COMPOUND SEMICONDUCTOR

November/December 1995 Volume 1 Number 3

Silicon Germanium:

The new "material of the future"?

Nitride News
See page 8

WORLD CLASS EPITAXIAL WAFERS

ADVANCED CUSTOM GALLIUM ARSENIDE (GaAs) AND INDIUM PHOSPHIDE (InP) TECHNOLOGIES.

TLC Precision Wafer Technology

is an experienced semiconductor manufacturing company that specializes in epitaxial wafer technologies and custom circuit design.

Research and Development

Wafers are manufactured for digital, analog, monolithic millimeter-wave (MMIC), and photonic devices and circuits for use in advanced avionics, communications and computers, satellites, military and auto applications and various commercial electronic and optical systems.

Lattice Engineering

- High In-mole fraction (up to 53% on GaAs, 80% on InP)
- High Al-mole fraction insulating layers
- Engineered large ΔE_C and ΔE_V for high current densities
- Engineered material for multifunctional OEICs for .8 - 1.5 micron light.

Foundry-Compatible Epitaxial Wafers

- Custom circuit, device and material modeling and design.
- Tailored growth to desired Rs, V_T and optimum Gm.
- Excellent morphology and Rs uniformity for high circuit yields.
- Special capabilities for low noise and high power circuit performance.

Technical Achievements

- World's fastest MODFET (HEMT) devices.
- Advanced C-HFET (PHEMT) with world record N&P channel performance.
- High performance 3" InP based HEMT.
- World's first dielectric insulated gate MISFET E/E logic circuit with <10pA gate leakage @ Vg± 4.0 volts.
- World's first epi GaAs based 4K-SRAM.

Dedicated services and customized wafer and circuit designs at an affordable price.
Contact: Dr. Timothy Childs

TLC Precision Wafer Technology, Inc.

661 5th Avenue North, Suite 160 • Minneapolis, MN • 55405-1521
(612) 341-2795 FAX (612) 341-2799

Circle 119 on Reader Service Card

NOVEMBER/DECEMBER 1995 VOLUME 1 NUMBER 3

COMPOUND SEMICONDUCTOR

COVER STORY

21 Is Silicon Germanium the New "Material of the Future"?
SiGe has been proven capable of delivering impressive HBT performance in the laboratory, but is there a place for it in the market?

26 Beyond HBTs
HBTs are the highest profile application for SiGe, but researchers are also investigating optoelectronics, MODFETs, and heterojunction CMOS, as well as fundamental improvements in the material itself.

31 Tutorial
High frequency performance of SiGe HBTs.

48 Guest Editorial
Rob Christ of TriQuint Semiconductor provides a marketing perspective on the match-up between GaAs MESFETs and SiGe HBTs.

OTHER FEATURES

8 Nitride News from Japan
Stimulated emission from a current injected InGaN/GaN structure reported...Nichia demonstrates LEDs from violet to orange...Panasonic and Toyoda Gosei team up to offer blue LEDs.

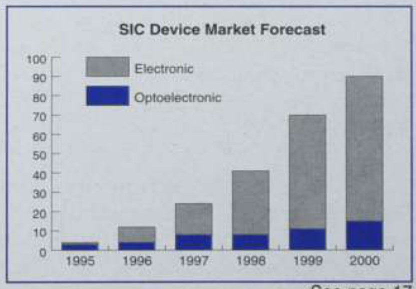
9 Looking for Blue Light Substrates
ARPA funds its third "blue light" consortium and a variety of research into new substrates for nitride growth.

10 Technology Update
GaAs ICs with improved radiation hardness characteristics

17 The Forecast for Silicon Carbide

18 Preview of the 1995 IEDM Conference

32 Conference Reports
The 1995 International Conference on II-VI Devices and Compounds and the 1995 North American MBE Conference.



See page 17

40 A Retrospective on the MIMIC Program
ARPA's MIMIC Program was intended to cut costs for military systems, but along the way it helped to establish a commercially viable GaAs industry in America.

DEPARTMENTS

2 Letters

4 New Devices
New FETS from HP...wireless products from OKI, National/Panasonic...Vitesse expands GaAs IC product line...Green LEDs from Nichia...DFB lasers from Mitsubishi, Sensors Unlimited...Siemens IR data transceivers.

6 Device Feature
MOPA Lasers from SDL - high power from a small package

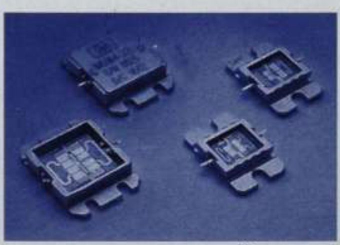
12 News Briefs
M/A-COM buys Cray's fab...New standard for next-generation CDs..."MBE in space" update...TRW wins MAFET contract...Akasaki, Ralston honored at 1995 ISCS...TI seeking commercial market for its GaAs capability...All-Si chipset for 2.4 GHz announced... plus financial reports from several companies.

Editor
Marie Meyer
Compound Semiconductor Magazine
Franklin Publishing
250 Selby Avenue
Suite 48
Saint Paul, MN 55102 USA
Tel [1]612 227 5397
FAX [1] 612 227 5499
e mail mmeyer@compsem.com

Features Editor
Robert A. Metzger
Compound Semiconductor Magazine
6605 Williamson Drive NE
Atlanta, GA 30328 USA
Tel [1]404 705 8475
FAX [1] 404 255 9867
e mail rametzger@aol.com

Compound Semiconductor
is published six times yearly by
Franklin Publishing
250 Selby Avenue
Suite 48
Saint Paul, MN 55102 USA
Tel [1]612 227 5397
FAX [1] 612 227 5499
For subscription information
see page 19 or contact the editor.

POSTMASTER
Second class postage paid at
Waconia, MN and at
additional mailing office.
Send address changes to:
CS Subscriptions
250 Selby Avenue
Suite 48
Saint Paul, MN 55102 USA



See page 4

LETTERS

From the editor:

Welcome to our third issue. Allow me to update you on some important changes in our magazine.

New and Expanded Features

On page 6 you will find our new "Device Feature", wherein we take an in-depth look at an interesting product from a leading manufacturer, providing more background and detail than is possible in the "New Devices" section. The subject for this issue is a high power semiconductor laser from SDL. We launched the feature in our last issue with a story on a novel GaAs IC from TRW, and we plan to continue alternating between electronic and opto devices.

Also in this issue is our newly expanded "Research Review" section. We received several requests to extend our coverage in this area, so we have introduced a new category and increased the space allocation. "Research Review" is now divided into three sections - compound semiconductor materials; electronic devices and circuits; and optoelectronic devices. The research for this section of the magazine is done the old-fashioned way: writers go to the library and read paper journals. We do not solicit contributions in this area. However, a few authors have sent in preprints of very recently published papers, knowing that it may be several weeks before the journal appears in the library. This courtesy is greatly appreciated.

Feedback

Back in July we started Compound Semiconductor with an idea about the magazine's mission: to provide a focal point for the global compound semiconductor industry. We then tried to design a publication, that would best suit that mission. The result is the collection of "Features" and "Departments" which you see in this issue. So far, it seems quite successful - we have received a great deal of positive feedback regarding the magazine's "readability" and organization. But more input is always helpful. You can use the Reader Service Cards on page 29 as an easy way to let me know what you like and dislike about the magazine.

The expansion of the "Research Review" section was largely motivated by input from the Reader Service Cards. However, not all suggestions can be acted upon. We have received several requests to expand our coverage to include technical papers and reviews. While I appreciate the suggestions, it is not possible at this time, due to space constraints. Every story competes for space with other stories, and while there are already outlets for that type of technical writing, there is no other forum for the news- and applications-focused content that currently fills our magazine. In a similar vein, we shy away from most "soft news" stories from vendors (designed to promote one company's viewpoint for their commercial advantage), in order to make more room for "hard news" stories.

I don't want all this to sound too forbidding. Although we have a clear vision of what we want our magazine to be, we do appreciate input from our readers, and all substantive suggestions are given serious consideration. A good example is the Technology Update piece on page 10 of this issue, which started out as a phone call from NRL saying "We've got some really interesting stuff here - are you interested in having a look at it?" The result was a very informative story. We want to hear from you, too. Use the reply card, phone, FAX or e-mail, but please do let us know what you think.

1996 Subscription Policy

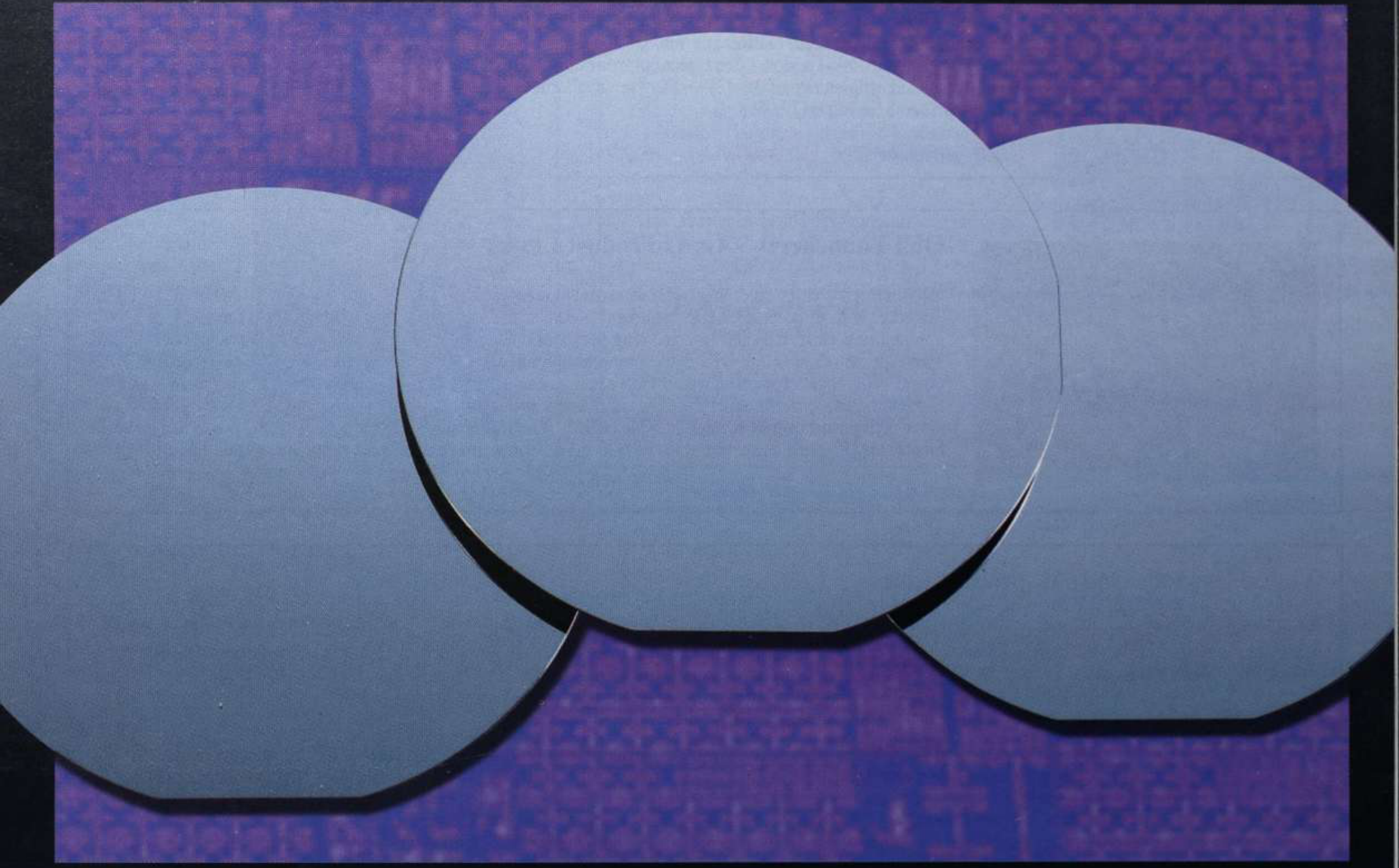
All of the introductory free subscriptions to Compound Semiconductor expire with this issue, which means that you must purchase a subscription if you wish to continue receiving our magazine. You will find a 1996 subscription form on page 19.

Very large industries - like the "silicon business" or the optics industry - can support free circulation magazines which derive all of their income from advertising. Publications for smaller industries, where there are fewer advertisers, need subscription revenue to offset the cost of production and postage. Moreover, in those large industries there is still a need for paid-subscription publications to provide more substantial analysis and coverage. Some of you might be thinking "why not cut costs by publishing on the Internet?" This is, of course, an option we considered we when started the magazine. However, in any type of communication there is an intimate relationship between form and content. The "net" is the wrong medium - the wrong form - for delivering the type of thorough, thoughtful content that we provide. Electronic publishing is excellent for gathering facts and snippets of information, but it fails as a medium for more substantive exchanges. Given that we are seeking to provide a focal point for the industry, we prefer the more concrete distribution, the relatively greater permanence, and the superior aesthetic impact of paper publishing to the bustling stream of "information" that one picks up while surfing the net.

We've set our subscription prices at very reasonable levels, so as to be affordable for everyone within the industry. We are also providing a special "courtesy discount" for scientists and engineers, in recognition of your pivotal role. I hope that you all will take a moment to complete and return the form as soon as possible, to ensure an uninterrupted supply of reliable news and information about compound semiconductors throughout the coming year.

Marie Meyer
Editor
Compound Semiconductor

To Build Your Business
On GaAs Technology, Start With
The Right Foundation.



There's no more solid GaAs foundation than what you'll find at M/A-COM. We have unsurpassed capabilities in substrate manufacturing. That means we can provide the highest purity, most consistent SI-GaAs substrates available. So you can provide your customers with the low-cost, high quality device solutions they're looking for.

Our product line features substrate diameters of 3", 100mm and 150mm. These substrates are manufactured to meet the highest international standards for quality, including ISO 9001. And they deliver unmatched technical performance.

We are also committed to superior customer and technical support, regardless of the size of your business. We're better able than ever to quickly process customer requests. In addition we provide extensive technical support whether you require standard or custom products.

When you work with M/A-COM, you get the expertise that can only come from being the industry's most experienced SI-GaAs supplier. With a 15-year record of refining and improving the growth of semi-insulating gallium arsenide.

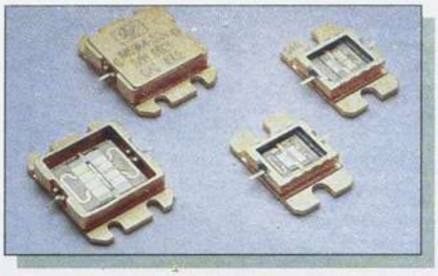
To learn more, contact us today. You'll find what we have to say very constructive.

Call for more information: in Europe, at 44 (1344) 869 595; in the USA at 1-800-366-2266; or in Asia/Pacific at 81 (03) 3226-1671. Or contact us via E-mail at gaas-wafers@macom.com.

Circle 6 on Reader Service Card

M/A-COM
an **AMP** company

Power GaAs FETs from Hewlett-Packard



Hewlett-Packard has announced a new family of 5.9 to 6.4 GHz internally matched power GaAs FETs for use in solid-state power amplifiers for C-band satellite earth station and microwave communications transmitters. The four new products, called the IM5964 series, offer typical power outputs ranging from 4.5W to 32.0 W, with typical power-added efficiencies of 36-42%. They are available from stock, with prices ranging from $244/pc (4.5W) to $1,300/pc (32.0W).

OKI Launches 3-V GaAs Product Line

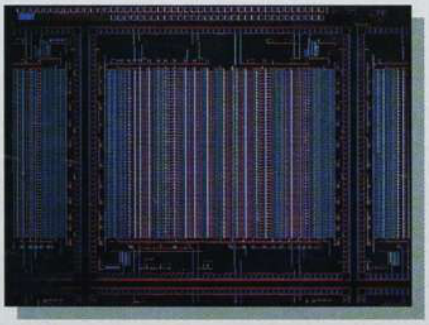
OKI Semiconductor has introduced three new GaAs RF devices, operating from 850 MHz to 2.4 GHz. Together with three new CMOS baseband products, the new devices represent OKI's targeting of 3-volt applications, especially the fast-growing personal communications services (PCS) market. A company spokesperson claims that OKI is the first manufacturer to offer a 3-V chip set capable of exceeding 70% power efficiencies for cellular and PCS applications. The new products include two 3-V power amplifiers with peak current capabilities of >5.5 amps at digital frequencies and >4.5 amps for PCS applications. RF power output is rated at >31.5 dBM. The third GaAs product is a medium-power driver self-biased MMIC with a power output of >20 mW. Prices are in the $8-12 range in volume quantities.

Vitesse Expands GaAs IC product Line

Vitesse Semiconductor Corporation has expanded its GaAs IC product line with two new offerings. The first consists of two new ICs for Fibre Channel Arbitrated Loop (FC-AL), a Gbit/sec networking system for high-data servers, clients, and disk drives. With the introduction of these new chips, Vitesse now offers all of the physical layers ICs necessary to implement Fibre Channel. The new chips are a 1.0625 Gbit/sec Quad Port Bypass Circuit (PBC) which can be used to connect up to four FC-AL disk drives in a single loop. The other new chip is a Fibre Channel Repeater and Hub chip, combining a clock recovery unit (CRU), a signal detect unit (SDU), and a PBC.

Also new from Vitesse is the GLX™ family of gate arrays, which the company claims is "the next major advancement in high-performance ASICs", capable of dramatically reducing both device power and cost over all other previous ASICs targeted at the 100-800 MHz performance range. According to a company spokesperson, "with per-gate power as low as 0.07 mW and volume pricing below 0.1 cent per usable gate, GLX arrays make a perfect high-performance companion to CMOS ASICs where CMOS technology does not provide the necessary level of performance". TTL I/O designs can be powered from a single +3.3V supply. All GLX macrocells are available in either full speed (approx. 0.13 mW per gate) or half power versions. GaAs Power Management™ is used to further reduce power in low frequency portions of the design by powering down combinational logic during periods of inactivity. The new ICs have from 25,000 to 250,000 raw gates with a utilization factor ranging from 60-70%.

"GLX has effectively removed power as a barrier to high performance technology. Power dissipated in CMOS and BiCMOS gate arrays increases proportionately with the system clock rate. In the Vitesse gate arrays, however, power dissipation is independent of frequency," said Bob Nunn, Vice President and General Manager of ASIC products at Vitesse. "In addition, GLX combines the cost benefits of a high yielding process, reduced die sizes, and low cost thermally enhanced plastic packaging to produce a gate array family that falls on or below the CMOS price/performance curve." The new ICs are targeted for switching networks, serial links, high-speed data bus transfers, DSP functions, and critical timing blocks in communications, ATE/instrumentation, and computer applications. Designs for all members of the GLX family are being accepted now with prototypes available in first quarter of 1996 and production in second quarter of 1996. GLX arrays sell for less than 0.1 cent per gate in volume with NRE starting at about $30K.



GaAs MMICs from National/Panasonic

National/Panasonic has announced the availability of a new family of GaAs MMICs and amplifiers for use in the Personal Handyphone System (PHS). The new products include: 1) a 3.5-V low-noise power amplifier MMIC offering low power consumption; 2) a 3-V gain control amplifier which features low power consumption (20mA) with 35dB gain; 3) a PHS front end MMIC, low frequency converter, 5mA power consumption; 4) a PHS MMIC switch, with single power supply; and 5) a PHS station amplifier.

Green LED from Nichia

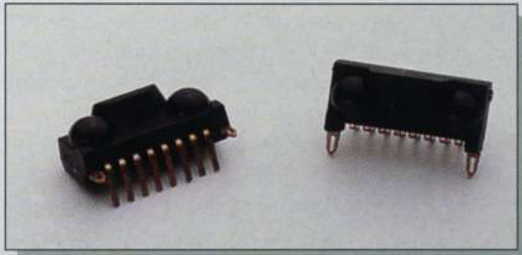
Nichia Chemical has announced the first nitride-based green LED. The new device provides 6cd of 525nm light at 20mA, which is 60 times brighter than best conventional yellow-green LEDs which emit at 555nm. They are sample-priced at 1,000 yen. They are also available in a full-color LED unit integrating 16x16 LEDs for 300,000 yen. The company reports that volume production will begin next spring. *For more information about Nichia LEDs, see page 8.*

DFB Lasers from Mitsubishi

Two new distributed feedback (DFB) laser diodes have been introduced by the Electronic Device Group (EDG) of Mitsubishi Electronics America. The first is a wavelength selected module that allows for wavelength division multiplexing of four separate wavelength lasers (1434nm to 1558.5nm) operating at 2.5 Gbit/sec into a 10 Gbit/sec datastream. Pricing is set at $7,000 for 100 piece quantity. Evaluation units are currently available, with production beginning in late 1995.

Also available is a new high power 1550 nm DFB laser diode module with polarization maintain fiber. This device is targeted toward high-speed SONET and cable television (CATV) transmissions. It's specified output power is 15mW, which "makes it optimal for high-speed transmissions of up to 10Gbit", according to Mike Trapp, Mitsubishi EDG optoelectronics marketing manager. "It compliments our existing 1480nm erbium-doped fiber amplifier and 980nm pump laser diodes, which are also targeted at high-speed fiber optic transmissions." Pricing is $6,600 for 100 piece quantity. Evaluation units are now available for qualified customers.

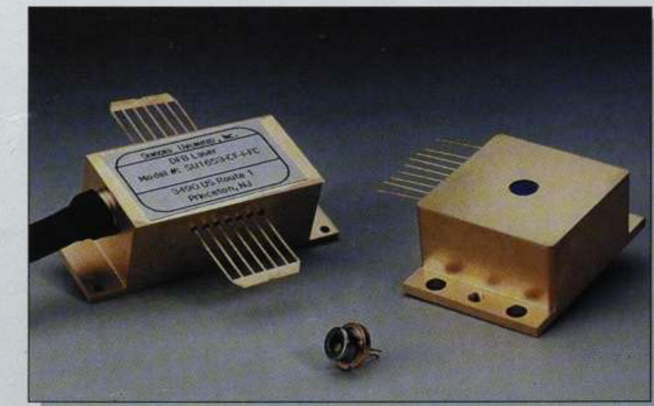
Transceivers for Infrared Data Transmission from Siemens



Siemens Optoelectronics Division has announced the availability of two new infrared data transceivers for use in portable infrared wireless products adopting the Infrared Data Association (IrDA) standard. Siemens estimates that market for IrDA applications will grow from 18 million units in 1995 to over 47 million units in 1997.

The new products are fully contained transceivers incorporating GaAs IR-LEDs and Si BiCMOS circuitry into compact surface-mount packages. They perform the transmit and receive functions required for IR data transmission up to 115.2 kilobits per second. Design features include a wide dynamic range that allows the user to transmit data regardless of how close or who far they are located relative to the receiving unit (with a maximum distance of 3 meters, consistent with IrDA specifications); and a shutdown feature that reduces the supply current from 1 mA to 0.1 mA for power-savings, which is critical for portable systems which rely on batteries.

Pricing in 1,000-piece quantities will be about $4 each. These two devices are the first in what will be a family of IR transceivers. Future versions will include 1 megabit per second (Mb/s) and 4 Mb/s to meet upcoming IrDA data transmission schemes, as well as address applications based on ASK, DASK, FSK and PPM modulation schemes.



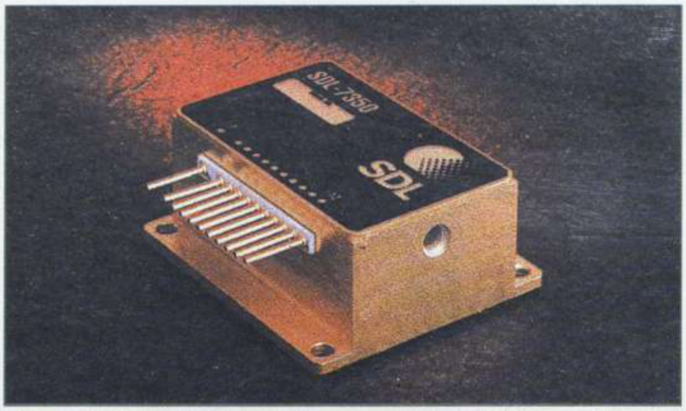
DFB Diode Lasers from Sensors Unlimited

Sensors Unlimited, Inc. has expanded their line of InGaAs DFB diode lasers to include the 761 nm, 1393 nm, 1602 nm, 1653 nm, and 1950 nm wavelengths. Custom wavelengths are also available. These devices are targeted at applications such as remote sensing, chemical detection, pollution monitoring, and spectroscopic systems. Features include stable single-mode operation and narrow linewidth output. They are thermally and current tunable with a 5 nm bandwidth. Typical output powers are 5 mW. Packaging options include standard CD (TO46) can packages, or TO37 packages with a thermoelectric (TE) cooler and fiber pigtail.

Future expansion is planned into the 2-3 µm range. A 2.6 µm Fabry Perot laser is currently available. these lasers are designed for room temperature operation utilizing a custom developed 3-stage TE cooler with output powers of 1 mW at 200 K.

MOPA Lasers from SDL

SDL offers Monolithic Master Oscillator Power Amplifiers (MOPA) lasers capable of very high power, diffraction limited output



The SDL-7350 MOPA which operates at 670-680 nm with a cw output power of 500 mW. The packaged device occupies less than 3.0 in^3 including collimating optics and an internal thermoelectric cooler.

SDL Inc. [San Jose, CA] recently introduced two high power Monolithic Master Oscillator Power Amplifier lasers. These "MOPAs" are, essentially, semiconductor lasers with built-in amplifiers that are capable of extremely high power output (up to 1 W in commercially-available models, up to 3 W in demonstration units). They are suitable for a wide range of applications, ranging from coupling to single mode EDFAs to replacing Krypton and HeNe lasers.

Two models are currently available: a 985 nm unit which provides 1 W cw power; and a 670-680 nm unit which provides 500 mW cw power. According to David Welch, Vice President of Research at SDL, "the 670-680 version is a good replacement for many applications that were previously being handled by gas lasers, and the 5 nm spectral bandwidth allows efficient energy coupling into Cr-doped solid state laser host crystals or print media, or it can be used as a highly visible display beam, suitable for use in laser light shows." He also points out that "the 985 nm version of the MOPA provides excellent coupling to single mode Erbium Doped Fiber Amplifiers (EDFAs). In addition, this wavelength is ideal for frequency doubling with potassium niobate crystals, giving a 490 nm blue laser which would have applications that would include optical data storage at high data densities, color separation, printing, and a variety of biomedical applications." Welch describes one of the most interesting applications for these MOPAs as creating "optical tweezers", where the potentials created by the high power lasers are used to manipulate cells and genes, making them suitable for DNA experimentation.

Figure 1 shows a chip schematic of MOPA consisting of a Distributed Bragg Reflector (DBR) master oscillator coupled to a flared power amplifier. The epitaxial growth required for this device includes a single quantum well active region (InGaAs for the 985 nm device, InGaP for the 670-680 nm device), surrounded by AlGaAs confining and cladding layers. The gratings for the DBR master oscillator are second order and defined holographically in a $Al_{0.05}Ga_{0.95}As$ layer and overgrown with $Al_{0.65}Ga_{0.35}As$. The output of the DBR laser is injected into the power amplifier, where the gain of the flared amplifier is tapered linearly at an angle slightly larger than the free diffraction of the injected source in order to minimize the introduction of edge diffraction effects. These lasers are extremely compact, with the 670-680 nm device occupying a volume of only 3.0 in^3, which includes both the collimating optics as well as an internal thermoelectric cooler which is used for temperature control of the emission wavelength.

The future direction for MOPA technology lies in increasing output power (up to 3 W has already been demonstrated), as well as introducing a high speed modulation capability, which would make MOPA technology suitable as a transmission element in high speed intersatellite communications. For example, SDL has demonstrated the monolithic integration of a multiquantum well electroabsorption modulator placed between the DBR master oscillator and the tapered power amplifier of a MOPA. The MOPA's output power exhibited an extinction ratio of -20 dB with a modulator bias of -4 V. High frequency measurements were performed, in which the modulated output light was fiber coupled through an optical isolator and was detected by a 25 GHz bandwidth photodiode. The small signal modulation response exhibited a 5 GHz 3-dB modulation bandwidth, making this device theoretically suitable for free-space communication rates in excess of 2.5 Gbit/s.

For additional information, see: "2.0 W CW, Diffraction-Limited Operation of a Monolithically Integrated Master Oscillator Power Amplifier", R. Parke, et al, IEEE Photonics Technology Letters, 5(3) 297 [1993]; and "1 W Diffraction-Limited Semiconductor MOPA with a Monolithically Integrated 5-GHz Electroabsorption Modulator", S. O'Brien et al, Technical Digest Proceedings CLEO '95 [May 21-26 1995, Baltimore, MD] 355.

