1] 651 633 5934
tho@topvu.com

Specializes in chip design and microsensor systems. Technical services include design, layout and test of digital and analog integrated circuits (chip design - Si, GaAs and InP). Developing GaAs based microsensor systems: 1) microsensors/micromachines; 2) readout electronics; 3) A-to-D converters; and 4) digital signal processors. More information is found at www.topvu.com

Torr International
18 Columbus Street
New Windsor, NY 12553 USA
Contact: Masud Naraghi
TEL: [1] 914 565 4027
FAX: [1] 914 561 7731
torr.intl@juno.com

TORR International, Inc., specializes in the manufacture of high quality R&D sputter deposition system, reactive ion etchers and, custom made vacuum systems. Total system packages range from single source DC planar magnetron coaters to multiple source DC/RF systems. Units offered are turbo pumped, table top with manual or menu-driven PC control.

Trikon Technologies Inc.
Ringland Way
Newport NP6 2TA UK
Contact: Dave Thomas
TEL: [44] 1633 414027
FAX: [44] 1633 414180
dave.thomas@trikon.com

Trikon offers the following products for compound semiconductor manufacturing: Metallization: Sigma 204 cluster tool for advanced sputtering processes. Hi-Fill: long throw configuration gives highly directional deposition suitable for lift-off schemes. ETCH: Omega 201 with ICP, PERIE, RIE or MORI source for etching GaAs, InP, dielectrics and metals.

UES Inc.
4401 Dayton-Xenia Road
Dayton, OH 45432 USA
Contact: Rabi Bhattacharya
TEL: [1] 937 426 6900
FAX: [1] 937 426 5718
rbhattacharya@ues.com

UES is a research, development and technology transfer company. UES' expertise includes high energy (MeV) ion implantation in semiconductors, advanced surface modification technologies, conventional and advanced metallic, intermetallic, ceramic and composite material systems, and materials processing and process modelling.

Union Carbide Crystal Products
750 S. 32nd Street
Washougal, WA 98671 US
Contact: Keith Heikkinen
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FAX: [1] 360 835 9848

World's foremost supplier of sapphire substrates for GaN epitaxial growth. 2" and 3" diameter c-plane (0001) substrates are available with single side polished or both sides polished in production quantities. Also available are research kits with single side polished pieces.

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Electro - Optic Materials
Watertorenstraat 33
B - 2250 Olen Belgium
Contact: Marleen Van Den Bergh
TEL: [32] 14 24 55 97
FAX: [32] 14 24 55 34
marleen.vandenbergh@um.be

UM Electro - Optic Materials has been providing germanium wafers for electronic applications since the early sixties. We offer large size epi - ready germanium substrates with unique crystallographic perfection that are a state-of-the-art solution for epitaxial growth of GaAs or other III-V compounds.

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Contact: Jack S. Yeh
Tel: [886] 3 5678000 ext 521
Fax: [886] 3 5678753
jack@uec.com.tw

Offers AlInGaP, AlGaAs GaAsP, and GaP chip and epitaxial wafers. MOVPE customer epiwafers for infrared high power LED, visible UHB LED, laser diode and MMIC.

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Contact: Irwin Drangel
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UMC source of the finest high purity materials for MBE and crystal growth. We stock Furukawa As, Rasa Ga, In, Red P, B203, and Dowa Sb in purities to 7N5, each supplied with certification by GDMS, MS AA, in a variety of forms and packaging. Our rapid customer response is well known.

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Terminal Drive
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Contact: Fran Brennen
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FAX: [1] 516 349 8321
fbrennen@aol.com

Veeco is a worldwide leader in Metrology tools; and etch and deposition process equipment used in the compound semiconductor industry.

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Suite 407-J
Beverly, MA 01915 USA
Contact: Phil Sullivan
TEL: [1] 978 524 1041
FAX: [1] 978 524 1077
vgmbe@aol.com

VG Semicon is the leading supplier of MBE equipment for research and production. The V80H is the World's leading research MBE system providing a superior platform for advanced materials research and the industry-leading V100 system is the World's most advanced and well-proven MBE system for commercial applications.

