

COMPOUND

SEMICONDUCTOR

March/April 1996

Volume 2 Number 2

Indium Phosphide



Sony demonstrates ZnSe Laser
with 100+ Hour Lifetime



See page 7

FROM SUBSTRATES TO SUPERLATTICE OUR QUALITY IS CRYSTAL CLEAR

Single & Poly Crystal

GaAs • InP • InSb
GaSb • InAs

Sumitomo Electric has been supplying a full range of III-V materials for more than 20 years. During this period we have developed a repertoire

of epitaxial processes that include LPE, VPE & MBE. One of our latest substrate advances has been growth of super-long LEC ingots with

Epitaxy

VPE • LPE • MBE • OMVPE

the most electrically consistent properties available. Our proprietary InP VCZ material has crystal uniformity that is unmatched.



SUMITOMO ELECTRIC

Semiconductor Division 1-1-1, Koya-kita, Itami, Hyogo, 664 Japan Tel.: +81 (727) 72-2281 Fax: +81 (727) 71-0282

SEUSA (New York, USA) Tel.: +1 (212) 308-6444 Fax: +1 (212) 308-6575 • SEMIA (San Francisco, USA) Tel.: +1 (415) 765-1124 Fax: +1 (415) 765-1180

SEESA (UK) Tel.: +44 (71) 723-6693 Fax: +44 (71) 724-2102

Circle 100 on Reader Service Card



COMPOUND

SEMICONDUCTOR

SPECIAL FEATURE

- 7 **Sony ZnSe Laser Breaks the 100 Hour Barrier**
Reductions in defect density allow the longest operating lifetime ever reported for a II-VI laser diode.
- 8 **Commentary: Defects in Blue/Green Light Emitters**
Prof. Robert Gunshor of Purdue University offers observations on the different roles that defects play in the ZnSe and GaN material systems.
- 9 **Conference Report I**
International Symposium on Blue Lasers and Light Emitting Diodes

COVER STORY

- 12 **The Growing Market for InP Laser Diodes**
Fiberoptic lasers - 99% of which are based on InP - will see a CAGR of 18.75% and a worldwide market value of \$1.5 billion by 2000.
- 20 **The Capabilities of InP Electronics and Optoelectronics**
Secure in optoelectronics, can InP find a spot in GaAs's microelectronics niche?
- 29 **Trends in Wafer Sizes**
When will we see 6" GaAs and 3" InP in production? Would you believe 1998??
- 33 **Directory of Substrate Suppliers**
- 35 **Tutorial**
Material and Device Fundamental of InP-based Microelectronics and Optoelectronics
- 52 **Guest Editorial**
Paul Greiling of Hughes Research Laboratories discusses the opportunities and challenges facing InP microelectronics for commercial and military applications.

OTHER FEATURES AND DEPARTMENTS

- 2 **From the Editor**
A guide to some of the new items in this issue.
- 4 **New Devices and Circuits**
- 6 **Device Feature**
TriQuint's GaAs Transceiver for Telecommunications and High Data Rate Applications
- 13 **News Briefs**
TRW and RF Micro Devices are teaming up for a fab dedicated to GaAs HBTs. Also: ranking the top 10 compound semiconductor manufacturers, news from Japan, Bell Labs' new parent, and more.
- 17 **Research Review**
- 41 **Conference Report II**
RF GaAs at the 1995 GaAs IC Symposium
- 45 **Other Materials**
What's new in "other materials", like silicon?
- 48 **Portfolio**
- 50 **Employment**
- 51 **Calendar**



There are reasons to smile in the indium phosphide field. Coverage begins on page 12. Also shown on this issue's cover is Sony's ZnSe laser diode which recently exceeded 100 hours of room temperature operation. See page 7.

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 25 or contact the editor.

©Copyright 1996 by Franklin
Publishing - all rights reserved.

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

FROM THE EDITOR

The events of the first quarter of 1996 suggest that this is going to be an interesting year in our field. Sony's new 100 hour ZnSe laser (see page 7), coupled with Nichia's GaN laser breakthrough reported in our last issue are generating excitement in the research field, while plans for a new fab for GaAs HBTs (see page 13) and scaling-up to 6" wafers (see page 29) are important new exhibits in the mounting pile of evidence showing that GaAs is firmly establishing itself in the semiconductor market.

As a new publication we are still in the process of trying out new ideas for the design and content of our magazine. Our goal is to establish the structure which is best suited to our mission statement: the provision of a focal point for the global compound semiconductor industry. The items mentioned above provide a fairly good illustration of the variety of topics that we must cover to fill that role: several different material systems; different categories of semiconductor devices (the largest categories being, of course, optoelectronics and microelectronics); and developments in both research and production. And, on top of that, we need to provide coverage with an international viewpoint, as more than half of our readers are from outside of North America. You will find in this issue a number of new features which are designed to enhance the breadth and depth of our coverage of the compound semiconductor industry as it progresses through this exciting phase of its history.

Where Do the Ideas Come From?

You may wonder about the sources of the ideas for items that appear in this magazine. The quickest and easiest way for you to offer suggestions or express your opinion is to take advantage of the "Feedback" section on the Reader Service Card provided on page 27. Several of the new features were motivated by the input we receive from this source. But if you would prefer to speak with us directly, especially if you are interested in contributing to the magazine, please feel free to contact us at the locations given on the preceding page.

New Features

New items you will find in this issue include:

- **Employment:** See page 50 for our new "classified ads" of employment opportunities in the compound semiconductor industry. If you are an employer with a position you would like fill, please see the instructions at the top of the page and contact us as soon as possible so that we can include you in our next issue.
- **Invitation to contribute to our new "Forum" section:** We believe our magazine would benefit tremendously from quality contributions from our readers in their areas of expertise. Therefore we will be launching our new "Forum" section later this year. "Forum", is an excellent old Latin word, meaning "a public place for meeting and discussion", and it reflects our goal of getting more members of the international compound semiconductor community involved in our publication. You can find the guidelines for contributions on page 39.
- **Other Materials:** We are pleased to be one of the few publications in the electronics industry that can discuss silicon as an alternative semiconductor material. From time to time we will report on developments in silicon and other materials that may have an impact on the compound semiconductor industry. For our first installment, Bob Metzger reports on the highlights of two major silicon-related conferences. See page 46.
- **News from Japan:** We define ourselves as an international magazine, which means that coverage of events outside of North America is an important part of our job. Therefore we have obtained the services of a Japanese news service specializing in the electronics industry. For an example of our newly improved coverage of Japan, see page 15.
- **Portfolio:** On page 48 you will find the first update on our "Compound Semiconductor Portfolio" - a hypothetical investment in seven compound semiconductor-related stocks. As we said when we introduced the Portfolio in our last issue (*CS* 2(1), p. 46), this is your opportunity to take a vicarious foray into the stock market, and perhaps gain a few insights into the forces that drive our industry along the way.

In our Next Issue

If you are interested in optoelectronics, you will not want to miss our next issue, which will cover a variety of topics from that area. The stories we are working on include full-color LED displays, laser diode pick-ups for the next generation of CD players, IR data links, and trends in the market for optoelectronic semiconductor devices. We will also have plenty of coverage from the microelectronics side of the industry, including a story from Japan about the release of the first fully integrated, one-chip GaAs RF front end for a wireless handset.

If you are not already a subscriber to *Compound Semiconductor*, please complete and return the enclosed order form as soon as possible to ensure prompt delivery of all of our future issues. Remember, *Compound Semiconductor* is now available only through paid subscriptions. Don't miss out - send in your form today.

Marie Meyer

Advertising in

COMPOUND SEMICONDUCTOR

Have you considered advertising in *Compound Semiconductor*? Here are five reasons why you should:

#1 Large circulation - no other publication has a larger circulation or broader distribution within the compound semiconductor industry.

#2 Quality readership - our readers are scientists, engineers and technology managers who influence the buying decisions for a wide range of products. In other words, our readers = your prospective customers.

#3 Valuable content - we provide unique, interesting and informative content. This ensures that our magazine is read "from cover to cover", which means that your ad will be seen by thousands of prospective customers.

#4 Attractive layout - your ad will look it's best in *Compound Semiconductor*.

#5 Thorough coverage - our content encompasses all aspects of compound semiconductors. As a result, our readers are drawn from all segments of the industry: III-V's, II-VI's, and IV-IV's; optoelectronic and electronic devices and circuits; research and production. No matter which area you are targeting with your products, *Compound Semiconductor* is the best vehicle for your advertising message.

Would you like to know more about advertising opportunities in *Compound Semiconductor*? Please call, or use the Reader Service Card to request a copy of our 1996 Media Guide.

Compound Semiconductor Magazine
250 Selby Avenue, Suite 48
Saint Paul, MN 55102 USA
TEL [1] 612 227 5397
FAX [1] 612 227 5499
E mail info@compsem.com

Circle 1 on Reader Service Card

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!

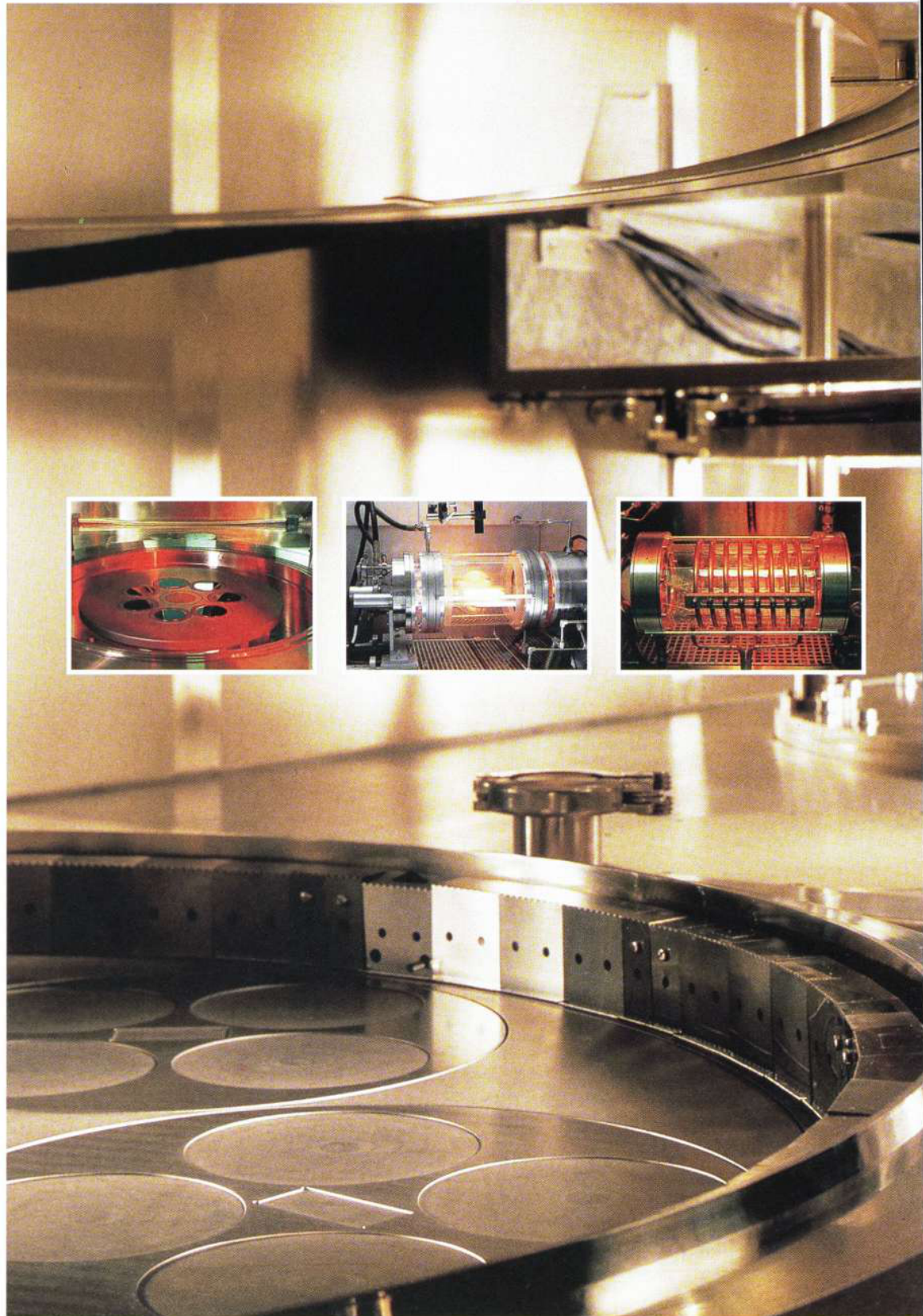
AIXTRON was the first MOCVD company worldwide to receive the ISO 9001 Certification - the internationally recognized quality symbol.



WHAT BETTER GUARANTEE OF OUR

Commitment to AIXcellence

AIXTRON®



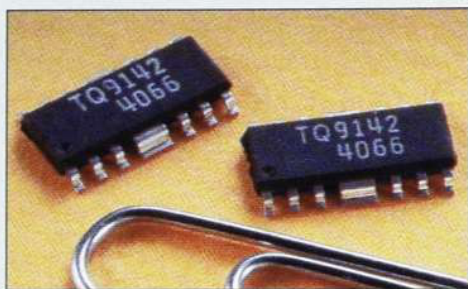
European Headquarters
Aachen, Germany
AIXTRON GMBH
Kackertstraße 15-17, 52072 Aachen
Germany
Phone: +49 (241) 89 09 - 0
Fax: +49 (241) 89 09 - 40
Customer Service Line
Phone: +49 (241) 89 09 - 91

US Headquarters
Chicago, IL
AIXTRON Inc.
1569 Barclay Blvd.
Buffalo Grove
IL 60089, USA
Phone: +1 (847) 215 - 73 35
Fax: +1 (847) 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

Integrated Circuits



TriQuint's new GaAs MESFET power amplifiers for analog cellular phones based on the AMPS standards

Three New ICs for Wireless Communications, Signal Processing

TriQuint Semiconductor has introduced the first product from its new line of GaAs MESFET RF power amplifiers for wireless communications. The new IC, part # TQ9142, is a 1 Watt power device designed for use as the front-end transmit amplifier in analog cellular phone handsets based on the AMPS standard. The annual market for such handsets is estimated at >9 million units per year. The TQ9142 operates over the 824-849 MHz frequency range, achieving a typical efficiency over 60 percent for a power output of 30.5 dBm (1W) while operating at 4.8 volts, the typical output provided by four nickel cadmium (NiCd) or nickel metal hydride (NiMH) batteries. According to Chris O'Conner, marketing and applications manager for TriQuint's Wireless Communications Division, "the TQ9142 delivers real price/performance benefits, with a competitive price and high efficiency. It essentially provides GaAs hybrid module performance at discrete transistor price." The IC has three stages of gain and is capable of amplifying a 1 mW input signal up to a 1 watt power output, eliminating the need for extra circuitry to drive the power amplifier. Most of the RF matching is integrated on-chip. The TQ9142 is available from stock at a unit price of \$4.25 in quantities of 50,000 per year.

Vitesse Semiconductor has introduced the VSC7125, an integrated Fibre Channel transceiver which is part of what the company describes as "the industry's most complete family of Fibre Channel physical layer IC solutions". Fibre Channel is an emerging standard for high speed serial data communications, defined to serve both local area networking and peripheral I/O communications needs. It promises to provide a five to tenfold performance increase over existing technologies. In particular, its throughput of 100 MB/s solves system performance bottlenecks over distances of up to 30 meters using copper media and extending to 10 km using fibre optics. John Schaefer, Vitesse's Product Marketing Manager, predicts that "Gb/s connectivity, the ability to connect up to 126 devices, and low adoption costs will fuel the growth of Fibre Channel as the mainstream storage and networking interconnect". The VSC7125 is Vitesse's fourth generation of transmit/receive products for FC. It provides a 1.0625 Gbit/s baud rate (100 MB/s data rate), requires only a single +3.3V supply (an industry first), and reduces power dissipation to 650 mW from the 2.5W required by previous generations of FC transmitter-receiver chip sets. In addition to this new transceiver Vitesse also offers all of the remaining ICs and OEICs required to implement the FC physical layer.

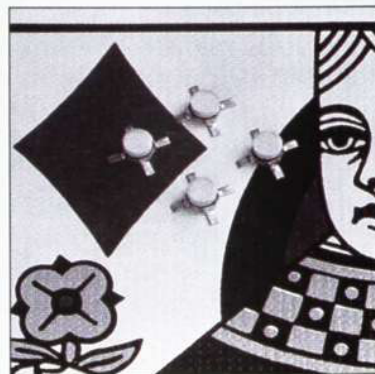
Anadigics has introduced a new GaAs wideband limiting amplifier for use in optical receiver chains. This single device replaces a three-stage discrete amplifier solution typically needed after trans-impedance amplifiers or PIN-amps in this application. The new amplifier converts data input voltage ranging in amplitude from 30-1000 mV to a constant output voltage of 500 mV. The new amplifier is designed for use with SONET OC-12 and European SDH STM-4 standards. Features include a single +5 V supply, 25 dB small signal gain, 50 ohm output impedance, low pulse distortion, and limited output swing. According to a company spokesperson, typical silicon IC's do not offer the wide bandwidth of this new solution (50-622 MB/s), and the use of GaAs permits broader dynamic range at the input. Cost savings for the customer are expected because of less time spent tuning, matching and designing circuits with this fully integrated devices. Anadigics also believes that in addition to fiber optic trunk lines, the new amps are suitable for other signal processing applications requiring a high dynamic range and wide bandwidth.

Discrete Microelectronic Devices

Motorola Launches GaAs Rectifier Line: Motorola has introduced a series of new products which may signal the emergence of a new application for GaAs: high frequency rectification. The new devices are a series of 180 and 250 V, 10 and 20 ampere GaAs rectifiers which convert high frequency ac voltages to a regulated dc voltage, enabling the design of high frequency converters that reduce the physical size of reactive components. The unique characteristics of GaAs rectifiers are the fast reverse recovery times and low peak reverse currents which result in low stored charge during the reverse recovery time. Unlike silicon rectifiers, their characteristics vary only slightly with increasing temperature. This enables the device to operate at high frequency with minimum power loss during the reverse recovery time over a broad temperature range. According to a company spokesperson, the resulting improvements in efficiency for high-frequency applications more than compensate for the added cost of using GaAs in place of silicon. Prices range from \$6.00 to \$14.65 in 100-999 unit quantities.