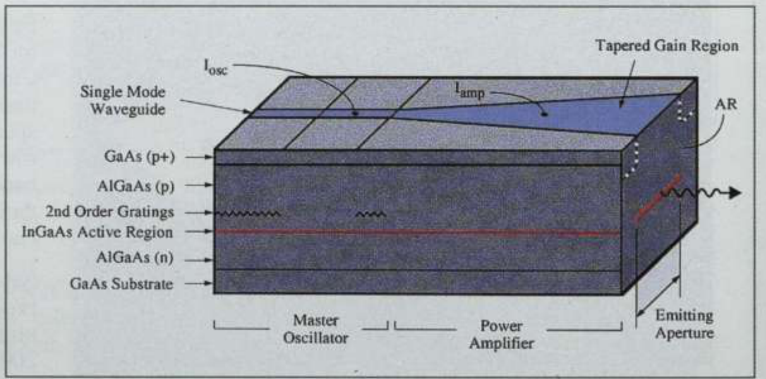
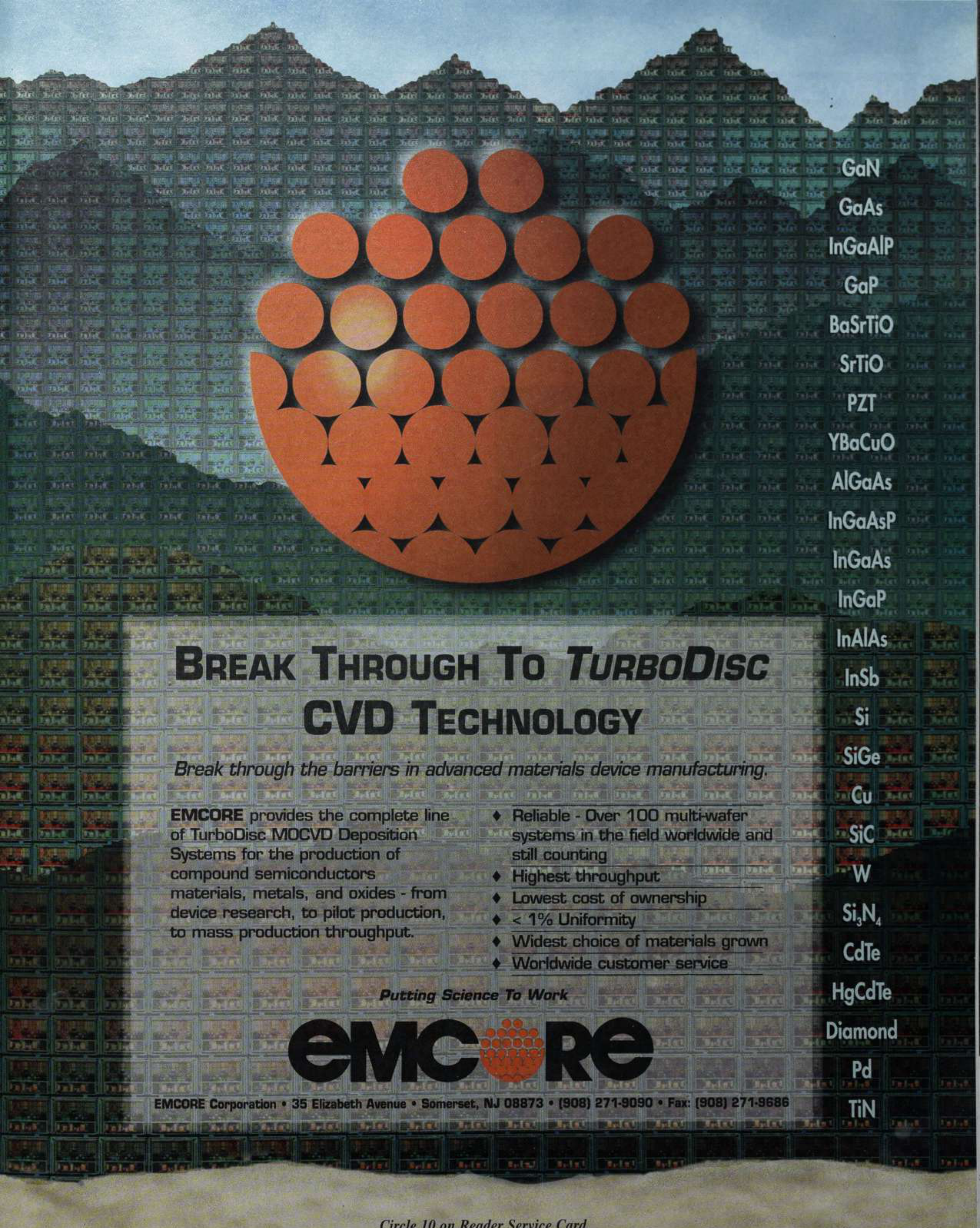
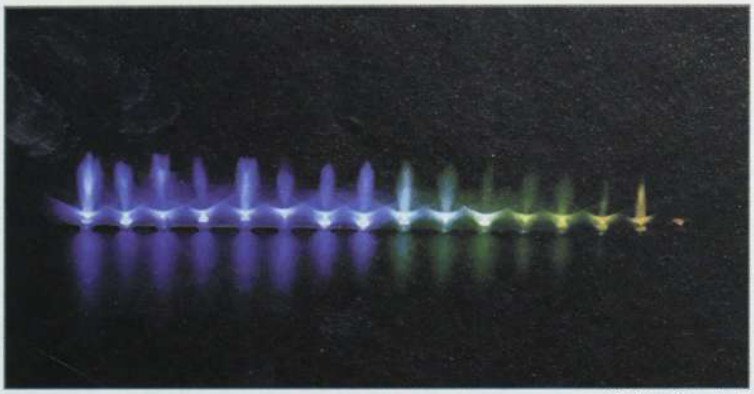


Figure 1. Chip Schematic for the 985 nm, 1 W cw power MOPA.



Nitride News from Japan

Nitride LEDs from Nichia



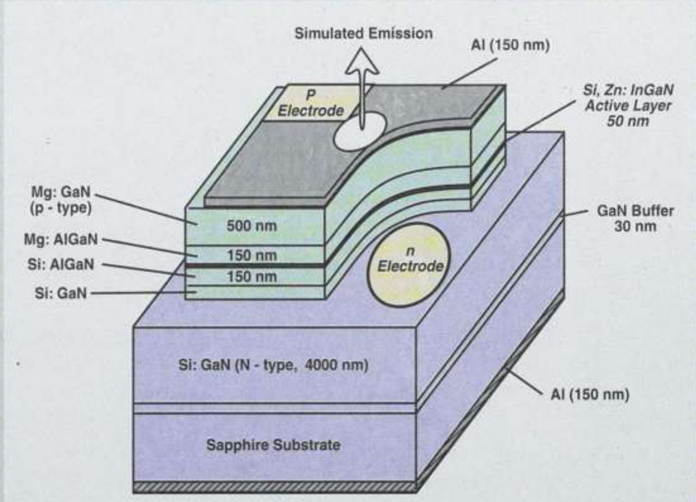
Nichia Chemical

Shown above is the range of LEDs that Nichia Chemical Industries have successfully fabricated from the GaN material system. At the far left is a violet LED with a peak wavelength of 400 nm; at the far right is an orange LED with a peak wavelength of 600 nm. According to Nichia's Shuji Nakamura, all of these LEDs were fabricated from GaN with single quantum well (SQW) InGaN active layers. The indium mole fraction is varied between 0.2 and 0.7 to change the peak wavelength from the blue region toward the yellow region. A noticeable decrease in intensity occurs at the longer wavelengths, likely due to decreasing crystal quality in the InGaN, caused by lattice mismatch and the difference in thermal expansion coefficients between the well and the barrier layers.

Nichia's first blue and blue-green LEDs were fabricated from InGaN/AlGaN double-heterostructure (DH) layers. Although they provided high-power light output (> 1 cd), they had a broad emission spectrum (FWHM = 70 nm) with the light output ranging from the violet to the yellow-orange spectral region, making the output appear "whitish-blue" to the human eye. Greatly improved performance, in terms of both color purity and intensity, have been achieved using the SQW structures. For example, the FWHM for blue LEDs (450 nm) has been reduced to 20 nm, with brightness up to 2 cd; while green LEDs (520 nm) with FWHM = 30 nm and luminous intensity of 12 cd have also been reported. (See page 36). Popular applications for these devices, such as full color displays, are well known; but, according to Nakamura, it is also time to begin thinking about combining blue and green InGaN LEDs with red AlGaAs LEDs for the production of white LED lamps for use in place of incandescent light bulbs or fluorescent lamps. Nakamura also reports that, at present, Nichia is not working on commercialization of the yellow LEDs, in favor of concentrating on the blue and green devices.

Stimulated Emission from a Current Injected InGaN/AlGaN Diode

An important milestone in the quest for nitride lasers has been reached. Takashi Egawa of the Nagoya Institute of Technology [Nagoya, Japan] will present a late news paper at the International Electron Device Meeting (IEDM) that announces the first observation of stimulated emission from a current injected InGaN/AlGaN double-heterostructure diode. A schematic of the MOCVD-grown structure is shown below. An optical multi-channel analyzer was used to observe the surface emitting spectra under pulsed conditions (0.4 μsec, 2 kHz) at 300 K, for injected currents up to 1000 mA. Below 300 mA, a broad emission was observed at 440 nm together with a weak emission at 380 nm. However, above 400 mA, the emission at 380 nm became strong and sharp, while that at 440 nm did not appreciably change. The emission at 380 nm originates from band-to-band emission in the InGaN layer, while that at 440 nm is attributed to impurity related emission in the InGaN layer. The intensity of the 380 nm emission increased rapidly at an injection current of 400 mA, and at higher currents exhibited a superlinear dependence on the injected current. Furthermore, the stimulated emission at 380 nm was clearly observed above the 400 mA threshold injection current.



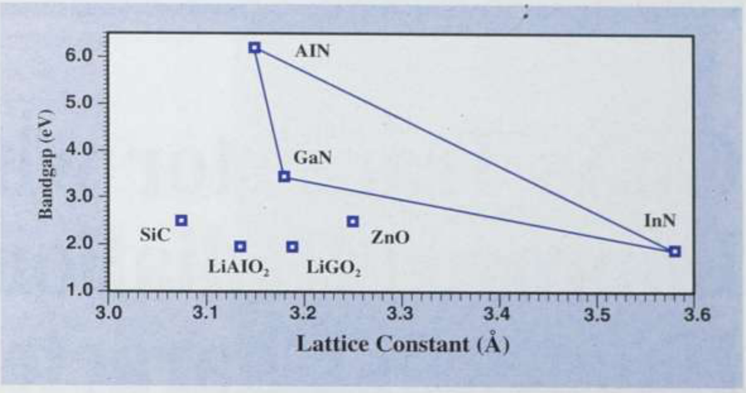
Nagoya Inst. of Tech. & IEDM

Panasonic and Toyoda Gosei Team Up to Offer Blue LEDs

Panasonic and Toyada Gosei have announced that they are teaming up to offer high brightness blue LEDs. Toyoda Gosei, which is backed by auto giant Toyota, has been developing blue light emitters in collaboration with Professor Isamu Akasaki of Meijo University (see *CS* 1(1), p. 38). The new LEDs, which provide 2000 mcd output of 450 nm light at 3.6V, are fabricated from GaN grown on sapphire substrates and will be available in quantities of 1 million units/month from November, 1995. The devices are capable of withstanding high temperatures and high humidity conditions, making them suitable for use in outdoor displays. Under the new arrangement, Toyoda Gosei will make the LED chips and Panasonic will take responsibility for packaging.

Looking for Blue Light Substrates

ARPA funds its third blue light consortium and research into GaN, ZnO, and lithinate substrates.



Bruce Chai - University of Central Florida

Bandgap vs lattice constant of nitrides and substrates being evaluated for nitride epitaxial growth.

SDL Inc.[San Jose, CA], Hewlett Packard Company [Palo Alto, CA] and Xerox Corporation [Stamford, CT], form the principal industrial elements of a new ARPA-sponsored consortium whose goal is to develop blue LEDs and lasers through the use of nitride-based alloys. Also participating are American Crystal Technologies (AXT) [Dublin, CA], Advanced Technology Materials Inc. (ATMI) [Danbury, CT], Boston University, and the University of Texas at Austin. $4 million was awarded to the consortium for a two year period, with additional matching funds being provided by the members.

Joe Major of SDL, the program manager of the consortium, characterizes the three principal industrial participants as being in the advantageous relationship in which none of the three are traditionally competitors, and this thereby allows for full cooperation in the pursuit of blue emitters. "SDL is in the market of manufacturing high power semiconductor lasers," says Major, "while Hewlett Packard is a world leader in the manufacturing of LEDs. The manufacturing of both lasers and LEDs then couples nicely into Xerox, which produces a wide range of system and document processing products which are suitable for the insertion of blue LEDs and lasers. In addition, Xerox brings a wide range of materials characterization to the consortium, including optical, electrical and TEM analysis." He views the participation of Boston University and the University of Texas at Austin, as being very important, in that the universities will attempt to explore more high risk/high payoff avenues of research. At the end of the contract period (June, 1997), Major says that two major goals should be accomplished: "to bring blue LEDs close to production, as well as having demonstrated a functioning blue laser diode." He believes that even though blue eight emitters have already been demonstrated there is much work still to be done, because manufacturing and production have their own requirements beyond the material science and device physics which must be understood in order to demonstrate a LED.

GaN Substrates

One of the consortium's goals is the improvement of GaN material quality through the reduction of defects The majority of nitride work is currently being done on sapphire ($\propto$-Al_2O_3), which has a 14% lattice mismatch to GaN. As a result, defects commonly range from 10^7-10^{10} cm^{-2}. Since the best substrate for GaN epitaxial growth would be one with perfect lattice matching, AXT and ATMI have been brought into the consortium to investigate methods of producing GaN substrates. AXT is working with the Polish Academy of Sciences in evaluating the growth of GaN crystals under high temperature (1800°C) and high pressure (20,000 atmospheres) conditions, such high pressure being required to keep nitrogen within the growing GaN. Researchers at the Polish Academy have produced 100 µm thick single crystal platelets which are approaching 1 cm in diameter, and are exhibiting defects of less than 10^5 cm^{-2} - a significant improvement over epitaxial GaN. These substrates will soon be available to members of the consortium for homoepitaxial growth experiments. ATMI is also evaluating methods of producing GaN substrates, either through bulk growth efforts, or through epitaxial methods that may be based on their GaN/SiC heteroepitaxial growth experience. ATMI recently entered into the commercial market for SiC substrates, and it plans to offer GaN on SiC later this year.

Other Materials

ARPA is also sponsoring other efforts in the pursuit of suitable substrates for GaN growth. Eagle-Picher [Miami, OK] has been awarded a $1.2 million, two year program for the growth of ZnO substrates (mismatch to GaN of 2.2%) using Eagle-Picher's seeded physical vapor transport (SPVT) technology that was developed to produce ZnSe substrates for the growth of II-VI-based blue emitters. Bill Harsch of Eagle-Picher comments that "although we have been very involved in producing substrates for II-VI blue emitters, we are not immune to what is occurring in the nitride area, and this is why we are involved in the growth of ZnO". Evaluation of GaN growth on these ZnO substrates will be performed by J.J. Song and R. Hauenstein of Oklahoma State University [Stillwater, OK]. It is the intent of Eagle-Picher to have these substrates commercially available by the end of the contract.

Another ARPA sponsored effort is being performed by Bruce Chai at the University of Central Florida [Orlando, FL], on the growth of $LiGaO_2$ (mismatch to GaN of 0.2%) and $LiAlO_2$ (mismatch to GaN of 1.4%). These materials can be grown by conventional Czochralski melt pulling techniques. See above for lattice constants and bandgaps of these various substrates. Boules of 1.5 inch in diameter and 6 inches long are being grown at a rate of 2 mm/hr. These substrates are currently under evaluation for GaN growth, both by MOCVD and MBE, at MIT Lincoln Laboratories, University of Illinois, Northwestern University, Hughes Research Laboratories, University of Florida at Gainesville and at North Carolina State University. Jan Schetzina and coworkers at NCSU have reported GaN grown on $LiGaO_2$ that exhibited a X-ray FWHM of 103 arc-sec, while a AlGaN/GaN MQW grown on $LiGaO_2$ exhibited emission at 3.460 eV, with a FWHM of 107 meV.

Like many others at American universities, Bruce Chai has set up a small company on the side to try to commercialize his developments. $LiGaO_2$ and $LiAlO_2$ are commercially available through Crystal Photonics [Oviedo, FL] in 1.5 inch diameters for $300/wafer.

GaAs Transistor with Improved Radiation Hardened Characteristics

NRL demonstrates new techniques which could make GaAs more competitive in space-borne applications.

Recent developments from the US Naval Research Laboratories (NRL, Washington, DC) may create new opportunities for GaAs ICs in satellites and other applications which require radiation hardened devices. With the end of the Cold War the market for radiation hardened electronic devices has dropped, and in the last decade the number of radiation hardened IC manufacturers has shrunk from 40-50 to just a handful - including Harris Semiconductor, Honeywell, Loral and GEC Plessey Semiconductor, and others. However, radiation hardened electronics is still a $500 million a year industry. According to Lucien Debacker (San Diego, CA), a consultant specializing in radiation hardened electronics, the market is divided into four areas: satellites (commercial and military); upgrading nuclear missiles; medical applications; and nuclear power reactors. The satellite segment is the key: it accounts for 80% of the total radiation hardened IC market.

Todd Weatherford at the Naval Research Laboratory (Washington DC) describes the radiation environment that satellites are exposed to "as experiencing a dose of 10^3 rad/year. As a comparison, in the vicinity of a nuclear explosion the dose might be on the order of 10^9 rad/sec, while on the surface of the earth where the atmosphere protects us, the dose is basically nothing." It is well known that GaAs exhibits a superb tolerance to a total ionizing dose of radiation. However, the use of GaAs ICs in satellite applications is restricted by their poor tolerance to single event upsets (SEUs) caused by high energy ion strikes. SEUs are usually temporary malfunctions which do not destroy the device, but they are a major challenge for system designers. For example: a typical SEU occurs when the charge produced by the ion strike collects at a sensitive node of a circuit, such as the drain of a transistor. If that charge is big enough, it can change the state of the transistor, meaning that a transistor which had been turned off can suddenly appear to be on. The potential implications for a sensitive application - say, a telemetry system for a multimillion dollar communications satellite - are enormous.

Standard methods for SEU hardening involve redundancy at both the system and circuit level, or the use of software-level error detection and correction schemes. These approaches suffer from reduced speed, increased design complexity, decreased circuit density and increased power consumption. For example, triple redundancy in circuits is not uncommon. A satellite might be equipped with three identical circuits to do one job. The SEUs are weeded out by having the three circuits "vote". If two read "off" and one reads "on", it is assumed that the "on" circuit has suffered a SEU, and it is "overruled" by the other two.

Rad Hard LT GaAs

While software solutions and redundant designs are working for now, the best solution to the SEU problem would be to develop materials which are insensitive to the ion strikes themselves. According to Weatherford, two mechanisms have been proposed to explain why ion strikes in the channel of a device produce an excess charge: a channel-modulation effect in which excess holes beneath the active regions of the device backgate the channel; and a parasitic bipolar transistor mechanism in which electrons are injected from the source implant into the substrate and collect at the drain.

Weatherford and coworkers have found that GaAs ICs can be hardened to ion strikes by using Low Temperature (LT) GaAs in the buffer region beneath the active device. When GaAs is grown by MBE in the temperature range of 200-250°C, arsenic precipitates form in the epitaxial layers, producing altered characteristics. LT GaAs exhibits very short carrier lifetimes (on the order of 200-1000 fs) meaning that electron-hole pairs generated by an ion strike should quickly recombine. Figure 1 shows a schematic diagram of a 0.8 µm gate length enhancement mode n-channel GaAs MESFET, with gate-drain and source-gate spacing of 1.0 µm, in which a 6 MeV ∝ parti-

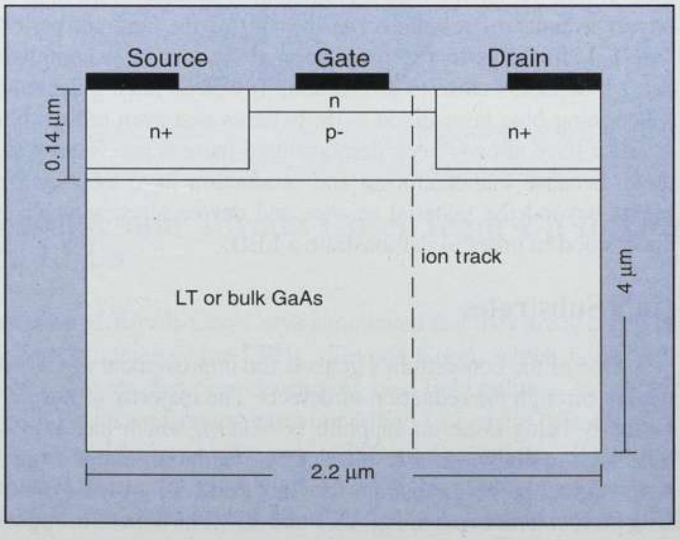


Figure 1. Schematic diagram of a 0.8 µm gate length enhancement-mode n-channel GaAs MESFET with gate-drain and source-gate spacings of 1 µm. A particle track due to a 6 MeV ∝ strike is shown between the gate and drain.

cle strike takes place in the channel region near the drain. Two versions of the MESFET were fabricated - one with a LT buffer layer, and one on a conventional GaAs substrate. Figure 2 shows an electron density contour plot for both versions 8 ps after the ion strike. In the case of the MESFET using the LT Buffer, the electron density in the vicinity of the ion track has been reduced by two orders of magnitude below that of the conventional device. Weatherford says that "these results suggest that LT GaAs circuits will be insensitive to proton-induced SEU, which has been a significant problem for GaAs ICs located in the Van-Allen radiation belts."

According to Jerry Witt of AFOSR, "the results produced by Weatherford and co-workers, if reduced to practice with performance comparable to their calculations, should put GaAs circuits in a very competitive position for insertion into space-borne and other military (and civilian) systems."

In fact, reduction to practice is already occurring. Paul Marshall and coworkers of the Naval Research Laboratories, in collaboration with Honeywell Systems and Research Center (Bloomington, MN) presented results at the IEEE Nuclear and Space Radiation Effects Conference in Madison WI (17-21 July 1995), on heavy ion SEU immunity of a GaAs Complementary Heterostructure Insulated Gate FET (HIGFET) 336 stage serial shift register fabricated on a LT GaAs buffer. Each stage of the shift register consists of a D-flip flop, in which the input to the device was held constant at either a low or high state while the device was under radiation exposure, and the output monitored for any change in state which would occur during a SEU. The shift registers and D-flip flops were fabricated with and without the LT GaAs buffer and tested at the Brookhaven National Laboratory Heavy Ion Van De Graff Test Facility (test ions ranged in energy from 98-280 MeV). Bit error cross sections for 100 Mbps serial data rates of as high as 10^{-6} cm^2/bit occurred for the MESFET with a conventional GaAs substrate. A fluence of 10^7 particles/cm^2 was used in all test cases, unless good SEU statistics with >100 upsets were obtained at lower fluence. However, for the case of the MESFET with the LT buffer, not a single upset could be observed for exposures ranging from 2.5 to 90.7 MeV-cm^2/mg.

This experiment provides clear evidence that the LT GaAs modeling of Weatherford is correct, and that the reduced carrier lifetimes in LT GaAs buffers have a dramatic impact on reducing SEUs in GaAs-based ICs. When this SEU immunity is combined with GaAs-based ICs inherent total ionizing dose immunity, it makes LT GaAs-based ICs a prime candidate for use in the $400 million radiation-hardened satellite IC market.

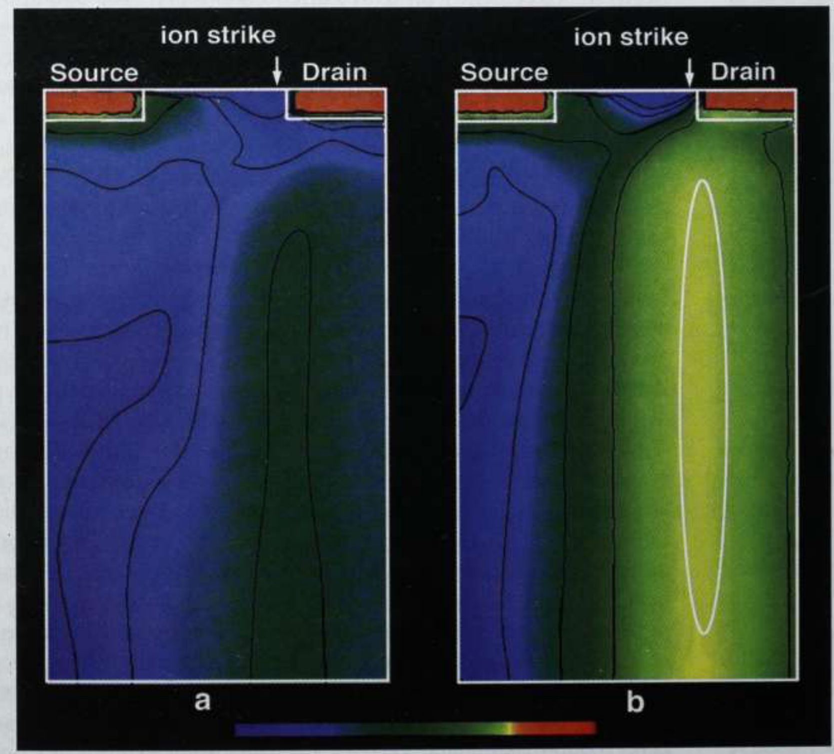


Figure 2. Electron density contour plots of the MESFET described in Figure 1 utilizing either a LT GaAs buffer (a) or a conventional GaAs substrate (b), 8 ps after a 6 MeV ion strike.

Also in the issue:

Oak Industries Buys Lasertron

Oak Industries [Waltham, MA] has acquired semiconductor laser manufacturer Lasertron, Inc. [Burlington, MA] in a stock purchase deal with approx. $110 million. Oak is the parent company of a number of operating units which manufacture components for the cable television (CATV) and telecommunications industries and controls for the appliance, avionics, and test & measurement industries. Oak's pre-acquisition annual sales were $249 million. Lasertron recorded revenues of $30 million for its fiscal year ending January 31, 1995, which represented an increase of 39% over the previous fiscal year. Lasertron employs 220 people at its Burlington facility. It also has a 50% interest in the Wuhan Telecommunication Devices Company (WTO), a manufacturing joint venture with the Ministry of Posts and Telecommunications of the People's Republic of China. WTO is intended to position Lasertron to participate in the growth of the Chinese telecommunications market as equipment manufacturers begin to source fiber optic components locally in order to meet "domestic content" requirements.

Lasertron was founded in 1980 by J. Jim Hsieh and Kenneth Nill, researchers at MIT Lincoln Laboratory, to capitalize upon the fundamental quaternary laser patent held by MIT. By 1992 they were the world's largest independent manufacturer of 1300 and 1550 nm lasers and detectors for fiber optic communications. That same year Hsieh was awarded the David Sarnoff Award "for the invention and commercialization of the GaInAsP semiconductor laser for fiber optic communications."

Today Lasertron's hottest product is a single quantum well InGaAs/AlGaAs 980 nm pump laser which they manufacture under a licensing agreement with IBM Zurich Laboratory. The 980 nm laser is used in erbium doped fiber amplifiers (EDFAs) for boosting light signals at the 1550 nm wavelength over land-based long distance fiber spans. The 980 is often preferred over the mature 1480 nm technology because of its higher slope efficiency ("more bang for the mA", according to Lasertron's sales literature), superior noise characteristics, and higher small signal gain. Lasertron was the first company to commercialize 980 nm pump lasers, and today they claim the largest market share and largest installed base.

According to William S. Antle III, President and CEO of Oak Industries, "the Lasertron acquisition fits our strategy to grow our business by acquiring leading suppliers of critical components to high growth communications markets". The 980 technology is not the only Lasertron asset of interest to Oak. Antle also cites Lasertron's pursuit of growth opportunities for fiber optic components in the CATV and wireless communications markets: "Optical amplification technology is gaining increasing acceptance in CATV hybrid-coaxial networks for head-end consolidation and long distance trunk lines. The market for Lasertron's products will continue to grow as these networks are upgraded to provide interactive capabilities. Fiber optic links are also expected to be deployed in cellular and PCS applications and to extend microcell coverage in areas with poor reception and in dense urban areas with high capacity requirements. As a leading supplier to the CATV and wireless communications markets through our other subsidiaries, Oak should facilitate Lasertron's penetration of these markets." Antle also characterizes Lasertron's joint venture in China as a "significant growth opportunity", given that the Ministry of Posts and Telecommunications is expected to invest heavily to expand China's telephone network.