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Contact: Thomas Digges
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vasemi@juno.com

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FAX: [886] 3 470 6567
vpec@ms18.hinet.net

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Wafer Technology Ltd.
34 Maryland Road
Tongwell
Milton Keynes, Bucks MK15 8HJ
United Kingdom
Contact: Karen Lamb
TEL: [44] 1908 210 444
FAX: [44] 1908 210 443
klamb@wafertech.co.uk

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Contact: Sean Quinn
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FAX: [1] 561 842 2677
sales@waferworld.com

Manufactures silicon wafers in small diameter for reclaim, test, prime and double-side polish specifications in research and production quantities. Customer supplier Germanium and GaAs can be reclaimed or polished.

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UK
Contact: Lloyd Sinclair
TEL: [44] 1705 664 911
FAX: [44] 1705 697 864
cjb@cjbdev.demon.co.uk

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March 1-3, 1999 • Catamaran Resort Hotel • San Diego, California USA

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- ◆ Stan Bruederle, Chief Analyst – Dataquest, Inc.

CONFERENCE CO-CHAIRS:

- ◆ Jennifer Palella, Strategic Marketing Manager, *ANADIGICS, Inc.*
- ◆ William Kroll, Executive Vice President - Business Development, *EMCORE Corp.*
- ◆ Frank Steranka, Manufacturing Manager, *Hewlett-Packard Optoelectronics Div.*

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- ◆ AIXTRON Inc.
- ◆ Compound Semiconductor Magazine
- ◆ Electronicast Corporation
- ◆ EMCORE Corporation
- ◆ Epichem, Inc.
- ◆ Oxford Instruments, Inc.
- ◆ Philips Analytical
- ◆ Polaroid Corporation
- ◆ Riber, Inc.
- ◆ Solkatronic Chemicals Inc.
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January

Photonics West

January 23-29
San Jose, CA
Contact: SPIE
TEL: [1] 360 676 3290
FAX: [1] 360 647 1445
spie@spie.org
http: www.spie.org

February

1999 Int'l Solid-State Circuits Conference (ISSCC '99)

February 15-17
San Francisco, CA
Contact: Diane Suiters
Courtesy Associates
TEL: [1] 202 973 8667
FAX: [1] 202 331 0111
isscc@courtesyassoc.com

1999 Optical Fiber Conference (OFC)

February 21 - 26
San Diego, CA
Contact: Ms. Lisa Myers
OSA Conference Services
TEL: [1] 202 416-1980
FAX: [1] 202 416-6100
ofc.info@osa.org
http: www.osa.org

March

Compound Semiconductor Outlook '99

March 1-3
San Diego, CA
Contact: Chris Jones
Gorham Intertech Consulting
TEL: [1] 207 892 5445
FAX: [1] 207 892 2210
gorham@goradv.com
http: www.goradv.com

11th Int'l Conf. on the Microscopy of Semiconducting Materials

March 22-25
University of Oxford, UK
Contact: Richard Beanland
GEC-Marconi Materials Technology
TEL: [44] 1327 356363
FAX: [44] 1327 356389
richard.beanland@gecm.com
http: www.iop.org IOP Confs MSM

10th European Workshop on MBE

March 28 - April 1
Les Arcs (Savoie), France
Abstract Deadline: January 1
Contact: Eric Tournie,
CRHEA/CNRS
TEL: [33] 4 9395 4224
FAX: [33] 4 9395 8361
et@crhea.cnrs.fr

April

1999 Spring MRS Meeting

April 5-9
San Francisco, CA
Contact: MRS
TEL: [1] 724 779 3003
FAX: [1] 724 779 8313
info@mrs.org
http: www.mrs.org

Quantum Optoelectronics 1999 (QOE '99) Ultrafast Electronics and Optoelectronics (UEO '99)

April 12-16
Aspen, Colorado
Abstract Deadline: December 10, 1998
Contact: OSA Conference Services
TEL: [1] 202 416 1980
FAX: [1] 202 416 6100
infor@osa.org
http: www.osa.org

1999 International Conference on Gallium Arsenide Manufacturing Technology (GaAs MANTECH)

April 19-22
Vancouver, BC, Canada
Contact: Ding Day
Network Device Inc.
TEL: [1] 408 734 9888 x1118
FAX: [1] 408 734 9889
dday@network-device.com
http: www.GaAsMANTECH.org