12 GHz FET from NEC: California Eastern Laboratories has announced the availability of a new 12 GHz GaAs Pseudomorphic Hetero-Junction FET from NEC. Low noise performance (NF=0.40 dB typical at 12 GHz) with high associated gain ($G_p = 12.5$ dB typical at 12 GHz) make the device suitable for low noise amplifier applications, especially in the Ku-band. The NEC Pseudomorphic Hetero-Junction FETs use the junction between Si-doped AlGaAs and undoped InGaAs to create very high mobilities. The new device is priced at \$1.55 in production quantities.

Two New 3-V GaAs Power FETs from Oki: Oki Semiconductor has introduced two new low-cost 3-V GaAs RF power amplifiers targeted at the AMPS cellular phone market. They operate at frequencies up to 850 MHz. The new products, fabricated using a 0.5 micron implant process, both feature a power output of > 31.5 dBm and operate with peak current capabilities of >4.5 A at cellular frequencies. The KGF1607 model is housed in a ceramic package and provides >70 % power efficiency; the lower-cost KGF1637 model uses a plastic package and provides >60% power efficiency. The new products compliment a line of 3-V power amps for other standards such as GSM, PHS and PCS which Oki introduced late last year. The new devices are in full production, and are priced at \$8.76 for the KGF1607 or \$7.60 for the KGF1637 in volume quantities.



New AlGaAs/InGaAs Pseudomorphic Hetero-Junction FETs for 12 GHz applications, manufactured by NEC and available in North America from CEL.

Optoelectronics

Boston Electronics, in association with **Laser Components GmbH**, is now offering **SiC UV Photodiodes for remote sensing of wavelengths < 400 nm**. The diodes share many characteristics of conventional silicon diodes, simplifying implementation. However, unlike silicon, SiC is transparent to long wavelengths, which allows them to be used for UV applications without costly and sometimes ineffective optical filters. **Three new fiber coupled pump diode lasers** have been released by **SDL**. The new "SDL-3400-P6" series fiber coupled laser diodes provide high cw power, low numerical aperture and wavelengths at the absorption bands of common solid state laser systems. Models delivering up to 16 W cw power from a 600 μ m core fiber are available.

He knows he's got the world's best MBE system. Wouldn't you like that peace of mind?

VG SEMICON



If you buy MBE epi GaAs, chances are it was grown on a V100. So if you're thinking of purchasing a production MBE system, the choice is easy.

All the world's leading epi companies choose the V100. Not simply because it is the best product. But also because we deliver on time, get you up and running quickly and give you great training and documentation. Our experienced worldwide team then provides direct help with technical and applications information and fast response for consumables and service.

The V100 has the highest throughput capacity for 3", 4" and 6" GaAs wafers for the lowest cost per wafer and the highest return on investment. Designed for high uptime in the production environment, our simple, uncomplicated designs are rugged, reliable and easy to maintain. Our proven automation technology minimizes wafer handling for low contamination and exceptional reproducibility.

Quite simply, the V100 delivers the best epi material, time and time again. For more information on the only MBE systems that come with peace of mind, why not call us. Or check us out on the Internet at <http://www.surface.fisons.co.uk/>

VG SEMICON - United Kingdom

The Birches Industrial Estate, Imberhorne Lane
East Grinstead, West Sussex, RH19 1XZ, UK
Tel. +44 1342 325011, Fax +44 1342 315800.
e-mail: sales@surface.fisons.co.uk

CHINA. VG China, Apt. 1008, Beijing Yanshan Hotel,
138A Haidian Road, Beijing 100086.
Tel. (86) 10 2564811.

FRANCE. Fisons Instruments, 85 Avenue Aristide
Briand, 94117 Arcueil, Paris. Tel. (1) 4740 4819.

GERMANY. Fisons Instruments, Postfach 73,
Peter-Sander-Strasse 43, 55252 Mainz-Kastel.
Tel. (6134) 2890.

JAPAN. Marubun Corporation, 8-1 Nihombashi
Odenmachi, Chuo-ku, Tokyo 103.
Tel. (81) 33 639 9652.

KOREA. VG Instruments Korea,
Ssang Bang Building 4F, 210 Nonhyun Dong,
Kangnam-gu, Seoul. Tel. (2) 548 2983.

SWEDEN, NORWAY, FINLAND.
Fisons Instruments Nordic AB,
Gardsfogdevägen 16, S-16170 Bromma.
Tel. (8) 629 2400.

TAIWAN. Scientek Corporation, 4F, No. 2, Lane 47,
Nankang Road, Sec. 3, Taipei. Tel. (8862) 788 7841

USA. Fisons Instruments, 55 Cherry Hill Drive,
Beverly, MA 01915. Tel. (508) 524 1000.

Circle 63 on Reader Service Card

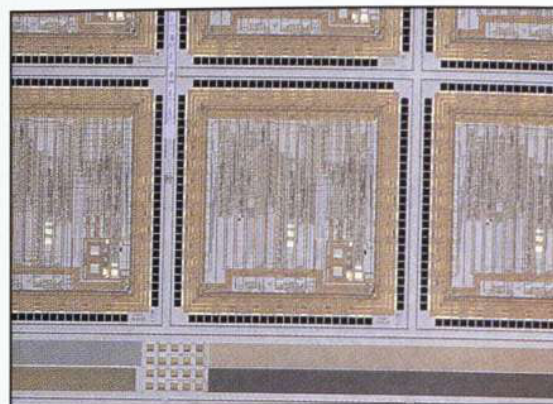
TriQuint's GaAs Transceiver for Telecommunications and High Data Rate Applications

Optical communication systems require transceivers to act as links between the optics (either the laser/LED transmitter or the photodetector receiver) and the communications processing where both switching and digital signal processing takes place. The heart of a high speed data transceiver is a multiplexer/demultiplexer (MUX/DEMUX) which converts serial data into a parallel data format and vice versa. Transceivers of this type require high speed devices, high performance passive elements, and modest gate counts, all of which make them ideally suited to a digital GaAs process.

TriQuint Semiconductor [Beaverton, OR] has recently introduced a new high speed GaAs transceiver, the TQ8105, which complies with SONET/SDH¹ standards and is suitable for both 622 Mb/s and 155 Mb/s operation². Besides the 8:1 MUX and 1:8 DEMUX which is the heart of this device, the circuit also includes SONET/SDH framing circuitry used to synchronize data boundaries, and a phase lock loop (PLL) clock synthesizer (running at 2488.32 MHz). This integration approach couples the conversion of serial and parallel SONET/SDH data with bit alignment and clock synthesis into a single device. In addition, the TQ8105 has enhanced diagnostic capabilities which include Loss of Reference (LOR) indications when the reference clock is absent, Loss of Signal indications producing both high and low outputs (SOL and NSOL), and Receiver LOCK (RLOCK) indications, whenever the incoming DEMUX clock drifts more than 500 ppm from the reference frequency.

The Circuit

The new transceiver can operate in many different modes. In a typical application, optical signals are received from a SONET/SDH fiber system and converted into a NRZ (non-return-to-zero encoded) serial data stream in which the clock is extracted from the data. The serial data can then be demultiplexed into a parallel word (byte), and the framing circuit monitors the demultiplexed data to sense boundaries within the data stream which can then realign these boundaries if necessary. At this point, data can then be passed along for further routing and signal processing. The reverse operation can also be implemented, with parallel data being converted into serial data. In addition to these operations, other loopback modes can be implemented, in which both serial and parallel data can be looped through the TQ8105 without being converted. The TQ8105, which is fabricated on 4 inch GaAs substrates, utilizes TriQuint's new QED2 enhancement/depletion ion implanted SCFL (Source Coupled FET Logic) MESFET process. This process uses 0.6 μm gate length transistors which exhibit f_t values of 20 GHz. Four layers of Au coupled with dielectric isolation are used for metalization, with each metal layer exhibiting a 4 μm pitch (2 μm line and spaces). The TQ8105 utilizes 1800 equivalent two input gates and has an area of 3.56 x 3.43 mm². It can operate with a single 5 V supply and dissipates 2.3 W.



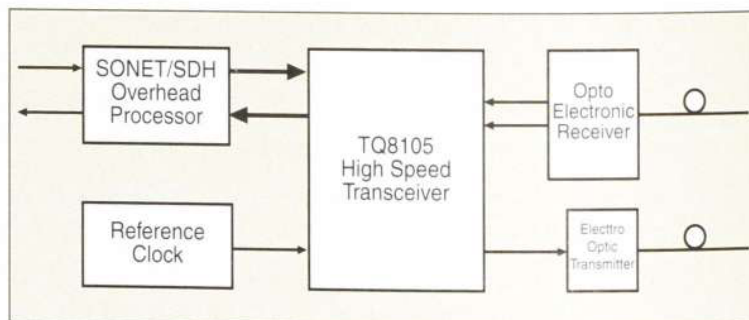
Photomicrograph of the TQ8105 transceiver. The actual area of each circuit is 3.56 x 3.43 mm².

Markets

TriQuint foresees a burgeoning business in high speed transceivers. The reasons include not only the continuing overall growth of telecommunications, but also the fact that the 622 Mb/s data rate, which used to be found only in long distance telephone lines, is becoming common in local networks. According to Andy Turudic, Strategic Marketing and Applications Manager of TriQuint, "this type of transceiver was originally used for fiber-based telephony systems, and this still represents a significant portion of the business for this device. However, we are starting to see a lot of computer data applications for this chip. Even though the computer data applications are still in the embryonic stage, this market is already as large as the more mature telephony market is for us." The emerging markets for 155 Mb/s and 622 Mb/s links for data networking is occurring in both LANs (local area networks) and WANs (wide area networks).

Pricing is a key issue for any GaAs IC which hopes to find a high volume computer data application. An earlier version of the TriQuint transceiver sold for \$300. The increasing volume in today's markets and continuing improvements in yields allows the TQ8105 to be introduced at \$53, even through it has greater diagnostic capabilities than its predecessor. Turudic says, "this lower price enables people to use this technology in applications that they had not envisioned before, and this is helping to fuel the growth in the computer data transmission area."

The future direction for these transceivers is at higher data rates, the next being OC-48 at 2.5 Gb/s. TriQuint has in fact been fabricating GaAs-based ASICs (application specific ICs) capable of handling those data rates since 1988. Turudic says, "we are not currently producing large volumes of 2.5 Gb/s parts because the demand is simply not there yet. When there is a significant enough market, we will migrate up to 2.5 Gb/s." He believes that the technology is available and ready to used - as soon as the market develops.



Schematic of a typical application for TriQuint's new high speed transceiver, which acts as a link between the III-V optical components and the silicon data processing chips.

¹ Synchronous Optical Network/Synchronous Digital Hierarchy.

² A 622 Mb/s data rate meets SONET OC-12 standards in North America and STM-4 in the rest of the world, while a 155 Mb/s data rate meets the SONET OC-3 and STM-1 standards.

Sony ZnSe Laser Breaks the 100 Hour Barrier

Reductions in defect density allow the longest room-temperature operating lifetime reported to date for a II-VI semiconductor laser

In early February Sony Corporation announced that its Research Center had succeeded in fabricating a green ZnSe laser diode with a room temperature continuous wave operating lifetime in excess of 100 hours. This is the longest lifetime ever reported for a II-VI laser, and it improves on the previous record of 4.5 hours (also set by Sony) by more than an order of magnitude.

The timing of the announcement could not have been better, as it closely follows Nichia Chemical's report of the first successful laser diode fabricated from the GaN materials system. (See CS 2 (1) p. 7). The ZnSe and GaN materials systems both provide the wide bandgap needed to produce short wavelength light emitters, but in the past few years most of the momentum in this field has shifted to the GaN side. ZnSe is the more mature of the two technologies, and it yielded the first blue-green and blue semiconductor lasers five years ago (achievements reached independently first by 3M and the Brown/Purdue group in the US, and then Sony in Japan). But since then research in the nitride system has been progressing rapidly. Nichia has already success-

fully commercialized blue and green LEDs based on GaN materials, and their announcement of a nitride laser was seen by some as possibly obviating the need for future work in II-VI light emitters. But this new result may re-ignite interest in developing both technologies side-by-side.

The active layer in the Sony diode was a single ZnCdSe quantum well, surrounded by ZnSSe guiding layers and ZnMgSSe cladding layers. The major weakness of the ZnSe system, especially in comparison with the nitrides, is the rapid multiplication and propagation of existing defects into the active layer due to the material's relatively weak bond strength. Therefore it is not surprising that Sony attributes the extended lifetime of the new diode to a significant reduction in existing defect density, down to less than 10^4 cm^{-2} , compared to 10^5 - 10^6 cm^{-2} for previous work. Sony did not disclose all of the methods used to reduce the defects, but a spokesperson did report that improvements were made in the quality of the interface between the GaAs substrate and the II-VI epi layers. This would likely reduce the number of stacking faults and dislocations

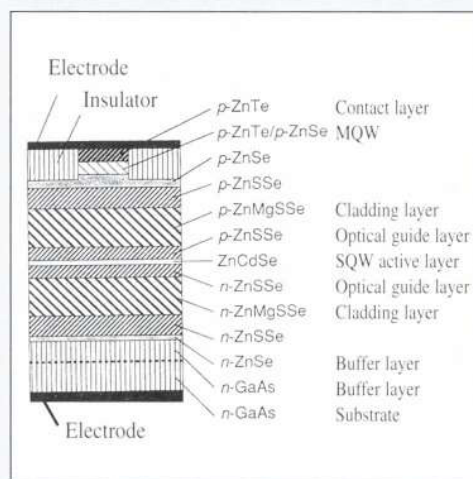
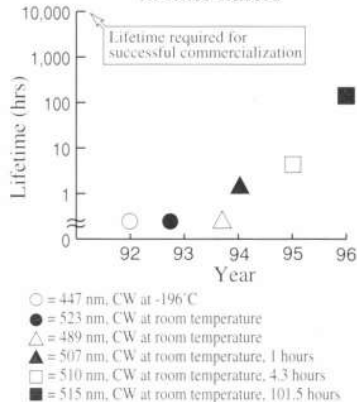
which arise because of interface roughness and lattice mismatch between the II-VI alloys and the GaAs substrate. Japanese newspapers reported the use of Zn passivation on the GaAs buffer layer before the growth of the n-type ZnSe buffer layer.

Lifetime and Wavelength

Sony's plans for publishing the complete results have not been announced. However, they did report that their next steps will include reducing the wavelength and further extending the lifetime. As of this writing there have been no reports of CW operation of a nitride laser, which means that Sony is far ahead in terms of demonstrating long lifetimes for short wavelength laser diodes. The current Sony diode operates at 515 nm, which is in the green region of the spectrum. There are potential applications for true green laser diodes as pointing and alignment tools, as well as uses in the reprographics and biomedical areas. However, the biggest potential application for such devices is optical data storage, and here the GaN system has the natural advantage because its wider bandgap (3.36 eV @ 300K, compared to 2.71 eV for ZnSe) allows shorter wavelength lasing. The Nichia nitride laser operates at 417 nm, the shortest wavelength ever reported for a semiconductor laser. The $\approx 100 \text{ nm}$ difference between the Sony/ZnSe and the Nichia/GaN diodes is extremely important, as it translates into a difference in maximum storage density of ≈ 1.5 times.

The key to reducing the emission wavelength lies in increasing the bandgap of active layer material. For the current ZnSe structure that requires reducing or eliminating the Cd content in the ZnCdSe quantum well. But as the bandgap of the active region increases, the bandgap of the ZnMgSSe cladding layers and the ZnSSe guiding layers must also increase, in order to maintain the electrical confinement of carriers and the optical confinement of photons. While this is easily done from an alloy growth perspective, there is evidence that the p-type doping efficiency for the ZnMgSSe cladding layers drastically decreases as the bandgap increases. For example, Sony has shown that the maximum p-type carrier concentration in ZnMgSSe with a bandgap of 2.96 eV is $1.2 \times 10^{17} \text{ cm}^{-3}$, while at a bandgap of 3.05 eV, the maximum p-type doping level drops to $2.5 \times 10^{16} \text{ cm}^{-3}$. Since the p-type cladding layer needs minimum doping levels at the 10^{17} level, the usable bandgap of the ZnMgSSe alloy is currently restricted to less than 3.0 eV, putting a severe limitation on the operational wavelength. Therefore it appears that some important and fundamental materials science work remains to be done before ZnSe-based lasers will be able to record further significant progress in wavelength reduction.

Charting Sony's Milestones in ZnSe Lasers



Left: A plot of Sony's major milestones in ZnSe lasers since 1992. Right: The structure of the Sony laser diode used in the current work. A photo of that device in operation is shown on the front cover of this issue.

COMMENTARY

Defects in Blue/Green Light Emitters

PROF. ROBERT GUNSHOR, PURDUE UNIVERSITY
[WEST LAFAYETTE, INDIANA, USA]

The development of production-worthy light emitters has traditionally required substantial efforts aimed at extending device lifetime by reducing crystalline defect densities. The many years that elapsed between the first demonstrations of lasing in the AlGaAs/GaAs system and the commercialization III-V laser diodes were primarily occupied with efforts at defect reduction. It was discovered that most of the extended defects, such as dislocations, found in the active layer of those devices propagated up from the GaAs substrate. As improved substrates became available and epitaxial growth techniques were refined, defect densities were reduced and device lifetimes ceased to be a bar to further development.