M/A-COM Acquires Cray's GaAs Facility to Meet Increasing Demand for GaAs ICs

M/A-COM [Lowell, MA] has purchased the GaAs foundry assets of Cray Computer in Colorado Springs, CO. According to Richard Clark, M/A-COM CEO and president, the purchase "will allow M/A-COM to provide the world's first dual sourcing for GaAs ICs, supporting our customers' needs for increased volumes and reduced risk of supply interruption."

Cray Computer filed for bankruptcy protection in March of this year, leaving behind a 40,000 square-foot GaAs facility which had been starting 100 four inch wafers per week and running both a 10 mask level D-mode MESFET process as well as a 16 mask level E/D MESFET process. More than 100 different GaAs digital circuits were being fabricated at the time of bankruptcy, all for use in the Cray-4 supercomputer. Former Cray Computer employees will continue to work in the facility, under the direction of Bryant Welch, who was Cray's Vice President in charge of Circuit Production. M/A-COM plans to lease the building which houses the foundry. The purchase price was not disclosed.

The spiraling demand for RF GaAs ICs motivated M/A-COM to make the purchase. According to Rick Hess, General Manager of M/A-COM's IC Business Unit, "our Massachusetts GaAs facility is presently producing more than 1 million GaAs ICs per month, with projections to go to 2 million within the next few months. In addition, we are currently converting from three inch to four inch GaAs substrates. But despite the increase in production and wafer size, M/A-COM has been experiencing such a significant increase in demand for GaAs ICs, especially for wireless applications at 900 MHz, that the Colorado facility is needed to further increase our production capabilities." M/A-COM's RF IC process has been transferred to the Colorado facility, where initial production runs of RF switches and attenuators will begin in mid-October, with 50 wafer starts/week. As for the future, Hess believes that "as the degree of integration of our MMICs increases, we will see some mixed function MMICs produced in Colorado, in which digital logic functions will be integrated into some of the RF MMICs. However, we have no plans to fabricate the type of digital-only ICs that Cray had been producing." Hess believes that M/A-COM will continue to see strong growth in GaAs-based MMICs in the areas "where we are not fighting silicon", which includes switches and attenuators, power amplifiers where high power added efficiencies are required, LNAs where low noise figures are important, and wireless chip sets operating at 2.4 GHz.

Single Standard for High Density CD-ROM

The major manufacturers of CD players have "agreed to agree" upon a single standard for the next generation of CD technology. Two different proposed standards were floated by rival camps a little over a year ago, conjuring up images of the Betamax/VHS conflict in VCR technology. However, insiders say that neither side would have gone forward with its own standard without the backing of the entire industry.

The new standard, which is the first change in this area since 1982, is intended to be the intermediary step on the way to the "blue laser format". Several details have not yet been worked out. Among them, apparently, is a name for the new technology: some refer to it has "high density CD-ROM", while others call it Digital Video Disk (DVD) or Super Density Compact Disk (SD-CD). It is known that it will require a red semiconductor laser, but the exact wavelength has not been determined. The power requirements will, at first, be similar to the 3-5 mW 780 nm lasers currently in use. However, the addition of read-write capability in 2-3 years is being discussed, which may mean that higher power lasers will be required at that time.

The new standard will allow a dramatic increase data storage capability. Today's CDs hold up to 680 MB of data, whereas the new standard will accommodate up to 18 GB. The new CDs can be either single or double sided, and each side can hold one or two data layers. A single sided, one layer CD will store 4.7 GB of data. That's enough to hold a full length movie, and it is also sufficient to meet virtually all current CD-ROM applications. In cases where more bytes are needed, a second data layer can be added to raise capacity to 9.6 GB. For even larger applications one or two data layers can be added to the other side of the CD. (In this case the user will flip the disk over to access the other side, just as in some antiquated data storage methods, such as LPs. A proposal to add a second semiconductor laser to read the second side was apparently rejected.)

According to Rob van Eijk, Director of CD-Recordable Products for Philips, the tremendous gains in data storage capability are made possible by a number of features. One is, of course, the use of the shorter wavelength laser. Equally important at this stage are engineering advances that allow the use of a smaller track pitch and enhanced format efficiency, which requires less disk space for system overhead. The two-layer CDs will be manufactured using a semireflective material to back the first data layer and aluminum to back the second layer. The two layers will be separated by just 40 μm, which is well within the capability of the focal mechanisms which are currently in use.

The new high density CD players will be backward compatible with existing CDs. No estimates of the potential market penetration are currently available. The current market for CD players - both audio and CD-ROM - is in excess of 100 million units per year. Participants in the new agreement include Philips, Sony, 3M, Thomson, Toshiba, Matsushita, Hitachi, Pioneer, and JVC. The new systems should be available within a year.

Space Shuttle Experiment Yields Four Epi Samples

The most recent flight of the space shuttle Endeavor, concluded in mid-September, included the second flight of the Wake Shield Facility (WSF), an "MBE in space" experiment designed by the Space Vacuum Epitaxy Center of the University of Houston. (See *CS* 1(2), p. 8). The WSF successfully met its first mission objective by flying free and establishing its own orbit ≈40 miles away from the shuttle. Four GaAs/AlGaAs epi samples were then grown over the next three days: a silicon-doped calibration layer; a 2 μm thick AlGaAs layer on a GaAs buffer; a modulation doped heterostructure; and a HEMT. An aluminum oxide layer was also grown to investigate the utilization of the atomic oxygen which is found in low earth orbit. The samples were retrieved from the shuttle upon its return to earth and distributed to several sites for analysis and characterization.

The experiments were beset by mechanical problems, all of which will sound familiar to operators of terrestrial MBE systems. The first growth was delayed and eventually cut short because it took longer than planned to get the WSF set up and working properly. A power supply problem curtailed the second growth. The third growth was executed exactly as planned, but then a temperature sensor detected an overload and tripped the loadlocks, causing the entire system to power down. Problems with arsenic flux instabilities and sticky aluminum shutters were also reported.

The WSF was also equipped with vacuum gauges and a mass spectrometer for analysis of the environment created in the orbiter's wake. The total pressure gauges bottomed out as the pressure fell below 10^{-11} Torr. The mass spectrometer readings will require post-flight analysis, but the preliminary data indicates wake pressures at, or below, 10^{-12} Torr. The background pressures during growth are believed to have been "at least as low as 10^{-11} Torr".

A third flight for the WSF is scheduled for November, 1996.

TRW Wins $22 Million MAFET Award

TRW has received a $22 million contract from ARPA's new MAFET (Microwave and Analog Front End Technology) Program. Under the terms of the contract, TRW will develop and demonstrate new ways to fabricate and package GaAs and InP MMICs. The contract also calls for TRW to develop new processes and procedures for automated assembly of millimeter wave multi-chip assemblies (MCAs).

According to George Bock, TRW's MAFET program manager, TRW's participation in this contract will "not only increase the variety of mature MMIC devices available to our customers, but also, and more importantly, it will demonstrate the new, automated chip packaging and assembly techniques required to create smaller, less expensive systems". Efforts will be focused on HBT and HEMT MMICs from both the GaAs and InP materials systems. Bock predicts that in the years to come InP will challenge GaAs as the material of choice for many applications. "Our current GaAs HBTs operate most efficiently from 2 to 20 GHz," he says. "We've already demonstrated InP HBTs in our laboratories that can operate as high as 50 GHz. These new HBTs give our customers more than twice the information-carrying capacity of GaAs HBTs, but consume only about one-fourth as much power." The smaller the power requirements, adds Bock, the more attractive these devices become for applications such as wireless communications systems.

The 36-month, cost-plus-fixed fee contract will be managed by the U.S. Army Research Laboratory, Fort Monmouth, NJ.

Akasaki, Ralston Honored at 1995 ISCS

Prof. Isamu Akasaki of Meijo University and Dr. John Ralston of SDL, Inc. were honored at the 1995 International Symposium on Compound Semiconductors. Prof. Akasaki was awarded the Heinrich Walker Gold Medal for his pioneering and outstanding contributions in the field of III-V nitride compound semiconductor research. He has been working on the vapor phase epitaxial growth of nitrides for over twenty years. According to the award citation, "his persistent efforts led to a number of important breakthroughs...[which] have led to the commercial development of high performance blue LEDs and very low threshold UV stimulated emission, establishing III-V nitrides as promising material for the optoelectronics applications in the blue-UV spectral region." Since 1992 he has been a professor emeritus at Nagoya University, and he is currently a visiting professor in the Research Center for Interface Quantum Electronics at Hokkaido University.

The Young Scientist Award was presented to Dr. Ralston for his outstanding contributions in the field of high-speed high-power semiconductor laser. While at the Fraunhofer IAF in Freiburg, Germany, Dr. Ralston established, managed, and was intimately involved in the research program which lead to the demonstration of the first semiconductor lasers to achieve direct modulation bandwidths of 30 and 40 GHz. He is currently at the Research Department at SDL, Inc., where he is involved in the commercialization of semiconductor diode lasers for high-speed and high-power applications.

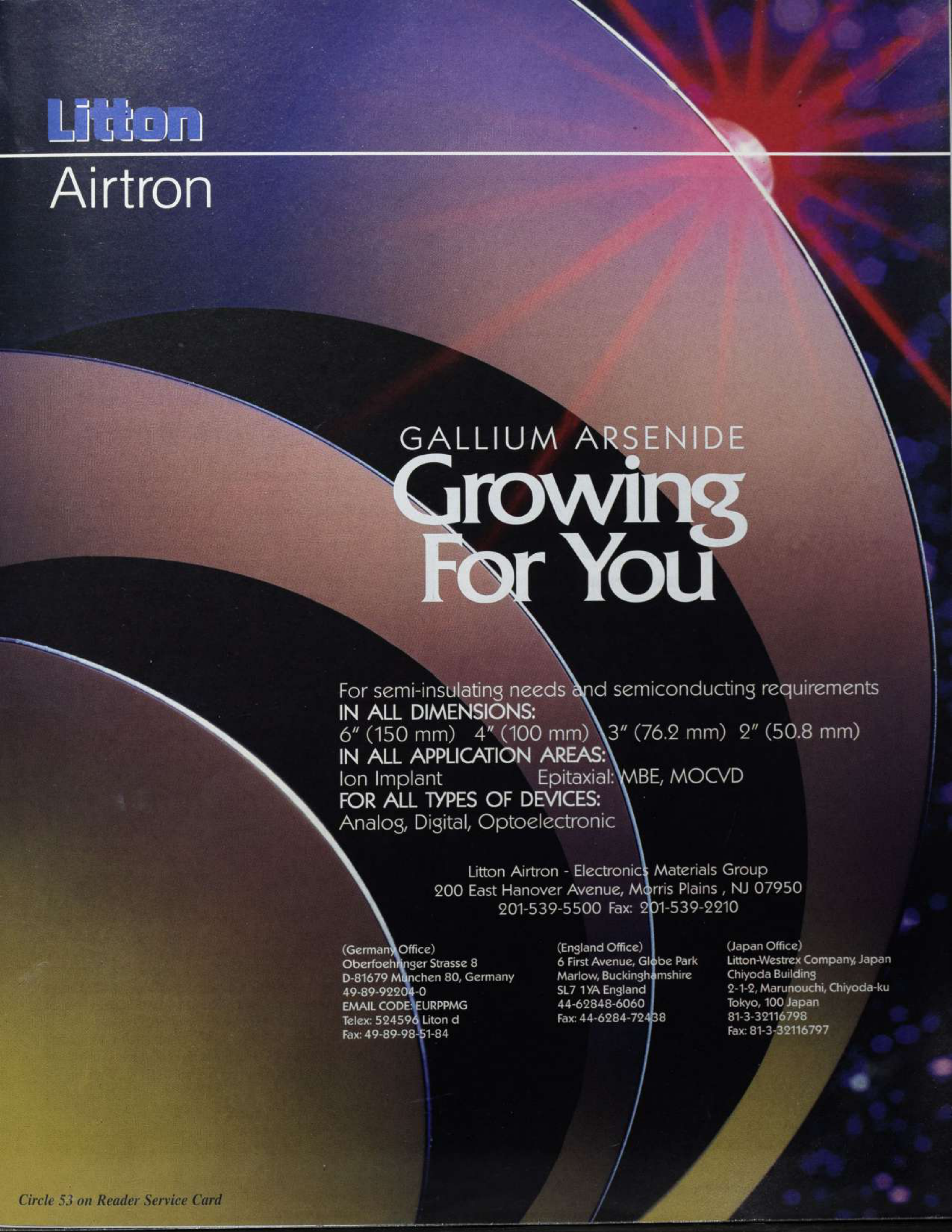
TI Seeking to Leverage GaAs into Commercial Market

Texas Instruments has announced that it will be pursuing the emerging market for microwave-band data transmission systems for local Multipoint Distribution Services (LMDS). LMDS systems provide two-way capability for digital wireless video, voice and data transmissions; applications include delivery of entertainment and high performance telephony to areas which lack a "hardwired" infrastructure. Within the U.S., LMDS is one of a number of possible solutions available to providers of integrated communications and interactive entertainment.

TI's fundamental GaAs technology is a 0.25 µm PHEMT process that was developed, in part, under the MIMIC program (see page 40). Like many other participants in that program, the company would like to leverage its GaAs capability into commercial applications. Until now TI's GaAs capability has been focused on military markets. According to Gary Lerude, TI's Manager of Microwave GaAs Products, "we are pursuing the LMDS networks because it will allow us to enter the commercial market at the system level". A prototype LMDS network operating at 28 GHz has already been demonstrated.

Harris Announces All-Silicon Chipset for 2.4 GHz

Harris Semiconductor [Melbourne, FL] has announced that it will release an all-silicon chipset for 2.4 GHz in early 1996. The set, which is targeted for direct-sequence spread-spectrum (DSSS) wireless local area network (WLAN) applications, will include a DSSS baseband processor with on-board A/D converters, a integrated IF/QMODEM, a 2.4 GHz RF/IF converter, and an RF power amplifier. The last two ICs are normally made from GaAs, but Harris claims that it can execute them using a "specialized version of our in-house UHF bonded-wafer bipolar CMOS technology". The chipset will operate down to 2.7 V, and complies with Type II-PCMCIA standards. OEM pricing is set at $51.26 in quantities of 10,000.



Litton

Airtron

GALLIUM ARSENIDE

Growing For You

For semi-insulating needs and semiconducting requirements

IN ALL DIMENSIONS:

6″ (150 mm) 4″ (100 mm) 3″ (76.2 mm) 2″ (50.8 mm)

IN ALL APPLICATION AREAS:

Ion Implant Epitaxial: MBE, MOCVD

FOR ALL TYPES OF DEVICES:

Analog, Digital, Optoelectronic

Litton Airtron - Electronics Materials Group
200 East Hanover Avenue, Morris Plains , NJ 07950
201-539-5500 Fax: 201-539-2210

(Germany Office)
Oberfoehringer Strasse 8
D-81679 München 80, Germany
49-89-92204-0
EMAIL CODE: EURPPMG
Telex: 524596 Liton d
Fax: 49-89-98-51-84

(England Office)
6 First Avenue, Globe Park
Marlow, Buckinghamshire
SL7 1YA England
44-62848-6060
Fax: 44-6284-72438

(Japan Office)
Litton-Westrex Company, Japan
Chiyoda Building
2-1-2, Marunouchi, Chiyoda-ku
Tokyo, 100 Japan
81-3-32116798
Fax: 81-3-32116797

Circle 53 on Reader Service Card

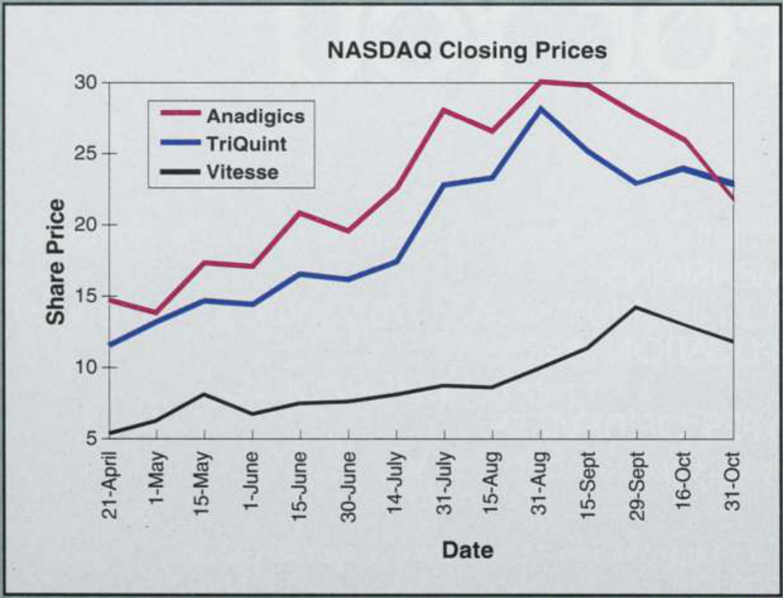
Financials

Good News for Shareholders of Independent GaAs IC Foundries

Financial reports for the period ending September 30, 1995 show that America's independent GaAs IC manufacturers - Anadigics, TriQuint and Vitesse - are enjoying a good year. All three posted substantial improvement in income for the quarter and the year-to-date, and their combined quarterly revenues of $38.4M were 56% higher than for the comparable period last year. See Table for their individual results.

In September, TriQuint completed a secondary public stock offering in which it sold two million shares and raised approximately $48 million. Vitesse and Anadigics have both recently been named to "recommended purchase" lists by investment analysts: Robertson Stephens & Co. [San Francisco] picked Vitesse; Goldman Sachs [New York] picked Anadigics. In the period from April 21, 1995 (the date of Anadigics' initial public offering) to October 20, 1995, the combined share price for the three companies has risen 95%. See Chart.

The CEOs of all three companies attribute their recent success to demand generated by wireless communications. Anadigics, TriQuint and Vitesse trade on the Nasdaq market under the symbols ANAD, TQNT, and VTSS



Share prices for America's three independent GaAs IC Manufacturers (since the date of Anadigics' IPO).

COMPANY	REVENUE				INCOME			
	3rdQ 95	3rdQ 94	1st 9 Mo 95	1st 9 Mo 94	3rdQ 95	3rdQ 94	1st 9 Mo 95	1st 9 Mo 94
Anadigics	13.6M	9.2M	37.0M	24.6M	2.3M	560K	4.6M	894K
TriQuint	12.7M	5.7M	33.3M	22.9M	1.4M	(7.5M)	2.6M	(8.5M)
	4thQ 95	4thQ 94	FY 95	FY 94	4thQ 95	4thQ 94	FY 95	FY 94
Vitesse	12.1M	9.7M	42.9M	35.6M	1.2M	174K	1.5M	(4.1M)

Summary of the financial reports for the quarter ended September 30 and the year-to-date from Anadigics, TriQuint and Vitesse. Data for the same periods last year is provided for comparison.

Alpha Industries Reports 2nd Q Results

MMIC manufacturer Alpha Industries [Woburn, MA] has announced its results for the second quarter ended October 1, 1995. Net sales increased 30% and totaled $23.7 compared with sales of $18.3 million for the same period last year. Net income for the quarter was $1.1 million, compared with $659,000 for the same period last year - an increase of 64%. Alpha's share price, which has been climbing steadily throughout the year, closed at 16.25 on October 20, up from 6.75 at the beginning of the year.

Cree Completes Private Offering

Cree Research [Durham, NC] has raised in excess of $19.8 million in a private placement of securities, with net proceeds of approximately $17.7 million. Cree issued 800,000 shares of common stock to investors in the offering. Neal Hunter, President of Cree, said "We are pleased with the investment community's reception to our offering. Cree's biggest current challenge is trying to produce sufficient quantities of products to fill orders. The capital raised in this offering will give us the financial resources we need to increase our production capacity." The proceeds of the offering will be used to purchase manufacturing equipment, expand facilities, and for working capital and general corporate purposes.

ATMI Secondary Offering, 3Q Results

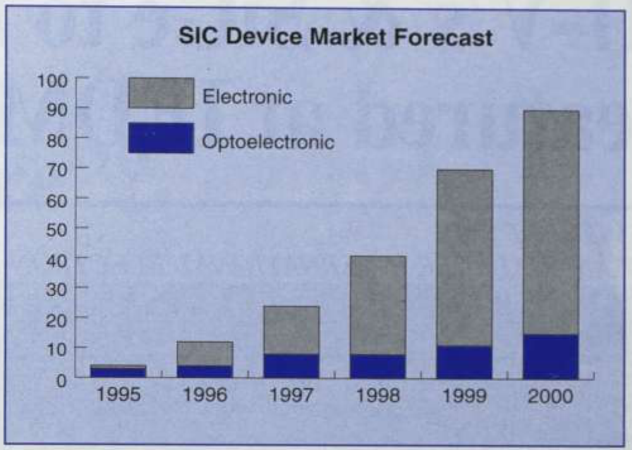
Advanced Technology Materials, Inc. (ATMI) [Danbury, CT] a manufacturer of SiC and diamond semiconductor materials, has announced results for the quarter ended Sept. 30, 1995. Revenues for the third quarter were $7,996,000, 49% greater than third quarter 1994 revenues of $5,361,000. Product revenues during this period improved 61%, to $5,785,000 from $3,587,000 in the same quarter in 1994. For the first nine months of 1995, revenues increased 45% to $21,247,000, compared with $14,676,000 for the first nine months of 1994. ATMI reported net income for the quarter of $201,000, compared with $3,427,000 in the year earlier period. The 1994 third quarter results included non-recurring income of $3,593,000.

In early October ATMI completed a secondary stock offering of 1,425,000 shares which yielded net proceeds to the company of $16,100,000. Anticipated uses of the proceeds include acquisitions, capital expenditures, R&D, working capital and general corporate purposes.

The Forecast for Silicon Carbide

A new study on silicon carbide technology status and market applications predicts an increasing number of optoelectronic and electronic devices entering the market over the next decade, with the value of these components rising to $200 million by 2005.

*ROBERT STEELE, STRATEGIES UNLIMITED,
MOUNTAIN VIEW, CALIFORNIA*



Strategies Unlimited 1995

The projected market for SiC devices (other than blue LEDs) from now until the year 2000.

Although SiC has been the subject of intensive research for the past two decades, the development of commercial components (with the exception of blue LEDs) has been slow to take place. However, recent technological progress has substantially increased the probability that SiC will achieve its potential in both electronic and optoelectronic components in the near future.

SiC has superior physical properties compared to other materials such as silicon, GaAs and InP. Compared with these materials, it has a higher bandgap, higher saturated electron drift velocity, higher breakdown electric field, lower dielectric constant and higher thermal conductivity. These properties give SiC a strong advantage for use in high-temperature, high-power and high-frequency electronics applications. In addition, its emission spectrum in the blue region of the spectrum allows it to be used as a blue light emitter.

In the past few years, significant technology advances have occurred in SiC crystal growth, epitaxial deposition, contact and interconnect formation, and packaging, which are the keys to unlocking the application of SiC components in commercial and military markets. The principal electronic applications which show promise for SiC components are those requiring high-temperature, high-power and high-frequency operation. Device types include RF and microwave power devices, rectifiers, power switches, MESFETs, MOSFETs and JFETs. The principal optoelectronic applications for SiC are low-intensity blue LEDs and substrates for gallium nitride (GaN)-based high-intensity blue LEDs and blue laser diodes.

Exciting new developments in SiC technology are being achieved across a broad spectrum of applications. High-frequency power devices are being developed at Motorola for microwave and RF applications. General Electric is developing power and high temperature devices including sensors for jet engines. Westinghouse has fabricated very high-frequency MESFETs that perform at up to 26 GHz. In Sweden, ABB is working on high-power, high-voltage SiC rectifiers and other low-frequency power devices for industrial and utility use. Cree Research is shipping millions of SiC blue LEDs to markets around the world, and has recently begun shipping high-intensity blue LEDs made from GaN epitaxial layers on SiC substrates.

New high-temperature SiC devices are being developed for aircraft and automotive engine sensors, jet engine ignition systems, transmitters for deep well drilling, and a number of industrial process measurement and control systems. High-power SiC devices offer promise in solid-state lamp ballasts, surge suppressers and power supplies. High-frequency power SiC devices are being developed for applications in high-frequency power supplies, cellular phone base stations, phased array radar systems, and small lightweight RF and microwave transmitters.

Small companies such as Cree Research and Advanced Technology Materials, Inc. (ATMI), as well as large companies such as Motorola, GE, Westinghouse and ABB, are at the leading edge of SiC technology development. Government support ranges across a wide variety of agencies, including ARPA, the U.S. Air Force Wright Laboratory, the Office of Naval Research, and NASA Lewis Research Center, among others.

While present sales of SiC devices are essentially limited to blue LEDs, enormous growth potential exists for SiC electronic components to meet requirements in the military/space, communications, automotive and aircraft sectors. Optoelectronics (primarily blue LEDs) and military/space applications are projected as the dominant market sectors for SiC devices over the next few years. By 2000, the military/space applications will rank first, followed by communications, optoelectronics, automotive and aircraft applications. The total SiC device market is forecast to increase from $4 million in 1995 to $90 million in 2000. These figures do not include the use of SiC as a substrate material for GaN LEDs and laser diodes.

Because of the long lead times necessary for qualification in automotive and aircraft applications, these two market sectors will not become significant until after 2000. Growth in these sectors, along with continuing growth in the other market sectors, will bring the total SiC device market to over $200 million in 2005.

Strategies Unlimited, a sixteen-year-old market research consultancy located in Mountain View, California, provides market research and strategic planning services for optoelectronics, compound semiconductors, wireless communications, and photovoltaic systems and components. If you would like to receive more information about their new report, *Silicon Carbide 1995: Technology Status and Applications Analysis*, ***Circle 9 on the Reader Service Card.***

III-V's & SiGe to be Featured at IEDM

PREVIEW OF THE
41ST ANNUAL IEEE INTERNATIONAL ELECTRON DEVICE MEETING
DECEMBER 9-13, 1995
WASHINGTON, DC

The International Electron Device Meeting (IEDM) is the premier device meeting of the year - a venue to present state of the art device results, where competition is so stiff to get a paper accepted, that 2/3 of the abstracts submitted this year were rejected. Even though this conference is dominated by silicon-based devices, of the conference's 38 sessions, five are specifically devoted to compound semiconductors, while the Bipolar session, which traditionally presents Si-BJT results, was this year almost exclusively filled with SiGe-based papers. Following are some of the highlights:

FETs

Wireless requirements continue to drive FET improvements, particularly in the area of power added efficiencies (PAEs) and low voltage operation, both of which have a direct impact on extending battery lifetimes. Tanaka et al of Matsushita will present details on GaAs power FET process improvements which enable high PAE (65%) operation at a drain bias of 1.5 V and a frequency of 900 MHz, while Inosako and coworkers of NEC will report on the 950 MHz operation of a double-doped AlGaAs/InGaAs/AlGaAs Hetero-junction FET, which for 1.2 V operation, delivers 1.1 W at a PAE of 63%. On the circuit front, Enoki et al of NTT will report on the first demonstration of the monolithic integration of high performance InAlAs/InGaAs 0.1 µm gate length MOCVD-grown HEMTs in which a 19 stage SCFL static frequency divider operates at 40 GHz - this being the highest toggle frequency every reported for a static frequency divider. Wada and coworkers of NEC will describe the first successful fabrication of a MOMBE-grown and all dry etched AlGaAs/GaAs 0.1 µm gate length HJFET, which exhibits an f_t of 121 GHz and an f_{max} of 144 GHz.