May

195th Meeting of the Electrochemical Society

May 2-7
Seattle, Washington
Abstract Deadline: January 2
Contact: ECS
TEL: [1] 609 737 1902
FAX: [1] 609 737 2743
ecs@electrochem.org
http: www.electrochem.org meet-ings 195 symp.html

11th International Conference on InP & Related Materials (IPRM '99)

May 16-20
Davos, Switzerland
Abstract Deadline: December 5, 1998
Contact: Hans Melchior
Swiss Federal Institute of Technology
TEL: [41] 1 633 2101
FAX: [41] 1 633 1109
h.melchior@iqe.phys.ethz.ch
http: www.iqe.ethz.ch/iprm99

1999 IEEE Custom Integrated Circuits Conference (21st CICC)

May 16-19
San Diego, California
Abstract Deadline: December 2, 1998
Contact: Melissa Widerkehr
CICC
TEL: [1] 301 527 0902
FAX: [1] 301 527 0994
cicc@his.com

9th Biennial Workshop on Organometallic Vapor Phase Epitaxy

May 23-29
Ponte Verda Beach, FL
Contact: Marlene Karl, TMS
TEL: [1] 724 776 9000 x234
FAX: [1] 724 776 3770
karl@tms.org
http: www.tms.org Meetings Specialt y OMVPE99 OMVPE99.html

1999 Conference on Lasers and Electro-Optics (CLEO '99) Quantum Electronics and Laser Science 1999 (QELS '99)

May 23-28
Baltimore, Maryland
Contact: OSA Conference Services
TEL: [1] 202 416 1980
FAX: [1] 202 416 6100
infor@osa.org
http: www.osa.org

1999 International Symposium on Power Semiconductor Devices & ICs (ISPSD)

May 25-28
Toronto, Ontario, Canada
Contact: Mr. Dan Kinzer,
International Rectifier
TEL: [1] 310 726-8561
FAX: [1] 310 252-7167
dkinzerl@inf.com
http: www.utoronto.ca/ispsd99

Workshop on Compound Semiconductor Devices and Integrated Circuits (WOCSDICE) 1999

May 25-27
Paris, France
Contact: Joachim Würfl
Ferdinand-Braun-Institut
FAX: [49] 30 6392 2685
wocsdice@fbh-berlin.de

3rd International Workshop on MBE Growth Physics and Technology (MBE-GPT'99)

May 23-28
Warsaw, Poland
Contact: Prof. Marian Herman
TEL: [48] 22 83 15154
FAX: [48] 22 83 12160
itp@warman.com.pl
http: www.warman.com.pl ~itp MBE-GPT99

June

1999 MTT-S International Microwave Symposium (IMS) and RFIC '99

June 13-18
Anaheim, California
Abstract Deadline: December 4, 1998
Contact: Steve Maas
Nonlinear Technologies, Inc.
TEL: [1] 562 426 1639
FAX: [1] 562 426 1639
smaas@nonlntec.com
http: www.mtt.org ims1999

57th Device Research Conference (DRC)

June 28-30
University of California,
Santa Barbara
Abstract Deadline: March 1
Contact: Bart Van Zeghbroeck
University of Colorado
TEL: [1] 303 492 2809
FAX: [1] 303 492 2758
bart.vanzeghbroeck@colorado.edu
http: eee-www.colorado.edu ~drc

41st Electronic Materials Conference (EMC)

June 30-July 2
University of California,
Santa Barbara
Contact: TMS
TEL: [1] 724 776 9000
FAX: [1] 724 776 3770
esc@tms.org

July

3rd Int'l Conf. on Nitride Semiconductors (ICNS-3)

July 5-9
Montpellier, France
Abstract Deadline: March 1

Contact: Pierre Lefebvre
Université de Montpellier
TEL: [33] 4 67 14 37 60
FAX: [33] 4 67 14 37 56
icns3(a)ges.univ-montp2.fr
http: bilbot.ges.univ-montp2.fr icns3.htm