Most of the work done to-date in ZnSe-based light emitters has also involved growth on GaAs substrates. Defects are generated at the II-VI/III-V interface, due to the lattice-mismatched/heterovalent nucleation. Densities on the order of $5 \times 10^6 \text{ cm}^{-2}$ or higher have been observed. The degradation of ZnSe-based lasers occurs as a result of nonradiative recombination at the point where a threading dislocation (originating as a stacking fault at or near the II-VI/III-V interface) passes through the quantum well region. Because of the large bandgap energy a significant local heating of the lattice takes place at the point of a nonradiative recombination event; the result of the concentration of thermal energy is the production of point defects which interact with the threading dislocation in such a way as to extend a dislocation structure further into the quantum well. A positive feedback condition results where extended regions of nonradiative

recombination cause more point defects, which further extend the dislocations along the quantum well until the gain in the quantum well region falls below threshold for laser oscillations. The mechanisms are similar to those occurring in an AlGaAs laser when threading dislocations intersect the active region.

Several groups are working toward a better understanding of the defect problem in ZnSe-based lasers. Discoveries have included the observation of 3D island-like nucleation of ZnSe on a Se-reacted GaAs surface and a high density of structural defects due to the presence of sulfur species at nucleation. As a result, techniques have been developed to reduce defect densities, and several groups are reporting improved results. For example, our own group, the Brown University/Purdue University consortium, has achieved defect levels below $5 \times 10^3 \text{ cm}^{-2}$ over a 3" wafer on a consistent basis. Further improvements will be required to achieve commercially viable devices, but the Sony report provides encouraging evidence that such a goal is within reach.

The situation for the nitride material system is quite different. We have seen very rapid development of commercial blue LED devices despite reported defect densities of 10^{10} cm^{-2} or more! The ZnSe and AlGaAs experiences would dictate that virtually all injected charge carriers would recombine nonradiatively at centers associated with the defects, and no photons would be emitted; but instead, in the nitride system these defect structures are seemingly benign. There is active research aimed at explaining this surprising phenomena. There has even been speculation that the defects may be *beneficial* toward achieving the requisite doping levels. The defects tend to group around low angle grain boundaries oriented along the c-axis, the result being almost isolated crystallites having the same c-axis orientation, but also exhibiting a small in-plane rotation with respect to each other. Nevertheless, we have recently seen the successful demonstration of a blue pulsed laser in the GaN system. And while it is clear that workers in the ZnSe system must continue to attack the defect problem, it is not yet clear how the nitride crystal structure will limit attempts at long-lived room temperature cw operation.

Resolve the Difference

For
Semiconductor
Characterisation



OXFORD

MonoCL-2 high spatial resolution imaging & spectroscopy

Our MonoCL-2 system leads the way in cathodoluminescence imaging and spectroscopy of semiconductor and optoelectronic materials in the SEM.

- Used to study both bulk and epitaxial materials, including sub-surface profiling.
- Characterises defects, low dimensional structures and strained layers.
- Allows sub-micron resolution of optical emission centres and mapping of their distribution.
- Application notes include:-
CL characterisation of strained semiconductors
CL characterisation of extended defects in Si & SiGe alloys
CL studies of Gallium Nitride epilayers

**Oxford Instruments,
Scientific Research Division
Research Instruments**

130A Baker Avenue, Concord, MA 01742
Tel: (508) 369 9933, Fax: (508) 369 6616

UK Tel 44 (0) 1865 882855; France Tel (1) 69
41 89 90; Japan Tel (3) 3264 0551; Germany
Tel (611) 76471

International Symposium on Blue Lasers and Light Emitting Diodes

CHIBA UNIVERSITY, JAPAN
MARCH 5-7, 1996

Challenges for both II-VI and Nitride-based emitters continue to center around reduction of defects and improvements in p-type doping levels

Breakthroughs in the development of blue emitting devices have been occurring at a rapid rate. In just the past few months, researchers at Nichia Chemical Industries have demonstrated the first GaN-based laser; that was quickly followed by the Sony ZnSe laser result reported on page 7. The timing was, therefore, perfect for an international conference on the subject of blue light emitters, such as the one held at Chiba University in early March. No new fundamental breakthroughs were reported there. Instead, of the 131 papers presented, most dealt the basic problems which have challenge the nitride and ZnSe systems; namely, large defect levels due to poor epi layer/substrate interfaces, and the inability to obtain high p-type doping levels and good ohmic contacts.

II-VI's

The limited lifetimes in II-VI devices are the direct result of defects within the material. Sony attributes their record breaking lifetime to the reduction in stacking faults from the typical 10^5 - 10^6 cm⁻² level to the 10^4 cm⁻² level. Many of these dislocations and stacking faults are the result of growing II-VI materials on GaAs, where even though lattice matching can be maintained by using ZnMgSSe, the growth at the II-VI/GaAs interface often does not proceed in the two-dimensional (2D) manner required for low defect material, but breaks down into three-dimensional (3D) growth which results in the formation of stacking faults and dislocations. J. Han and R. Gunshor of Purdue University [West Lafayette, IN] have used Migration Enhanced Epitaxy (MEE) at 260°C in order to enhance the 2D nature of the II-VI growth. Using this method they have

seen a reduction in etch pit density (EPD) from 10^6 cm⁻² to 10^4 cm⁻², an indication of greatly improved material quality. Lasers are currently under fabrication with this material, and it is anticipated that improved lifetimes will be obtained. S. Saito and coworkers from Toshiba Corporation [Kawasaki, Japan] reported on enhanced 2D ZnSe growth when the As-terminated GaAs surface is first exposed to Zn flux for 30 seconds. Under those conditions an EPD count of 2×10^5 cm⁻² is obtained as compared to a EPD count of 8×10^7 cm⁻² for the case of no Zn flux prior to growth.

The other approach to enhance 2D growth is to grow directly on ZnSe substrates. F. Nakanishi and coworkers from Sumitomo Electric Industries [Osaka, Japan] reported on the growth of ZnSe on semi-insulating ZnSe substrates. By exposing the 450°C heated substrate to activated hydrogen derived from a plasma source, a streaky C(2x2) reflected high energy electron diffraction (RHEED) pattern was obtained for a Zn-stabilized surface. As evidenced by the continued streakiness of the RHEED pattern once ZnSe growth began, the growth was 2D in nature. Stacking faults and dislocations were not observed by TEM for these films, but no EPD values were reported. The resulting ZnSe film showed a X-ray FWHM of 18 arcsec, which was as narrow as that obtained for the substrate. J.F. Schetzina of North Carolina State University [Raleigh, NC] reported on the growth of ZnSe-based lasers on n-type ZnSe substrates which had been fabricated by Eagle-Picher [Miami, OK] using their Seeded Physical Vapor Transport process. Green LEDs were fabricated from the structures, with the best devices exhibiting lifetimes of 750 hrs while operating at current densities of 15 A/cm² (40% degraded), with some

devices operating for as long as 10,000 hours - the length of time generally considered necessary for a commercial device.

The other major challenge of II-VI based devices is that of p-type doping. Even though p-type doping levels up to $1-2 \times 10^{18}$ cm⁻³ have been obtained, this appears to still be too low to produce low resistance contacts to p-type material. High resistance contacts result in both a voltage drop across the contacts as well as joule heating which can lead to device failure. The current approach to circumventing this doping problem is to grade the ZnSe p-type contacting layer to that of ZnTe, which can be p-doped to the 10^{19} cm⁻³ level, and then use the ZnTe layer to make contact. This approach also has its limitations. Han and Gunshor of Purdue explained that even though the contact resistance to heavily doped ZnTe is 2.4×10^{-4} ohm-cm², the series resistance of the Zn(Se,Te) graded region is 4×10^{-4} ohm-cm², and that after the device turns on, the operating resistance approaches the 10^{-3} ohm-cm² level, a value that they feel is still one order of magnitude too high for a good device. The other problem with this approach is that ZnTe is lattice mismatched from ZnSe, and the resulting strain may induce defect generation which will degrade device lifetime. A multitude of new approaches were presented to improve this situation. G. Landwehr and A. Waag of the University of Wurzburg [Wurzburg, Germany] reported for the first time on the growth of BeTe/ZnSe superlattices (SLs) which can be lattice matched to GaAs, and in which a p-type doping level in the BeTe of 8×10^{17} was obtained (this was reported to be nonoptimized). LEDs using BeMgZnSe-ZnSe QWs and BeTe/ZnSe placed between the p-type GaAs substrate and the active device, produced an LED which could be run at a current density of 70 A/cm² and a voltage of 7V. Other approaches included that by A. Ohki and coworkers at NTT [Kanagawa, Japan] of growing p-type Ge on ZnSe which is lattice matched to ZnSe, and can be heavily p-doped, and that of S. Yoshii et al of Matsushita Electric [Osaka, Japan], reporting on Au-Ag/Ni/Te for ohmic contacts to p-type ZnSe and ZnSSe. Lastly, C.D. Song and coworkers from Tohoku University [Sendai, Japan] reported on inserting a single monolayer of nitrogen doped ZnTe into 3.0 nm layers of both ZnSe and ZnS, to obtain net acceptor doping levels of 1.7×10^{18} cm⁻³ and 5×10^{17} cm⁻³, respectively.

Even if different contact schemes can be utilized to circumvent the p-type doping limitation in ZnSe-based materials, this doping limitation is still an issue in the operation of the device. Because p-type doping quickly falls off in the ZnMgSSe cladding layers for Mg content above 30% (corresponds to a band gap of 3.0 eV), this in turn limits the wavelength of the laser. Since the bandgap difference between the cladding layers and active layers

must be on the order of 500 meV in order for the laser to operate, this limits the CdSnSe to a bandgap of approximately 2.5 eV, and therefore a wavelength of approximately 500 nm. W. Faschinger et al from Universitat Wurzburg [Wurzburg, Germany], reported on three approaches which may improve the p-type dopability of II-VI materials: the use of SLs instead of mixed crystal quaternary layers, the altering of the surface Fermi level during growth by modification of the surface through segregation effects, and an increase in growth temperature - where this last technique may not be applicable to most II-VI compounds which can not be grown at high temperatures.

Nitrides

Like the II-VI materials, defects are a key issue in the growth of nitride-based materials. The major cause for dislocation densities which can approach the 10^{10} cm^{-2} level, is that much of the growth is being done on sapphire, which exhibits a lattice mismatch of approximately 14% to GaN. In order to grow GaN on sapphire it has been found necessary to use a low temperature GaN or AlN buffer. K. Uchida and coworkers of Hitachi [Tokyo, Japan] reported on the details of initial GaN growth on sapphire in which they determined that growth proceeds by a crystal-amorphous-crystal (CAC) sequence. Prior to growth, initial nitridation takes place at 1050°C during which the crystalline sapphire which is exposed to NH_3 is transformed into an amorphous layer consisting of $\text{AlO}_{1-x}\text{N}_x$. After this nitridation, the substrate temperature is typically lowered to 550°C , where a fine grain low temperature GaN buffer is deposited, and then the substrate temperature raised back up to the 1050°C at which a thicker GaN layer with almost single crystal quality can be grown. They observed that the amorphous-like nitrided layer disappeared after 70 nm of GaN growth. The almost-single crystal nature of the GaN was studied by F.A. Ponce of Xerox [Palo Alto, CA]

by TEM, where he observed that the microstructure of the GaN is columnar in nature and that this structure originates from the low temperature buffer layer. The columnar structure is bounded by low angle grain boundaries and by both edge and screw dislocations which have been generated in order for the material to retain coherency.

An obvious method to lessen dislocation densities is to grow on a substrate more closely lattice matched to GaN, such as 6H-SiC. With a mismatch of approximately 3% to GaN, SiC has several distinct advantages over sapphire: it can be made electrically conducting; it has much higher thermal conductivity; and it possesses natural cleavage planes which allow the formation optical cavities required for laser operation. I. Akasaki and H. Amano of Meijo University [Nagoya, Japan] reported on the growth of GaN/GaInN MQWs on SiC which exhibited dislocation densities of $2 \times 10^8 \text{ cm}^{-2}$, a value one order of magnitude lower than those typically obtained for most GaN growth on sapphire. Using this structure, they grew a AlGaIn/GaN/GaInN SCH laser structure with a 7.5 nm well width, and were able to obtain a threshold lasing action under optical pumping at a level of 27 kW/cm^2 - the lowest value to date reported for this type of structure, and a value that is approaching those of II-VI photopumped lasers.

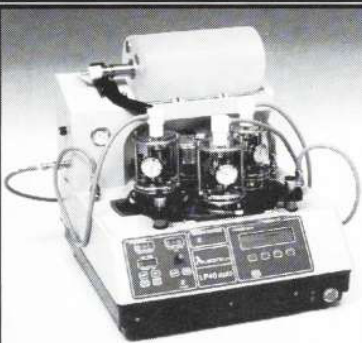
Quite possibly the optimum substrate for GaN growth is that of GaN itself. S. Porowski and coworkers of the High Pressure Research Center Polish Academy of Sciences [Warsaw, Poland], reported on the formation of 5 mm wide GaN platelets which were grown from the solution of liquid Ga under N_2 pressure (up to 20 kbar), and over a temperature range of 1400 to 1600°C . It typically takes 40-50 hours to grow these GaN plates. X-ray diffraction measurements showed FWHM values of 20-30 arcsec for 1 mm crystals and 30-40 arcsec for 1 to 3 mm crystals. GaN homoepitaxial growth was performed on these substrates, producing material which exhibited dislocation densities of 10^6 to 10^7 cm^{-2} - a value several orders of magnitude less than produced by other methods. It was determined by M. Godlewski and coworkers at the Institute of Physics Polish Academy of Sciences [Warsaw, Poland] that the GaN epitaxial layers were found to exhibit bound excitons with energies of 3.471 eV and 3.472 eV, and lifetimes of 650 and 700 ps, respectively, which is much higher than for GaN grown on sapphire (70 and 140 ps, respectively), an indication the superior quality of these epitaxial layers.

Despite the reported high level of dislocations, which most researchers believe need to be reduced to the 10^5 - 10^6 cm^{-2} level for the successful fabrication of nitride-based cw lasers operating at room temperature, the current high level of dislocations do not seem to result in the degradation of GaN-based LEDs. M. Osinski and D.L. Barton of the University of New Mexico [Albuquerque, NM] reported on the stressing of Nichia LEDs to operating currents up to 70 mA (rated at 30 mA) for a total of 2650 hours, in which defect densities are measured at $2.2 \times 10^9 \text{ cm}^{-2}$. Under these conditions, little degradation in light output was observed, and they concluded that, "Nichia devices enjoy a remarkable longevity in spite of their high density of defects."

As in the case of II-VI materials, the contacting of p-type layers is a major issue. S. Nakamura of Nichia reported on the reduction of the turn on voltage of their GaN-based MQW laser from that originally reported at 34 V to 22 V, but contact resistance to p-type GaN still needs to be improved in order to further reduce these operating voltages. H. Amano and coworkers from Meijo University reported that although GaN could be p-type doped with Mg to levels as high as $2 \times 10^{19} \text{ cm}^{-2}$, that the contact resistivity is typically $5 \times 10^{-3} \text{ ohm-cm}^2$, a value which is even higher than typically obtained when contacting p-type II-VI materials. As a result of these high contact resistivities, Amano and coworkers propose to use an inner stripe geometry structure for laser fabrication, which will allow a wide area of p-contact to help reduce the high contact resistivity. It is quite apparent that issue of contact resistance will remain an important one in the future fabrication of nitride-based devices.

PROCESSING III-V MATERIALS

Logitech offer complete machine systems for preparing III-V wafers including wafer slicing, lapping, polishing, chemical and chemo-mechanical polishing.



WAFER THICKNESS
CONTROL TO $\pm 2 \mu\text{m}$

WAFER THICKNESS
UNIFORMITY TO $\pm 2 \mu\text{m}$

OPTIMUM SURFACE
FINISH

AUTOMATIC PLATE
FLATNESS CONTROL

30 Years of Precision Materials Technology

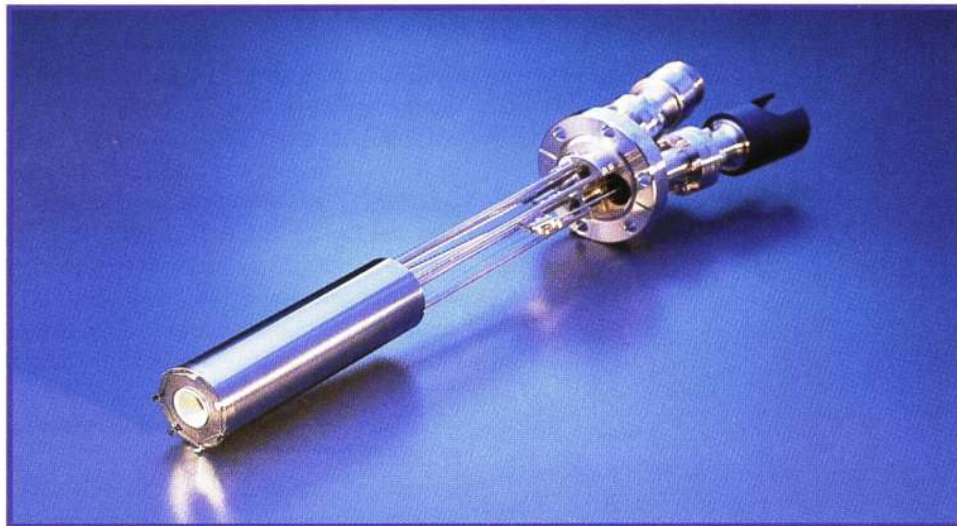
Logitech Products, Div of Struers
Radiometer America Inc., 810 Sharon Drive
Westlake, Ohio 44145
216-871-0071 Phone
216-871-8188 Fax



Circle 49 on Reader Service Card

Introducing the New SUMO™ Effusion Cells from EPI

EPI Redefines Effusion Cell Technology



The EPI SUMO™ Effusion Cell – an important advance in MBE equipment technology, available for any production or research MBE system

The new EPI SUMO™ effusion cell is nothing short of revolutionary. It optimizes material quality while maintaining very low levels of morphological defect densities and background doping levels. The beam equivalent pressure remains consistent throughout the life of the material charge, greatly enhancing reproducibility and operator convenience. Shutter activation-related flux transients are virtually undetectable, while providing state-of-the-art uniformities. All models have large useful capacities, and configurations available for both research and multi-wafer systems.