HBTs

As in the case of FETs, much of the HBT work which will be presented at the IEDM is driven by wireless requirements, where both low voltage operation, as well as high PAEs are required. In an invited paper by Yoshimasu of Sharp Corporation, the use of high power AlGaAs/GaAs HBTs for mobile communications systems in the 1-2 GHz regime will be examined for both nonlinear and linear applications, and the potential advantages of HBTs over MESFETs will be detailed. Ohara and coworkers of Fujitsu will examine the performance of MOCVD-grown InGaP/GaAs power HBTs in the 1-2 GHz regime, where an output power of 31 dBm (1.2 W) is obtained at a low bias of 2.4 V. At a collector bias of 3.5 V, this Fujitsu HBT delivers 33.8 dBm (2.4 W) at a PAE of 60.9%. Nguyen et al of the Hughes Research Laboratories will describe a novel AlInAs/GaInAs HBT which uses a chirped superlattice at the collector-base, where this transistor exhibits record power levels at 9 GHz with 14 V collector bias, enabling power cells with 720 μm^2 emitter areas to deliver a peak output power of 2.62 W, corresponding to a power density of 7.2 W/mm and 57% PAE. Zampardi and coworkers of Rockwell will demonstrate a family of MOCVD AlGaAs/GaAs HBT-based circuits, including 40 Gb/s 4:1 multiplexers, 0-26 GHz limiting amplifiers (AGCs), and transimpedance amplifiers with 3 dB bandwidths in excess of 20 GHz. For high speed operation, Yanaghira et al of Matsushita will describe a AlGaAs/GaAs MOCVD grown HBT using a 70 nm carbon-doped base ($4x10^{19}$ cm^{-3}), and extremely low contact resistance ($2x10^{-7}$ ohm-cm^2) Ni/Ti/Pt/Ti/Pt base contacts, to obtain an f_t of 83 GHz and a world record f_{max} of 253 GHz, with the device exhibiting a dc current gain of 20.4 at V_{CE} of 1.7 V.

SiGe HBTs will also be well represented. Meister et al from Siemens will report on a SiGe HBT with a 74 GHz f_{max}, resulting in a record CML gate delay of 11ps. Schuppen and coworkers at Daimler-Benz will report a record f_{max} of 160 GHz, for a SiGe HBT operating at a V_{CE} of 8V, surpassing their previous record value of 120 GHz. Terpstra et al of Philips Research Laboratories, using SiGe HBTs, will demonstrate a record ECL gate delay of 14 ps and bandwidth of 13.2 GHz, for a DC-coupled wideband amplifier circuit, where these characteristics make this SiGe HBT suitable for 20 Gbit/s optical communication systems.

Quantum and Novel Devices

Novel techniques and devices will also be presented at the IEDM. Passlack and coworkers of AT&T Bell Labs will report on in-situ deposition of Ga_2O_3 in an MBE system by E-beam evaporation of a single crystal $Gd_3Ga_5O_{12}$ source onto GaAs, resulting in an extremely low midgap interface state density as determined by C-V measurements and QW PL measurements to be in the 10^{10} $eV^{-1}cm^{-2}$ range, making the GaAs-Ga_2O_3 interface suitable for fabrication of inversion/accumulation type devices. A semi-metallic quantum well FET, formed using two adjacent quantum wells of GaSb and InAs, will be described by Yang and coworkers of the Naval Research Laboratory. Both a 2 D electron gas and 2D hole gas were observed to coexist. With a single gate, the carrier concentration of this device can be continuously tuned from $2.2x10^{12}$ electrons/cm^{-2} to $1.3x10^{12}$ holes/cm^{-2}, as the gate voltage is varied from +8V to -8V. And, lastly, Horiguchi et al of Fujitsu will present details on the electron transport properties of InAs self-assembled quantum dots embedded in the GaAs channel of a HEMT structure. By examining the V_G-I_D characteristics of the HEMT at 0.4 K, current peaks are observed, which are attributed to electron transport via channels which consist of three or four sequential InAs self-assembled dots under the gate. This is the first observation of coulomb-blockade-like electron transport observed in InAs self-assembled quantum dot HEMTs.

For information regarding the 1995 IEDM contact:
Melissa Widerkehr
101 Lakeforest Boulevard
Gaithersburg, MD 20877 USA
Tel: (301) 527-0900
Fax: (301) 527-0994

Is Silicon Germanium the New "Material of the Future"?

R&D groups are fabricating some very impressive HBTs from SiGe. However, eight years after the first reports in this field, there is not a single SiGe device in production. Is this about to change?

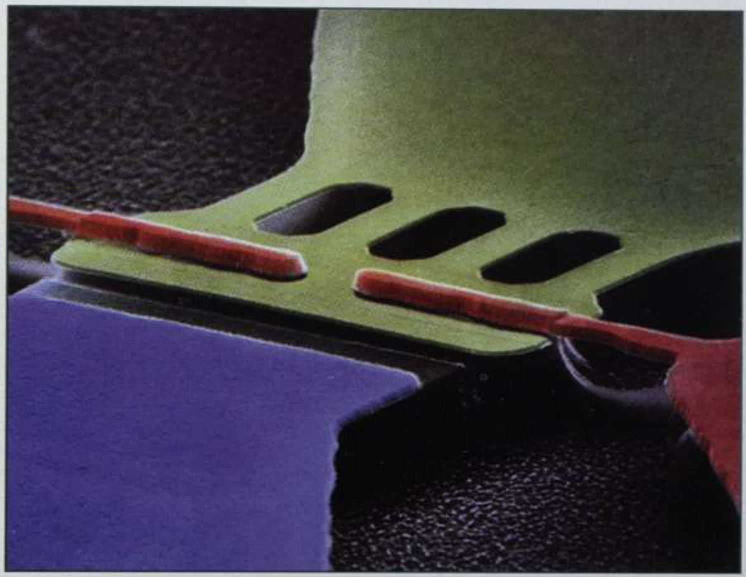
ROBERT A. METZGER

Since the first report of SiGe HBTs in 1987 there have been numerous demonstrations of its impressive potential: for example, f_t and f_{max} values in excess of 100 GHz. SiGe has often been touted as the natural compliment to silicon for high frequency applications, and many believe that it can combine the "low cost" nature of silicon with the "high performance" nature of heterostructures, thereby eliminating the need for GaAs. The symbolic embodiment of this line of thinking was IBM's decision to disband its GaAs program in favor of SiGe. Other large companies, most notably Daimler-Benz and NEC, have also established SiGe development programs. Their results demonstrate quite clearly that SiGe can out perform conventional Si. However, as many in the GaAs digital community have learned, performance alone does not guarantee marketplace success.

As of this writing there are no SiGe devices or circuits on the commercial market, and it may be another 1-2 years before they emerge. What direction will these initial SiGe offerings take, and what type of competition will they find from both Si and GaAs? We've all heard it said at least a hundred times: "GaAs is the material of the future - and it always will be!" But GaAs is, at last, finding high volume markets - especially in wireless communications. Can SiGe make the same transition? Or is it destined to become the new "material of the future"?

IBM

To many people, SiGe has become synonymous with IBM and Bernard Meyerson. During the mid 1980s, Meyerson pioneered a UHV/CVD SiGe growth technology at the T.J. Watson Research Center [Yorktown Heights, NY], which has now been transferred to IBM's 200 mm BiCMOS line at East Fishkill, NY. Meyerson says that "the SiGe HBT effort has been spun into its own business unit within the Microelectronics Division at East Fishkill - we are in essence our own company". And as with any other company, in order to survive and grow, it must establish a product and find the customers. At the moment, that product is not in the form of a specific device or circuit, but in the form of a technology.

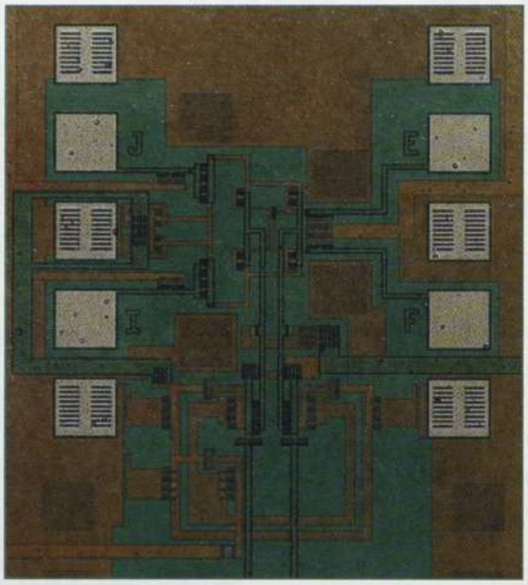


Daimler-Benz Research Center

SEM of Daimler-Benz Double Mesa SiGe HBT.

The IBM SiGe HBT approach typically uses a graded Ge profile in the base, in which a 1-2% Ge content is used at the emitter-base junction, and increased to 8-10% at the base-collector junction. All aspects of the SiGe HBT fabrication sequence are compatible with the CMOS portion of the BiCMOS process. The SiGe growth step is inserted into the BiCMOS process flow after the growth of a 7 nm gate oxide for the CMOS structure and a conventional CVD deposition of a thin polysilicon layer which protects the gate oxide. This polysilicon layer is then patterned and removed over the n-p-n active area (where the SiGe HBT will be fabricated) by a highly selective (polysilicon to oxide) RIE etch. Exposed polysilicon and silicon surfaces are then hydrogen passivated and the SiGe epitaxial base is grown by the UHV/CVD process. The polySiGe which is deposited over the field oxide as the epitaxial SiGe base is being grown is later utilized as extrinsic base electrodes. The remaining processing consists of a conventional dual poly BiCMOS processes. IBM believes that the future of SiGe technology lies in this merged process - combining high frequency SiGe HBTs for RF applications, with Si CMOS for digital applications, in which both analog and digital functions are capable of high levels of integration. As an example of this technology, IBM has recently demonstrated 0.25 µm electrical channel length nFET and pFET CMOS devices fabricated on the same wafers with SiGe HBTs which exhibit f_{max} and f_t values of 49 GHz and 39 GHz, respectively, measured at a V_{CE} of 1V. CMOS circuits including ring oscillators (stage delay of 49 ps) and 64 K SRAMs were fabricated alongside SiGe HBT analog circuits which included ECL Ring oscillators (stage delay 25 ps) and voltage controlled oscillators. This kind of capability is in essence the product which IBM is offering.

In an effort to develop a customer base for its technology, IBM has been working with outside companies in the development and investigation of SiGe-based HBT circuits. Jack Glenn and coworkers at Delco Electronics [Kokomo, IN] and the Hughes Research Laboratories [Malibu, CA] in collaboration with IBM, reported at the 1995 BCTM on a 12 GHz Gilbert Mixer, using both a Si only epitaxial base, as well as a SiGe epitaxial base. They found that the Si-only base Mixer exhibited a f_{max} and f_t of 50 and 39 GHz, respectively, resulting in a gain-bandwidth product of 18.5 GHz, while the SiGe base mixer exhibited a f_{max} and f_t of 60 and 47 GHz, respectively, giving a gain-bandwidth product of 22.5 GHz. These results demonstrate that the SiGe-base structure improved RF performance by some 10-20%. However, they also clearly show that IBM's Si-only bipolar process, when using an epitaxial-grown base, is extremely fast. Meyerson comments on this by saying that "our bipolar process is outstanding, with the SiGe just one factor among many which makes it extremely fast. What the SiGe does is give the Si-only process an added kick".(1)



Delco Electronics

A 12 GHz SiGe-based HBT Gilbert Mixer, jointly fabricated by Delco Electronics, Hughes Research Laboratories and IBM, exhibiting a voltage-gain bandwidth product in excess of 22 GHz.

Analog Devices

The most prominent among IBM's collaborators is Analog Devices Incorporated [Norwood, MA]. In 1993 they announced results on a SiGe-based 1 GHz, 12 bit, current output, D/A convertor with an ECL interface. The converter contained 2854 SiGe HBTs, 1465 poly-silicon resistors, a patterned p+ ground plane to speed signal settling, and three levels of metal for interconnections. This is still the highest level of integration attained to date for any SiGe technology. However, that product did not make it to the market, and since then Analog Devices has not published any other SiGe-based device results. Charles Fadel, marketing manager at Analog Devices, says that "delays occurred after the initial work on the 12 bit DAC as the SiGe technology was being transferred from IBM Yorktown to Fishkill, but a run of devices has just been completed which includes LNAs, mixers and prescalers, intended for 1.8 GHz operation. We will soon be evaluating their performance." In the meantime Analog Devices' conventional Si-bipolar processes have continued to improve, resulting in what marketing manager Rupert Baines, characterizes as "a good 25 GHz [f_t] process". He goes on to say that, "we thought we would need SiGe for 1.8 GHz applications, but now we don't need it there - conventional Si can handle it." For frequencies above the 2.0 GHz level Baines says, "it is not clear if we will need SiGe at that point, but it is not a decision that we have to make now. We feel that, at the moment, the WLAN market at 2.4 GHz is small and undefined, and we have the time to make our decision as to which technology to choose - SiGe or Si." Baines' sentiments are echoed by Jerald Fishman, president and CEO of Analog Devices who has said that he feels that bipolar in standard silicon is now capable of operating at up to 2 GHz, while there may still be some opportunity for SiGe in very high-speed communications.

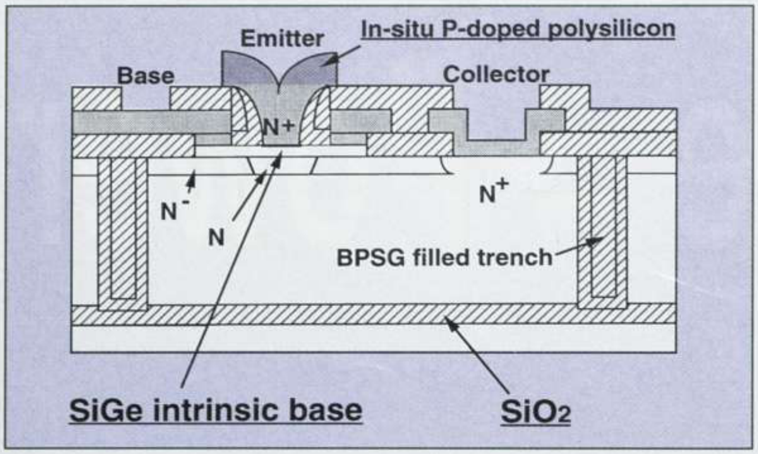
NEC

The NEC [Kanagawa, Japan] approach relies on the formation of a selectively grown SiGe base region. Initial work in the early 1990's relied on Gas Source MBE to perform the selective work, but this has now been transferred to a cold wall UHV/CVD system, an approach which is very similar to IBM's. NEC utilizes a self aligned structure in which a polysilicon overhang is placed above the region where the SiGe base will be grown. As the selective SiGe epitaxial base grows upward, polySiGe is also selectively being grown downward from the exposed polysilicon overhang. As growth continues, the single crystal SiGe from the base and the polySiGe from the extrinsic base contact meet during selective growth to form the extrinsic base contact. This process is referred to as the Super Self-aligned Selectively grown SiGe base (SSSB) bipolar transistor. NEC uses base thicknesses which vary from 45 to 60 nm, using both a graded Ge profile similar to IBM's, as well as a trapezoidal-like structure (a combination of the graded and flat Ge profile), where for both cases, a maximum Ge content ranging from 10-15% at the collector-base junction is used. Boron base doping is typically $7x10^{18}$ cm^{-3}, a value similar to that used by IBM. In order to improve RF performance, a bonded silicon on insulator (SOI) substrate with BPSG-filled trench isolation is used to reduce collector-substrate capacitance. Using the SSSB approach, f_{max} and f_t values of 50 and 50 GHz, respectively, for V_{CB} of 1 V, are obtained.

Sato and coworkers at NEC have applied this technology in the development of the ICs required to implement a 20 Gbit/s optical communications system, as reported at the 1995 BCTM. These circuits include a SiGe-based HBT preamplifier IC which employs a dual feedback loop circuit, and exhibits a 19 GHz bandwidth with a 38 dB-ohm transimpedance gain, and a decision IC which consists of a gain controllable amplifier, and a D-flip-flop which operates at 20 Gbit/s with 200 mV_{p-p} input sensitivity. In addition, this technology has been applied in the fabrication of 0.6 µm design rule SiGe HBTs in used in ECL circuits, producing 19 pséc gate delays.

---

(1) Other recent collaborative work has been performed with a team consisting of Carleton University and Northern Telecom [Ottawa Canada]. Weinan Gao and coworkers at Carleton University and Northern Telecom have fabricated an HBT Comparator which can operate up to sampling rates of 5 GHz using SiGe HBTs with fmax and ft of 50 and 40 GHz, respectively, while dissipating 89 mW from a 3-V supply. Also reporting at the 1995 BCTM were Mike Case and coworkers at Hughes Research Laboratories on a 23 GHz static 1/128 Frequency Divider using SiGe HBTs. In order to obtain such high frequency results on a lossy silicon substrate, it was found necessary to fabricate microwave elements above a 13 mm thick layer of benzocyclobuten (where the BCB was used for wave propagation).



NEC Corporation

A cross sectional view of NEC's super self-aligned selectively grown SiGe-base (SSSB) HBT fabricated on Silicon on Insulator (SOI).

Daimler-Benz

The SiGe effort at the Daimler-Benz Research Center [Ulm, Germany] is based an MBE-grown, mesa-structure HBT. Using 1000 ohm-cm Si substrates, where the high resistivity substrate is used to enhance RF performance, the typical Daimler-Benz MBE grown HBT utilizes the flat SiGe base profile, which consist of a 25 nm boron doped $1x10^{20}$ cm^{-3} SiGe layer, with a 30-40% Ge content. The remainder of the HBT consists of a 50 nm Si emitter, Sb doped to $2x10^{18}$ cm^{-3}, and a Si collector which may vary in thickness from 130 to 400 nm with doping ranging from $2x10^{16}$ to $5x10^{17}$ cm^{-3}, where this range is used to trade f_t off against f_{max}, an example of which can be seen in Table 1.

Daimler-Benz utilizes three different SiGe HBT processes, all based on MBE growth of the SiGe epi. The first is a non-passivated double mesa technology, using dry etching and self aligned liftoff to define the emitter, base and collector; the second is a passivated double mesa technology, in which self-aligned oxide/nitride sidewall spacers are used for passivation; and the third is a differential HBT process used to reduce parasitic collector-base capacitances, where the collector is grown by CVD, and the base and emitter layers are grown by MBE, while a recessed LOCOS (Local Oxidation of Silicon) technology is used to define the active HBT area.

Daimler-Benz plans to announce at the 1995 International Electron Device Meeting (IEDM) that the double mesa SiGe HBT structure has achieved a record-breaking f_{max} of 160 GHz (with a corresponding f_t of 30 GHz) at a V_{CE} of 8 V. However, this high operating voltage makes this device inappropriate for many wireless applications. A more applicable structure for wireless applications will also be reported which utilizes a higher collector doping (increasing from $1.5x10^{16}$ to $2x10^{17}$) where at a VCE of 3 V, gives an f_{max} of 90 GHz, with a f_t of 65 GHz. Some of the other highlights of Daimler-Benz's SiGe HBT technology include: a DC-18 GHz wideband amplifier exhibiting 9.5 dB of gain while drawing only 50 mW from a 3 V supply; a 26 and 40 GHz VCO which exhibits a tuning range of more than 3 GHz, with the output power behind the on-chip 10 dB attenuator reaching -13 dBm; a Ka band MMIC amplifier producing 4 dB of gain at 26 GHz,; and a C-band (4-8 GHz) power amplifier producing 20 dBm of power at a 30% PAE.

Daimler-Benz has begun transferring its technology to its subsidiary, TEMIC Telefunken [Heilbronn, Germany], to begin commercialization of both discrete- and circuit-based SiGe components. TEMIC currently produces bipolar Si devices with f_t up to 15 GHz for wireless applications. It plans to implement Daimler-Benz's technology to create a UHFSiGe process (f_t up to 50 GHz). TEMIC is currently using the differential HBT process (MBE/CVD), with CVD defined collectors for the UHFSiGe process, but plans in the future to go to complete CVD structures - a critical step which may prove challenging when considering how MBE-dominated the Daimler-Benz effort has been up until this point. TEMIC is specifically targeting wireless applications. They hope to begin with production of discrete devices in the first half of 1996, and to start production of circuits by the end of next year.

Competition

SiGe, Si and GaAs device technologies compete among each other in two fundamental categories: performance and cost. Success in the market place occurs for those who offer a device at the minimum cost which can just meet a performance specification. No one is willing to pay extra for performance that they do not need. Using these two criteria, how well does SiGe compete against both Si and GaAs?

IBM, NEC and Daimler-Benz have clearly demonstrated that SiGe can produce a high performance HBT technology. SiGe-based HBTs exhibit ft and fmax values above 100 GHz (values which are 50% higher than the best Si-BJT, but some 2-6 times lower than the best GaAs devices). IBM has reported power added efficiencies at 1 GHz of 66%, which is slightly better than the best Si BJT, but somewhat less than those obtainable in GaAs. Though somewhat inferior in noise characteristics over the 1-2 GHz range as compared to GaAs, SiGe-based HBTs offer superior corner frequencies, f_c, with values down to 100 Hz as compared to GaAs which generally exceeds 2 KHz. Furthermore, IBM has demonstrated the capability of integrating CMOS with SiGe HBTs, where the resultant SiGe HBTs operated comparably to state of the art BJT performance levels. These characteristics show that the performance of SiGe-based HBTs is for the most part superior to conven-

TABLE 1
DEVICE PARAMETERS

MBE sample	w_c [nm]	N_c [cm^{-3}]	β	R_{bi} {Ω/□]	f_T [GHz]	f_{maz} [GHz]
B2845[8]	130	$5 \cdot 10^{17}$	22	950	46	49
B 2982	180	$2 \cdot 10^{17}$	32	450	17	55
B2984	250	$8 \cdot 10^{16}$	60	360	30	78
B2991	250	$5 \cdot 10^{16}$	60	360	33	2
B2992	300	$5 \cdot 10^{16}$	55	340	30	72
B2994	300	$5 \cdot 10^{16}$	55	380	34	100
B2993	400	$2 \cdot 10^{16}$	55	400	32	120

Daimler-Benz Research Center, and IEDM

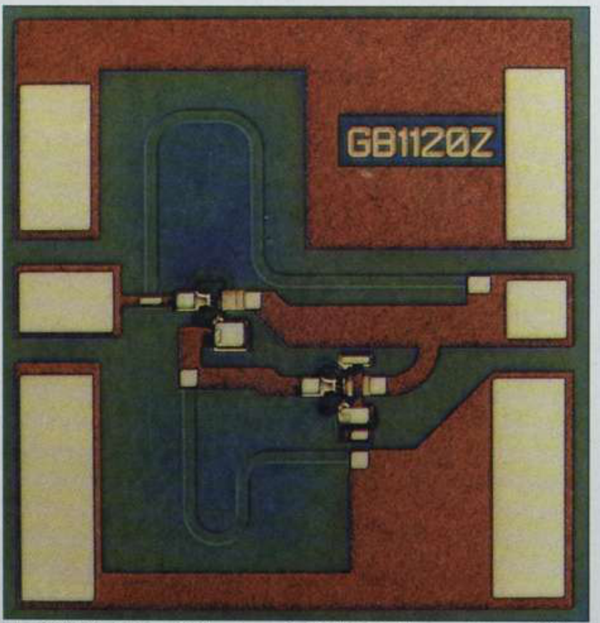
Table 1. Device parameters for Daimler-Benz SiGe HBT, illustrating the relationship between f_t, f_{max} and collector structure. For w_c - collector width, N_c - collector doping, β - dc current gain, and R_{bi} - base resistance.

tional Si BJTs, while in some areas are becoming competitive with GaAs based devices, and in the case of f_c, even superior.

The most important "real-world" considerations are the characteristics required for a specific application. IBM and TEMIC both hope to pursue the RF segment of the wireless market, which currently requires discretes and MMICs which can operate over the frequency range of 900-1900 MHz, with some small growth starting to occur at 2400 MHz for WLAN applications. SiGe can readily meet the RF requirements for most wireless applications in this frequency range - but so can Si and GaAs. In reality, competition in this area is not so much determined by performance, but by cost. As a result, both Si and GaAs-based MMICs currently face stiff competition from discretes. MMICs currently occupy around 25% of the market, and they will be able to increase their share only if they can compete on a cost level with discrete solutions, or offer a needed performance enhancement. IBM reported at the 1995 BCTM that they believe that an important application for their SiGe BiCMOS technology will be "single chip solutions" for wireless - a single SiGe BiCMOS chip which would handle both RF and digital functions. But this vision is contrary to that shared by the vast majority of the wireless community, where a "mix-and-match" approach is utilized to tailor both digital baseband circuitry and RF components for specific phones and applications. It is not clear at all that the wireless market is looking for large levels of RF integration, let alone integration of RF with digital baseband functions. If IBM is correct, then they are far ahead of current practice.

The first SiGe-based HBT MMICs will likely be targeted toward a cost/performance point somewhere between that of Si and GaAs MMICs. Unfortunately, this region is getting smaller. Silicon's performance is improving. It is already suitable for applications below 2 GHz, and at least one "all-Si" chipset for 2.4 GHz operation has been announced (see page 14). At the same time, GaAs-based devices and MMICs continue to get cheaper. TRW's GaAs HBT Darlington amplifiers are now being sold through RF MicroDevices for less than $1 each. Hewlett Packard can sell PHEMT based LNAs, which are both MBE-grown and whose gates are E-beam defined, for less than $1. And TriQuint sells a wide range of MESFET-based LNAs, as well as up and down converters for less than $2 each. Industry wide GaAs MMIC production levels are already approaching 10 million per month, and will see continuing rapid growth with the introduction of TDMA and CDMA digital cellular services, as well as expansion of cellular services into the PCS band (1800 MHz) within the next two years. This increase in production will only further decrease GaAs-based MMIC costs.

Despite having demonstrated a high performance technology, neither IBM, NEC or Daimler-Benz have yet entered into the phase where they are producing any MMICs for insertion into commercial devices. All three are still in the investigational/demonstration mode, with Daimler-Benz looking like it will be the first to enter the market. Those SiGe parts will enter into a very competitive arena, especially if they take another 1-2 years to arrive. During that time both Si- and GaAs-based MMICs will continue to improve in performance, increase production, and drop in cost. SiGe is undoubtedly capable of producing a high speed bipolar technology, but it remains to be seen whether this technology can make the leap from the laboratory to the production line.



A DC-18 GHz SiGe-based HBT Wideband Amplifier, fabricated by Daimler-Benz and University of Ulm. Providing 9.5 dB of gain from DC through 18 GHz, this 3 V supplied amplifier consumes 50 mW.

Beyond HBTs

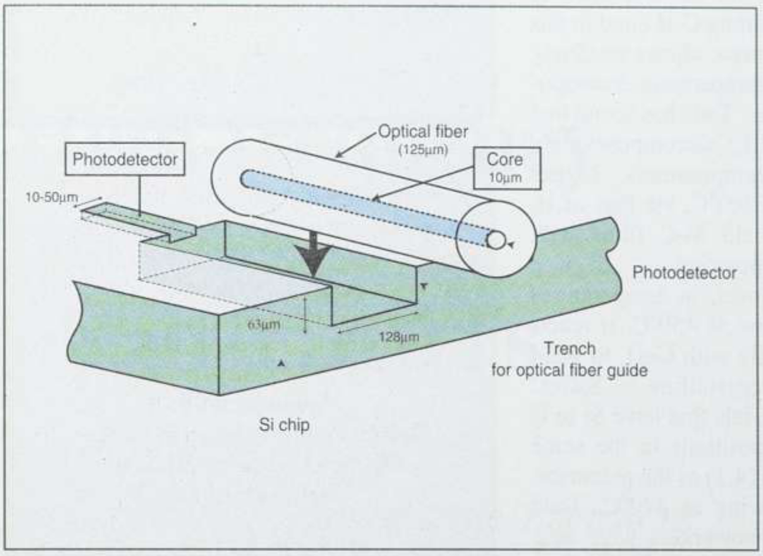
Other SiGe development areas, ranging from optoelectronics to MODFETs and Heterojunction CMOS.

Most of the SiGe work done to date has focused on HBTs. However, a wide spectrum of research and development is occurring in fundamental material development and non-HBT device areas, where the introduction of heterostructures in a traditional Si-only technology is being applied to enhance a wide range of optical and electronic devices.

Optoelectronics

The optoelectronics realm has traditionally been reserved to III-V and II-VI compound semiconductors, due to the availability of direct transitions and heterostructures. However, the introduction of Ge allows heterostructures to be fabricated in traditional Si-only technologies, which expands the potential of Si optoelectronics.

Researchers at NEC are investigating whether Si-Based OEIC receivers can be fabricated using SiGe. Mitshuiro Sugiyama and coworkers have developed a selective epitaxial SiGe/Si Planar photodetector using the same cold wall UHV/CVD SiGe technology that has been developed for NEC's HBT process. This P-i-N planar SiGe/Si photodetector exhibits a high external quantum efficiency (η_{ext}) of 25-29%, an internal quantum efficiency (η_{int}) of over 90%, a low dark current of 0.5 pA/um^2, and is capable of 10 Gbit/s operation at λ=0.98 μm. The absorption layer for this detector consists of a 30 period 30Å $Si_{0.9}Ge_{0.1}$/320 Å Si superlattice, which is selectively grown in a recessed trench. A novel method for stable and alignment free coupling to an optical fiber has



Mitshuiro Sugiyama, NEC and IEDM

Schematic view of the integrated SiGe/Si planar photodetector with the trench used as an alignment-free optical fiber guide.

been achieved by forming a 63 μm deep/128 μm wide trench which is used for guiding the optical fiber to the photodetector. See above. A key element to the high performance of this photodetector is the use of silicon on insulator (SOI) substrates (also utilized in NEC's SiGe HBT process), where the η_{ext} of photodetectors fabricated on SOI substrates is found to be six times higher than that of photodetectors fabricated on a bulk Si substrate, because of the incident light which is reflected by the buried SiO_2. NEC believes that these results will enable the realization of low cost and high performance Si-based OEIC receivers with a planar photodetector.