6th Int'l Workshop on Femtosecond Technology (FST '99)

July 13-15
Chiba, Japan
Abstract Deadline: April 16

Contact: FST'99 Secretariat
Femtosecond Technology Research Association
TEL: [81] 298 47 5181
FAX: [81] 298 47 4417
fst(a)festa.or.jp
http: www.festa.or.jp meeting fst99-e.html

1999 Integrated Photonics Research Topical Meeting (IPR '99)

July 19-21
Santa Barbara, CA
Abstract Deadline: March 17

Contact: OSA
TEL: [1] 202 416 1985
FAX: [1] 202 416 6100
info(a)osa.org
http: www.osa.org

7th International Conference on Chemical Beam Epitaxy (ICCBE-7)

July 27-30
Tsukuba, Japan
Abstract Deadline: Feb 15, 1999

Contact: Dr. Makoto Konagai
Tokyo Institute of Technology
TEL: [81] 3 5734 2554
FAX: [81] 3 5734 2897
konagai(a)pe.titech.ac.jp
http: solid.pe.titech.ac.jp cbe-7

August

11th American Conf. on Crystal Growth & Epitaxy (ACCGE-11)

August 1-6
Tucson, Arizona
Abstract Deadline: February 28

Contact: Tony Gentile
ACCGE-11 Secretariat

TEL: [1] 805 492 7047
FAX: [1] 805 492 4062
aacg(a)lafn.org
http: www.aml.arizona.edu aacg

1999 International Microwave and Optoelectronics Conference (IMOC '99)

August 9-12
Rio de Janeiro, Brazil
Abstract Deadline: March 8

Contact: Ms Denis Consonni
LME-EPUSP, Brasil
TEL: [55] 11 8185255
FAX: [55] 11 8185585
imoc99(a)dmo.fee.unicamp.br
http: www.mc21.fee.unicamp.br/imoc99

1999 International Symposium on Compound Semiconductors (ISCS '99)

August 22-26
Berlin, Germany
Abstract Deadline: April 12

Contact: ISCS'99 Secretary
Paul-Drude-Institute
TEL: [49] 30-20377-352
FAX: [49] 30-20377-201
ISCS99(a)pdi-berlin.de

September

3rd Int'l Conf. on Mid-Infrared Optoelectronics - Materials and Devices (MIOMD-3)

September 6-7
Aachen, Germany
Abstract Deadline: July 2

Contact: Klaus Heime
TEL [49] 241 807745
FAX [49] 241 8888 199
mailbox(a)iht.rwth-aachen.de
http: www.iht.rwth-aachen.de miomd.html

International Joint Conference on Silicon Epitaxy and Heterostructures (IJC-Si)

September 13-17
Miyagi, Japan
Abstract Deadline: April 30

Contact: Prof S. Zaima
Nagoya University
TEL: [81] 52 789 2762
FAX: [81] 52 789 3818
zaima(a)alice.xtal.nagoya-u.ac.jp

1999 IEEE Bipolar/BiCMOS Circuits and Technology Meeting (BBCTM '99)

September 26-28
Minneapolis, Minnesota

Contact: Janice Jopke

CCS Associates
TEL: [1] 612 934 5082
FAX: [1] 612 934 6741
jjopke(a)aol.com

October

1999 US Workshop on the Physics & Chemistry of II-VI Materials

October
Las Vegas, Nevada

Contact: Jay Morreale
Palisades Institute
TEL: [1] 212 460 9700
FAX: [1] 212 460 5460
jmorreale(a)newyork.palisades.org

European GaAs and Related III-V Compounds Application Symposium (GAAS '99)

October 4-8,
Munich, Germany
Abstract deadline: March 19

Contact: Hans Hartnagel
Technische Hochschule Darmstadt
TEL: [49] 6151 162 162
FAX: [49] 6151 164 367
hfmwe001(a)hrz2.hrztu-darmstadt.de
http: www.eumw.com

18th North American MBE Conference (NAMBE-18)

October 10-13
Banff, Canada
Abstract Deadline: June 1999

Contact: Dr Z Walewski
National Research Council
TEL: [1] 613 990 4557
FAX: [1] 613 941 4667
zbig.walewski(a)nrc.ca