- **Excellent Material Quality**
- **Extremely Low Defect Densities**
- **Increased Flux to Power Ratios**
- **Long-Term Stability - more consistent beam equivalent pressures over the lifetime of the charge**
- **Virtually Undetectable Shutter Activation Related Flux Transients**
- **State-of-the-Art Deposition Uniformity**
- **Significantly Increased Useful Capacity**

*If you are looking for a way to maximize your MBE system up-time, increase throughput, improve material quality and reproducibility, and make your life a little easier, contact your local EPI sales office for more information about the EPI SUMO™ Effusion Cell. Be sure to ask for **The EPI SUMO™ Application Note, February, 1996.***

EPI

**MBE Products
Group**

EPI
1290 Hammond Road
Saint Paul, MN 55110 U.S.A.
Phone: (1) 612-653-0488
Fax: (1) 612-653-0725
e-mail: info@epimbe.com

EPI Europe
147 Chorley New Road
Horwich, Bolton BL6 5Q
Greater Manchester, U.K.
Phone: (44) 1-204-668366
Fax: (44) 1-204-668466
e-mail: europe@epimbe.com

Japan
Techscience, Ltd.
2-64 Miyamotocho,
Koshigaya-shi
Saitama-ken 343 Japan
Phone: (81) 489-64-3111
Fax: (81) 489-65-1800

The Growing Market for Indium Phosphide Laser Diodes

Fiber optic lasers will see a CAGR of 18.75%, worldwide market value of \$1.5 billion by 2000

Laser diodes based on InP and related compounds occupy an enviable niche: they are one of the enabling technologies for single mode fiberoptic transmission systems. Therefore, as fiber networks continue to proliferate throughout the rest of this decade, the demand for InP lasers will remain steady and strong, resulting in a worldwide market value of nearly \$1.5 billion by the year 2000.

The total market for all single-mode optoelectronic components used in fiber-optic systems in 1995 was valued at \$1.25 billion. That market should grow at a compound annual growth rate (CAGR) of 20%, reaching a value of \$3.1 billion by 2000, according to a study recently released by KMI Corporation. KMI's Richard Mack reports that laser diodes will represent about one half of the total component market. As shown in Figure One, KMI values the current market for laser diodes used in fiberoptics at \$700 million, with a forecasted CAGR of 18.75% until 2000.

Mack reports that increased competition among carriers is leading to fiber-based networks being built in all regions of the world. When preparing their report, KMI examined all fiberoptic applications. Obviously, telecommunications is the biggest segment: local, long distance, and submarine networks were all analyzed. Non-telecom networks, such as CATV (cable television), satellite, radar and microwave downlinks, and cellular system links were all included; as well as "private" networks (operated by an entity other than a public service provider) including building and campus-wide LANs. They identified several factors which are contributing to the demand for fiberoptic systems, including increased requirements for higher-bandwidth transmis-

sion equipment; infrastructure building in developing countries; network architecture improvements which take advantage of fiberoptics in transport and switching; strong networking standards, and lower costs in optoelectronics and interconnect products, making fiberoptic systems more cost effective. In fact, KMI has identified only one possibly stagnant area - the submarine cable sector seems likely to see a slowdown after this year due to a saturation of demand.

Building and servicing the world's fiberoptic networks will require more than 2.5 million laser diodes per year by 2000. See Figure 2, which illustrates the total growth in worldwide demand for fiberoptic laser diodes and also shows the segmentation according to device type. Fabry-Perot devices will suffice for most applications, but the more sophisticated distributed feedback (DFB) lasers will be needed for more demanding cases, especially at high data rates. The use of DFB lasers will likely be especially prevalent in CATV applications, which demand very high levels of performance from the fiberoptic system.

KMI has also segmented the market by wavelength. Figure Three provides the breakdown for 1995. Significant changes to this pattern are not predicted before 2000, with the exception that 980 nm pump lasers will likely overtake 1480 nm pump lasers, due to the predicted slowdown in the submarine market. Of the four categories shown in Figures One and Three, all but the 980 nm pump lasers are fabricated on InP substrates.

There are 30 or more manufacturers of diode lasers for fiberoptics around the world, according to KMI's analysis. The largest among them (minimum of \$20 million in diode lasers for fiberoptics in 1995) include Alcatel Optronics, AT&T Microelectronics/Lucent Technologies, Fujitsu Compound Semiconductor, Hewlett-Packard, Hitachi, Lasertron, Mitsubishi Electronics, NEC, Nortel (Northern Telecom Optoelectronics), and Ortel. Seven of the ten (all but Hewlett-Packard, Lasertron and Mitsubishi) also manufacture transmission systems. KMI characterizes the market for fiberoptic laser diodes as "fairly evenly divided" between merchant and captive production.

Given the generally positive forecast for the market, there should be opportunities ahead for many component manufacturers, and continuing strong interest in the InP materials system for optoelectronics applications.

"Worldwide Markets for Fiber Optic Single-Mode Transmitter and Receiver Components", KMI Corporation, America's Cup Avenue at 31 Bridge Street, Newport, RI 02820 USA, TEL [1] 401 849 6771, FAX [1] 401 847 5866. If you would like to receive more information from KMI about this report or any of their other products or services, **Circle 25 on the Reader Service Card.**

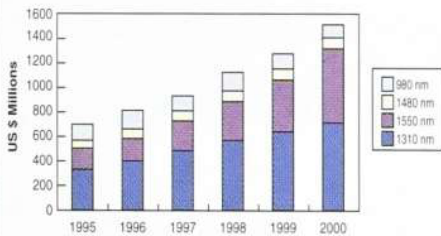


Figure 1. Worldwide market forecast for laser diodes used in fiberoptics.

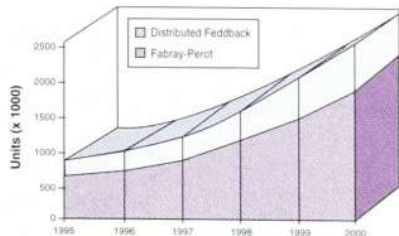


Figure 2. Worldwide forecast for fiberoptic laser diodes, number of units required.

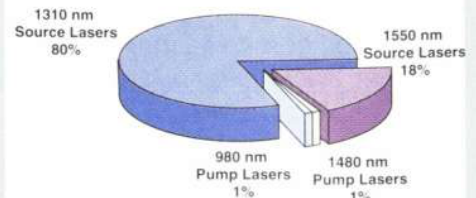


Figure 3. Worldwide market for fiberoptic laser diodes by wavelength, unit quantities, 1995

TRW & RF Micro Devices Team Up for a New Fab Dedicated to GaAs HBTs

TRW and RF Micro Devices (RFMD) have announced the formation of a strategic alliance to develop, produce and distribute GaAs HBTs (heterojunction bipolar transistors) as radio frequency integrated circuits (RFICs) for the wireless communications market. Under the terms of the agreement TRW will make investments in RFMD that will allow the latter to either build or acquire a high-volume GaAs fab. TRW will then transfer its epi growth process and HBT chip manufacturing technology to RFMD. The new fab, which will have a capacity of up to 25,000 4" wafers/year, is scheduled to be operational in late 1997 or early 1998. In the meantime, TRW will more than double its internal capacity of 5,000 3" wafers/year to 11,000 wafers/year to meet current demand. The new alliance deals exclusively with HBT technology for commercial wireless applications at <10 GHz. TRW will continue with its GaAs foundry and its own defense- and systems-related GaAs program, and is, according to a company spokesperson, also exploring possible commercial opportunities for its HEMT-based technology and other possible commercial applications for HBTs.

This new move represents RFMD's first foray into fully vertically integrated IC manufacturing. RFMD, which is located in Greensboro, North Carolina, and TRW first teamed up in 1992, and until this point RFMD has acted as a "fabless" design house which tested, packaged and distributed chips supplied by TRW. As a small (<100 employees) and innovative company, RFMD has established a reputation for designing and introducing new RFICs to the market quickly. By working together, the TRW/RFMD team has been able to popularize TRW's HBT circuits to an extent that TRW, a traditional defense and aerospace contractor, might not have been able to achieve on its own. At last count, TRW was shipping more than 500,000 HBT chips a month for RFMD, which offers 50 different HBT circuits. According to RFMD's Jerry Neal, GaAs accounts for ~60% of their business.

The new alliance looks like a "win/win" situation for both parties. TRW gains access to high volume markets for its technology and RFMD gains a mature and sophisticated manufacturing technology that it probably could not afford to develop on its own. Another winner is GaAs HBT technology itself. Most of the GaAs RFICs which are currently available are based on MESFETs, and HEMT technology is also available from several companies. Thus far, HBTs have remained relatively uncommon. However, Bob Van Buskirk, the Executive Director of TRW's Commercial GaAs Applications, reports that several of their OEM customers have come to the conclusion that for certain wireless components, especially linear power amplifiers for transmit functions, HBTs offer the best performance characteristics and the best cost potential. But, he says, those companies did express reservations about the availability of a secure supply. Now, with this new alliance, it will be possible for the TRW/RFMD team to service higher volume applications than was previously possible.

TRW & RFMD are already the clear volume leaders in the HBT area, especially with regard to MMICs for wireless applications. Van Buskirk believes that the key to success thus far has been TRW's proprietary epi process. He recalls that "there was a period in the early 1990's when there were a lot of concerns about the reliability of HBTs. Much of the problem stemmed from the epitaxial growth, and specifi-

cally the doping of the epitaxial layers. But we developed techniques, based on MBE growth, that dealt with the issues, so reliability has not been a problem for us." Jerry Neal of RFMD says "when we first started offering the HBT devices to commercial customers, there were two major issues that we had to address: reliability and cost." The reliability issue was solved by TRW's data (for example, their ability to get their HBT circuits certified for space use) as well as RFMD's own lifetime testing. The solution to the cost issue, according to Neal, lies the small scale of the devices. As a vertical structure, HBTs offer advantages not shared by HEMTs and MESFETs, which are horizontal structures that often utilize gate widths of several millimeters. And, according to Neal, RFMD adds their design expertise, which also helps to keep the sizes small. As a result, they have proven that they are able to yield thousands or even tens of thousands of ICs from a single 3" wafer.

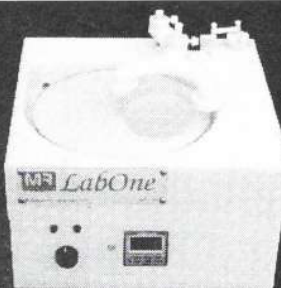
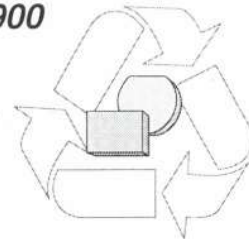
RFMD reports that their current customer list includes major wireless OEMs such as Qualcomm, Motorola, NEC and Samsung, as well as others which are confidential. The value of TRW's investment in RFMD and the possible locations for the new fab were not disclosed.

Recycle your expensive substrates and

SAVE

Complete *LabOne*[™] re-polishing packages, including processes start at **\$2,900**

- Take control with a proprietary process for final polish.
- Fully chemically resistant.
- Easily upgradeable.



- Superconducting
- III/V's
- II/VI's
- Nitrides
- SiC
- Oxides
- & many more

Call 800-832-1518 **today** for further information.

MR
semicon

MR Semicon Inc.
6200 Eubank Blvd. N.E. #415
Albuquerque, NM 87111
Tel 505-294-5761 Fax 505-294-5772
E-mail mrrsemi@rt66.com

Circle 15 on Reader Service Card

Who is Number One?

The Silicon Top Ten

(worldwide 1995 sales of all semiconductors in \$M)

Rank	Company	Revenue
1	Intel	13,997
2	NEC	10,632
3	Toshiba	9,619
4	Motorola	9,278
5	Hitachi	8,607
6	Samsung	7,787
7	Texas Instruments	7,782
8	IBM	6,601
9	Fujitsu	5,367
10	Mitsubishi	5,164

Source: VLSI Research, Inc.

Total 84,834

The Compound Semiconductor Top Ten

(worldwide 1995 sales of III-V semiconductors in \$M)

Rank	Company	Revenue
1	Hewlett-Packard	675
2	NEC	491
3	Sharp	461
4	Toshiba	401
5	Matsushita	360
6	Rohm	305
7	Fujitsu	297
8	Stanley	270
9	Siemens	269
10	AT&T	200

Source: Strategies Unlimited

Total 3,729

In late January several Silicon Valley consulting firms released their annual rankings of the largest semiconductor suppliers, based on 1995 sales. The table above, left, shows the numbers issued by VLSI Research, Inc., based on both merchant and captive sales. VLSI estimates the total worldwide market for semiconductors in 1995 was slightly more than \$150 billion. The top ten suppliers accounted for nearly \$85 billion in sales, which is 55-60% of the industry total. Obviously, these calculations are based almost entirely on silicon semiconductors; the presence of firms such as Intel and IBM demonstrates the dominance of traditional "silicon-only" preserves, such as microprocessors for personal computers and memory chips.

In December Strategies Unlimited published its report on the top 50 optoelectronic semiconductor manufacturers. We then asked them to add III-V microelectronics to their calculations; the result, the "Compound

Semiconductor Top Ten", appears above, right. This list includes both merchant and captive production. Hewlett-Packard, buoyed by its massive position in the LED market and strong wireless components business, leaps from oblivion on the silicon list to first place; followed by NEC, which occupies the same spot on both lists; and Sharp, which, like Hewlett-Packard, failed to make the silicon list. Both optoelectronic and microelectronic devices were included in the calculations, but it should be noted that optoelectronics, and specifically LED sales, dominate the figures.

Overall, Strategies Unlimited reports that sales of compound semiconductor devices approached \$7 billion in 1995, with the top ten suppliers accounting for \$3.7 billion, or roughly 55% of the total. According to these figures the compound semiconductor industry now accounts for around 4% of worldwide semiconductor sales.

UPDATE

1996 INTERNATIONAL CONFERENCE ON GALLIUM ARSENIDE MANUFACTURING TECHNOLOGY

APRIL 28 TO MAY 2, 1996

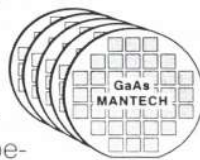
SAN DIEGO, CALIFORNIA

UPDATE

The initial attendee and exhibitor response to the first International Conference on Gallium Arsenide Manufacturing Technology has surpassed all expectations.

Exhibitor space has been fully booked by internationally renowned firms who will exhibit and provide the latest available information on state-of-the-art materials, analytical services, foundry services and devices for RF and digital applications.

Over 60 papers authored by internationally recognized decision makers and manufacturing directors will be presented during this three day conference. The Interactive Forum has been retained and expanded to foster face-to-face exchanges between authors and attendees. Workshops with limited on-site registration will be available to explore yield manufacturing issues. Techniques utilized by



the giants of the semiconductor industry will be shared that could enhance your yield improvement programs.

A limited number of registrations and conference rate rooms remain at the Hotel Del Coronado, in San Diego, California, the home for our first International Conference on Gallium Arsenide Manufacturing Technology.

Don't be left out. Make your decision to register now. Come join us in lovely San Diego and learn about the latest breakthroughs in GaAs manufacturing technology while discovering business opportunities and acquiring problem solving techniques unique to GaAs manufacturing.



Registration/Local Arrangements:
General Information & Publicity:
Technical Program Information:

Kuohsiung Li - Anadigics
Dave Miller - Litton Airtron
Jim Oakes - Raytheon

(908) 668-5000, Ext. 5207 FAX: (908) 668-5068
(201) 539-5500 FAX: (201) 539-2210
(508) 470-9779 FAX: (508) 470-9744

News From Japan

Sony to Install New Compound Semiconductor Line

Sony is spending ¥10 billion (\$100 million) to install a new compound semiconductor processing line at its production subsidiary, Sony Shiroishi Semiconductor Inc. The move is in anticipation of an increase in demand for laser couplers and laser diodes for CD-ROM, MD (mini disk), and DVD (digital video disk) applications. The company already produces 7 million laser diodes and 2.5 million laser couplers per month. The laser materials are processed at Sony's Atsugi Technology Center and the devices are assembled at Shiroishi. When the new line becomes operational in spring, 1997, it will allow laser coupler production to increase up to 7 million units per month. The complete ramp up is expected to be complete in 1998. Diodo production will remain unchanged. Currently the company is producing 780-680 nm devices, and it reports that 650nm and 635nm devices are in development.

Project to Develop 1 TB Optical Recording Technology Based on UV Laser

Japan's MITI has launched a project to develop an optical recording technology which will achieve a capacity up to 1 terabyte (8×10^{12} bits) of data. In comparison, current CD technology has a maximum capacity of 680 megabyte (5.44×10^9 bits), and the new DVD standard which will be introduced later this year will have a maximum capacity of 9.6 gigabyte (7.68×10^{10} bits). The new project's objectives include developing an ultraviolet (300 nm) laser diode, and using process technology borrowed from scanning electron microscopes, to create a narrow-tip optical fiber probe which reduces the laser spot size to a fraction of its wavelength, thereby allowing high density recording.

The project will be run by MITI's National Institute for Advanced Interdisciplinary Research (NAIR) at the Tsukuba Science Center in Tsukuba, Ibaraki prefecture. NAIR will cooperate with the Optoelectronic Industry and Technology Development Association, which includes major electronics manufacturers such as Hitachi and NEC. The Institute anticipates signing a research agreement with each of the project member firms in Spring, 1996. Approximately ten companies are expected to join the project. A new laboratory will be constructed in Tsukuba by the end of FY 1997.

NAIR is headed by Dr. Yasuhara Suematsu, a recognized authority on optoelectronics who was formerly the president of the Tokyo Institute of Technology. Dr. Suematsu will lead the terabyte project and plans to make it one of the Institute's core projects for the future.

Tokushima University to Construct Nitride Semiconductor Lab

Tokushima University will construct a "Nitride Photonic Semiconductor Laboratory" facility at its Engineering Department campus in Tokushima City. According to Prof. Shiro Sakai, the new lab will study both bulk growth of GaN and epitaxial growth of nitride materials, and it will also manufacture nitride materials to supply to its public and private partners outside the university. The lab will be built using funds granted by the Ministry of Education's Satellite Venture Laboratory project. More than ¥1.17 billion (\$114.7 million) will be spent on the 4-story facility, which will be ready for use in 1997.