Light Emitters

The benefits of the NEC photodetector technology would be greatly enhanced if it could be coupled with a method of producing light emission from similar materials. $Si_{1-x}Ge_x$ quantum well structures exhibit type-I band-alignment where most of the band offset occurs in the valence band when the Ge concentration is low. This type of structure allows for only holes to be effectively confined in the quantum wells (QWs), whereas to form an emitter, it is necessary to also confine electrons in the conduction band. Noritaka Usami and coworkers at the University of Tokyo have developed a neighboring confinement structure (NCS) using $Si_{1-x}Ge_x$ which consists of a single pair of spatially-indirect adjacent QW layers for both electrons (tensile strained) and holes (compressive strained) sandwiched by barrier layers to create an asymmetric type-II structure. Before the MBE growth of the NCS structure, a $Si_{0.82}Ge_{0.18}$ buffer is grown in which a 3.8 μm step-graded $Si_{1-x}Ge_x$ layer with x ranging from 0 to 0.18 is grown, and then capped with a uniform 2.5 μm $Si_{0.82}Ge_{0.18}$ layer. The NCS structure is then grown on the $Si_{0.82}Ge_{0.18}$ in which a tensile strained 10 Å Si-only QW is grown for electron confinement, and a 10 Å $Si_{0.64}Ge_{0.36}$ QW is grown for hole confinement. This structure allows for a nearly "direct" transition as evidenced by orders of magnitude enhancement of no-phonon low temperature photoluminescence, as compared to SiGe QWs using type I and symmetric type II QWs. The NCS technique, when coupled with growth on relaxed SiGe buffers, is a promising approach in the production of Si-based light emitters.

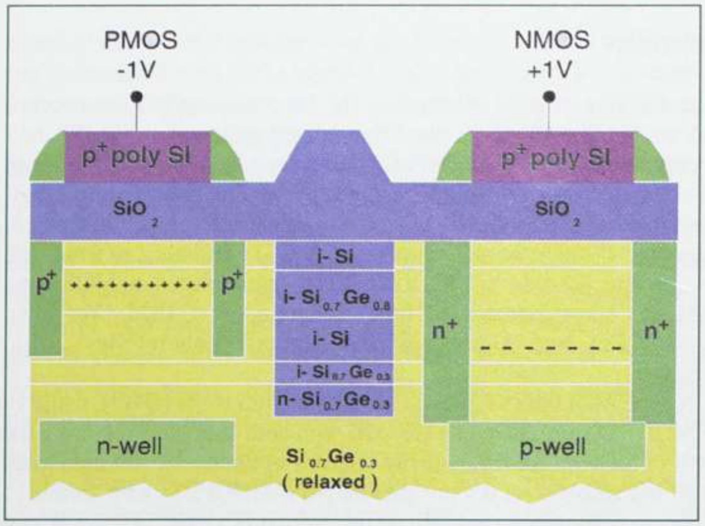
Electronics

In the area of SiGe electronics, the bulk of the effort has concentrated on HBTs. However, the inherent capabilities of a Si/SiGe heterostructure can also be applied to create SiGe-based Modulation-doped field-effect transistors (MODFETs), as well as being inserted into metal-oxide-semiconductor (MOS) structures to create heterojunction complementary metal-oxide Semiconductor (HCMOS) transistors, in which the Schottky-gate used in a MODFET has been replaced a MOS-gate. Efforts are being pursued in both technologies at IBM [Yorktown Heights, NY] and Daimler-Benz Research Laboratories [Ulm, Germany].

N-type MODFETs typically use Si quantum wells (QWs), while P-type MODFETs use SiGe or a Ge QW, with both structures requiring the growth of SiGe buffer layers many microns in thickness. Khalid Ismail of IBM has reported on 0.4 μm gate length n-MODFETs with measured peak transconductance of 420 mS/mm, which is about a factor of two higher than Si n-MOSFETs. This MODFET exhibited an f_t and f_{max} of 33 and 40 GHz, respectively. Ulf Konig and coworkers at Daimler-Benz have found that the introduction of graded SiGe buffers dramatically increases two-dimensional electron gas (2DEG) mobilities, having obtained values as high as 180,000 $cm^2/Vsec$ at low temperatures for n-MODFETs. However, what is more important for device applications are room temperature mobilities, which are found to range from 2,000 to 3,000 $cm^2/Vsec$ - a factor of four to six times greater than for Si-only MOSFETs. For p-MODFETs, Ismail reports on 0.7 μm gate length devices with transconductances of 200 mS/mm, in which similar transconductance values for Si-only p-MOSFETs can only be achieved with gate lengths reduced to 0.2 μm or below. This devices exhibited an f_t and f_{max} of 10 and 18 GHz, respectively, along with room temperature mobilities of 1400 to 1800 $cm^2/Vsec$ - a factor of six to nine times those above standard p-MOSFETs with comparable doping. Ismail and coworkers have modeled the performance of complementary MODFET structures where they have found that for 0.1 μm gate length devices, that the peak conductance of n-MODFET is 820 mS/mm, while that of the p-MODFET is 610 mS/mm, making them comparable to what is achievable with III-V-based materials.

Heterostructure

The incorporation of SiGe heterostructures in a CMOS device in order to produce a HCMOS structure might take the shape of the one as proposed by Ismail, above right, where the electrons flow through a strained Si channel and the holes through a stained SiGe channel. Mark Armstrong and coworkers at MIT [Cambridge, MA] and IBM [Yorktown Heights], will present at the 1995 IEDM details on the design of this planar HCMOS structure, where simulations indicate that this structure will show a 5 to 6 fold reduction in power-delay product over that of bulk CMOS for room temperature operation. Konig and coworkers point out that HCMOS has many advantages over conventional CMOS, due to barrier confined carrier transport in QWs with higher mobilities, higher saturated carrier velocities, and higher two-dimensional electron and hole gas (2DEG and 2DHG) concentrations. These advantages should translate into higher transconductances, higher speeds, lower gate delays, lower noise and lower power consumption. The Daimler-Benz researchers have proposed an arrangement of stacked p-Ge channels and n-Si channels to form HCMOS, and are presently attempting to fabricate this structure. The key advantages of implementing SiGe heterostructures in CMOS, would be the potential ability to obtain high frequency capabilities in the same device which already exhibits excellent digital capabilities.



Khalid Ismail, IBM T.J. Watson Research Center

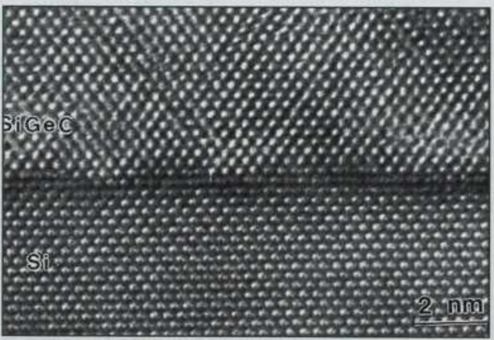
Proposed SiGe heterostructure CMOS (HCMOS) structure where electrons flow through a strained Si channel and the holes through a strained SiGe channel.

Material

A limitation faced in all SiGe technology is the 4% lattice mismatch between Si and Ge. This mismatch results in a compressive strain within the SiGe film, where the strain increases both for increasing Ge concentration as well as for increasing SiGe film thickness. If the strain becomes too great, it will be relieved by the generation of dislocations which can severely degrade device performance.

A possible way to eliminate the strain is the introduction of another element, with carbon being a leading candidate. Diamond (C) has a lattice constant of 3.545 Å, which is significantly smaller than those of Si (5.43 Å) and Ge (5.646 Å). Incorporation of C should reduce the lattice mismatch between SiGe and Si, with the smaller size of C compensating for the larger size of Ge. Using Vegard's law (where the resultant lattice constant of an alloy is simply the weighted average of its constituent element's lattice constants), it would be expected that a Ge to C ratio of 9:1 would produce a $Si_{1-x-y}Ge_xC_y$ alloy which is lattice matched to Si. Work on the incorporation of C into SiGe has been ongoing since the early 1990's, by techniques such as MBE and solid phase epitaxy (SPE). These attempts have resulted in maximum incorporation levels only 1-2 at. % of C, which would only allow a limited range of Si:Ge compositions under lattice matched conditions (Ge content up to 18%). Recently, Michael Todd, John Kouvetakis and coworkers at Arizona State University [Tempe, AZ] have used a novel C-H free carbon precursor - $C(SiH_3)_4$, with mixtures of SiH_4 and GeH_4 in a UHV/CVD system similar to that employed by IBM, in the growth of SiGeC films on Si. Absence of the strong C-H bond in this precursor allows relatively low temperature decomposition. Todd has found that $C(SiH_3)_4$ decomposes only at temperatures higher than 700°C, via loss of H_2 to yield Si-C films with composition $Si_{0.8}C_{0.2}$. However, at temperatures as low as 450°C, it reacts readily with GeH_4 to yield polycrystalline SiGeC materials that have Si to C compositions in the same ratio (4:1) as the precursor. Growing at 470°C, Todd and coworkers were able to produce SiGeC films with C content as high as 4-6% as determined by Rutherford Backscattering. With a growth rate of 0.6 nm/min, $Si_{1-x-y}Ge_xC_y$ layers were grown where x=0.31 to 0.35 and y=0.04 to 0.06, to produce 110 nm thick layers which were nominally lattice matched to Si. The figure below shows a high resolution TEM cross section of the Si-SiGeC interface for a C content of nominally 4%, where a high degree of crystalline perfection was obtained through the interface. Currently, the optical and electrical properties of the SiGeC films are being analyzed. The introduction of C into SiGe films will offer another degree of freedom in the design of epilayer structures, not only with respect to lattice matching, but also with respect to bandgap engineering.

Although all these avenues of research are less mature than that occurring for SiGe-based HBTs, they all offer the possibility of expanding the capabilities of Si-based devices, while blurring the distinctions in capabilities and performance between Si-based and III-V-based electronic and opto-electronic devices.



John Kouvetakis, Arizona State University

High-resolution cross sectional TEM image showing heteroepitaxial growth of $Si_{1-x-y}Ge_xC_y$ (y=0.04) on Si.

Compound Semiconductors at Spring MRS Meeting

A number of compound semiconductor-related symposium are scheduled for the Spring Meeting of the Materials Research Society, to be held April 8-12, 1996 at San Francisco, CA.

*

Symposium B:
Defects and Interfaces in Lattice-Mismatched Semiconductor Heterostructures

*

Symposium C:
Compound Semiconductor Electronics and Photonics

*

Symposium D:
Rare-Earth Doped Semiconductors

*

Symposium E:
III-Nitride, SiC, and Diamond Materials for Electronic Devices

*

Symposium F:
GeSi and Related Compounds

*

Symposium G:
Semiconductors on Insulators - Fundamentals and Technology

*

Symposium J:
Thin Films for Photovoltaic and Related Device Applications

*

For more information, contact:

Materials Research Society
9800 McKnight Road
Pittsburgh, PA 15237-6006 USA
TEL [1] 412 367 3004
FAX [1] 412 367 4373
E mail: INFO@MRS.ORG

As always, a major exhibit will be held in conjunction with the meeting. Companies interested in exhibiting should contact Ms. Mary E. Kaufold at the above address.

High frequency performance of SiGe HBTs

D.C. HOUGHTON
HEAD, EPITAXY GROUP
INSTITUTE FOR MICROSTRUCTURAL SCIENCES
NATIONAL RESEARCH COUNCIL OF CANADA
OTTAWA, ON CANADA K1A OR6

The concept of inserting heterojunctions into bipolar transistors was first suggested by Herb Kroemer in 1957 but it was not until 1987 that a SiGe Heterojunction Bipolar Transistor (HBT) was demonstrated. The introduction of Ge into the base of an n-p-n Si-Bipolar Junction Transistor (BJT) alters transistor performance in several fundamental ways. The most obvious change is that of a reduction in the bandgap of the SiGe alloy in the p-doped base, compared to Si in the n-doped emitter and collector regions. The bandgap discontinuity creates the heterojunctions needed for the enhanced performance of a SiGe HBT.

In an HBT, unlike traditional BJT's, the doping level in the base is not directly coupled to current gain, permitting additional degrees of freedom in device and circuit optimization. The presence of a heterojunction gives rise to several advantages of HBT's over BJT's: (i) improved frequency response due to higher current gain and lower base resistance; (ii) higher emitter efficiency due to reduced minority carrier injection from the base into the emitter; and (iii) reduced tunneling current and emitter-base capacitance. Additional benefits are also realized in higher Early voltage (a measure of the ease with which the base is depleted) and breakdown voltage as well as a new freedom for the designer to customize HBT performance to suit specific applications in either analog or digital circuits.

The current gain, β, of a SiGe HBT, where the Si/SiGe bandgap difference is ΔE_g, is approximately,

$$\beta_{SiGe} = \frac{N_e W_e D_p}{N_b W_b D_n} \exp\left(\frac{\Delta E_g}{kT}\right)$$

where N and W are the doping level and width of the emitter and base and D_p and D_n are the minority carrier diffusion coefficients for holes(p) and electrons(n). The extra gain from the bandgap difference, ΔE_g, (up to ≈250meV is available and where kT≈25meV) can be several orders of magnitude. This increase in gain and the ability through epitaxial growth to shrink base widths (to reduce base transit time) has led to record high cut off frequencies. Although high values for f_t, the current gain cut-off frequency, grab headlines, it is f_{max}, the maximum oscillation frequency, that is far more important since it relates directly to circuit performance. In an HBT, f_{max} and f_t are related to each other through the expression:

$$f_{max} = \left(\frac{f_t}{8\pi R_b C_{cb}}\right)^{\frac{1}{2}}$$

where R_b is the base resistance and C_{cb} is the collector-base capacitance. To achieve high f_{max}, the base resistance, R_b, must be kept low at small base widths through increasing base doping, Nb, to the 10^{19} to 10^{20}cm^{-3} range. The additional gain available in an HBT can be traded off for higher base doping, N_b without compromising circuit speed. For the case of BJTs, a decrease in β with increased base doping limits base doping levels to the 10^{18} cm^{-3} range, with higher doping rendering β too low (<20) to make a useful BJT. However, in the case of the HBT, where the introduction of the heterojunction can increase β by orders of magnitude, much higher levels of base doping can be tolerated before the overall β of the HBT becomes too low. It has been experimentally verified that useful gains in HBTs can be obtained with base doping levels in the 10^{20} cm^{-3} range, some two orders of magnitude higher than can be obtained in a BJT. The simultaneous achievement of high cut off frequency while maintaining a low base resistance is a key advantage of SiGe HBT over the Si BJT. This dramatically increases the maximum oscillation frequency, f_{max}, and potentially brings the performance of SiGe HBTs into contention with GaAs based devices.

To speed up SiGe HBT's even further the transit time through the base can be reduced by grading the Ge fraction (e.g. 0-15%Ge from the emitter to the collector) thereby building in a drift field (~20kV/cm) through bandgap narrowing(~7.5meV for each 1% Ge). The Ge grade encourages electrons to move quickly through the base, improves frequency response and simultaneously produces a high gain-Early voltage product which is important for high speed analog applications. Tailoring the Ge base profile allows devices to be optimized for high current gain as is often required in analog designs. Alternatively, a trade off in gain may be made to allow higher base doping for example in a digital application.

If a pinch of Ge provides significant benefits for SiGe HBT's over Si BJT's, why not build the entire base in pure Ge? Unfortunately, the ~4% lattice mismatch between Ge and Si sets an upper limit to the thickness and Ge fraction permissible in a practical HBT, due to compressive strain in the SiGe layer. Strain energy builds up at high Ge concentrations (or large SiGe thicknesses) and eventually misfit dislocations are injected to relieve the strain with catastrophic effects on HBT performance due to shunts through the base. This means that for a given Ge content, there is a critical thickness of SiGe which can be grown before the onset of dislocation formation. The higher the Ge content in the film, the thinner the critical thickness becomes. It is these strain considerations which limit the maximum Ge content in the SiGe base.

In the graded profile approach (IBM and NEC) a ramp from 0% at the emitter up to 8-15% Ge content at the base-collector junction (over base widths of 50-100 nm) is typically used. For the flat profile approach (Daimler-Benz) a Ge content of up to 40% (for base widths of 25 nm) is being used. Recent reports from Daimler-Benz indicate that a collector-emitter breakdown voltage of 9V and f_{max} of 160 GHz may be achievable utilizing their high Ge (flat -profile) double mesa HBT design. From the IBM approach record low ECL gate delays (16ps) exceptional noise figures and process integration leverage are claimed. Both these approaches have been successfully employed to achieve f_t and f_{max} values in excess of 100 GHz, which are substantially higher than the best obtained for conventional Si BJT structures. A significant difference between the two approaches is that the IBM and NEC structures are structurally stable (SiGe layers are below their "critical thickness") and can be conventionally processed in a Si VLSI line, whereas the Daimler Benz HBT is metastable and must be processed with a greatly reduced thermal budget. The advantages of Si process integration and manufacturability inherent in the IBM and NEC approach are thus not realized in the Daimler-Benz methodology.

Seventh International Conference on II-VI Devices and Compounds

ZnSe based blue laser diodes dominate.

CHRIS BLOMFIELD
SHEFFIELD HALLAM UNIVERSITY, UK

Blue green laser diodes based upon ZnSe and related compounds dominated the 7th International Conference on II-VI Compounds and Devices held at Heriot-Watt University, Edinburgh, Scotland August 13-18. During the three sessions devoted to the topic, several groups demonstrated the ability to produce continuous wave (CW) laser operation in the blue green region at room temperature. At present device lifetimes are of the order of minutes rather than the desired 10^4 hours. However, device characteristics of MBE grown II-VI wide gap emitters are becoming as good as those of established III-V red devices. The key issues of growth, doping and degradation were all addressed through a number of invited presentations from key players in the field.

Laser Design and Contacts

Akira Ishibashi of the Sony Research Centre [Yokahama, Japan], pioneers of ZnMgSSe technology, described the current state of the art in both MBE and MOCVD growth of laser diodes based upon this quaternary. The addition of Mg into the ZnSSe system has allowed the utilisation of a wide range of E_g's from 2.8 eV to 3.4 eV (77K), while maintaining a complete lattice match to the GaAs substrate. Similarly addition of Mg to ZnCdSe allows utilisation of E_g from 2.4 to 3.4 eV (77K) while maintaining a lattice match to InP. These developments have lead to a dominance of such quaternary materials in blue-green devices. Ishibashi predicted that addition of Mg to CdSeTe would open up a new range of E_g's accessible through a lattice match to InAs or GaSb substrates. Sony's present work centres upon both MOCVD and MBE growth of ZnMgSSe single confined heterostructure laser diodes. Both modes of growth have resulted in photo pumped room temperature operation and CW operation of MBE grown devices. The Sony devices minimise the threshold current required for laser operation by engineering the difference in ΔE_g between the active and cladding regions, ΔE_g, to satisfy the criterion; $\Delta E_g > 0.35$ eV. With this criterion fulfilled the predominant loss mechanism becomes mirror loss through the Fabry-Perot cavity facets. At present facets are uncoated and hence quantum efficiencies are reduced. Ishibashi reported room temperature CW operation of an uncoated device at 517nm with a lifetime of 98 min. Power output for a 50 µm stripe, pulsed device of 834 mW was achieved. For CW operation with a 10 µm stripe, power outputs of 30mW (sufficient for high density rewriteable optical storage devices) were reported. Ultimately reducing the wavelength of these devices depends upon doping limitations of the active region. Ishibashi proposed that by engineering the valence band with a superlattice of $(ZnSe)_m (ZnMgSSe)_n$ where $m \approx 4\text{-}6$ and $n \approx 10\text{-}15$ an increase in dopant concentration of up to one order of magnitude could be achieved.

The inherent problems of p-doping ZnSe not only limit the operating wavelength but increase the specific contact resistance of laser devices. Some progress has been made with the introduction of graded p-Zn(Te)Se multi-quantum well structures which allow injection of holes from heavily doped p-ZnTe into ZnSe via the ZnTeSe pseudograded bandgap region. The graded ZnTe contact is at present utilised by most groups reporting room temperature CW operation of blue devices. The contacting of ZnSe remains a fundamental problem and understanding contacts to ZnSe and ZnTe is a key issue as demonstrated by the large number of poster contributions in this area.

Doping & Device Degradation

Several issues concerning doping of p-ZnSe were addressed by Robert Gunshor of Purdue University, Indiana, USA. By utilising a graded ZnTe contact structure his group have been able to correlate classical transport measurements (Hall-effect) with SIMS data from both ZnSe and ZnTe. ZnSe has been doped with free hole concentrations of 2-3 x 10^{17} cm^{-3}. Under similar conditions it is possible to produce free hole concentrations in ZnTe exceeding 1 x 10^{19} cm^{-3}. There are generally two explanations for his discrepancy between the level of p-doping in the two materials, (i) that of "self compensation" by either defects or lattice relaxation or (ii) limitations imposed by the solubility of dopant atoms. Comparing temperature variable Hall-effect measurements of N acceptor concentrations with SIMS data for N concentrations, Gunshor concluded that doping limitations "originated in the solubility of the N acceptor as compared to ZnTe". A corresponding investigation into the origin of the increased resistivity of ZnSe as both Mg and S are added to form ZnSSe and ZnMgSSe concluded that the increased resistivity could be attributed to increases in acceptor activation energy. This phenomenon was ascribed by Gunshor to a lattice relaxation similar to that exhibited by DX centres in n-type AlGaAs. Evidence was given to support this claim which included persistent photoconductivity and large differences between thermal and optical ionisation energies.

Device degradation is the primary limiting factor preventing commercialisation of blue green laser diodes. Devices appear to fail due to a reduction in gain in the active region following the growth of dark line defects. Both TEM and real time electroluminescence observation are now being applied to the analysis of degradation. An example was given of how an original stacking fault, nucleated at the ZnSe/GaAs interface, resulted in a threading dislocation in an otherwise pseudomorphic structure. In turn this threading dislocation produced a network of dislocations in the quantum well region destroying laser action. In addition to such "grown in" defects there is a strong contribution to degradation from point defects, the concentration of which is sensitive to growth conditions. It was shown that the electron beam employed in TEM investigations can instigate further growth of the classic dark patches associated with defect networks. The concentration of these defects and the understanding of them is seen as crucial in understanding degradation mechanisms. One point which was apparent was that the density of stacking faults could be greatly reduced by growing the II-VI laser device on a GaAs epitaxial buffer layer as opposed to directly onto the single crystal substrate surface.

Waveguides

Maarten Buijs of Philips' Briarcliff Manor Laboratories, New York, USA presented a paper on one of the key issues to be addressed for data storage applications of blue-green lasers, that of lateral waveguiding. Buijs made a comparison between index and gain guided separate-confinement heterostructure edge emitters with a stripe geometry. All devices were operated under pulsed mode at room temperature with stripe widths of 5 and 10 µm. In the gain guided structure non-uniform heating under the narrow stripe led to a lateral profile of the index of refraction. This heating which was up to several tens of degrees reduced the carrier induced difference in the index of refraction between the region under the stripe and that immediately adjacent within a few microseconds of the beginning of the pulse. The heating effects induced a significant reduction in current density in the gain guided devices. In index guided devices the built-in lateral difference in index of refraction completely dominated any transient effects which produced a near constant threshold during the laser pulse.

With their eyes firmly focused on the commercialisation of these devices, Sony presented a post deadline paper describing the first II-VI inner stripe channelled substrate planar waveguide device. The device consisted of a 2.5 µm p-GaAs blocking layer grown on a Si doped (100) substrate by MOCVD. Channelled stripes 6 µm wide were chemically etched into the p-GaAs layer onto which was grown the ZnMgSSe laser structure. The spectrum peaked at 512 nm with a threshold current density of 240 A/cm^2, which is the lowest value so far reported for II-VI laser diodes.

Other Areas

Several other areas were also represented. Dr. Mariette of the CEA-CNRS Grenoble, France gave a summary of recent progress in CdTe based quantum wires and dots. At present there are two approaches for producing these quantum devices In one regime CdTe/CdZnTe quantum wells were processed into wires and dots by electron beam lithography and ion beam etching. With a final anodic etching down to 100 nm wires and 250 nm dots, photoluminescence spectra are similar to those of the original quantum well. A second approach involves the growth of the quantum well structure on top of a strained super lattice. The resulting bandgap of the CdTe/CdZnTe quantum well has a spatial variation due to strain induced by the CdTe/CdZnTe superlattice substrate. The resulting photoluminescence of the quantum well wires is then shifted to the red in comparison with the original quantum well spectra.

Dr. Ashenford from the University of Hull, UK presented a poster contribution concerned with enhancing the efficiency limit of CdTe based PiN photovoltaic solar cells, currently < 30% corresponding to an optimum bandgap of 1.5 eV. Recently interest has been shown in enhancing the insulating region by incorporating multiquantum well structures. CdMnTe PiN structures were grown by MBE with 15 10nm CdTe quantum wells. Photovoltage spectroscopy studies of cells with and without the modified interlayer showed a sharp cut-off at 700nm (1.77eV) for those without and 800 nm (1.55eV) for those with the quantum well structure. The extension in the absorption and corresponding increase in the photovoltage was attributed to absorption of light within the CdTe quantum well structures. Devices employing this type of structure would then exhibit a higher quantum efficiency approaching the theoretical maximum.

The 8th International Conference on II-VI Compounds and Devices will be held at Grenoble in 1997.

See page 37 for a report from the 1995 North American MBE Conference.

Research Review

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

Compound Semiconductor Materials

Growth of GeSn/Ge strained layer superlattices

The unstrained $Ge_{1-x}Sn_x$ alloy is expected to have a direct energy gap and show high electron mobilities for Sn mole fractions ranging from 0.2 to 0.7, and even at lower Sn concentrations for strained layer structures. Research in the area has been fueled by the prospect of an "all-group IV" material system for optoelectronic devices. Despite difficulties such as a large lattice-mismatch between Ge and Sn, and the potential surface segregation of Sn during growth, the feasibility of growing fully strained metastable single crystal $Ge_{1-x}Sn_x$/Ge layers by low-temperature ($T < 150$°C) MBE has been demonstrated for $x < 0.24$. Work performed at University of Illinois [Urbana, IL] and Linkoping University [Liknoping, Sweden]. See "Growth of metastable $Ge_{1-x}Sn_x$/Ge strained layer superlattices on Ge(001)2x1 by temperature-modulated molecular beam epitaxy", O. Gurdal et al, Appl. Phys. Lett. 67(7), 956 [14 August 1995].

Resonant tunneling through ErAs quantum wells

The co-integration of epitaxial metallic (or semi-metallic) layers and compound semiconductors for applications such as buried Schottky contacts or permeable base transistors hangs on the availability of thermodynamically stable (semi)metal/ semiconductor heterostructures. Thin ErAs semi-metallic quantum wells clad by 20 Å AlAs layers and n+ GaAs electrodes were grown by MBE. The ErAs well and the overgrown semiconductor layers were grown at a substrate temperature of 450 and 500°C, respectively. The overgrown GaAs layers were found to be somewhat defective, but resonant tunneling devices were nevertheless successfully fabricated. The devices exhibited negative differential conductance (with the top contact positively biased) for temperatures up to 150K. The asymmetry in the device characteristics arises from the defective layers grown above the ErAs well. Work performed at University of California [Santa Barbara, CA], University of Minnesota [Minneapolis, MN], and Arizona State University [Tempe, AZ]. See "Resonant tunneling through ErAs semimetal quantum wells", D.E. Brehmer et al, Appl. Phys. Lett. 67(9), 1268 [28 August 1995].