21st Annual GaAs IC Symposium

October 17-20
Monterey, CA

196th Meeting of the Electrochemical Society

October 17-22
Honolulu, Hawaii
Abstract Deadline: May 14

Contact: ECS
TEL: [1] 609 737 1902
FAX: [1] 609 737 2743
ecs(a)electrochem.org
http: www.electrochem.org

46th National American Vacuum Society (AVS) Symposium

October 25-29
Seattle, Washington

Contact: Marion Churchill, AVS

TEL: [1] 212 248 0200
FAX: [1] 212 248 0245
Marion(a)vacuum.org
http: www.vacuum.org

November

Int'l Conference on II-VI Compounds (II-VI '99)

November 1-5
Kyoto, Japan
Abstract Deadline: May 20

Contact: Prof. Shizuo Fujita
Kyoto University
Tel: [81] 75 753 5364
Fax: [81] 75 753 5898
fujitasz(a)kuce.kyoto-u.ac.jp
http: fujita.kuce.kyoto-u.ac.jp 26kyoto

International Workshop on High Performance Electron Devices for Microwave and Optoelectronic Applications (EDMO '99)

November
London, UK

Contact: Ali Rezazadeh
Kings College London
TEL & FAX: [44] 171 873 2879
ali.rezazadeh(a)kcl.ac.uk
http: www.ieee.org

Lasers and Electro Optics Society Annual Meeting (LEOS '99)

November 8-11
San Francisco, California

Contact: IEEE LEOS
TEL: [1] 732 562 3989
FAX: [1] 732 562 8434
m.estrin(a)ieee.org
http: www.ieee.org society leos

1999 Fall MRS Meeting

November 29-December 3
Boston, MA
Abstract Deadline: June 21

Contact: MRS
TEL: [1] 724 779 3003
FAX: [1] 724 779 8313
info(a)mrs.org
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December

1999 IEEE International Electron Devices Meeting (IEDM)

December 5-8
Washington, DC

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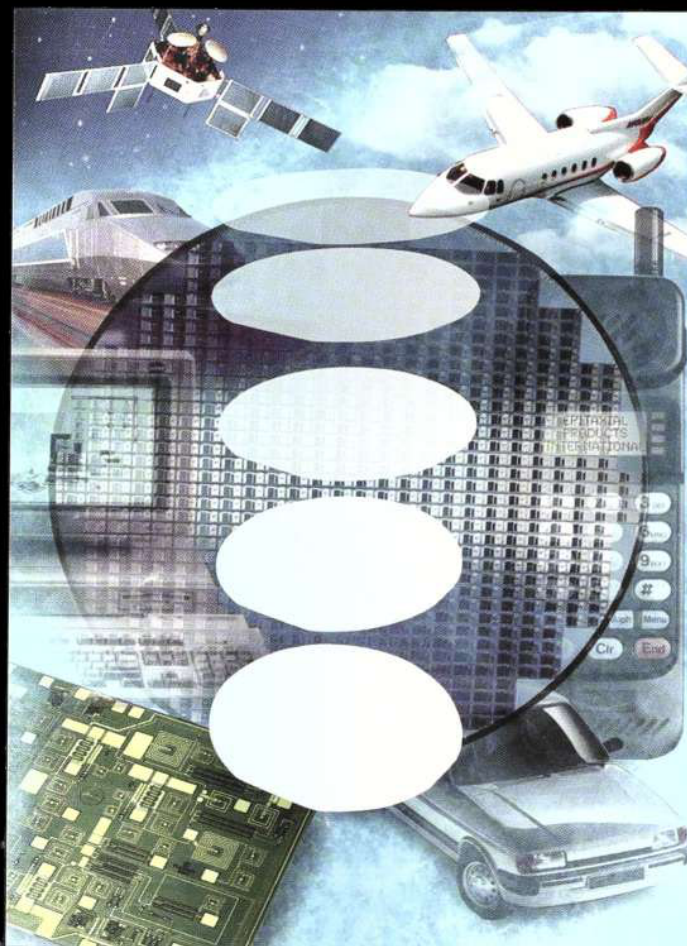
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