Sumitomo Electric Predicts Continued Growth

In a previous issue (CS 2 (1) p. 10) we reported that Japanese manufacturers of compound semiconductor wafers were enjoying a period of healthy growth, following a period of stagnation in the early 1990's. Now we have the first signs that this trend is likely to continue. Sumitomo Electric, the world's largest supplier of compound semiconductor wafers, reports that its fiscal 1995 compound semiconductor material sales will reach ¥7 billion (\$66 million), and increase of about 10% over the previous year. A company spokesperson projects a 15-20% growth rate for the 1996 fiscal year.

VENDOR NEWS

Sumitomo Metal Mining to boost GaP Production

Sumitomo Metal Mining has announced that it plans to boost production of GaP single crystal materials. New GaP crystal pullers, and slicing and polishing machines will be installed at its Ome plant (northwestern Tokyo) in order to increase production by 20%. The expansion should be complete by March, 1996. A company spokesperson reports that this move is a response to growing demand for LEDs in China and Southeast Asia.

Sumitomo Electric to Market 4-inch GaAs Epi Wafers

Sumitomo Electric has announced that it will begin offering 4" MBE-grown GaAs epi wafers for microelectronics applications in April. Sampling of new products began in January. The company currently offers 3" MBE-grown epi wafers, as well as LPE- and OMVPE-grown epiwafers for optoelectronics. According to a company spokesperson Sumitomo spent ¥300 million (\$2.4 million) in 1995 to expand its MBE epi wafer production capability, including the purchase of a new multi-wafer MBE system from VG Semicon. Plans call for beginning production with 300 units per month in April, expanding to 1,000 units per month by October, and expanding to 3,000 units per month by the second half of 1997.

New Entry into the MOCVD Equipment Market

A new company has entered the MOCVD equipment market. Japan Process Engineering, Ltd., headquartered in Minoo, Osaka, was established in February 1994 as a compound semiconductor equipment manufacturer. The company produces MOCVD equipment and projects sales of ¥1.2 billion (\$12 million) for the fiscal year ending October, 1996, up more than 90% from the previous year. The company, which designs and develops compound semiconductor equipment at its Atsugi Design Center in Atsugi, Kanagawa, and manufactures at its Hashimoto plant in Sagami-hara, Kanagawa, will rent a 1,500 sq. meter facility near Atsugi in order to expand capacity. The company also plans to construct its own plant in Atsugi in 1997. The company also reports that it will shortly start offering epi wafers for microelectronic and optoelectronic applications.

Iwaki Handotai to Increase GaP Production by 30%

Iwaki Handotai Co., Ltd., a joint venture between Furukawa Co. and Shin-Etsu Handotai Co. Ltd., will increase its GaP single-crystal wafer production by 30%. The company produces GaP and GaAs wafers and supplies all of its wafer production to Shin-Etsu Handotai rather than sell the material under its own name. Iwaki, which uses the LEC growth method, is a leading GaP wafer supplier which took an early lead in 100mm production. They report that 100mm GaP now accounts for over 20% of its GaP production. The expansion plans call for installing additional 100mm crystal pullers within fiscal 1995.

DOWA Mining to Expand Compound Semiconductor Business

DOWA Mining has announced plans to expand its compound semiconductor materials business. The company's subsidiary DOWA Semiconductor produces semi-conducting VGF and semi-insulating LEC GaAs wafers. Previous monthly output of VGF material already exceeded 1,000 units (two-inch), and now the company has effectively doubled its output by launching production of three-inch wafers. The company attributes much of the increased demand to the increasing market for IR LEDs used for data transmission in wireless LANs.

TriQuint Semiconductor to Relocate

TriQuint Semiconductor has purchased land for the construction of a new GaAs fab in Hillsboro, OR. The new facility will include a 45,000 square foot manufacturing facility and a 120,000 square foot office complex. The new site will house all of the company's manufacturing and engineering functions that are currently located in two leased facilities in nearby Beaverton, OR. According to a company spokesperson, the new facility will be commissioned for 4" wafer processing but provisions are also being made to insure compatibility with conversion to 6". The new facility will provide a maximum capacity which is 2-3 times larger than current levels, and company expects that the new facility will provide sufficient production capacity until the year 2000. It is scheduled to be operational in mid-1997. The total cost of the project is approximately \$40 million. Funding will come from a combination of the company's existing resources, proceeds from a public offering of stock completed in September 1995, cash flow from operations, and other credit instruments.

Vixel Prepares for Production

Vixel Corporation [Broomfield, CO] has announced the receipt of \$11.2 million in equity financing in late 1995. The investment will be used to transition the company from engineering to production of fiber optic interconnect products based on Vertical Cavity Surface Emitting Laser (VCSEL) technology. The company, which was formerly known as PRI or Photonics Research, Inc., was founded in 1991 as a spin-off from Sandia National Laboratories. In 1994 they acquired the manufacturing facility previously occupied by Bandgap Technologies. The company reports that the equity financing was led by two venture capital firms, and other investors included Nissho Electronics, Stanford University, and, most interestingly, Herb Alpert and Jerry Moss. Alpert is the former leader of the Tijuana Brass; Alpert and Moss together are the founders of A&M records.

Bell Labs and AT&T Microelectronics Meet Their New Parent: "Lucent Technologies"

AT&T has announced the new name for its new systems and technology company: "Lucent Technologies". The move is the result of the previously announced restructuring which will split AT&T into three separate companies. Lucent Technologies will include AT&T Microelectronics and Bell Laboratories. The new name will be linked with the endorsement line "Bell Labs Innovations", and will also be associated with a rather unique new logo which the company calls "the innovation ring". As for the name, according to a company press release, "Lucent is a word found in the dictionary that means 'marked by clarity' or 'glowing with light'." The company reports that "As part of the naming process, Lucent Technologies conducted interviews and focus groups with employees, customers, technical leaders and industry analysts around the world...The focus groups and interviews told us that Lucent Technologies differentiated us from AT&T and at the same time was a strong, simple memorable name. It suggests clarity of thought, purpose and vision, and had a technological feel."

Lucent Technologies
Bell Labs Innovations



You Now Have a Choice

CVD PRODUCTS is fast becoming *THE CHOICE SUPPLIER OF PBN* to leading edge technology companies all over the world. We have the experience, personnel and resources to produce *PBN (Pyrolytic Boron Nitride)* components which are the best in the industry. In fact, our *Pyrosyl™ PBN* has become the crucible and plate choice for many of the world's *MBE USERS AND CRYSTAL PULLERS*.

We carry common size crucibles, plates and components in stock for immediate delivery, or we can fabricate to print. All sales, design and engineering functions are performed in-house assuring fast responses to inquiries and shorter lead times for custom parts. Custom packaging is available to meet your specific needs.

For more information call *TOLL-FREE 1-800-700-1CVD* and request a copy of our free, full-color brochure.

MAKE CVD PRODUCTS YOUR CHOICE FOR PBN.



CVD Products, Inc.
4 Park Avenue Hudson, NH
03051-3927 USA
PHONE (603) 598-9122
TOLL-FREE 800-700-1CVD
FAX (603) 598-9126

Circle 138 on Reader Service Card

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

Real Space Observation of GaAs Surfaces in MBE and MEE

Adatom surface mobility plays a critical role in obtaining smooth, high-quality epitaxial layers. The growth technique known as migration enhanced epitaxy (MEE), in which an alternating supply of As and Ga/Al is delivered to the growing surface, has been found to greatly enhance the surface diffusivity of adatoms at lower substrate temperatures in contrast to MBE growth. So far, the MEE process has mainly been studied by RHEED, but now the results of comparative *in situ* scanning electron microscopy (SEM) measurements of surface morphologies have been reported. The measurements were performed using a UHV SEM/MBE system operated in the secondary electron (SE) imaging mode. For MBE growth, the adatom surface mobility is low and small islands form and the surface appears to be rough. Upon growth termination, the islands remain even after an 8 minute anneal. For MEE, islands also appear but the density is lower than in MBE, and monolayer steps remain visible. The islands disappear with a 3 minute anneal at 500°C. In MEE the islands form because the Ga supply slightly exceeds 1 monolayer/cycle; when the supply is less than 1 monolayer/cycle, holes become visible in the SE images. Work performed at NTT Research Laboratories, [Tokyo, Japan]. See "Direct Comparison of GaAs Surface Morphology Between Migration Enhanced Epitaxy and Molecular Beam Epitaxy using In Situ Scanning Electron Microscopy," Y. Homma et al, Appl. Phys. Lett., 68(1), 63 [1 January 1996].

Indium Surface-Segregation and AlGaAs/InGaAs/GaAs HEMT Performance

Indium is known to segregate at the growth surface during the MBE growth of (Ga,In)As/(Al,Ga)As quantum wells on GaAs. This leads to a variation of indium content that smears the intended band profile and prevents the growth of square potential wells because the bottom side of the well is indium deficient, while the top interface is characterized by a graded indium cut-off. A near-ideal square potential profile can, however, be recovered by pre-depositing indium before the InGaAs QW growth, and by thermally removing the excess indium at the end of the QW. A recent work investigates the effect of indium QW profiles on the performance of 0.25 μm MBE-grown HEMTs. The study reveals that "squaring up" the bottom portion of the charge carrying channel with an In pre-deposition step is useful in improving the RF performance of the AlGaAs/InGaAs HEMTs: such a profile resulted in a 0.25 μm cut-off frequency of $f_T = 93$ GHz, while the conventional smeared profile led to $f_T = 80$ GHz. Work performed at Wright State University [Dayton, OH]. See "Effects of In Profile on Material and Device Properties of AlGaAs/InGaAs/GaAs High Electron Mobility Transistors," D. C. Look et al, J. Appl. Phys., 79(1), 540 [1 January 1996].

2,000,000 cm^2/Vs Mobility MOCVD GaAs 2DEGs Grown with TBA

Tertiarybutylarsine (TBA) is a low pressure, less toxic liquid precursor of great interest as a potential replacement for arsine in the MOCVD growth of III-V compounds. To date there has been some concern about the purity of material grown with carbon-containing TBA precursors. However, a new work demonstrates the use of TBA in the MOCVD growth of GaAs/AlGaAs 2DEGs with 0.3K electron mobilities up to 2,000,000 cm^2/Vs . Similar samples grown with arsine showed lower mobilities. By studying thick GaAs and AlGaAs samples, the researchers found that the use of TBA instead of arsine reduces both the carbon and donor impurity incorporation. Work performed at Sandia National Laboratories [Albuquerque, NM]. See "2 x 10⁶ cm^2/Vs electron mobility by metalorganic vapor deposition with tertiarybutylarsine," H. C. Chui et al, Appl. Phys. Lett., 68(2), 208 [6 January 1996].

8-13 μm InAsSb heterojunction photodiode operating at near room temperature

Can III-V compound semiconductors challenge the better-established HgCdTe technology for infrared optoelectronic components? III-V materials should in principle display manufacturability and performance advantages. For example, some of the perceived advantages of III-V compounds for infrared devices include higher carrier mobilities, high-quality lower-cost substrates, and better compositional control and uniformity. InSb/InAs_{1-x}Sb_x heterojunction photodiodes operating near room temperature in the 8-13 μm spectral region have recently been implemented. At 300K, the single pass absorbance at a wavelength of 10 μm was measured to be ~30%, and corresponds to an absorption coefficient of ~1300 cm^{-1} . The diodes exhibited a photovoltaic response up to a wavelength of 13 μm at room temperature. The InAsSb photodiodes were characterized by a low thermal response compared to that of HgCdTe/CdTe devices. The reduced thermal response was credited to the higher thermal conductivity of the GaAs substrates (0.5 W/cm K) in comparison to that of CdTe substrates (0.05 W/cm K). The room-temperature I-V characteristics of 400x400 μm^2 devices were linear while diode behavior was observed below 200K. Work performed at Northwestern University [Evanston, IL]. See "8-13 μm InAsSb Heterojunction Photodiode Operating at Near Room Temperature," J. D. Kim et al, Appl. Phys. Lett., 67(18), 2645 [30 October 1995].

Room Temperature Operation of CoSi₂ - CaF₂ Resonant Tunneling Transistors

The prospect for higher-functionality semiconductor devices such as resonant tunneling transistors has provided much momentum to the area of III-V semiconductor devices because such devices in principle enable the implementation of higher logic functions with a reduced number of circuit elements. Because of high-quality hetero-epitaxial growth technologies, III-V compounds have presented themselves as promising candidates for the implementation of higher-functionality logic devices over the past decade. However, as is generally the case with more conventional devices such as FETs and BJTs, silicon-based technologies keep on rising to meet the performance challenge of III-V compounds.

Researchers at the Tokyo Institute of Technology have successfully implemented triple-barrier metal (CoSi₂) - insulator (CaF₂) resonant tunneling transistors (RTTs) and demonstrated the first transistor action with a large peak-to-valley ratio at 300K. The operating principle of the metal-insulator RTT is similar to that of III-V resonant hot electron transistors (RHETs): at a certain resonance bias, hot electrons are injected across a base layer and travel to a collection layer.

Resonant tunneling devices based on metal-insulator heterostructures have been studied since the 1960s, but difficulties in obtaining high-quality multilayer ultrathin films have impeded progress in this area until recently. The typical device developed in this work consists of a single-crystalline structure consisting of two metal (CoSi₂) quantum wells with thicknesses of 22Å and 16Å, three 9Å thick insulator (CaF₂) barriers and a top metal layer grown on an n-(111) silicon substrate. CoSi₂ and CaF₂ were chosen because they crystallize in the fluorite structure and have relatively small mismatches (-1.2% and +0.6% respectively) with Si at room temperature. The epitaxial layers were grown by ion beam epitaxy for CaF₂ and by a two-step growth technique for CoSi₂.

The authors report the successful operation of triple-barrier RTTs at room temperature. Common-emitter characteristics display clear negative differential resistance regions with large peak-to-valley ratios (at least as high as ~10 as per rough estimates based on I-V characteristics displayed in the article) at room temperature.

See "Theoretical and Measured Characteristics of Metal (CoSi₂)-Insulator (CaF₂) Resonant Tunneling Transistors and the Influence of Parasitic Elements," T. Suemasu et al., IEEE Transactions on Electron Devices, 42(12), 2203 [December 1995].

Optoelectronic Devices

InGaN-Based Multi-Quantum Well Structure Laser Diodes

Shuji Nakamura and co-workers of Nichia Chemical have announced the first laser diode that uses III-V nitride materials. (See also CS 2(1), p. 7.) The lasing wavelength, 417 nm, is the shortest wavelength ever by a laser diode in any material system. The laser's epitaxial structure used two different compositions of InGaN to form a multi-quantum well active layer that was sandwiched between two AlGaIn cladding layers. It was grown by MOCVD on a sapphire substrate with a (0001) orientation (C face). Because of the difficulty in cleaving sapphire, the mirrors were formed by reactive ion etching. High reflectivity (60-70%) coatings were applied to the mirrors to decrease the lasing threshold. The determination that the device was actually lasing was made based on spectral line narrowing and the far field pattern. Below threshold, the spontaneous emission exhibited a linewidth of 20 nm of wavelength; above lasing threshold, the emission narrowed to 1.6 nm. Simultaneously with the spectral narrowing, the far field pattern developed an elliptical pattern. Broad area devices exhibited threshold current densities of 4 kA/cm² and threshold currents of 1.7 A under pulsed, room temperature conditions. The device could be run up to 2.3 A, producing an output power of 215 mW. Its operating voltage of 34 V suggests some room for improvement in contacts or doping densities. The measured differential quantum efficiency was 13% per facet. See "InGaN-Based Multi-Quantum Well Structure Laser Diodes", S. Nakamura et al, Jpn. J. Appl. Phys., 35(1B), L74 [15 January 1996].

Longitudinal Mode Control in Green Diode Lasers

Simple cleaved-cavity Fabry-Perot lasers typically exhibit longitudinal multimode emission at several closely-spaced wavelengths. Use of grating mirrors in distributed Bragg reflector (DBR) lasers is a standard approach to produce single longitudinal mode lasers. For some applications, such as gas sensing, single longitudinal mode lasers are needed in the green and blue-green region of the spectrum. Such wavelengths are obtainable using ZnSe-based diode lasers but, until recently, *single* longitudinal mode versions of these lasers did not exist. The recent work employed an MBE-grown structure with MgZnSse cladding layers, a ZnSse waveguide and CdZnSe quantum well active region. Third order gratings with a period of 295 nm were constructed by electron beam lithography and wet etching. The grating was 200 microns long and located 100 nm above the active layer of the laser. The device exhibited single longitudinal mode edge emission at a wavelength of 517 nm. Sidemodes were suppressed by greater than 25 dB. The threshold current density was 2.3 kA/cm², measured under pulsed, room temperature conditions. In a second part of the study, several different period gratings were constructed. It was found that the laser emission energy could be varied over 40 meV by changing the grating period from 298 to 291 nm. Work performed at the University of Würzburg [Würzburg, Germany]. See "ZnSe-based DBR-laser diode", G. Bacher et al, Electron. Lett. 31(25), 2184 [7 December 1995].

High Performance 765 nm Wavelength VCSELs

Vertical cavity surface emitting lasers (VCSELs) in the 760 - 766 nm wavelength range are good candidates for oxygen-sensing applications due to their single mode operation, tunability, beam quality and potential for low cost mass production. A recent work demonstrates significant improvements in the characteristics of VCSELs that operate at these key wavelengths. Using MOCVD-grown AlGaAs structures, threshold currents of 0.6 mA, threshold voltages of 1.9 V and output powers of 5 mW were reported. These numbers represent improvements by factors of 2 - 7 over previous best 765 nm VCSELs. The wallplug efficiency of the devices exceeded 10%, the slope efficiency was 0.46 W/A. The epitaxial structure consisted of a 40 period AlAs /Al_{0.3}Ga_{0.7}As lower reflector, a three well Al_{0.3}Ga_{0.7}As/Al_{0.12}Ga_{0.88}As active layer (one wavelength thick) and a 25 period AlAs/Al_{0.3}Ga_{0.7}As upper reflector. The electrical resistance of the reflectors was reduced by linearly grading the AlGaAs compositions over 20 nm regions between the AlAs and Al_{0.3}Ga_{0.7}As layers. Circular air post devices with 20 micron diameters were fabricated with standard lithography and dry etching. Work performed at Paul Scherrer Institute [Zurich, Switzerland]. See "High performance near-IR (765nm) AlAs/AlGaAs vertical cavity surface emitting lasers", K. H. Gulden et al, Electron. Lett. 31(25), 2176 [7 December 1995].