2-D gas in GaN/AlGaN heterostructures

$GaN/Al_{0.1}Ga_{0.9}N$ 2DEGs were fabricated using trimethylamine-alane (TMAA) as the aluminum precursor in a low pressure MOCVD system. The absence of Al-C bonds in TMAA is expected to lead in a reduction of carbon and oxygen incorporation in the epitaxial layers as compared to when triethylaluminum (TEAl) is used as the Al precursor. In the present experiment, $GaN/Al_{0.1}Ga_{0.9}N$ 2DEGs grown with TMAA at 76 Torr and 1000°C displayed low temperature (150K) electron mobilities as high as 5,000 cm^2/Vs, and represent an improvement by a factor of 3 relative to similar structures grown with TEAl as the Al precursor. However, SIMS analysis of the AlGaN layers revealed that the background carbon and oxygen levels were nearly identical for layers grown with TMAA and TEAl. The use of TMAA resulted in an improved photoluminescence efficiency in AlGaN/GaN samples. Both the improved low temperature mobility and the improved PL efficiency were attributed to an improvement of the AlGaN/GaN interface quality associated with the use of TMAA. Work performed at APA Optics [Blaine, MN] and University of Virginia [Charlottesville, VA]. See "Two-dimensional electron gas in GaN-AlGaN heterostructures deposited using trimethylamine-alane as the aluminum source in low pressure metalorganic chemical vapor deposition", M. A. Khan et al, Appl. Phys. Lett. 67(10), 1429 [4 September 1995].

Sub-half-micrometer pseudomorphic InGaAs/InP HEMT's with very high f_T values

Aluminum free strained channel $InP/In_xGa_{1-x}As/InP$ HEMT's with channel indium compositions of 0.74 and 0.81 were grown by low-pressure MOVPE at 20 mbar and 640°C with standard sources for layer materials, and with H_2S and DEZ for n- and p-type doping. It was reported that 0.3 µm gate Al-free $InP/In_xGa_{1-x}As/InP$ HEMT's were characterized by off-state breakdown voltages VDSbr(OFF) of 10.5 V, which are considerably higher than what is usually achieved in conventional $AlInAs/In_xGa_{1-x}As/InP$ HEMT's with a similar gate length. The improved high breakdown voltages were achieved by keeping the quantum well thin, by using a p+ InP thin layer to enhance the gate Schottky barrier height, and because the valence band offset in the $InP/In_xGa_{1-x}As$ system (0.4 eV) is twice as high as that in the AlInAs/GaInAs case (0.2 eV). Work performed at Institute fur Halbleitertechnik [Aachen, Germany]. See "Sub-half-micrometer pseudomorphic $InP/In_xGa_{1-x}As/InP$ HEMT's with very high f_T values", A. M. Kusters et al, IEEE Electron Device Letters 16(9), 396 [September 1995].

InAs-InAsSb Type II Superlattice Midwave Infrared Lasers Grown on InAs Substrates

Stimulated emission near 3.4 µm was been observed with CW optical pumping at temperatures as high as 95 K in midwave infrared (MWIR) laser structures-based on a staggered (aka "type II") lineup $InAs-InAs_xSb_{1-x}$ superlattice (SL) active region. The SL laser active layers were grown on nearly lattice-matched InAs substrates by modulated beam MBE at temperatures of 480 to 500°C, using cracked arsenic and antimony sources. $AlAs_{0.16}Sb_{0.84}$ cladding layers were used to provide both optical and carrier confinement for the SL active layer. Equivalent threshold current densities of 3.3 A/cm^2 and 56 A/cm^2 at 5 K and 95 K suggest a laser characteristic temperature T_0 of 32 K. Because of the staggered band lineup at $InAs/InAs_xSb_{1-x}$ interfaces, electrons and holes tend to be spatially separated with holes residing in the $InAs_xSb_{1-x}$ layers -however, a small electronic effective mass leads to extended conduction band states that result in a relatively good electron and hole wavefunction overlap in the growth direction. The longest measured lasing wavelength was 3.4 µm with a pumping power of 500 mW at 40 K.

The large band offset value between InAs and InSb suggests that wavelength as long as 5 µm could be achieved even with relatively low antimony mole fractions (~12 %): the low Sb content should permit the growth of the superlattices without running into severe lattice-mismatch limitations. Indeed, room temperature PL measurements revealed emission at 5.2 µm in properly designed samples. One interesting feature of the staggered gap $InAs-InAs_xSb_{1-x}$ superlattice system for MWIR laser applications is that the degree spatial separation of electrons and holes, and the compressive strain in the ternary layers can likely be engineered to tune out the Auger recombination mechanism that has proven so deleterious in long wavelength lasers.

Work performed at Hughes Research Laboratories [Malibu, CA]. See "$InAs-InAs_xSb_{1-x}$ Type II Superlattice Midwave Infrared Lasers Grown on InAs Substrates", Y.-H Zhang et al, IEEE Journal of Selected Topics in Quantum Electronics 1(2), 749 [June 1995].

Electronic Circuits and Devices

2-Dimensional MESFET

A 2-Dimensional MESFET utilizing sidewall Schottky contacts on either side of a very narrow 2-D electron gas is described. These devices were fabricated on pseudomorphic AlGaAs/InGaAs heterostructures which exhibited a room temperature mobility, and sheet carrier concentration, of 6000 cm^2/V-s and $2x10^{12}$, respectively. Pt/Au Schottky gates were defined by E-beam lithography and applied to the sides of the device active area. Transconductances of 295 and 130 mS/mm were achieved in 1.0 and 0.5 µm devices, respectively. Ring oscillator simulations predict a power-delay product of less than 0.1 fJ/gate for room temperature operation, which would make this power-delay product amongst the lowest for any FET technology, suggesting that this device may be applicable for ultra low power electronics. Work performed at University of Virginia [Charlottesville, VA]. See Narrow Channel 2-D MESFET for Low Power Electronics," William C.B. Peatman et al, IEEE Transactions on Electron Devices, 42(9), 1569 [September 1995].

Normally-off GaN MODFETs

Wide-bandgap GaN devices are expected to be able to operate successfully at high temperatures and in chemically hostile environments, due to this material's excellent thermal conductivity, reduced concentration of intrinsic carriers, large electron saturation velocity, large breakdown voltages, and resistance to caustic chemicals. A GaN-based MODFET grown on sapphire is described, with gate and channel lengths of 3 and 5 µm, respectively, which exhibits extrinsic transconductance of 120 mS/mm at a current of 300 mA/mm and a gate bias of 3 V. This device yields extrinsic transconductances 3-5 times greater than similar MODFETs with gate lengths ranging from 1.0 µm to 0.23 µm, as well as exhibiting a sheet carrier concentration of 10^{13} cm^{-2}, which is some 3-5 times greater than MODFETs fabricated in the AlGaAs/GaAs and AlInAs/InGaAs systems. Work performed at University of Illinois [Urbana, IL]. See "High Transconductance-Normally-Off GaN MODFETs," A. Ozgur et al, Electronics Letters, 31(16), 1389 [3 August 1995].

A DC-10 GHz HBT low noise direct-coupled amplifier

Low Noise direct-coupled microwave amplifiers are useful for high data-rate (Gbps) optical communications, instrumentation, ISM wireless applications, cellular telephone and satellite receiver applications. An AlGaAs/GaAs MBE-grown HBT is described which exhibits a nominal gain of 22.5 dB and a noise figure of 3.0-3.65 dB over a dc-10 GHz band, while consuming less than 55 mW of dc power through a 5 V supply. This is the lowest reported noise figure to date for a direct-coupled HBT amplifier at X-band frequencies. Because the amplifier can be compacted into a 0.3x0.3 mm^2 area, a 3-inch GaAs wafer can yield as many as 30,000 die, making this device applicable as a standard off-the shelf microwave product suitable for high volume commercial applications. Work performed at TRW [Redondo Beach, CA]. See "A DC-10 GHz High Gain-Low Noise GaAs HBT Direct-Coupled Amplifier," K.W. Kobayashi et al, IEEE Microwave and Guided Wave Letters, 5(9), 308 [September 1995].

A high power GaAs RF switch for digital mobile communications systems

The need for integrated receive/transmit switches is being driven by the rapid growth of cellular communications. GaAs-based monolithic switch ICs that can operate with nearly zero power dissipation have been recently developed, but exhibit some distortion of the waveform as the transmitting power is increased. In this work, a high power GaAs monolithic RF switch IC is described which can handle powers of up to 5 W, with a control voltage of 5 V, while exhibiting an insertion loss of less than 0.8 dB at 1 GHz. This high power performance was achieved by using a novel circuit configuration that makes possible the feeding forward of the signal to the gate of the shunt FETs. Work performed at Matsushita Electronics Corporation [Osaka, Japan]. See "A GaAs High Power RF Single Pole Dual Throw Switch for Digital Mobile Communication System," Kazuo Miyatsuji et al, IEEE Journal of Solid-State Circuits, 30(9), 979 [September 1995].

A 4.5 kV silicon carbide rectifier

SiC's large bandgap (3 eV in 6H-SiC), high thermal conductivity, high breakdown voltages and high saturated electron drift velocity make it suitable for high power, high temperature device applications. A reactive ion etched SiC mesa pin diode fabricated with CVD and grown on 6H-SiC is described, which exhibits a voltage blocking capability as high as 4.5 kV - twice as large as the previous best reported value. The epitaxial structure consists of a low-doped ($1x10^{15}$ cm^{-2}) 45 µm thick n- active base layer and a 1.5 µm thick highly doped ($1x10^{18}$ cm^{-3}) emitter layer on top. A high minority carrier lifetime of 0.43 ms is obtained in the base region, while a typical forward voltage drop of 6 V at 100 A/cm^2 is observed. Work performed at Linkoping University [Linkoping, Sweden]. See "A 4.5 kV 6H Silicon Carbide Rectifier," O. Kordina et al, Appl. Phys. Lett., 67(11), 1561 [11 September 1995].

Epitaxial Lift-Off Applied to HBTs

Integrating semiconductor devices with different functions, structures and materials on the same substrate offers the potential for greater flexibility in device and circuit operation. Researchers at the National Chiao Tung University [Hsinchu, Taiwan, ROC] have recently demonstrated for the first time the transfer of GaAs/AlGaAs HBTs from a host GaAs substrate to a Si substrate using the epitaxial lift-off (ELO) technique. This technique was demonstrated for both a preprocessed HBT layer, in which HBT fabrication took place prior to the film being bonded to the Si substrate, as well as to a postprocessed HBT structure in which the HBT was fabricated after being bonded to a Si substrate. Both devices exhibited nearly identical transistor characteristics and Gummel plots, demonstrating that the ELO technique did not degrade the preprocessed device. HBTs with current gain of 550 were transplanted to a Si substrate without showing any degradation, where this current gain is the highest reported for a GaAs HBT on Si substrate by any technique. See "AlGaAs/GaAs Heterojunction Bipolar Transistors on Si Substrate Using Epitaxial Lift-Off," J.C. Fan et al, IEEE Electron Device Letters, 19(9), 393 [September 1995].

In addition to transfering devices to different substrates, the ELO technique can also be used to remove the substrate and then permit processing to the underside of the device in order to enhance device performance. In HBTs, one of the primary limitations to increasing the power gain cut-off frequency, f_{max}, is the large base-collector capacitance, C_{cb}, which is an artifact of the self-aligned mesa structure approach typically employed in HBT fabrication. In a recent work reported by the University of California [Santa Barbara, CA], an AlInAs/InGaAs collector-up HBT was grown by MBE on InP. A 1 µm wide Schottky-contact (Ti/Pt/Au) is used to contact the collector, and then the wafer is inverted, expoxied to a GaAs substrate, and the InP substrate removed by selective etch. The emitter and base structures are then fabricated above the Schottky contact defiend collector. This device was compared to a conventionally mesa fabricated HBT with a 11 µm wide collector, in which little difference was observed in the current-gain cuttoff frequency, f_t, while the f_{max} of the Schottky defined collector was improved by a factor of 2.5 from 24 to 61 GHz, this improvement reflective of the reduced C_{cb}. It is estimated for an optimized HBT structure using this processing approach, that an f_{max} value approaching 500 GHz may be obtained.

Work performed at University of California [Santa Barbara, CA]. See "Transferred Substrate Schottky-Collector Heterojunction Bipolar Transistors: First Results and Scaling for High f_{max}," U. Bhattacharya et al, IEEE Electron Device Letters, 16(8), 357 [August 1995].

New Record for Laser Diode Threshold Current Density

A laser diode with a threshold current density of 44 A/cm^2 was recently reported. This result is the lowest room temperature threshold current density for a diode laser in any material system. The result was obtained in a 3 mm long laser with an InGaAs/GaAs strained quantum well that emitted at a wavelength of 987 nm. Shorter cavity lengths of 1 mm and 400 microns produced threshold current densities of 61 A/cm^2 and 83 A/cm^2, respectively. The internal loss of the laser was measured to be 0.70 cm^{-1}. This exceptionally low loss is attributed to the very high quality of the material. The material was grown by a molecular beam epitaxy (MBE) machine that had demonstrated in other studies the growth of extremely pure GaAs. The MBE growth was somewhat unconventional, using the arsenic dimer species and growth temperatures ~50°C lower than those typically used for these materials. In addition to producing high quality material, the low growth temperature has the benefits of essentially eliminating problems associated with diffusion of the p-type dopant, beryllium, and with the desorption of gallium. The elimination of beryllium diffusion avoids free carrier loss caused by unintentional p-type doping of the laser core. The elimination of gallium desorption removes substrate temperature non-uniformity as a cause of emission wavelength variations across the wafer. In this study the center 40 mm of the wafer exhibited a total wavelength variation of only 2 nm.

Work Performed at National Research Council [Ottawa, ON, Canada] and Imperial College [London, UK]. See "Extremely Low Threshold Current Density InGaAs/GaAs/AlGaAs Strained SQW Laser Grown with As$_2$", M. Dion et al, to be published in Cdn. J. Phys.

Optoelectronic Devices

AlGaAs laser diodes frequency doubled to the violet with high efficiency

Frequency doubling of AlGaAs laser diodes is one of the methods being pursued for the construction of robust, compact solid state blue and violet light sources. Advances in the efficiency of such frequency doubling schemes depend on improved peak power densities from laser diodes as well as improved nonlinear optic materials and structures. A recent result produced 22 microwatts of 417 nm second harmonic by using a 1 cm long LiTaO$_3$ waveguide to frequency double a 2.2 mW AlGaAs laser diode. The nonlinear coefficient of the waveguide was periodically changed in sign by using proton exchange to create a grating that enables quasi-phase matching. The laser diode used a 23 cm external cavity and was driven with a strong RF modulation at 650 MHz. The conversion efficiency of this work is among the highest performances reported to date for frequency doubling laser diodes. Work performed at CNRS and Thomson-CSF [Orsay, France] See "High second-harmonic conversion efficiency of quasi-phase-matched LiTaO$_3$ waveguides pumped by single-mode pulsed AlGaAs laser diodes", A. Azouz et al, Appl. Phys. Lett. 67(16), 2263 [16 October 1995].

High efficiency green, blue and violet LED's

The efficiency record of short wavelength LED's improves almost monthly. The latest record has been produced by using devices containing strained single quantum wells of $In_xGa_{1-x}N$. Green (520 nm wavelength), blue (450 nm) and violet (405 nm) emission is produced by devices with indium compositions, x, of 45%, 20% and 9%, respectively. Green, blue and violet LED efficiencies are 6.3%, 8.7% and 9.2%, respectively. These are the highest efficiencies reported to date for short wavelength LED's. The nitride materials were grown by metalorganic vapor phase deposition on sapphire substrates. In addition to the improved efficiencies of these LED's, the use of quantum well active layers has caused a narrowing of the linewidths of the emission spectra down to 20-25 nm. The result is better spectral purity, important in full color displays. Work performed at Nichia Chemical Industries [Tokushima, Japan]. See "High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes", S. Nakamura et al, Appl. Phys. Lett. 67(13), 1866 [25 September 1995] and "Superbright Green InGaN Single-Quantum-Well Structure Light-Emitting Diodes", S. Nakamura et al, Jpn. J. Appl. Phys. 34, L1832 [15 October 1995].

Wide, continuous tuning of a single mode monolithic DBR laser

Single mode semiconductor lasers that are monolithic and tunable over a wide wavelength range have important applications, such as communication networks and fiber sensors. Thermal tuning in easy, but slow. Many tuning schemes mode hop, thus the tuning is not continuous. A recent result uses a gain section and phase shifter section between two distributed Bragg reflectors (DBR's). The DBR's are built of super-structure gratings consisting of 9 repetitions of segments that each contain 5 sections with slightly different grating periods. The result is a DBR with a low ripple reflectivity spectrum and a 60 nm linewidth. Tuning is accomplished by varying the current into the DBR's. Total wavelength tuning was reported to be 60 nm, with continuous tuning over 40 nm. This is the widest reported continuous tuning of a monolithic diode laser. The lasing wavelengths were in the range of 1.57 microns. Work performed at Royal Institute of Technology [Kista, Sweden]. See "Complete Single Mode Wavelength Coverage Over 40 nm with a Super Structure Grating DBR Laser", M. Oberg et al, J. of Lightwave Technology, 13(10), 1892 [10 October 1995].

High speed photodetectors for 1.3 micron wavelengths

Photodetectors with bandwidths above 100 GHz at 1.3 micron wavelengths are needed for ultrafast optical communications and measurement. Such detectors were reported several years ago in waveguide geometries, but only recently in vertically illuminated devices. The epitaxial structure of the detector consisted of an n-InP / i-GaInAs / p-InP double heterostructure. Hole trapping at the i-GaInAs / p-InP interface and p-contact resistivity limited the speed of similar earlier devices. These problems were alleviated in the present structure through the use of graded bandgap superlattices inserted between the main layers of the detector. The result was a 3-dB bandwidth of 110 GHz and a quantum efficiency of 32% at 1.3 microns. Work performed at University of California [Santa Barbara, CA] and Colorado State University [Fort Collins, CO]. See "111-GHz GaInAs/InP Double Heterostructure p-i-n Photodectors", Y-G Wey, et al, J. of Lightwave Technology, 13(7), 1490 [7 July 1995].

Self-pulsating diode lasers with quantum well saturable absorbers

The use of self-pulsating lasers is of potential benefit in applications such as disk readout where optical feedback causes excessive noise. Previous approaches for the construction of self-pulsating diode lasers have required lasers with two different longitudinal sections, one for gain and one for saturable absorption, and relatively complicated processing. A novel approach uses a saturable absorbing layer that is embedded inside the p-type cladding layer of the laser. The devices exhibit stable pulsations in the frequency range of 300 - 700 MHz. Work performed at Eindhoven University and Philips Optoelectronics Centre [Eindhoven, The Netherlands]. See "Self-pulsating lasers with quantum well saturable absorber", R.C.P. Hoskens et al, Appl. Phys. Lett. 67(10), 1343 [4 September 1995]

1995 North American Conference on Molecular Beam Epitaxy

University of Maryland, College Park
Maryland, September 17-20, 1995

Novel MBE Growth Techniques Produce both Self-Assembled and Pattern-Induced Structures which Exhibit Unique Physical Properties.

ROBERT A. METZGER

Presentations at the 15th North American MBE Conference covered the full spectrum of MBE-related topics, including the growth of III-V, II-VI, SiGe, and nitrides, and showing what impact MBE growth had on both electronic and optical devices. Interspersed amongst the different sessions was a recurring theme - that of expanding the limits of conventional MBE, to investigate both new growth approaches, and the materials and structures that could be produced from them. These new approaches fell into two general categories: those of novel self-assembling structures, driven by MBE growth parameters; and pattern and strain induced growth variations induced by artificially altering the stress and strain that a growing layer experiences, often by incorporating topography in a substrate. It will be those works highlighted in this report.

Self Assembled Structures

Three-Dimensional (3D) growth in MBE has generally been considered unsuitable for device fabrication, resulting in highly defected material, but in the early 1990s it was found that in some cases that SiGe/Si and InGaAs/GaAs strain induced islands would form Quantum Dots (QDs) that could be kept free of dislocations. Under dislocation free conditions, the electronic and optical properties of QDs will exhibit little inhomogeneous broadening, making them applicable for electronic/opto applications.

Glenn Solomon of Stanford University [Stanford, CA] presented work on InAs island growth on GaAs. Strain-induced islanding occurs through the Stranski-Krastanov (S-K) growth mode in which mismatched epitaxy is initially accommodated by biaxial compression in a layer-by-layer growth region that is often referred to as a wetting layer, and then proceeds to the point where heteroepitaxial islanding becomes more energetically favorable than planar growth. Figure 1 shows AFM images of InAs island growth on GaAs at 500°C, for coverages ranging from 2 to 6 monolayers (ML), illustrating islanding evolution from small isolated islands occurring at 2 ML coverage to a fully coalesced island phase occurring at 6 ML. Using 3 equivalent ML of InAs grown at 500°C under a low V/III ratio of 9 to increase island density, Solomon and coworkers were able to produce islands with heights of 50 Å and diameters of 180Å. It was found that by inserting 56 Å GaAs spacer layers between InAs layers, that the islands have a tendency to vertically align themselves, with Solomon and coworkers observing up to ten aligned InAs islands layers stacked atop each other. It is believed that the local strain relaxation that occurs by islanding in one layer facilitates preferential island formation directly on top of islands in subsequent layers. The islanding process not only reduces the interface energy by limiting the contact of InAs with the GaAs underlayer, but allows the InAs free surface to partially relax. Photoluminescence (PL) performed at 8 K, shows that by increasing the number of InAs island layers, that the PL peak position shifts to lower energies, while the peak intensity increases and the spectral linewidth decreases. Five InAs layers saw a shift of 31 meV, with 10 layers showing an additional 24 meV shift, where this shift in PL is attributed to vertical coupling between aligned InAs islands.

In similar work, Qianghua Xie and coworkers from USC [Los Angeles, CA] also studied InAs islanding formation on GaAs, in which they determined that the transition from 2D to 3D growth occurred at a InAs coverage of 1.8 ML. Like Solomon and coworkers, they observed the coalescence of smaller InAs islands into larger islands as InAs deposition was increased. At 1.8 ML InAs coverage they observed 11 islands/μm^2 which quickly increased to 327/μm_2 at 2.0 ML and then increased slowly to 600/μm^2 at 2.5 ML as individual islands began to grow in size. Also like Solomon and coworkers, they observed that the InAs islands could be vertically stacked (see Figure 2) when each InAs layer was interlaid with a 36 ML GaAs spacer. In addition, they observed that for the case of 5 InAs island layers, that strain was relieved by microtwins approximately every 0.5 µm as shown in Figure 2. PL of the stacked layers exhibited a shift to lower energies, as well as showing an increase in output intensity, where for the case for 5 stacked InAs layers using the 36 ML GaAs spacer, the integrated PL intensity increased by a factor of 10 - suggesting that insertion of this structure into a laser structure may increase laser output. As shown in the TEM in Figure 3, laser structures have been fabricated incorporating a 5 layer InAs island

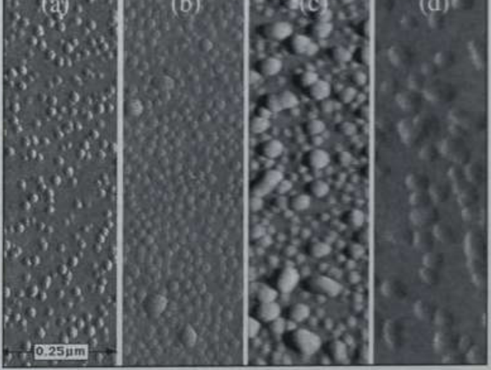


Figure 1. AFM images of InAs islands grown at 500°C with equivalent monolayer coverages of (a) 2 ML, (b) 3 ML, (c) 4 ML and (d) 6 ML, displaying the transition from the isolated island phase to the fully coalescent phase. Courtesy of Glenn Solomon - Stanford University [Stanford, CA].

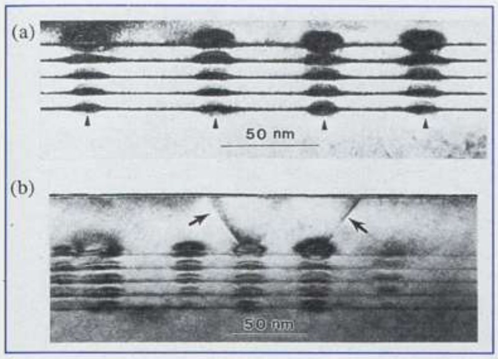


Figure 2. Panel (a) shows a dark field TEM image showing 5 stacked InAs islands separated by 36 ML GaAs spacer layers. Panel (b) shows a bright field image which delineates microtwins originating from the region close to the edges of InAs islands on the topmost set.

structure. This structure is currently being evaluated.

Keming Chen and coworkers at Oak Ridge National Laboratory, investigated the use of post growth annealing to nucleate and grow islands in the SiGe material system. For this work, 2 nm thick $Ge_{0.5}Si_{0.5}$ was grown by MBE at 400°C on Si - giving a 2% compressive strain. As determined by annealing experiments, it was found that the rate limiting step in the transition from 2D to 3D growth arises from an energy barrier to the transition, rather than from mass transportation via surface diffusion, as was evidenced by a sharp 2D-3D transition upon annealing at 560°C. Once islands started to grow, it was observed that there was a self-limiting behavior at later stages of island growth, i.e. the resistance of large islands to further growth. This behavior results in a narrow distribution of island sizes, which is important for QD formation, so that the optical and electronic quantum effects arising from the size of the QD, are uniform across all the QDs, making them more suitable for device applications.

Other material systems were investigated for the study of island formation, including InSb, AlSb, and GaSb on GaAs by Brian Bennett and coworkers at the Naval Research Laboratory [Washington DC]. They found that the onset of dot formation occurs after 1.5 ML of InSb or 2.5 ML of GaSb has been grown on GaAs by Migration Enhanced Epitaxy (MEE). 2 ML of InSb produced dots of 8 nm in height and 120 nm in diameter as determined by STM and with a diameter of 76 nm as determined by AFM (these differences are due to differences in probe tips used in STM and AFM). Between these relatively large islands were observed monolayer height islands or "platelets" of about 10 nm in diameter, which Bennett and coworkers believe are a precursor to QD growth. No Moire fringes (which are characteristic of dislocations) were observed for 2 ML of InSb deposition, indicating that the resultant QDs are coherently strained. 3 ML of GaSb growth produced QDs which exhibited a PL spectrum which was shifted 140 meV lower in energy, while seeing no increase in integrated intensity. In addition, Raman spectroscopy was used to investigate the chemical composition of the dots, where it was observed that Ga can segregate into AlSb dots.

Pattern and Strain Induced Growth Variations

Another method of obtaining spatial variation of material properties, is by physically altering the substrate, either by insertion of topography, or modifying its physical properties in such a way that the substrate can accommodate or alter the strain that a mismatched MBE grown film would experience.

April Brown, Carrie Carter, and coworkers from the Georgia Institute of Technology [Atlanta, GA] presented results on initial investigations of using thin film compliant substrates fabricated by epitaxial lift-off or substrate removal, and then bonding these compliant substrates to a mechanical host substrate for MBE growth. When this approach is coupled with patterning of the bonded surface to realize a lateral thickness variation, lateral strain variation in the a growing mismatched MBE layer can be obtained, which in turn can be used to modify MBE growth kinetics, such as cation desorption and migration. It was shown that growth of $In_{0.1}Ga_{0.9}As$ of 2000 Å and 4000 Å thicknesses on 2500 Å GaAs compliant substrates, exhibited less slip and cross hatching as observed by Nomarski microscopy, compared to identical films grown on 500 mm control substrates. This reduction in slip and cross hatching demonstrated the partial accommodation of strain generated by the mismatched InGaAs layer by the thin (2500 Å) compliant substrate.

It has been observed that the PL from epitaxial layers grown on ridges and grooves of patterned substrates with (n11) side walls, result in red shifted (lower energy) emissions. Kishore Kamath and coworkers at the University of Michigan [Ann Arbor], show that for the case of vertical sidewalls obtained by reactive ion etching, that PL does not shift to lower energy, but actually shifts to higher energy. They believe that the vertical side-walls act as kink sites for the migrating adatoms, instead of sources as in the case of (n11) side walls. A blue shift (higher energy) of up to 50 meV has been observed for InGaAs/GaAs QWs, where InGaAs is good candidate to see effects induced by variations in adatom migration lengths, since at typical growth temperatures, In adatoms diffuse approximately 25 μm while Ga adatoms diffuse only 1-2 μm. Growth on (n11) surfaces experience excess In on ridges and grooves due to this difference in adatom migration length. Kamath and coworkers grew 60 Å $In_{0.2}Ga_{0.8}As$ QWs on GaAs substrates which had ridges and grooves with dimensions and spacings ranging from 5 to 25 μm. They believe that a net indium migration towards, and subsequent incorporation at the vertical side-walls, is responsible for the indium depletion induced blue shift that is observed inside the groove areas. Unlike the bottom of the grooves, it is observed that PL from the top of the ridge is the same as that from large unpatterned areas. This demonstrates that a single growth can be used to obtain two different bandgap materials. The blue shift depends on the number of sinks within a distance of adatom migration length.