Zero Bias Voltage Operation of a 10 μm Intersubband Photodetector

GaAs/AlGaAs infrared photodetectors have potentially important applications for imaging arrays that operate in the atmospheric transmission window at 8 - 12 μm wavelengths. These intersubband detectors have traditionally been of the photoconductor type. Photoconductive detectors are operated under an electrical bias voltage so that a photo-induced resistance change can produce a change in the device current. Dark current is an important concern in such detectors. Dark current can be eliminated by moving to an un-biased (photovoltaic) detector. Although photovoltaic intersubband detectors have been made for operation in the 3-5 μm region, until recently very little was known about such detectors in the 8-12 μm region. A recent work reported photovoltaic intersubband detectors with a responsivity of 50 mA/W at 10 μm. Record detectivities at 77K were also exhibited. Work performed at the Fraunhofer IAF [Freiberg, Germany]. See "A 10 μm GaAs/Al_xGa_{1-x}As intersubband photodetector operating at zero bias voltage", C. Schönbein, et al, Appl. Phys. Lett. 68(7), 973 [12 February 1996].

High Speed Optical Modulator at Communications Wavelengths

Semiconductor multi-quantum well (MQW) optical modulators have important applications in high speed optical fiber transmission systems since they are capable of high speed operation at low operating voltages. Researchers at Hitachi Central Research Laboratories recently reported a MQW modulator that sets a new speed record for modulation near 1.55 micron wavelengths. The device exhibited a modulation bandwidth (-3 dB) of 50 GHz, at a 1.53 micron wavelength. It required a low drive voltage of 2.8 V, and had an insertion loss of 8 dB.

The device achieves optical modulation via electroabsorption in multi-quantum well (MQW) cores of InP-based waveguides. The device speed is limited by the capacitance of the structure, not by the speed of the electroabsorption mechanism. Fast devices need to be short to minimize the capacitance, but device lengths shorter than 100 microns are not easy to fabricate because of cleaving difficulties. This problem was solved by adding longer, undoped passive waveguide sections to the active modulator structure. The total device has an easily cleavable length of 1.5 mm, but the length of the active modulator section that determines the capacitance is only 63 microns. To further minimize the capacitance, the width of the waveguide in the active section is only 2.5 microns. The waveguide width tapers out to 4 microns over the length of the passive waveguide section. The total capacitance of the device is 120 fF.

The modulator section consisted of an MBE-grown MQW active region with compressively strained InAlAs and tensile strained InGaAs, and lattice-matched InAlAs cladding layers. Regions of the MBE-grown layers were selectively etched away using an SiO₂ mask to make room for the passive waveguide layers. The passive waveguides consisted of InP clads and InGaAsP cores that were added to the structure by using MOCVD re-growth. The active and passive sections were simultaneously dry-etched to form a self-aligned waveguide with the tapers.

See "MQW electroabsorption optical modulator for 40 Gbit/s modulation", T. Ido et al, Electron. Lett. 31(24), 2124 [23 November 1995]

THE COMPLETE PICTURE



Bio-Rad... the Semiconductor Characterization Specialists

For semiconductor characterization systems, look no further than Bio-Rad. With the industry-standard Electrochemical CV Profiler, Modular Hall Effect System, Hall Profiler, Fourier Transform Photoluminescence, Alloying Furnace and the world's most advanced DLTS System, *We'll give you the complete picture.*

Call for details

BIO-RAD

Semiconductor
Systems Division

USA

Bio-Rad Micromeritics, 520 Clyde Avenue, Mountain View, CA 94043-2212
Phone 415-961-6900 Fax 415-961-6715

Europe

Bio-Rad Micromeritics Ltd, Bio-Rad House, Maylands Avenue, Hemel Hempstead, Herts, HP2 7TD, UK
Phone +44 (0) 1442 232552 Fax +44 (0) 1442 234434

Japan

Nippon Bio-Rad Laboratories KK, Cosmo Park Bldg, 5-7-18 Higashinipponi, Arakawa-ku, Tokyo 116
Phone 03-5811-6288 Fax 03-5811-6273

Pacific Rim

Bio-Rad Pacific Ltd, Unit 1111, 11/Floor, New Kowloon Plaza, 38 Tai Kok Tsui Road, Kowloon, Hong Kong
Phone 852 2789 3300 Fax 852 2789 1257

Circle 58 on Reader Service Card

The Capabilities of Indium Phosphide Electronics and Optoelectronics

Secure in optoelectronics, can InP find a spot in GaAs's microelectronics niche?

ROBERT A. METZGER

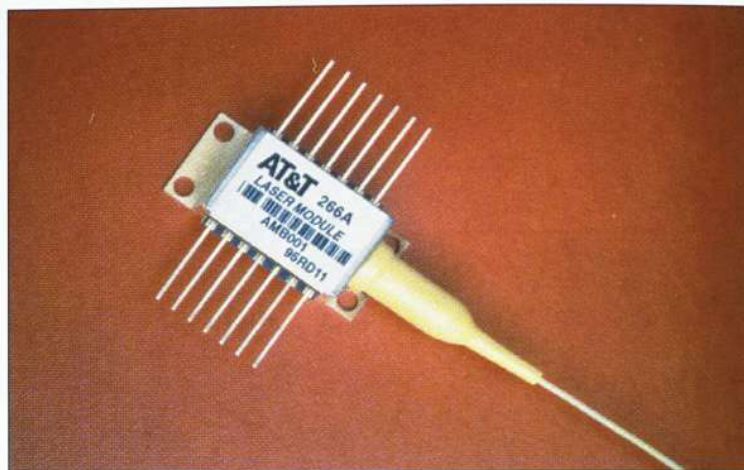
New technologies are rarely evaluated on the basis of their intrinsic characteristics. Instead they are judged by comparison with a more established approach. Given the realities of today's research and development environments, a new technology will quickly whither and die unless it can demonstrate some critical characteristic needed for tomorrow's applications and systems which can not be supplied by current technologies. Thus InP competes with GaAs, just as GaAs competes with Si, and SiGe competes with GaAs, etc. By contrasting InP, GaAs, and their related alloys one can determine the unique strengths which can be exploited for the future development of InP technology.

Electronics

InP and its related compounds, particularly InGaAs, possess several unique characteristics which clearly differentiate it from GaAs and its related compounds (see Tutorial, p. 35). Among the most important: GaInAs has an electron effective mass almost one-half that of GaAs, resulting in a 50% higher mobility. In addition, both InP and GaInAs can support higher peak electron velocities, while InP has a 50% higher thermal conductivity as well as significantly higher electric field breakdown characteristics than GaAs. Two device-types in particular have exploited these superior characteristics: the HEMT (high electron mobility transistor) and HBT (heterojunction bipolar transistor).

HEMTS

InP should provide the ideal platform for HEMTs because of the large conduction band discontinuity at the InAlAs/InGaAs heterointerface ($\Delta E_C = 0.5$ eV), which supports the formation of large 2DEG (two dimensional electron gas) concentrations, and because higher electron peak velocities and mobilities can be achieved in the channel formed by this heterostructure. Indeed, Nakayama and coworkers of NEC [Shiga, Japan] have fabricated InP-based HEMTs which exhibit mobilities as high as $18,300$ cm²/Vsec, which is nearly twice that of pseudomorphic GaAs-based PHEMTs. Nguyen and coworkers of the Hughes Research Laboratories [Malibu, CA] have fabricated HEMTs with f_t values of 340 GHz, while researchers at Lockheed Martin [Syracuse, NY] have



AT&T/Lucent Technologies' electroabsorption-modulated, isolated laser module, capable of 20 Gb/s operation - one example of InP's secure niche in optoelectronics. Can InP find similar commercial applications in microelectronics?

reported on f_{max} values of 600 GHz, making these InP-based HEMTs the fastest of any three terminal devices.

A variety of circuits have been developed to take advantage of the high performance capabilities and low noise figure (NF) characteristics inherent in InP HEMTs. Enoki and coworkers of NTT [Kanagawa, Japan] have fabricated HEMTs with transconductances of 1400 mS/mm with f_t and f_{max} of 200 GHz and 275 GHz, respectively. These HEMTs have been used in the fabrication of a 40.4 GHz SCFL static frequency divider, which is the highest toggle frequency ever reported for any static frequency counter. However, LNAs (Low Noise Amplifiers) and PAs (Power Amplifiers) for radar and satellite systems requiring operation at frequencies above 40 GHz have been the primary applications for InP-based HEMTs to date. Hughes Aircraft Company [El Segundo, CA] has assembled both a Q-band (32-50 GHz) and V-band (50-75 GHz) receiver chip set using InP HEMTs. A three-stage Q-band LNA operating at 44 GHz has been fabricated, which exhibits 22 dB gain with a 2.0 dB noise figure (NF), this being the best published performance of an LNA at this frequency. In total, the Hughes' chip set consists of 2 LNAs, 2 mixers, 2 downconverters, and 1 LO amplifier. Fabricated with 0.1 μ m gate length InP HEMTs, these devices exhibit electron sheet densities of 2.5 to 2.8×10^{12} cm⁻² and mobilities of 10,000 to 11,000 cm²/Vsec - values that are 20-30% better than can be obtained with GaAs PHEMTs.

TRW [Redondo Beach, CA] has both an InP HEMT process (similar to Hughes) as well as a high performance GaAs PHEMT process suitable for W-band [75-110 GHz] operation. Therefore, TRW is in a position to contrast these two high speed technologies. Dwight Streit, a TRW Technical Fellow says, "we have a 0.1 μ m gate length GaAs PHEMT process in production for W band, but InP has higher performance in this frequency range, making it suitable for those W-band systems which require the highest possible performance. I feel that W-band is the limit for GaAs, with InP needed at higher frequencies." Reflecting this opinion, TRW has fabricated a 140 GHz monolithic LNA (the highest operating frequency reported for a LNA) using 0.1 μ m gate length InP HEMTs, with transconductances of 1400 mS/mm and f_t and f_{max} values of 240 GHz and 400 GHz, respectively. This LNA exhibits a gain of 9 dB at 142 GHz, and more than 5 dB of gain from 138-145 GHz.

Philip Smith, Associate Director of Advanced RF Components for

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)
Oberfoehlinger Strasse 8
D-81679 München 80, Germany
49-89-92201-0
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

Lockheed Martin [Syracuse, NY] says, "compared with GaAs-based PHEMTs, the InP HEMT allows for a reduction of approximately 1 dB in amplifier NF at frequencies of 60 and 94 GHz." Using their 0.1 μm gate length HEMT process, which features 600 GHz f_{max} performance, Lockheed Martin has produced a 3 stage LNA for operation from 75-110 GHz, which exhibits a NF below 5.0 dB and a gain of 10.8 dB across the entire band. A minimum noise figure of 3.3 dB and a gain of 12.6 dB occurs at 92.4 GHz. Lockheed Martin has also been working on W-band PAs which Smith says "now exhibit output powers comparable to the best PHEMT with twice the power added efficiency (PAE), and 3-4 dB higher power gain." However, the technology for PAs using InP-based HEMTs is less mature than that of LNAs, and reliability remains an issue. "For power HEMTs the reliability is still largely unknown," says Smith. "We worry that the lower growth temperatures used for InP-based materials as compared to GaAs materials, and the lower ohmic contact alloying temperatures, may mean faster degradation at the high temperatures generated during operation. InP MMICs have fantastic performance, but we now have to show reliability and manufacturability."

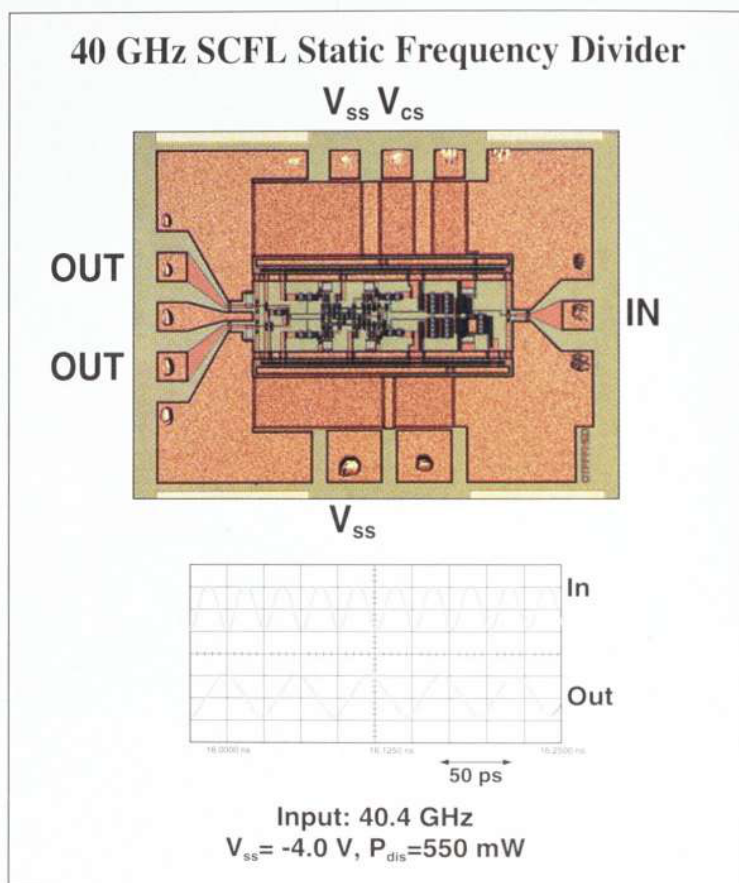
The general consensus is that InP-based HEMTs begin to compete with GaAs PHEMTs in the 40-50 GHz range, and become the clear technology winner for frequencies above 100 GHz. At the moment these frequency ranges are almost the exclusive domain of military and satellite applications, with little to no commercial activity. However, PAs and LNAs are not the only applications available for InP-based HEMTs. According to Takatomo Enoki of NTT, "we are trying to expand the application field of InP-based HEMTs to high speed digital and baseband ICs for OEICs needed in future optical communication systems. We are focusing on systems for 40 Gb/s rates, which we believe require devices with f_t values in excess of 160 GHz, which can be fabricated with InP-based HEMTs" To support this goal NTT workers have already fabricated preamplifiers, baseband amplifiers, limiting amplifiers, and a Gilbert cell, as the building blocks for 40 Gb/s receivers.

HBTS

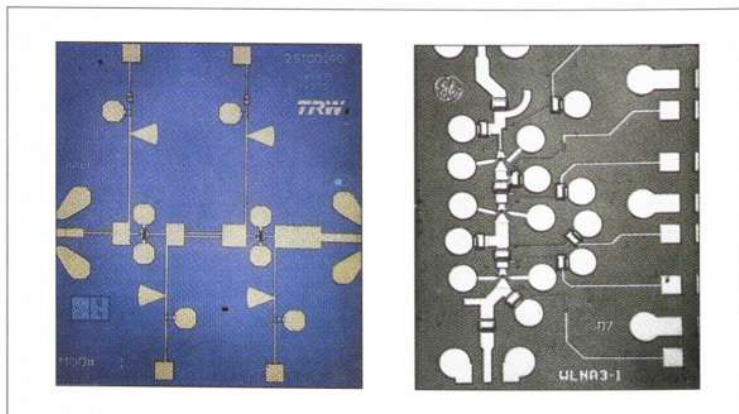
Due to the superior peak electron velocities of InP as compared to GaAs, the electron transit time through an HBT can be reduced, which in turn produces superior RF performance. Further improvements over GaAs-based HBTs are obtained when either a InP/InGaAs or InAlAs/InGaAs emitter-base structure are used, due to the small bandgap of InGaAs (0.75 eV) as compared to GaAs (1.42 eV). This results in turn-on voltages for InP-based HBTs which are several hundred of mV less than that of a GaAs-based HBTs - an important consideration for low voltage applications. When these characteristics are coupled with the higher thermal conductivity of InP, its higher breakdown fields, and a greatly reduced surface recombination velocity in GaInAs as compared to GaAs, one sees that an InP-based HBT can be fabricated which has the potential for superior RF characteristics as well as the ability to operate at higher power levels (thermal and breakdown effects) and at lower voltages (low bandgap GaInAs, and reduced surface recombination velocities). Unlike the InP-based HEMT which seems to have found its niche in the high frequency range, the InP-based HBT may find a much wider range of applications.

When it comes to HBT speed, Shoji Yamahata and coworkers from NTT [Kanagawa, Japan] are the reigning champions. Using an InP/InGaAs/InP DHB (Double HBT), they have obtained record level RF characteristics (over 220 GHz for both f_t and f_{max}) as well as having achieved the highest reported f_{max} (301 GHz) for an HBT fabricated from any material system. "My motivation for InP-based HBT work is ultra-high speed," says Yamahata. He views key applications for this technology to be lightwave communication ICs over 10 Gb/s, because they require low power dissipation, as well as using monolithically integrated HBTs with PIN diodes for photoreceivers. Y.K. Chen of AT&T Bell Laboratories [Murray Hill, NJ] also sees InP-based HBT work driven by

the needs of optical communication. He believes that "commercial insertion points for InP-based HBTs may be in wireless base stations, even for systems operating at frequencies as low as L-band (1.0-2.0 GHz), where the high speed and low power nature of the devices would make them suitable for high speed digital processing and in A/Ds and MUX/DEMUX operations." Other applications may develop due to the low surface recombination velocity of GaInAs, which, when coupled with the vertical nature of the device, leads to a low 1/f noise corner frequency. Chen and coworkers have obtained a 1/f noise corner frequency of 1.55 kHz, the lowest of any compound semiconductor. These characteristics result in very low phase noise, which is critical for VCOs (voltage controlled oscillators) - an essential component of most RF



NTT's InP HEMT-based SCFL Static Frequency Divider operating at 40.4 GHz - the fastest frequency of any static frequency divider.



Left: TRW's 140 GHz LNA which uses InP HEMTs. This is the highest frequency LNA fabricated by any technology. Right: Lockheed-Martin's 75-110 GHz InP HEMT LNA.

communication systems. AT&T, TRW and Hughes Research Labs are all actively pursuing InP-based HBT VCO work over a frequency range of 4 to 60 GHz.

One of the most extensive InP HBT efforts is taking place at the Hughes Research Labs. William Stanchina and coworkers are working on a wide range of InP-based SHBTs (Single HBTs) utilizing GaInAs collectors, for analog, digital, and optoelectronic ICs. Using GaInAs collectors results in devices with higher output conductance, and therefore less linearity, but it is a relatively mature technology for HRL, with which they have learned to design around the limitations of the GaInAs collector. Stanchina says, "Mother Nature gives us the cards, and the designers give us the strategy as to how to play those cards." Those strategies include the fabrication of high speed accumulators, second order delta-sigma modulators for A/D applications, as well as monolithic PIN PD/HBT optoelectronic receivers. A 15 bit accumulator utilizing over 1500 InP HBTs has recently been fabricated, making it the largest InP IC reported to date. They are currently involved in the monolithic integration of InP-based HEMTs with InP HBTs under contract work with the Air Force [Wright Patterson AFB, OH] for the fabrication of a two-stage LNA (InP-HEMT) plus a mixer and A/D elements (InP-HBT). Like both Enoki and Yamahata of NTT, Stanchina says "the first thing in this technology which may go into the commercial realm could be in the area of ICs for optical communication systems - particularly at 40 Gb/s operation." In addition to this single heterostructure work, David Rensch, Chan Nguyen, and coworkers are using DHBTs with InP collectors to improve breakdown and power performance, for the fabrication of power HBTs for X-band (8.0-13 GHz) radars. They are currently producing single power cells which emit 2W at 70% PAEs for 14 V operation, using DHBTs with f_t values of 70 GHz and f_{max} values of 100 GHz, with extremely high breakdown voltages of 35 V.

Reality Check

"There is definitely commercial interest for InP-based HBTs at 1.8 to 2.4 GHz," says Dwight Streit of TRW. "If we could supply InP HBTs tomorrow, we would have customers who would buy it." This low frequency demand is driven by the low turn on voltage of the InP HBT, making it ideally suited to wireless applications, where battery power and lifetimes between recharging are central issues. He goes on to say "substrates are the main limitation to commercialization of InP. Even if the quality were there, which it isn't always, at \$600 for a 3 inch substrate, this costs just as much as the epi, and that makes it too expensive for a commercial product. InP substrate technology is where GaAs was 10 years ago." Y.K. Chen of AT&T echoes these sentiments. "Cost is the issue to commercialization," says Chen. "The InP substrate is expensive. Between the cost of the substrate and the cost of the epi, this adds several thousand dollars to the cost of the process. If you are making VCOs you may get 1000-2000 per wafer, which means that there is an overhead of \$1-2 per device, which makes it very hard to compete with GaAs."

The situation with InP substrate production is a classic chicken and egg dilemma which is familiar to anyone in the compound semiconductor industry. The semiconductor manufacturers believe that volume applications cannot be developed at today's substrate costs; but the wafer manufacturers believe that substrate prices cannot be reduced until volume applications emerge. A similar deadlock in GaAs production in the United States was broken by the Department of Defense and Advanced Research Projects Agency through the MIMIC and Title III programs. Not surprisingly, the consensus opinion among American companies is that similar services will be needed to resolve the current dilemma.

A Commitment You Have Always Counted On

For over 30 years, Morton Metalorganics has consistently offered ultra-pure, high performance metalorganic precursors for MOCVD and MBE. We've grown with the market by providing not only innovative metalorganic solutions, but also a proven level of service that can only be supported by an international company with a 150-year history of exceptional customer relations.

With leadership positions in speciality chemicals, salt and automotive airbags you can continue to feel confident that Morton will expand on its commitment to offering products you can rely on, service you can depend on, and quality you can count on.



Morton

Morton Metalorganics
148 Andover Street
Danvers, MA 01923
tel: 508-750-9490
fax: 508-750-4298

Circle 23 on Reader Service Card

Optoelectronics

Optoelectronics represents an application where InP shines - both literally and figuratively. Because InGaAsP and InGaAs can both emit and absorb in the 1.3 to 1.55 μm wavelength region, which corresponds to the low dispersion and low loss regions of conventional optical fiber, InP-based optoelectronic devices have been a natural fit for fiber applications. This wavelength region simply can not be reached by the wider bandgap AlGaAs/GaAs/GaNiP material systems, making InP-based materials the *only* suitable material system for this application. There are around 30 manufacturers of InP laser diodes, and the total value of that market is estimated to be \$700 million, with the potential for good growth in the coming years. (See p. X for a more detailed discussion.)

Commercial Lasers

Lucent Technologies [formerly AT&T - see page 16] is a major supplier of 1.3 and 1.55 μm lasers and InGaAs-based photodetectors. Traditionally, commercial lasers in this frequency range centered around InGaAsP bulk active devices, consisting of thick InGaAsP emitting layers bounded by higher bandgap InGaAsP or InP to contain electrons and holes. However, this structure is giving way to InGaAsP multi-quantum well (MQW) structures, in which the InGaAsP well is placed under compressive stress. Compressively strained MQW structures are used to reduce laser threshold current, Auger recombination, and inter-valence band absorption through the reduction of the in-plane hole effective mass by a combination of biaxial strain and quantum confinement. According to Wei-Shin Tsay, Product Manager of Digital Laser Modules at Lucent Technologies, "laser structures for 1.3 and 1.55 μm operation are moving toward InGaAsP QWs, which not only result in higher efficiency but also higher performance and less temperature dependence." As a result, lasers of this type can be operated over a wider temperature range, which for many new products means that thermoelectric coolers are no longer needed, thereby reducing the cost of the device as well as its volume. Based on this type of MQW structure, Lucent Technologies has introduced two new transmitters, the Astrotec 1227Y and 1229, which can operate over a temperature range of -40 to 85°C without thermoelectric coolers, and meeting the full range of SONET/SDH requirements for 622 Mb/s long reach applications.

Besides the use of MQWs, the other trend in the commercial market place for 1.3 and 1.55 μm laser modules is the monolithic integration of laser diodes with modulators, where the modulator acts as a high speed switch, transforming the laser's output into the binary ones and zeros required for digital communication. When the modulator is externally interfaced with the laser, there are many inherent problems, including high insertion loss (typically > 3 dB), intracavity reflections, and the need for large optical components for external coupling. Lucent Technologies has just introduced one of the most sophisticated transmitters available to the commercial market, an electroabsorption-modulated isolated laser module, the 266 EM-ILM, which features a monolithically integrated modulator. The EML can be fabricated to operate at different wavelengths so that a selection of devices can be combined through WDM (wavelength division multiplexing) to obtain a higher total data rate. While current commercial long haul optical fiber systems can send up to 50,000 simultaneous conversations on a pair of optical fibers over distances as far as 200 km before signal generation is needed, eight 266 EM-ILM can be combined to transmit 400,000 conversations up to 600 km without regeneration. The device can transmit at a rate of 2.5 Gb/s over each of its eight wavelengths, resulting in a total transmission rate of 20 Gb/s. The increase in transmission distance without regeneration is due to the monolithic integration of the electroabsorption modulator, which results in very low levels of chirp. Because of the reduction in chirp, very low dispersion of the laser signal takes place, and the laser module can be run at triple the capacity of current laser configurations.

Other InP-based Lasers

The carrier leakage that can occur through the barriers that confine the QW is one of the most important factors causing laser performance degradation at high temperatures and high carrier densities (conditions which exist at high power levels). Due to the difference in effective mass, the electron with its lighter effective mass requires a tighter confinement than the hole. This tighter confinement can be achieved with deeper QWs. Two heterostructures which produce deeper QWs for electrons than the GaInAsP/GaInAsP and the GaInAsP/InP structures which are normally used, are InAsP and AlGaInAs QWs with either InP, GaInAsP, or GaInP barriers. An example of this, are the AlGaInAs/InP lasers being fabricated by C.E. Zah, R. Bhat and coworkers at Bellcore [Red Bank, NJ], which exhibit a maximum CW operation temperature of 185°C. They believe that since these lasers will not require thermoelectric coolers, and will be cheaper and more reliable than conventional lasers, that this technology will help in pushing fiber deployment closer to the home.

Vertical cavity surface emitting lasers (VCSELs) are potentially attractive sources for 1.3 to 1.55 μm operation in optical communication applications due to their single longitudinal mode characteristics, low dispersion, and easy coupling to single-mode optical fibers. A major difficulty in implementing these structures in InP-based materials systems is the lack of suitable materials with large differences in index of refraction which are required in the formation of distributed Bragg reflectors tuned to 1.55 μm which are required in the fabrication of the vertical cavity. D. Babic, J. Bowers and coworkers at the University of California [Santa Barbara, CA], have fabricated VCSELs by fusion bonding GaAs/AlGaAs DBRs both above and below a InGaAsP-based MQW laser. These DBRs not only have superior reflectivities as compared to any that can be fabricated with InP-based materials, but have better thermal characteristics, which is important in a device whose operation is limited by heating effects. Using the wafer bonding approach, N.M Margalit of UCSB has recently reported on operation up to a temperature of 39°C under CW conditions, and 70°C under pulsed conditions, with the lowest observed CW threshold currents of 1.3 mA at 25°C. To many, the wafer bonding approach is not considered a production worthy technique, but Hewlett Packard currently uses a wafer bonding technique in the fabrication of commercially available super-bright AlInP/AlGaInP LEDs which require the wafer bonding of transparent GaP substrates to the LED structure (see CS 2(1), p. 22).

Conclusion

It is clear that InP-based materials and optoelectronic devices for the 1.3 to 1.55 μm operation are a natural fit, and offer unique capabilities that simply can not be met by GaAs-based materials. As fiber-based telecom and datacom markets continue to grow, so will the market for these devices. However, the case for InP-based electronics is not so clear. In the area of HEMTs, the high performance and low noise characteristics have created a niche which GaAs PHEMTs can not quite reach, but the situation is not a static one. In the same type of battle that GaAs often faces with Si, the performance of PHEMTs continues to improve, moving into the territory now occupied by InP HEMTs. It appears that InP-based HEMTs may be relegated to only the highest performance applications such as military radars and satellite applications in the W and D band regions. The case for the InP HBT is somewhat different. Unlike the HEMT, which in some ways can be viewed as a type of "superior" GaAs PHEMT, the InP HBT has high speed, high power, low voltage, and low noise capabilities that does not restrict its application to only the high frequency regime. In the commercial arena, in such areas as wireless and telecom/datacom, where high speeds, high PAEs, low operating voltage, and high thermal conductivities are of major importance, the InP HBT may find commercial markets.

Trends in Wafer Sizes

When we will see 6" GaAs and 3" InP Wafers in production? Would you believe 1998?

MARIE MEYER

Visit the vendor exhibition at the GaAs MANTECH meeting or the InP & Related Materials Conference this April and you will likely see a few samples of 6" GaAs and 3" InP substrates. Impressive enough: but, at the silicon industry shows, one can see wafer samples the size of dinner plates. It is a well known fact that compound semiconductors are 2 - 4 generations behind silicon wafers, and given the enormous differences in volume, this is not surprising. Nevertheless, as the silicon industry prepares its new 300mm standard, one begins to wonder when the compound semiconductor industry will begin to migrate to the next generation of GaAs and InP wafer sizes.

Of the fifty or so GaAs processing lines in the world, about one-quarter run 4" wafers (see chart, next page). As is shown in Figure 1, most of today's consumption of semi-insulating GaAs is in the form of 3" wafers. But consumption of 4" GaAs will become dominant over the next two years, as several Japanese fabs are said to be planning conversion from 3" to 4". Production runs of 6" GaAs will debut - albeit in small quantities - around 1998. None of the world's GaAs fabs currently have a 6" line in operation¹; but if current market conditions persist, a few will be commissioned before the turn of the century, beginning in 1998.

¹ A few years ago it looked like Motorola was building a 6" GaAs line at its CS-1 Facility in Tempe, AZ. A company spokesperson confirmed that 6" wafers were manufactured for Motorola and said that engineering procedures for future activity are currently under review. Additional information was not available.

Semi-Insulating GaAs: 6" by 1998

Anadigics has been rather slow to convert to 4" wafers - in fact, they will continue some 3" processing until the end of this year. Charles Huang, Executive Vice President at Anadigics, attributes the delay to previously insufficient demand. However, he says that now "the levels of demand are greatly increased, and if we could, we would like to skip 4" altogether and go straight to 6". But we cannot do that, for technical, not business, reasons. So we will have to wait for those issues to be resolved." Like many others, he identifies the key technical issues as reliable supplies of quality, consistent 6" wafers, and processing equipment which has a demonstrated capability for handling 6" GaAs wafers. Looking to the future, Huang says that "the sooner 6" processing is available, the better for everyone. If current demand patterns hold out, we'll convert as soon as the technical issues are solved."

M/A-COM's Rick Hess points out that there will be processing issues that need to be addressed in order to make a successful migration to the larger standard. "Transitions from 2" to 3", and then 3" to 4", were done primarily without a large change in processes. To go to 6" is a much bigger leap, requiring much more adjustment. The time and money involved in developing a 6" process will be significant."

An obvious prerequisite for scaling-up is a reliable supply of quality 6" wafers, at the right price. Those wafers on display at conferences demonstrate that the vendors are already at work on the problem. Mechanical 6" samples are readily available, but there are



some important technical issues that remain to be dealt with to attain production quality material. S. Sawada of Sumitomo Electric summarizes the key issues in 6" GaAs production as dislocation densities resulting from increased thermal stress in the growth process, and higher residual strain than in 4" crystals, which can cause problems with slip line generation and wafer breakage. In addition, he points out that it is more difficult to achieve the desired wafer flatness and surface cleanliness in large diameter samples.

Although all of these problems are important, none of them seem insurmountable or prohibitive. Klaus Jurgen Schoepf, Technical Manager of Siemens' GaAs Device operation, sums up the situation as follows: "our conversion to 6" depends heavily on the availability of wafers which meet our specifications. Those that we have seen now would not enable us to convert today. But, within 2 years, the suppliers may be able to fulfill our requirements."

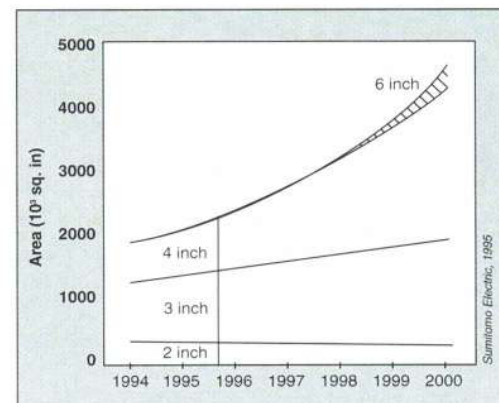


Figure 1. The worldwide market for semi-insulating GaAs by substrate size.

Bob Nunn, Vice President and General Manager of the ASIC Division at Vitesse Semiconductor reports that Vitesse feels confident that there will be a viable supply of 6" GaAs from multiple suppliers by 1998. Many other fab managers agree, but it is probably unrealistic to expect a perfectly smooth transition: JoAnne Dalton, Product Manager of M/A-COM's GaAs Materials Group, points out that none of the vendors can completely refine their products until at least one device manufacturer has begun consistently running 6" wafers on production equipment. She says, "All of the 6" wafers which we are currently shipping are being used as mechanicals - customers use them to qualify new processing equipment (to make sure that it is capable of future conversion). We can develop the product up to a point, but until our customers start processing the wafers and identify what the manufacturing issues are, we can't get the feedback that we need to further our development."

Price is also a major issue. Current demand is too small to establish the market price of 6" wafers - but no matter where it emerges, the customers will want it to be lower. And, as Schoepf describes it, quality, uniformity, and price all go hand-in-hand: "A major issue for us is the availability of as many wafers per ingot as possible, with uniform performance. Even at 4" there is room for improvement, and this is naturally even more valid for 6" material. Before we can convert the quality of the 6" material has to be identical to the current best 4" material, and the price per square inch has to be less than for 4 inch."

Die Size and Volume

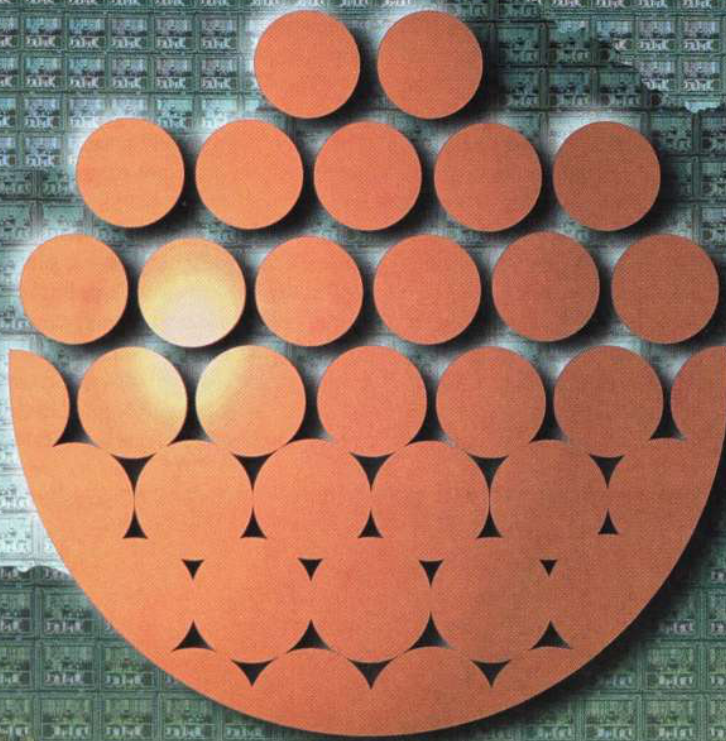
One 6" wafer provides 2.25 times more surface area than a 4" wafer and 4 times more than a 3" wafer. A fab manager will want to be sure that he has a use for that much real estate before he scales up. Processing lines work best when run continuously, with as few shut downs and interruptions as possible. Therefore the migration to larger wafer diameters needs to be perfectly timed with respect to demand. Converting too early - before demand levels can support the increased output - represents not only an unnecessary capital expense but also a possible reduction in yield, which is an unpleasant combination, at best. As M/A-COM's Rick Hess puts it: "If you gave me my choice between a 4" fab running at 80% of capacity or a 6" fab running at 40%, I'd take the 4" one."