Mike Melloch and coworkers of Purdue University [West Lafayette, IN] show that preferential movement of As precipitates (formed during annealing after low temperature GaAs growth) into the wells of MQWs with 10 nm GaAs QWs and AlAs barriers which ranged from 2 to 3.5 nm, can be accomplished without degrading the excitonic features of the QWs. It was demonstrated that by using a combination of Low Temperature Growth (LTG) to create excess As, and Migration Enhanced Epitaxy (MEE), that QWs could be grown which exhibited sharp excitonic features, but experienced a reduced lifetime as compared to QWs without the inclusion of As precipitates. Lifetimes as low as 6 ps were obtained for As precipitate filled QWs, making these structures suitable for ultra-fast photorefractive, electro-optic sampling and saturable absorption applications.

All these novel growth techniques expand the capabilities of MBE, offering new directions, and thereby more flexibility in device design and subsequent operation.

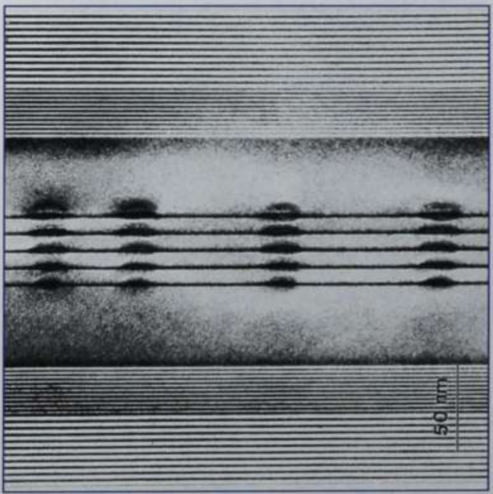


Figure 3. TEM image of an edge emitting laser structure with 5 sets of Vertically Self-Organized Growth (VSOG) induced InAs islands used as the active material.

A Retrospective on the MIMIC Program

ARPA's program made invaluable contributions to the infrastructure of the American GaAs industry.

ROBERT A. METZGER

Until recently the design, fabrication and testing of GaAs ICs for applications in the microwave and millimeter wave range was largely experimental, and extremely costly. In the mid 1980's the US Department of Defense (DoD) recognized that future military systems requirements could only be met through the establishment of affordable GaAs-based monolithic microwave integrated circuit (MMIC) capability - and therefore the "Microwave and Millimeter Wave Monolithic Integrated Circuits" (MIMIC) Program was initiated by the Advanced Research Projects Agency (ARPA).

From 1987 until earlier this year more than 50 different companies and research labs participated in the four-phase program. Its primary goal was to facilitate the fabrication of sophisticated MMICs for military requirements. In the course of pursuing that objective the program contributed to infrastructure enhancements for GaAs IC manufacturing in the areas of materials, devices, CAD, packaging and testing. The investment was relatively modest - $531 million over eight years. In return, the US government gained lower costs and greater sophistication for vital military electronic systems while several American manufacturing companies gained valuable expertise that will allow them to assume leadership positions in the rapidly growing RF and microwave electronics fields.

Accomplishments

Before the advent of the MIMIC program, a typical GaAs boule produced 20-40 2" inch substrates. Today 3" and 4" inch diameter GaAs substrates are standard, and more than 100 wafers are obtained per boule. 6" diameter wafers are becoming available as well. M/A-COM [Lowell, MA] and Litton/Airtron [Morris Plains, NJ] benefited greatly from the MIMIC program, and both companies now produce more than 800,000 in^2 of GaAs a year. Robert Ochrym of Litton/Airtron, comments that "MIMIC was the right program at the right time for the GaAs IC industry, and critical for our success."

In devices the state of the art in the mid-1980s was defined by 0.5 µm MESFETS. By the end of the program, this had given way to MESFETs and HEMTs with 0.1 µm gates, and HBTs with 2 µm emitters. HEMTs are now being used in W-Band (75-110 GHz) amplifiers with single stage gains of 6 dB and noise figures of 4-5 dB, while X-Band (7-11 GHz) power amplifiers based on HEMTs and HBTs are capable of producing up to 6 watts at 40% power added efficiencies (PAEs).

One of the major advances of the MIMIC program was reduction of the area of GaAs required to perform a given electrical function. Eliot Cohen, former ARPA program manager for MIMIC says "that this compaction of

The MIMIC Program

The primary objective of the Microwave and Millimeter Wave Monolithic Integrated Circuits (MIMIC) Program was to develop high performance, affordable, and available microwave and millimeter wave technology for building electronic systems to meet the needs of the US Department of Defense. It was ARPA's desire to provide a technology push to focus resources in DoD applications, develop high leverage chip sets for critical DoD systems, and to establish MMIC production capability in the U.S.

The program was divided into four phases: **Phase 0** ($12 million January 1987 - January 1988) - This phase represented a one year study and program definition effort, performed by 16 contractor teams whose objective was to help determine the scope and details of the MIMIC program.

Phase 1 ($235 million May 1988 - May 1991) - This three year effort was aimed at developing and integrating the technology necessary to achieve the affordability and performance required for MMICs to be used in the systems to be fabricated in Phase 2. This material/technology effort focused on CAD/CAM, packaging, establishment of pilot lines and foundries, chip and module fabrication, system brassboards, and first use of MMICs in fielded systems. 27 companies divided into four contractor teams participated in this effort.

Phase 2 ($228 million August 1991 - June 1995) - This four year effort continued the technology and product developments begun in Phase 1. Cost reduction of MMICs, circuit compaction and advanced widespread system demonstrations were the focus of this phase. 24 companies divided into three contractor teams participated in this effort.

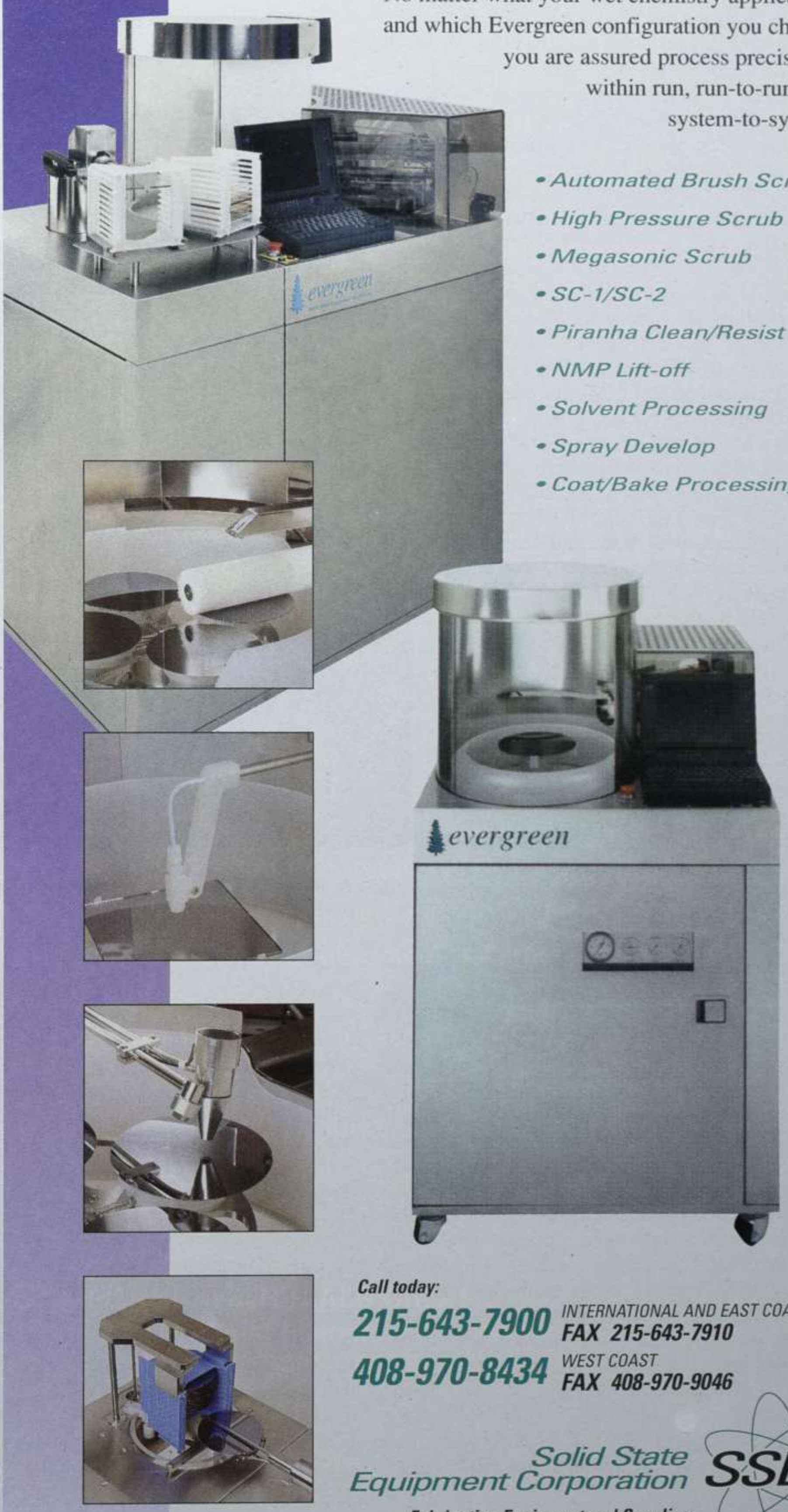
Phase 3 ($56 million January 1987 - December 1994) - Running concurrently with the other phases of the program, this phase was comprised of highly focused technology efforts aimed at increasing the probability that the MIMIC program would succeed. 26 companies participated in this effort.

A total of 57 different companies and research organizations participated in the program over its eight year span.

circuits has resulted in substantial cost reductions through much more effective use of GaAs real estate." For example: "between December 1991 and mid-1993, the cost of a low noise amplifier produced by M/A-COM was reduced from $80 to $13.50, where a major part of these savings occurred because four amplifiers are now being produced in the space previously needed for one." Packaging was also addressed. Jim DiLorenzo of Raytheon [Andover, MA] says that, "conventional Ku-Band packages cost $5-10 in small quantity in the early 1990's, where due to such improvements as simplified brazed lead design (1993) and direct bonding to adhere a copper lead frame to ceramic (1994) they have given way to a very low cost Ku-Band plastic package which in 1995 is available at $0.21." Lisa Sobolewski, the current MIMIC program, manager says that "the cost of packages made from Fe-Ni has dropped by about a factor of 5 during the course of the MIMIC program, from $50 to $10 in large quantities."

Testing has also seen a dramatic reduction in cost, due to time savings. DiLorenzo comments that "in 1988, using standard commercial test equipment, complete testing of a T/R (transmit/receive) module took approximately 40 minutes at a given test temperature. In 1995, using DSP for IF processing and digitally phase locked synthesized signal generators, test times for the same modules are under 1 minute." In a similar fashion, he has seen test times for single chip packages and die on-wafer range from 3 to 5 seconds, down from 15 to 30 seconds. Under the MIMIC program, Cascade Microtech [Beaverton, OR] developed on-wafer probing systems for both V-band (50-75 GHz) and W-band (75-110 GHz). These probes typically operate with less than 4.0 dB insertion loss and a return loss better than 9 dB, and can be used in excess of 500,000 contacts before the probe tips need be replaced. According to John Pence of Cascade Microtech, "as military projects have been downscaled, commercial applications like automotive collision avoidance radar and local area communication networks (LAN) have created a new demand for this testing technology.

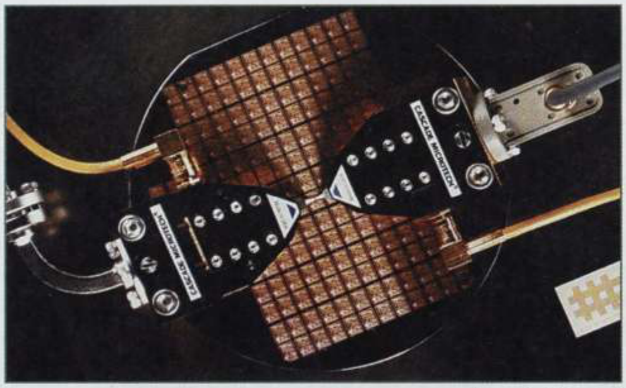
Because of the advancements in state of the art MMIC performance, as well as the establishment of a sound infrastructure, over 80 chip types were fabricated in Phase 1 of the program which were used in 16 MIMIC brassboards, while over 100 chips were fabricated in Phase 2 for use in 15 MIMIC brassboards and demonstrators. In addition, during the period of 1987 to 1995, the cost of solid state phased array modules for radar applications (a major insertion point for many MMICs) has seen a decrease in cost from $5000 to $1300. The many military systems using MMICs or planning to do so, include the Ground Based Radar system, airborne radars, AMRAAM, Gen-X, HARM and SCAMP.



Commercial Applications

It was not one of ARPA's direct objectives to establish a commercial MMIC capability in the US - but that is what happened. According to Sobolewski: "the primary objective of all ARPA programs is to meet the needs of the DoD. Commercial applications of the technology developed can be viewed as a bonus". In the current era of Federal budget cuts and military downsizing, the commercial applications for MMIC technology have become vital to the economic well being the MMIC manufacturers.

One of the best illustrations of "dual-use" (military & commercial) manufacturing is provided by HE Microwave [Tuscon AZ], a joint venture between Hughes Aircraft Company and Delco Electronics. They used processes developed under the MIMIC program to create a commercial radar system that warns school bus drivers of the presence of children in their "blindspots". This system uses an adaptation of HE Microwave's X-Band MIMIC radar chips. This MESFET-based radar operates at 10.5 GHz, and delivers 10 mW output at the antennas. According to Nick Morenc, Engineering Director of HE Microwave, "in essence, we have only one fabrication line at HE Microwave, where during any given week we might be doing military parts for 3 days and commercial parts for 2 days. Commercial and military parts use the same equipment, the some operators and the same procedures. The amount of time it takes to reconfigure the line between the military and commercial is on the order of 1/2 hour." Morenc finds that running commercial product on what had been a military fab line is actually an advantage to the overall production process. "Running commercial product increases the volume which runs on the line, where higher volume translates into higher yields as we continue to move up the production learning curve. As yields go up, the cost to produce the product goes down, and this means that the cost of military products actually goes down as a result of running the commercial products." New systems are currently being developed, including side detection systems operating at 24 GHz intended for trucks, and systems that would operate at 76-77 GHz for rear detection systems, forward-looking radar, and adaptive cruise control that monitors vehicles in the front of the driver and helps the driver to maintain a safe distance through limited braking and vehicle throttle control.



Cascade Microtech

Cascade Microtech's on-wafer W-Band (75-110 GHz) wafer prober.

Wireless communications is one of the the largest commercial uses of MIMIC technology. TRW [Redondo Beach, CA] performed extensive development in establishing HBT production capabilities to meet many of their MIMIC program circuit and system brassboard goals. According to Dwight Streit, assistant manager of the Microelectronics Product and Technology Development Department, and manager of the Advanced Materials Section, "we are currently shipping over 500,000 commercial HBT chips per month, built using MBE material that combines both low cost and high reliability." TRW HBT parts such as power amplifiers, CDMA chip sets, Darlington gain blocks and A/D converters are currently being inserted in high volume commercial products, including cellular phones, digital radio systems, local area networks, and digital oscilloscopes. Many of these commercial products are being offered through RF MicroDevices [Greensboro, NC]. One example is the RFMD 2103 HBT power amplifier which is suitable for use in cell phones and digital radio systems. It operates over a frequency range of 450-1000 MHz, delivering a maximum output power of 750 mW at 6.5 V, with a 47% PAE.

Many other MIMIC program participants are using their MMIC technology in commercial applications. Westinghouse Electronic Systems Group has adapted technology originally used in military fire-control radar systems, into their Modular Aviation Radar system (MODAR) intended to be used for air-transport weather radar. Raytheon is supplying HEMT-based chips for direct broadcast satellite receivers as well as MMICs for the Iridium Project, a joint venture between Motorola and Lockheed Martin that will provide worldwide cellular telephone service that is scheduled to be operational by the late 1990's. Texas Instruments is also spinning its MMIC technology into commercial areas, including, satellite communications, WLAN and cellular/PCS. (See Page 14.)

It is ARPA's belief that the MIMIC program has established a solid infrastructure for microwave monolithic integrated circuit technology. Two US GaAs substrate vendors are profitable and are selling material worldwide (M/A-COM and Airtron-Litton). US computer aided design vendors are profitable and dominate the world market for microwave CAD. More than six MIMIC program participants are providing MMIC foundry services to multiple customers worldwide. RF test equipment developed under MIMIC program sponsorship defines the state-of-the-art. The solid technology base developed under the MIMIC program has brought microwave monolithic circuits from experimental proof-of-concept demonstrations carried out in research and development laboratories to the status of the high yield, low cost, readily available products of today that are produced on highly automated fabrication lines. MMICs are contributing to improved communication capabilities (e.g. in wireless products and in transmission and reception to and from satellites, vehicle safety products (e.g. collision avoidance radar systems, and improved office equipment (e.g., wireless local area networks). A viable US microwave monolithic integrated circuit industry has indeed been established which will serve the needs of the microwave community for many years to come.

The Future

With the MIMIC program completed, ARPA is looking to the future in a new program, entitled "Microwave and Analog Front End Technology", or MAFET. (For news about the first award, see page 13.) According to Sobolewski "although the MIMIC program accomplished its goals and more, much work remains to be accomplished". Sobolewski says that "the top-level goals of this program are to: drive down system front-end costs, increase system capabilities, and enhance U.S. dominance in the world market. The MAFET program is sometimes incorrectly described as a follow-up to the MIMIC program. It is in fact a new undertaking. The confusion between the two stems from the fact that the MAFET program will naturally build upon the technology base that the MIMIC program established. And it is an impressive base. The MIMIC program permanently altered the US GaAs IC industry, leaving behind a rapidly expanding MMIC capability, which is not only finding its way into numerous commercial applications, but which also continues to meet the DoD's needs. In short, it was a success.

Thanks to Lisa Sobolewski and Eliot Cohen for their help in preparing this article.

Freiberger

Saxonian Accomplishment
for Highest Quality

QUALITÄTSSICHERUNG
GERMANISCHER LLOYD
QUALITY ASSURANCE

ISO 9001

Gallium Arsenide

substrates for micro and optoelectronics

○ Semi-insulating LEC-GaAs 2"- 4" diameter (6" under development)
○ Semi-conducting LEC-GaAs 2" and 3" diameter (n type (Te)/p type (Zn))
○ Bulk material with extremely low residual impurity concentration controlled carbon level and high uniformity of electrical parameters
○ One and double side polished wafers
○ Excellent surface quality for epitaxial growth processes (MBE, MOCVD)
○ Laser marking option
○ Comprehensive crystal and wafer characterization
○ Quick order turn around

FREIBERGER COMPOUND MATERIALS GmbH
Berthelsdorfer Straße 113, P.O. Box 211, D-09584 Freiberg/Sachsen, Germany
Tel.: (49) 37 31/27 85 72, Fax: (49) 37 31/27 82 34

Circle 3 on Reader Service Card

West-Europe except
Germany, Austria, UK & Ireland
Dr. Elie Prudhommeaux
Promecome
68, Av. du General Michel Bizot
F-75012 Paris
Tel.: (33) (1) 44 73 10 00
Fax: (33) (1) 43 46 85 92

United Kingdom & Ireland
Gerry Cooke
Semimat Ltd.
The Paddock, Waverley Avenue
Fleet, Hampshire
GU13 8NW UK
Tel.: (44) 1252 617 877
Fax: (44) 1252 812 362

USA
Donald J. Capo
FREIBERGER COMPOUND
MATERIALS/USA
68 John Dyer Way
Doylestown, PA 18901
Tel.: (1) 215-345-6445
Fax: (1) 215-345-6298

Republic of China
Albert Hong
V-TEK Co. Ltd.
No. 54, Lane 99, Sec 2, Tien Hsin Rd.
ROC-Taichung, Taiwan
Tel.: (886) 4527 4675
Fax: (886) 4527 8323

Korea
Jong Hyun Lee
Seokyo Commerce Co. Ltd.
Baekje Bldg. # 201
980 – 29, Bang Bae Dong, Seochoku Seoul
137 – 060, Korea
Tel.: (82) 2597 3961
Fax: (82) 2597 3964

NEW PRODUCTS

MESC Standard Modular Cluster Tool

Oxford Plasma Technology [Bristol, England] has introduced the Plasmalab System 100 modular cluster tool. It is designed primarily for R&D activities or ASICs production and is ideally suited to a production-oriented environment through its compliance with the MESC mechanical standard. Wafers up to 8" dia. or multiple smaller wafers can be accommodated. Processing capabilities include RIE, ECR, ICP, DSMW, PE, PECVD, RTP, PVD and ion beam etching and deposition. ***Circle 104 on Reader Service Card***

LPE System from General Air

General Air Corporation [Chatsworth, CA] has announced the availability of a new Liquid Phase Epitaxy Reactor for the growth of III-V alloys. It is designed to be an inexpensive tool for the development of opto-electronic devices. Features include high quality flow and temperature control devices, with gas lines fabricated from stainless steel tubing polished to RMS 14. Joints are VCR or Ultra-Torr type ensuring a high quality sealing and low leak rate. The system can be customized in its size, degree of automation, and options provided.
Circle 129 on Reader Service Card

Planar Magnetron Sputtering System

A new R&D planar magnetron sputtering system has been announced by Plasma Sciences [Lorton, VA]. The Model RF/DC ARC-12M system combines a number of unique ideas for small scale integration to provide a compact, convenient and economical system capable of providing a full scope of thin film coatings, both conductive and non-conductive, meeting rigid semiconductor and optical standards. Simultaneous or sequential sputtering from three 2" dia. planar magnetron sources with both RF/DC power is possible for multi-layer thin films. ***Circle 25 on Reader Service Card***

Cathodoluminescence System for the SEM

Oxford Instruments Scientific Research Division's EM divProduct Group, has introduced Mono CL-2, a cathodoluminescence imaging and spectrometry system for the SEM with offers the high spatial resolution currently available using this technique. It is particularly suited to the micro-characterization of electronic and optical properties of compound semiconductors. It provides the capability of detecting and analyzing the extremely low intensity optical cathodoluminescence signals that are emitted by semiconducting materials when bombarded with an electron beam. The system can display panchromatic and monochromatic CL and can also provide a high resolution spectral analysis.
Circle 132 on Reader Service Card

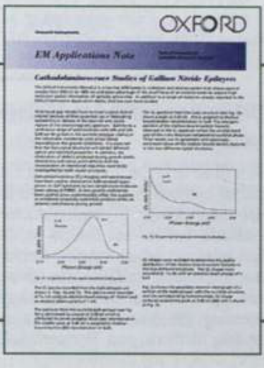
New Surfscan™ from Tencor

Tencor Instruments [Mountain View, CA] has introduced the Surfscan 6220 Unpatterned Surface Inspection System, designed for detecting scratches, pits and particles on bare wafers and wafers deposited with smooth films, and also for measuring haze on a broad range of surfaces. Based on the established Surfscan 6200 platform, the 6220 offers a number of new features including automatic film curve generation for greater productivity, a 25 time increase in dynamic range for more repeatable results and faster throughput, and direct export of defect data to popular applications software. ***Circle 150 on Reader Service Card***

NEW BROCHURES

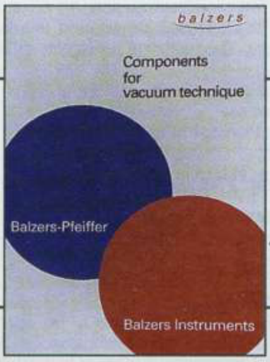
MOVPE Reactor from Thomas Swan

Thomas Swan [Cambridge, England] has released a new brochure describing their "Epitor GaN Reactor". This MOVPE system is designed to address the specific requirements of GaN deposition, with features including a gas delivery and exhaust system conditioned for ammonia and a vertical geometry water cooled stainless steel chamber with internal quartz liner. ***Circle 2 on Reader Service Card***



Application Notes on Cathodoluminescence

Oxford Instruments Scientific Research Division [Whitney, Oxon, England] has released three application notes describing the characterization of compound semiconductor materials by cathodoluminescence (CL). The subjects are 1) gallium nitride epilayers; 2) strained semiconductors and low dimensional structures; and 3) extended defects in SiGe. ***Circle 8 on Reader Service Card***



New Vacuum Products Catalog from Balzers-Pfeiffer

The 1996 Balzers-Pfeiffer Vacuum Products Catalog provides detailed information on vacuum pumps, gas analyzers, leak detectors, vacuum gauges and many other products for the production, measurement, and maintenance of medium to ultra-high vacuum. ***Circle 117 on Reader Service Card***

Electronic Pressure Controller Brochure from MKS

MKS Instruments has published a new brochure on its 640 Series Electronic Pressure Controllers, which are complete closed-loop electronic control systems in a 3" MFC-size package that can be used in both upstream and downstream applications. An integral Baratronr pressure transducer provides 0.5% of reading accuracy with full scale ranges as low as 10 Torr. ***Circle 185 on Reader Service Card***

Catalog for Specialty Chemicals

The new Advanced Specialty Inorganics Catalog from CERAC [Milwaukee, WI] highlights the firm's complete line of specialty inorganic chemicals, metals, alloys and ceramics. It includes information on both R&D lots and production quantities. ***Circle 11 on Reader Service Card***

1995 Fall Meeting of the Materials Research Society

The 1995 MRS Fall Meeting will be held November 27-December 1, 1995 in Boston, MA, USA. This conference includes 30 different symposia on topics ranging from beam-solid interactions and fullerenes to laser processing, GaN, and low-cost manufacturing of materials.
Proceedings: MRS Proceedings Series
Abstract Submission Deadline: Passed
Contact: M. Geil, Dir., Meeting Activities
Materials Research Society
9800 McKnight Road, Pittsburgh, PA 15237 USA
TEL [1] 412 367 3004 FAX [1] 412 367 4373
E mail info@mrs.org
Vendor Exhibit? Yes - contact Mary Kaufold, Exhibit Mgr.
Materials Research Society
9800 McKnight Road, Pittsburgh, PA 15237 USA
TEL [1] 412 367 3036 FAX [1] 412 367 4373
E mail kaufold@mrs.org

1995 Defect Recognition and Image Processing in Semiconductors

DRIP VI will be held Dec. 3-6, 1995 at Estes Park, CO. This is an international conference devoted to furthering understanding of defect inhomogeneitites in semiconductor materials and devices. Topics include, but are not limited to, 1) optical, electrical, and acoustical substrate defect imaging techniques as applied to semiconductor substrates, epilayers, nanostructures and devices for electronic, optoelectronic and optical applications; 2) techniques for processing the quantities of data coming from automated defect testing methods; and 3) correlation of device performance with defect density and distribution.
Abstract Submission Deadline: Sept. 1, 1995
Contact: Prof. Alan R. Mickelson
University of Colorado, ECE Dept.
Campus Box 425, Boulder, CO 80309-0425 USA
TEL [1] 303 492 7359 FAX [1] 303 492 2758
E mail mickel@boulder.colorado.edu

1996 IEEE Int'l Solid State Circuits Conference

ISSCC '96 will be held February 8-10, 1996 at San Francisco, CA. The theme for this year's conference is "Systems on a Chip". Papers targeting monolithic system integration in the following areas will be presented: analog; communications; digital; sensors, imagers, & neural networks; memory; signal processing; and technology directions.
Proceedings: Available from IEE
Abstract Submission Deadline: Passed
Contact: Diane Suiters
Courtesy Associates
655 Fifteenth St., NW, Suite 300
Washington, DC 20005 USA
TEL [1] 202 639 4255 FAX [1] 202 347 6109
Net or Web: diane+la+rcourtesy_associates@mcimail.com
Vendor Exhibit? No

Int'l Symp. on Blue Laser and Light Emitting Diodes

ISBLLED will be held March 5-7, 1996 at Chiba, Japan. The objective of this symposium is to provide a forum for bringing together specialists from both the ZnSe and GaN community at one place for stimulating discussions so that the direction for solving common problems can be derived. The symposium will consist of invited talks and oral/poster presentations of contributed papers. Original quality papers as well as papers whose subjects have been reported elsewhere but are suitable for this symposium will be considered for inclusion. Papers from the following areas are encouraged: substrates; epitaxy and doping; characterization; processing, including contacts; devices; device degradation mechanisms; and new materials.
Abstract Submission Deadline: Dec. 1, 1995
Contact: Prof. M. Kobayashi
Secretary, ISBLLED
Chiba Univ., E&EE Dept.
1-33 Yayoi-cho, Inage-ku, Chiba, Japan 263
TEL [81] 43 290 3330
FAX [81] 43 290 3360
E mail isblled@semi.te.chiba-u.ac.jp

3rd Int'l Conf. on the Physics of X-Ray Multilayer Structures

The 3rd International Conference on the Physics of X-Ray Multilayer Structures will be held March 3-7, 1996 at Breckenridge, CO, USA. This conference focuses on the interaction of x-ray and extreme ultraviolet radiation with multilayer structures, as well as multilayer growth, structures, and properties
Abstract Submission Deadline: Nov. 10, 1995
Contact: Ms. Marty Benson, Admin. Asst.
Univ. of Arizona, Dept. of Physcis
PAS #81, Tucson, AZ USA 85721
TEL [1] 520 621 2878 FAX [1] 520 621 4356
E mail pxrms-info@nanook.div111.att.com
Vendor Exhibit?: Yes, contact Ms. Marty Benson

1996 Spring Meeting of the Materials Research Society

The 1996 Spring MRS Meeting will be held April 7-11, 1996 in San Francisco, CA, USA. This conference includes 30 different symposia on semiconductor materials and processing, polymers, amorphous silicon, microwave processing, ceramics, and other topics.
Proceedings: MRS Proceedings Series
Abstract Submission Deadline: TBA
Contact: M. Geil, Dir., Meering Activities
Materials Research Society
9800 McKnight Road
Pittsburgh, PA 15237 USA
TEL [1] 412 367 3004 FAX [1] 412 367 4373
E mail info@mrs.org
Vendor Exhibit? Yes - contact Mary Kaufold, Exhibit Mgr.
Materials Research Society
9800 McKnight Road
Pittsburgh, PA 15237 USA
TEL [1] 412 367 3036 FAX [1] 412 367 4373
E mail kaufold@mrs.org

8th Int'l Conf. on Indium Phosphide and Related Materials

IPRM '96 will be held April 22-25, 1996 at Schwabisch-Gmund, Germany. Papers are requested in the following areas: optolectronics, electron devices, processing, epitaxy, bulk crystal growth, characterization and control.
Abstract Submission Deadline: Nov. 10, 1995
Contact: Volker Schanz
ITG/VDE
Stresemannaliee 15
60590 Frankfurt Main, Germany
TEL [49] 69 6308 360
FAX [49] 69 9631 5217
Vendor Exhibit? Yes - contact ITG/VDE

1996 Int'l Conf. on GaAs Manufacturing Technology

GaAs MANTECH '96 will be held April 28 to May 2, 1996 in San Diego, CA. This year's conference will be the first which is open to particpants from outside the USA. In keeping with this year's theme, "Manufacturing challenges in a Growing Global Market", papers are sought in the following areas: design, processing, manufacturing, testing/reliability, and applications. In addition, papers on on manufacturing equipment and facilities as applied to GaAs are also encouraged.
Abstract Submission Deadline: Passed.
Contact: Neal Mellen, Conf. Chair
Motorola
4800 Alameda NE
Albuquerque, NM 87113 USA
TEL [1] 505 822 8801 x236 FAX [1] 505 822 8812
Net or Web: gaas@ee.eustl.edu or
http://www.ee.wustl.edu/GaAs/
Vendor Exhibit? Yes - contact Neal Mellen.

3rd Int'l Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies

EXMATEC '96 will be held May 12-15, 1996 at Freiburg, Germany. The goal of this conference is to bring together research and development specialists involved in compound semiconductor material physics, process technology and device fabrication to address issues such as improvement of yield, reliability, performance, reproducibility and lifetime of micro- and optoelectronic devices and circuits through optimization and control of materials and process.
Abstract Submission Deadline: December 1, 1995
Contact: Dr. W. Jantz
Fraunhofer IAF
Tullastr. 72
D-79108 Freiburg I. Br.,
Germany
TEL [49] 761 5159 510
FAX [49] 761 5159 423
Vendor Exhibit? Yes - contact Dr. Jantz

20th Workshop on Compound Semiconductor Devices and Integrated Circuits

WOCSDICE '96 will be held May 19-22, 1996 in Vilnius, Lithuania. This annual European workshop is an important milestone in research activity directed toward applications where silicon devices seem to be inferior as compared to the performance offered by compound semiconductors and heterostructures with a wider spectrum of fundamental properties. Devices and circuits operating at high ambient temperatures, in microwave and terahertz frequency range, fast optoelectronic and low noise devices and circuits together with the related physical and technological backgrounds are the scope. The number of particpants will be limited to around 80.
Abstract Submission Deadline: March 1, 1996
Contacts: Ilona Matulioniene
Semiconductor Physics Institute
A. Gostauto 11
LT-2600 Vilnius, Lithuania
TEL [370] 2 618 101 FAX [370] 2 627 123
Net or Web: matulionis@uj.pfi.LT or
http://uj.pfi.LT/conf/wocsdice/wocs96.htm

1st European GaN Workshop

The 1st European GaN Workshop will be held June 2-4, 1996 at Rigi, Switzerland. It will encompass all areas of research relating to the physical properties and device applications of the Group III-Nitride semiconductors. The workshop will be formatted in 5-10 minute presentations followed by a longer open discussion period. In addition, a few distinguished people from outside of Europe will be invited to present their research in depth. It is the intention of the organizers that the GaN Workshop be as open as possible to permit maximum interaction amongst the participants.
Contact: Dr. Toby Strite
IBM Zurich Research Laboratory
Saumerstrasse 4
Ruschilkon CH-8803 Switzerland
TEL [41] 01 724 83 55 FAX [41] 01 724 17 89
Net or Web: srt@zurich.ibm.com
Vendor Exhibit? Yes - contact Dr. Strite

1996 European GaAs and Related III-V Compounds Applications Symposium

GAAS '96 will be held June 5-7, 1996 in Paris, France. This year's conference, the fourth in this series, aims to promote the discussion of recent developments and trends, and the exchange of scientific and technical information, in the area of applications of GaAs and other III-V or IV-IV compound semiconductors.
Abstract Submission Deadline: January 15, 1996
Contact: GAAS 96
ENSEA, 6 avenue du Ponceau
95014 Cergy Cedex, France
FAX [1] 33 1 30 73 66 27

8th Int'l Conf. on MOVPE

ICMOVPE 8 will be held on June 9-13, 1996 in Cardiff, Wales. This conference seeks to bring together specialists in growth, characterization and device applications of MOVPE and to present a forum for discussion of recent progress and the latest achievements in the field of both fundamental and applied research. Topic area include: precursors; process design/communication issues; developing applications of MO compounds; growth technologies; advances in devices by MOVPE; and characterization.

Proceedings: Journal of Crystal Growth
Deadlines: Abstracts - December 1, 1995
Late news - On-site, June 9
Contact: Glenda Bland
Global Meeting Planning, GMP 22 Plas Taliesin
Portway Village Marina, Penarth,
South Glamorgan CF64 1TN, Wales
TEL [44] 1222 700 053 FAX [44] 1222 700 685
E mail 100416.1402@compuserve.com
Vendor Exhibit? Yes - contact Prof. Colin Whitehouse
Univ. of Sheffield, EE Dept.
Mappin Street, Sheffield, S1 4DU UK
TEL [44] 1142 825 254 FAX [44] 1142 726 391

1996 Device Research Conference

DRC '96 will be held June 24-26, 1996 at Santa Barbara, CA, in conjunction with the Electronic Materials Conference (see below). The DRC is intended to bring together scientists, engineers, and students to discuss new and exciting breakthoughs and advances in the field of device research. Papers are solicited on a wide variety of novel device work.

Abstract Submission Deadline: March 1, 1996
Contact: Jim Sturm
Princeton Univ., EE Dept.
Olten Street.
Princton, NJ 08544 USA
TEL [1] 609 258 5610 FAX [1] 609 258 6279
Net or Web: sturm@ee.princeton.edu or
http://www. ee.princeton.edu/~sturm/drc.html
Vendor Exhibit? See below.

1996 Electronic Materials Conference

EMC '96 will be held June 26-28, 1996 at Santa Barbara, CA, in conjunction with the .Device Research Conference (see above). The conference is intended to provide a forum for topics of current interest and significance in the area of preparation and characterization of electronic materials. Individuals actively engaged or interested in electronic materials research and development are encouraged to attend this meeting, and papers in this general subject area are solicited.

Abstract Submission Deadline: Feb. 15, 1996
Contact: Customer Service
TMS
420 Commonwealth Dr.
Warrendale, PA 15086 USA
TEL [1] 412 776 9000 x241 FAX [1] 412 776 3770
Vendor Exhibit? Yes - contact Barbara Kampermann
TMS
420 Commonwealth Dr.
Warrendale, PA 15086 USA
TEL [1] 412 776 9000 x234 FAX [1] 412 776 3770

Would you like your conference to be included in future issues of *Compound Semiconductor*? Send the following information by E mail to calendar@compsem.com, or by FAX to [1] 612 227 5499, attention **"Calendar"**

* Full name of conference, plus acronym or abbreviation
* Dates and location
* Brief description of content, focus, or goals
* Abstract submission and late news deadlines
* Primary contact name, address, phone, FAX and E mail
* Whether there will be a vendor exhibit, and, if so, contact name, address, phone, FAX and E mail

Contributions must be received by December 1 to appear in our next issue.

23rd Int'l Conf. on the Physics of Semiconductors

ICPS-23 will be held July 21-26, 1996 at Berlin, Germany. All aspects of semiconductor physics including organic and inorganic materials and devices will be covered and highlighted by plenary and invited talks as well as contributed papers.

Abstract Submission Deadline: Feb. 19, 1996
Contact: Dr. Axel Hoffmann, Secretary
Institut fur Festkorperphysik
PN 5-1, TU Berlin
Hardenbergstr. 36
10623 Berlin, Germany
Vendor Exhibit? Yes

Ninth Int'l Conf. on Superlattices, Microstructures, and Microdevices

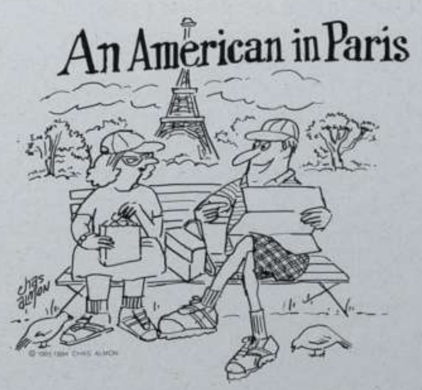
ICSMM-9 will be held July 14-19, 1996 at Liege, Belgium. The scope of this conference includes novel phenomena in semiconductor superlattices and quantum wells based on IV-IV, III-V, & II-VI compounds, as well as microstructures and superlattices based on other materials such as porous silicon, nitrides, metal/magnetic/semimagnetic materials, and semiconductor/metal microstructures. Also of interest are: nanostructures and low dimensional systems with strong emphasis on novel phenomena in quantum wires and quantum dots including dot-dot interaction; novel fabrication and probing techniques of quantum structures, including self-organized systems, ordered granular systems, and chemistry of nanoscale systems; STM, ATM, and novel technologies; photonic band gap materials and microcavities; and novel nanoscale devices including Si, SiGe, and SiC devices.

Proceedings: Will be published
Abstract Submission Deadline: March 15, 1996
Contact: Prof. Jean-Pierre Leburton
Univ. of Illinois
Beckman Institute, Urbana, IL 61801 USA
TEL 217 333 6813 FAX 217 244 4333
Net or Web: leburton@ceg.uius.edu
Vendor Exhibit? Undecided

Ninth International Conf. on Molecular Beam Epitaxy

MBE-IX will be held August 5-9, 1996 at Malibu, CA. This conference will cover the full spectrum of MBE-related topics. Subjects covered will include MBE growth of semiconductors, metals, insulators, and superconductors, as well as novel growth techniques , in situ control and characterization, and device applications of MBE technology.

Proceedings: Will be published in J. Vac. Sci. Techn. B
Abstract Submission Deadline: March 15, 1996
Contact: Dwight Streit
TRW
R6-2373, One Space Park, Redondo Beach,
CA 90278 USA
TEL [1] 310 814 1722 FAX [1] 310 812 4378
Net or Web: dwight.streit@trw.com
Vendor Exhibit? Yes. Contact David Grider
2060 Avenue Los Arboles, Suite 342,
Thousand Oaks, CA 91362 USA
TEL [1] 310 317 5007 FAX [1] 310 492 6262
Net or Web: rgrider@aol.com



"Let's grab a Big Mac then head for Disneyland."

1996 Topical Workshop on Heterostructure Microelectronics

TWHM '96 will be held August 19-21, 1996 in Sapporo, Hokkaido, Japan. The objective of this conference is address critical technical issues in the development and application of heterostructure microelectronic technologies by providing a forum for international collaboration. This year's workshop will focus on HBT and HEMT technologies based upon a range of heterostructure materials systems including III-V's, IV-IV's and wide bandgap materials such as GaN and SiC. Papers are solicited in areas of heterostructure materials and device development and circuit demonstration, as well as the application of heterostructure microelectronic technologies to wireless, telecommunications, and signal/data processing systems.

Abstract Submission Deadline: April 8, 1996
Contact: Dr. Takyiu Liu
Hughes Research Laboratories
Malibu, CA 90265-4799 USA
FAX [1] 310 317 5450 E mail tliu@msmail4.hac.com

23rd Int'l Symposium on Compound Semiconductors

ISCS-23 will be held September 23-27, 1996 in St. Petersburg, Russia. This conference is a premier forum on all aspects of compound semiconductors, including growth, processing, devices, and ICs. Materials covered include GaAs, InP, GaN, ZnSe, and SiC. ISCS is the successor to the "Gallium Arsenide and Related Compounds" conference series.

Abstract Submission Deadline: TBA
Contact: Dr. V. Grigor'yants
Ioffe Institute, 26 Polytechnicheskaya
St. Petersburg 194021, Russia
TEL [7] 812 247 22 55 FAX [7] 812 247 21 35
Net or Web: vgrig@eo.ioffe.rssi.ru
or
Prof. Michael Shur
Univ. of Virginia, EE Dept.
Charlottesville, VA 22903-2443 USA
TEL [1] 804 924 6109 FAX [1] 804 924 8818

Advertiser Index for Vol. 1 No. 3

Company	Page
Aixtron GmbH	OBC
Bede Scientific Instruments Ltd.	23
CVD Products Inc.	33
DCA Instruments	25
EMCORE Corporation	7
EPI MBE Products Group	38
Freiberger Elektronikwekstoffe GmbH	43
Litton Airtron	15
M/A-COM	3
MarketTech International	11
MCP Wafer Technology Ltd.	IBC
MR Semicon Inc.	14
Solid State Equipment Corporation	41
TLC Precision Wafer Technology Inc.	IFC
Wavemant Inc.	12

SiGe HBT and GaAs MESFET Technologies - A Market Perspective

Rob Christ, Senior Applications Engineer
TriQuint Semiconductor

SiGe HBT technology has garnered a lot of press during the last year or so. While it has been touted to be manufacturable and ready for high volume production, it has not yet been used for generally available commercial products. The technical aspects, or the "hows," of the transistors have been reported adequately enough, however the marketing reasons, or the "whys," have often been glossed over. Usually the marketing reasons read something like, "if it's silicon on big wafers, it must be cheap" and "we could see 'radio on a chip' integration soon, because the integration potential of silicon is well known." Unfortunately, there are several assumptions built into these arguments that don't stand up to closer inspection. Let's examine them:

Assumption #1: SiGe HBT offers enabling performance improvements over other high performance bipolar processes. The main advantage of SiGe is that it allows for higher base doping than is practical in conventional bipolar transistors. This allows for thinner bases and lower R_{base} values. These allow for higher cutoff frequencies. The more Ge in the base the better. Unfortunately, there is a practical upper limit on the Ge concentration in order to get low defect epitaxy. Therefore, the performance advantages in practical SiGe devices are relatively small compared the best high performance bipolar. To many bipolar users, there is a real question whether it is worth investing in a new technology for relatively minor benefits.

Assumption #2: Transistor performance is the main barrier for integrated silicon to penetrate wireless RF front-ends. While transistor performance is an issue, RF isolation and system costs are much bigger barriers. Since silicon substrates are conductive, it is not practical to build high quality passive elements on-chip. However, much of the cost in current RF systems using discretes comes from the passive elements. GaAs IC's are penetrating RF system designs based on system cost, not just performance. Integrated GaAs with onboard passive elements provide much greater consistency compared to discretes. This often results in higher radio yields and lower overall RF system cost.

Assumption #3: All silicon processing is inherently cheap. Not all silicon process technologies are equal on a cost basis. High performance bipolar and BiCMOS processes are more complicated and usually produced in lower volumes than CMOS memories and gate arrays. Simple GaAs MESFET processes are currently cost competitive with high performance bipolar and less expensive than BiCMOS for RF functions. For the same function, a typical GaAs MESFET process takes only 13 photolithographic layers compared to 21 layers for high performance bipolar with the same function. BiCMOS processes usually have 26 or so layers by comparison. As the infrastructure for GaAs grows, these differences will become more and more clear.

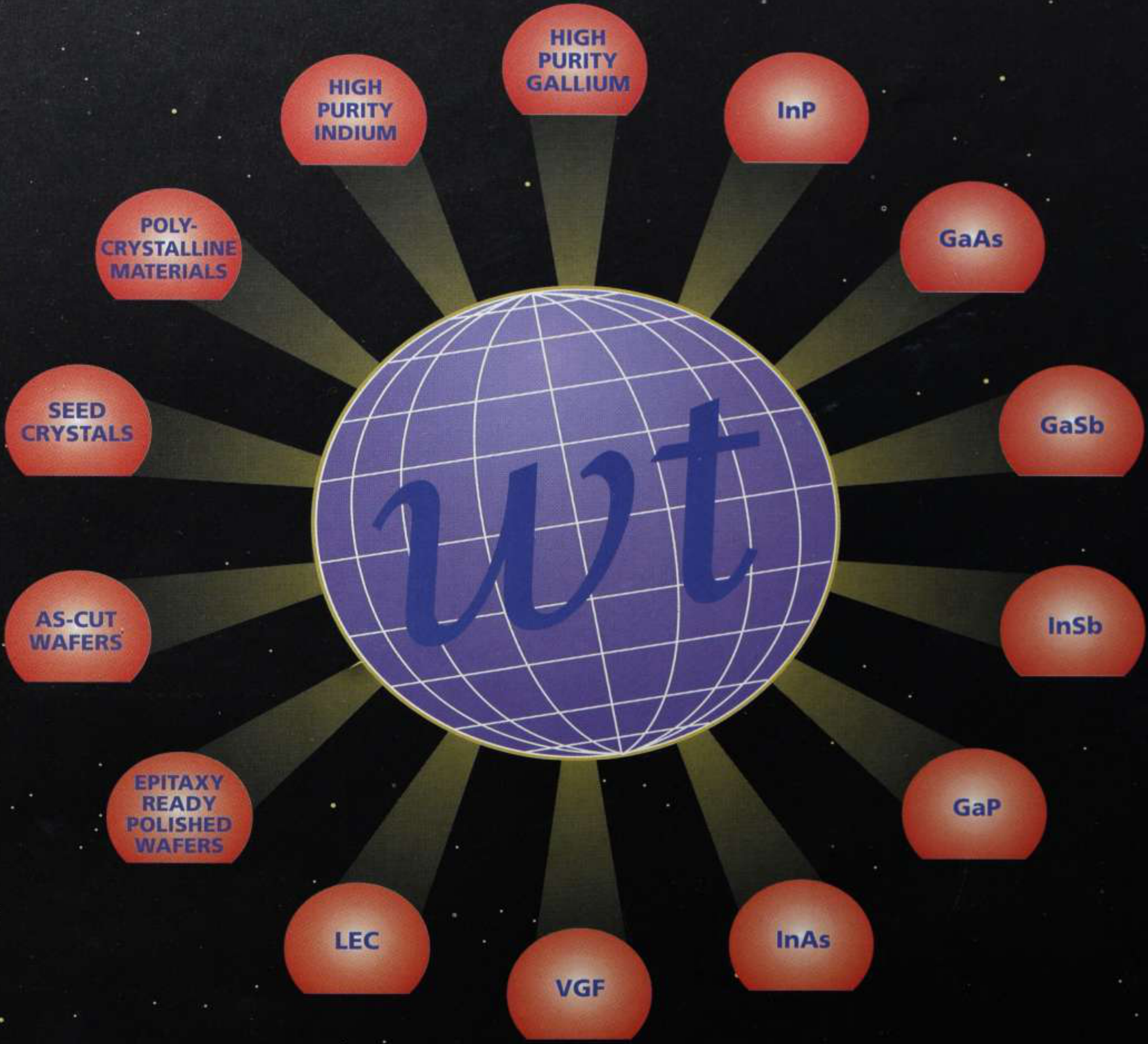
Assumption #4: It is always desirable to maximize the level of integration in RF systems. Some reporters mistakenly apply the pervasive digital integration paradigm that has dominated the computer industry to RF systems with the notion that "radio on a chip" is around the corner. Even if "radio on a chip" integration becomes technically possible, it would not be cost effective. It doesn't make sense to use real estate shared with very high performance RF transistors for baseband and signal processing functions. Likewise, it doesn't make much sense to force-fit high density CMOS with RF transistors. It is best to choose the appropriate technology for each function for both performance and cost reasons. Where integration is occurring, chip set makers and mobile terminal designers are slowly developing a consensus toward integrated GaAs MESFETs for RF front-ends, Bipolar or BiCMOS for IF/Baseband functions and CMOS for signal processing and logic. Since the characteristics of each function are so different, each of these technologies has its natural place.

SiGe will not replace GaAs in circuit applications where it has been demonstrated that GaAs has clear performance and cost advantages over integrated silicon bipolar. This is particularly true in RF power amplifiers for mobile communications. GaAs MESFET power amps provide greater power efficiency than bipolar power amps. Also, GaAs MESFET technology offers the linearity required for today's emerging digital systems. On the other hand, SiGe provides no such advantage over silicon bipolar for power amps.

Since TriQuint produces GaAs devices exclusively, we are sometimes asked whether we are concerned about the emergence of SiGe HBT technology. While we are interested in the developments of this technology, we do not consider it to be a threat. SiGe HBT is essentially a performance enhancement of existing bipolar technology with all of its attendant strengths and weaknesses.

Rob Christ is Senior Applications Engineer at TriQuint Semiconductor in Beaverton, Oregon. He is responsible for developing the customer interface and training customers to use TriQuint's foundry services. TriQuint Semiconductor, Inc. designs, develops and manufactures analog and mixed signal GaAs integrated circuits for high performance systems in wireless communications, telecommunications and computing applications. TriQuint is listed on the NASDAQ with the symbol TQNT.

The Universal Choice



With an unrivalled range of crystal growth techniques and leading-edge finishing procedures MCP Wafer Technology provides you with III-V materials tailored to your requirements.

Whatever your substrate demands we're equipped to respond.

MCP Wafer Technology – for all your III-V needs

Circle 130 on Reader Service Card

MCP WAFER TECHNOLOGY LTD
34 MARYLAND ROAD • TONGWELL • MILTON KEYNES MK15 8HJ • UK
TEL: +44(0)1908 210444 • FAX: +44(0)1908 210443

Quality system approved to BS EN ISO 9002:1994

The CVD Engineering Company™

IT'S A FACT
that no other MOCVD company in the world offers you the **unique, versatile,** and **constantly high quality** technology you're assured of from AIXTRON, whether you're producing LED's, Lasers, Detectors, HEMTs, HBTs, OEICs...
...And we can prove it!

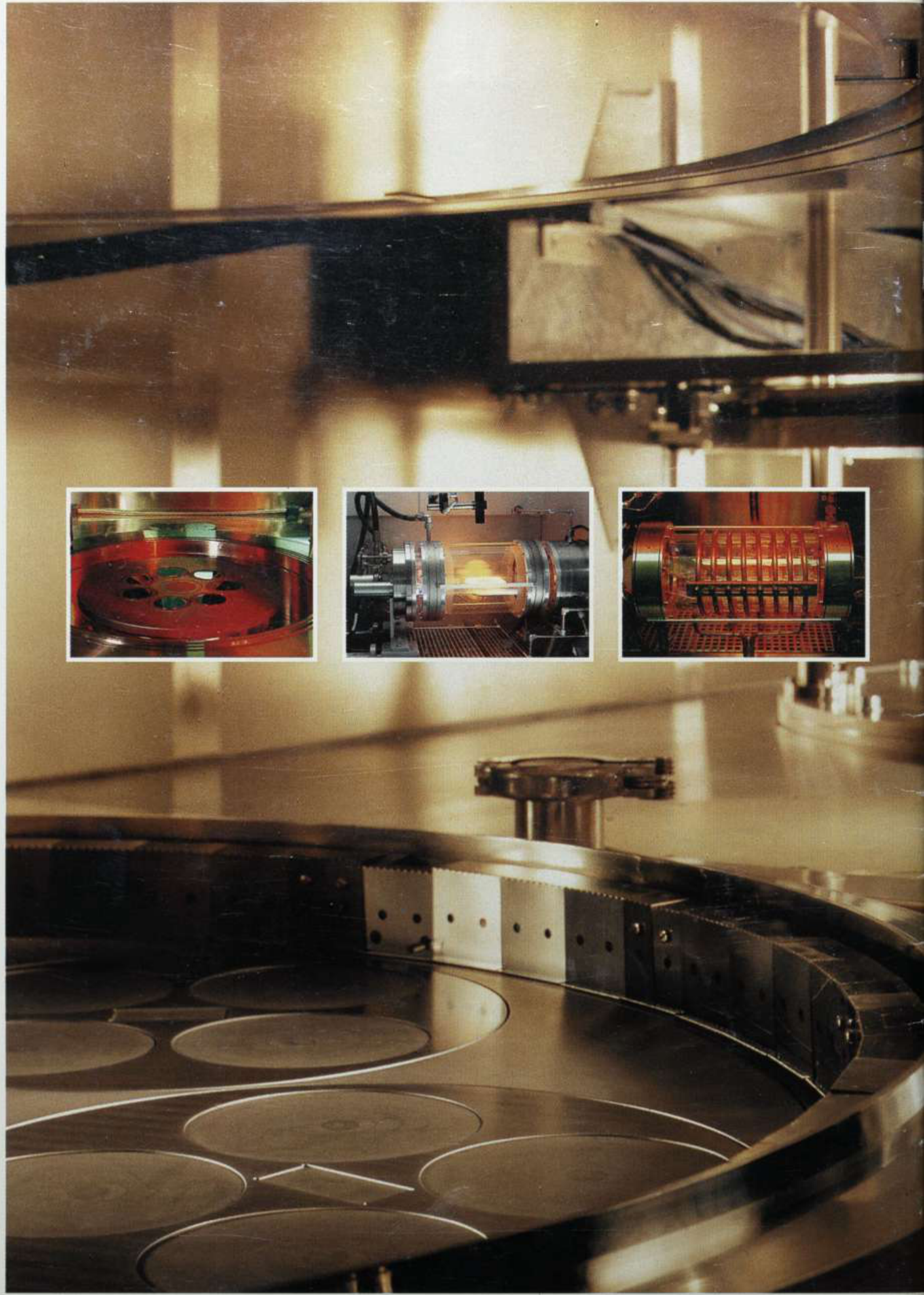
FACT!
No other company in the world offers you a complete MOCVD reactor line, based on a proven scaling concept, from R & D up to full-scale production (1x2" up to 95x2" wafers or equivalent 3", 4" wafers).

FACT!
AIXTRON is the only company in the III-V epitaxy field offering proven processes from mono layer thickness up to more than 200μm/h.

FACT!
AIXTRON was the first MOCVD company worldwide to receive the ISO 9001 Certification - the internationally recognized quality symbol.

CERTIFIED DIN 9001 ISO QUALITY SYSTEM

WHAT BETTER GUARANTEE OF OUR
Commitment to AIXcellence



AIXTRON®

European Headquarters
Aachen, Germany
AIXTRON GMBH
Kackertstraße 15-17, 52072 Aachen
Germany
Phone: +49 (241) 89 09 - 0
Fax: +49 (241) 89 09 - 40
Customer Service Line
Phone: +49 (241) 89 09 - 91

US Headquarters
Chicago, IL
AIXTRON Inc.
1569 Barclay Blvd.
Buffalo Grove
IL 60089, USA
Phone: +1 (708) 215 - 73 35
Fax: +1 (708) 215 - 73 41

Sales and Service
Tokyo, Japan
Moritani & Co., Ltd /AIXTRON
2nd Section, 3rd Machinery Dept.
4th Sales Division
1-4-22 Yaesu, Chuo-Ku
Tokyo 103, Japan
Phone: +81 (3) 32 78 - 61 31
Fax: +81 (3) 32 78 - 61 21

Circle 77 on Reader Service Card