Although the foundries agree that GaAs has finally found some secure niches in high volume markets, the majority of the managers

Major GaAs Device Manufacturers

	GaAs Products					Wafer Size(s)		
	FETs/HEMTs	Diodes	MMICs	Digital ICs	Foundry Service	2"/50 mm	3"/75 mm	4"/100 mm
NORTH AMERICA								
Alpha Industries	•	•	•		Yes		•	
AMP (MiSig)	•		•		Yes		•	
Anadigics			•		No		•	•
Celeritek	•		•		No		•	
Hewlett Packard	•		•		No		•	
HP - Avantek	•		•		No		•	
Honeywell			•	•	Yes		•	
Hughes	•	•	•		Yes		•	
ITT	•		•	•	Yes			•
Litton Solid State	•	•	•		Yes		•	
Lockheed Martin	•		•		Yes		•	
M/A-COM (Mass.)	•	•	•		Yes		•	
M/A-COM (Colo.)			•		No			•
Microwave Technology	•	•	•		No		•	
Motorola	•		•	•	No			•
Northern Telecom			•	•	Yes		•	
Raytheon	•		•		Yes		•	•
Rockwell			•	•	Yes		•	•
Samsung Microwave	•		•		Yes		•	
Texas Instruments	•		•	•	Yes		•	•
TriQuint			•	•	Yes			•
TRW	•	•	•	•	Yes		•	
Vitesse				•	Yes			•
Watkins Johnson	•		•		No		•	
Westinghouse	•		•		No		•	•
JAPAN								
Fujitsu		•	•	•	No		•	•
Hitachi	•		•	•	No		•	
Matsushita	•		•		No		•	
Mitsubishi Electric	•		•	•	No		•	
Murata	•		•		Yes		•	
NEC	•	•	•	•	No		•	
NEL	•		•	•	No		•	
OKI	•		•	•	No		•	
Sanyo	•		•		No	•		
Sharp	•		•		No		•	
Sony	•		•	•	No		•	
Toshiba	•		•	•	No		•	
EUROPE								
Alcatel Telettra	•		•		Yes	•	•	
Alenia	•		•		Yes	•	•	
Daimler Benz	•	•	•		Yes		•	
GEC-Marconi	•		•	•	Yes		•	
Phillips	•		•	•	Yes		•	
Siemens	•		•		Yes		•	•
Thomson (Orsay)	•	•	•		Yes		•	

Source: Magus Research, to be published in the forthcoming Second Edition of *GaAs Electronic Materials and Devices*, published by Elsevier Advanced Technology.



GaN
GaAs
InGaAlP
GaP
BaSrTiO
SrTiO
PZT
YBaCuO
AlGaAs
InGaAsP
InGaAs
InGaP
InAlAs
InSb
Si
SiGe
Cu
SiC
W
Si₃N₄
CdTe
HgCdTe
Diamond
Pd
TiN

BREAK THROUGH TO *TURBO*DISC CVD TECHNOLOGY

Break through the barriers in advanced materials device manufacturing.

EMCORE provides the complete line of TurboDisc MOCVD Deposition Systems for the production of compound semiconductors materials, metals, and oxides - from device research, to pilot production, to mass production throughput.

- ◆ Reliable - Over 100 multi-wafer systems in the field worldwide and still counting
- ◆ Highest throughput
- ◆ Lowest cost of ownership
- ◆ < 1% Uniformity
- ◆ Widest choice of materials grown
- ◆ Worldwide customer service

Putting Science To Work

emcore

EMCORE Corporation • 35 Elizabeth Avenue • Somerset, NJ 08873 • (908) 271-9090 • Fax: (908) 271-9686
Visit EMCORE on the World Wide Web at <http://www.Emcore.Com>

Circle 10 on Reader Service Card

we spoke to also believe that, technical issues aside, current volumes do not justify scaling up at the present time. Ironically, the boom in consumer-driven applications for GaAs RF and microwave products may be partly responsible for holding down wafer sizes. Before the commercial markets developed, virtually everything in the GaAs industry was driven by military applications. Filling orders for defense systems usually meant high frequency, high power circuits which required big die sizes. But the current markets for wireless handsets require lower performance devices with lower levels of integration - or even discretely. As Jim Oakes of Raytheon says, "the move from military to commercial markets has driven up our volume, but driven down our die sizes, which means that we can get a lot more out of a 4" wafer".

Die sizes were an important factor in many of the early 4" to 6" conversions in the silicon industry. Rob Christ, Senior Applications Engineer at TriQuint Semiconductor, recalls his experiences in the silicon industry in the early 1980's, when memory chips would only yield 20 dice per 4" wafer: "The benefit of the 6" wafers was much more than just the 2.25 times increase in area, because the large die could be tiled more efficiently. Later, die sizes were also a big driver for the early 8" wafer users, even when 6" processing was cheaper per square inch." But he does not see a similar trend in GaAs devices, even when considering a highly integrated circuits such as a "one chip" GaAs RF front end for handsets. "TriQuint currently yields around 1000 dice per 4" wafer on our biggest volume parts. Future devices, though more highly integrated, will benefit from our next generation processes that will allow us to further shrink die sizes by 30%. We do not believe that die sizes in GaAs will grow as quickly as they did for Si. Therefore, fab capacity will have to be the main driver."

Given the number of GaAs processing lines in operation worldwide, it does not seem that industry as a whole suffers from any capacity shortage. There are, however, individual manufacturers who are reaching the limits of their internal production capability. For example, Siemens, which is the largest GaAs foundry in Europe and one of the five largest worldwide, has seen its annual output increase from around 10 million devices/year in 1994 to 31 million in 1995 to a forecasted 53 million in 1996. And Siemens is experiencing not only volume demands, but also some pressure with regard to die sizes: some of their MMICs have reached a complexity which yields only a few hundred per 4" wafer. It is not surprising, then, to find that they are one of the companies that are contemplating conversion at an early date, possibly in 1998.

M/A-COM probably found the best possible solution to its capacity problems when it acquired the defunct Cray Computer facility in Colorado last fall (CS 1(3), p.13). Rick Hess reports "We were thinking a lot harder about 6" before the Cray acquisition! That was an excellent way to increase our capacity, and it was less expensive and less painful than a 6" conversion. Unfortunately, that was probably a once-in-a-lifetime opportunity." So what lies ahead? Hess states "like many others we are looking at the 1998 time frame as the point when we might need our next capacity increase...but we won't scale-up until we are sure that we can actually fill a 6" fab." Others, including TriQuint, also see 1998 as the "earliest possible" conversion date, but it appears that no company has set out a firm time table - with one exception. The overall mood is one of cautious optimism, perhaps typified by TriQuint's plan to build its

Vitesse is "aggressively pursuing" plans for a 6" GaAs fab to be operational in 1998. It is not surprising that they would take the lead in this area, because, as the world's largest manufacturer of digital GaAs circuits, Vitesse contends with more extreme die size pressures than other fabs.

new fab (see page 16) around 4" processing, though making provisions for 6" compatibility at the same time. Incidentally, TriQuint was the first company to begin 4" GaAs processing, all the way back in 1987, with full scale production beginning in 1989.

The first company to complete a full 4" conversion was Vitesse - and they are the lone exception mentioned above. Bob Nunn reports that Vitesse is "aggressively pursuing" plans for a 6" GaAs fab to be operational in 1998. It is not surprising that they would take the lead in this area, because, as the world's largest manufacturer of digital GaAs circuits, Vitesse contends with more extreme die size pressures than other fabs. Their biggest chip, an FX gate array with 1.2 million used transistors (roughly equivalent to an Intel 386 microprocessor), has an area of 15mm x 15mm, and therefore yields only 21 dice per 4" wafer. Switching to larger wafers will not only reduce the per-device processing costs, but will also make state-of-the-art processing equipment available. According to Nunn, "leading edge semiconductor equipment is becoming hard to find at the 4" level". And, perhaps most importantly,

strong growth in sales (up 25% over the past 15 months and 35% over the last two quarters) is creating a capacity shortage at Vitesse's current fab. Nunn reports that "we've grown to the point where we will be over capacity at our current fab by the end of 1998. We believe that the most effective solution to the problem is to begin construction on a new facility for

6" processing." If they adhere to their timetable, Vitesse seems certain to be the first company to convert to 6 inch.

Are We Lagging Behind?

Inevitably, one has to make a comparison with silicon. At first glance, the 300mm test wafers or the 200mm production wafers which are used in silicon suggest that the compound semiconductor industry is lagging behind. However, as stated earlier, the enormous difference in volumes makes such a comparison a bit pointless. Also, if you dig a little deeper, you will find that the gap is not actually as wide as it may at first seem. Daniel Rose, a Silicon Valley consultant, points out that between now and the year 2000 the 6" wafer - seemingly modest by silicon standards - will in fact be that industry's workhorse, consumed at a rate of 1000 MSI (million square inches) per year, which is about half of the current annual consumption. He believes that 6" silicon will not be eclipsed by the 200mm standard until the year 2000. Rose also notes that there is still a lot of 4" silicon around, with consumption today at the surprising rate of 300 MSI per year.

The state-of-the-art standards in silicon are tailored to the demands of microprocessor and memory chips. The goals in the digital arena are to produce the fastest, smallest and most tightly packed transistors, operating at the highest possible speed, and performing the greatest number of logic operations in a given time. Digital technology "pushes the envelope" to accommodate smaller transistor dimensions on wafers of constantly increasing diameter. Therefore it is not surprising that Vitesse, whose product line is 95% digital, would be the first GaAs fab to scale-up to 6".

But again, Vitesse is the exception to the rule. The majority of GaAs fabs produce mostly or only analog devices. If you look at their counterparts in the silicon industry, you will see little interest in those 200mm and 300mm wafers. As Larry Sample, Design Vice President of

Micrel Semiconductor puts it, "the high-performance silicon analog manufacturers are quite comfortable using wafer sizes that our digital colleagues abandoned years ago". In the analog side of the business, he says, "circuit cleverness is more the aim than component size or circuit density." Analog devices have to accommodate an often bewildering array of conditions. At the most basic level, digital circuits do pretty much one thing: turn transistors on or off under software or firmware control. They are required to respond to only a minimum set of conditions in order to execute these tasks. Analog circuits, on the other hand, have to respond to a host of different electrical occurrences and must accommodate a wide spectrum of voltage, current and frequency conditions. Consider, for example, the large number of standards currently in use in the wireless communications industry. Therefore for both silicon and GaAs analog device manufacturers one can expect to find a larger variety of solutions, each which sells over a long period of time but in small quantities compared to digital silicon circuits. This has the effect of holding down volume demands and enhancing the attraction of processing on smaller wafers.

Indium Phosphide

And speaking of processing on smaller wafers: the optoelectronics side of the compound semiconductor industry consists almost entirely of discrettes, and the number of devices which can be obtained from a single 2" wafer is enormous: 6,000-8,000 lasers, or 8,000-10,000 LEDs. Therefore motivation for scaling up to larger diameter semi-conducting wafers is virtually nonexistent.

Several articles in this issue make the point that InP's primary application is in optoelectronics. Although the annual market value of InP-based devices is >\$1 billion, the market for InP wafers is tiny. The worldwide market in 1993 (the last year for which complete figures are available) was just \$18 million. In that year 80% of the world's InP consumption (183,200 sq. in.) was for optoelectronic devices, and >90% of the wafers consumed were 2".

The dominant position of optoelectronics in InP consumption has a negative effect on the development of InP-based microelectronics. 3" is generally considered to be the minimum size for even modest volume production, but InP is not easy to grow, and 3" semi-insulating InP wafer technology is very immature. In addition, many customers want high quality, "epi-ready" surface finishes, which adds to the complexity of the problem. At the same time,

Directory of Substrate Suppliers

The following is a brief overview of 26 suppliers of substrates for compound semiconductor materials. To request more information, use the Reader Service Card provided on page 27.

<u>Company</u>	<u>Description</u>	<u>Reader Service Card Number</u>
Advanced Technology Materials Diamond Electronics - Wafer Products 7 Commerce Drive Danbury, CT 06810 USA	4H and 6H SiC substrates. SIMOX SOI from Nippon Steel, InP, InAs, InSb, SC and SI CZ & VGF GaAs and GaSb from MCP. SiC or GaN epi; III-V epi on GaAs and InP from Epitronics. Contact: Tim Murray TEL [1] 203 794 1100 FAX [1] 203 830 4116	148
Airtron A Division of Litton Industries Electronic Materials Group 200 E. Hanover Avenue Morris Plains, NJ 07950 USA	SI LEC GaAs, production quantities from 2" to 6". Slip-Free™ 100mm and 150mm GaAs wafers now available, will introduce Ready-For-Epi™ wafers in 1996. ISO 9002 Certified. Contact: Robert Ochrym TEL [1] 201 539 5500 FAX [1] 201 539 2210	150
American Xtal Technology 6780 Sierra Court Suite I Dublin, CA 94568 USA	SI and SC VGF GaAs and InP. 2", 3" and 4" round GaAs wafers characterized by their low EPD, low thermal stress, uniform and consistent mechanical and electrical properties. Contact: Theodore Young TEL [1] 510 833 0553 FAX [1] 510 833 2667	152
Crystacomm, Inc. 1599 North Shoreline Blvd. Mountain View, CA 94043 USA	SC and SI LEC InP. Sizes up to 3" available, in both bulk and wafer form. Proprietary low thermal gradient process produces EPD levels comparable to gradient freeze material. Contact: George Antypas TEL [1] 415 961 4311 FAX [1] 415 961 4364	154
Crystal Specialties International 2853 Janitell Road Colorado Springs, CO 80906 USA	SC HB, VB and HCF GaAs, available in a wide variety of sizes and shapes. Doped and undoped LEC InP, up to 3". SI LEC GaAs up to 4". Contact: George Sheese TEL [1] 719 540 0990 FAX [1] 719 540 0994	156
Crystal GmbH Ostendstrasse 2-14 Berlin D-12459 Germany	II-VI wafers in wide variety of sizes and materials, including CdS, CdSe, CdTe, CdZnTe, CdTeSe, ZnS, ZnTe and ZnSe. Bridgman or Seeded Vapor Phase Growth. Contact: Steffan Sander TEL [49] 30 695 387 0 FAX [49] 30 635 043 6	158
Dowa Mining Co. Ltd. New Materials Division Semiconductor Department 8-2 Marunouchi 1 Chome Chiyoda-Ku, Tokyo 100 Japan	Low EPD SC 2" and 3" VGF GaAs. SC and SI 2", 3" and 4" GaAs and 2" and 3" InP grown by LEC. Also available: AlGaAs LED chips. Contact: Nagahito Narita TEL [81] 3 3201 1067 FAX [81] 3 3201 1098	160
Firebird Semiconductors Ltd. 2950 Highway Drive Trail, BC V1R 2T3 Canada	The only substrate supplier focused solely on antimonide substrates. InSb to 3", GaSb to 3" and sample size GaInSb. Contact: Grant Fines TEL [1] 604 364 5605 FAX [1] 604 364 5643	162
Freiberger Elektronikwerkstoffe GmbH P.O. Box 211 D-09584 Freiberg Germany	SI LEC GaAs, 2", 3" and 4" sizes. 6" samples available. SC LEC GaAs 2" and 3" sizes. Contact: Volkmar Geidel TEL [49] 3731 278 572 FAX [49] 3731 278 233 In France: E. Prudhommeaux Promecome Electronics TEL [33] 1 4473 1072 FAX [33] 1 4473 1053	164 166
Furukawa Electric Co. Ltd. 2-6-1 Marunouchi Chiyoda-ku, Tokyo 100 Japan	SI and SC LEC GaAs in 3" and 4" sizes. Epi wafers also available. Contact: Hiroyuki Matsushita TEL [81] 3 3286 3219 FAX [81] 3 3286 3965	168
Hitachi Cable, Ltd. Chiyoda Bldg. 2-1-2 Marunouchi Chiyoda-ku, Tokyo 100 Japan	SC HB GaAs up to 3". SI LEC GaAs in 2", 3" and 4" sizes. LEC crystals have tight controlled resistivity from seed to tail and are suitable for implant and epi. Contact: Akihiko Kimura TEL [81] 3 5252 3465 FAX [81] 3 3213 0402	170
II-VI Incorporated 375 Saxonburg Road Saxonburg, PA 16056 USA	High purity II-VI compounds for MCT epitaxial growth and optical and electro-optical applications. Single crystal substrates include CdTe, CdZnTe, CdTeSe and ZnSe. Contact: Tom Neff TEL [1] 412 352 1504 FAX [1] 412 352 4980	172
Japan Energy Corporation Compound Semiconductor Division 10-1, Toranomon 2-chome Minato-ku, Tokyo 105 Japan	SI LEC GaAs, 2", 3" and 4" sizes. InP (Fe, Non, S, Sn and Zn doped) in 2", 3" diameter. CdTe and CdZnTe wafers. Contact: M. Suzuki TEL [81] 3 5573 6592 FAX [81] 3 5573 6779 In Europe: T. Ishii Japan Energy U.K. FAX [44] 171 629 3602 In N. America: Hiroshi Miura NIMTEC Inc. TEL [1] 602 732 9857 FAX [1] 602 899 0779	174

wafer manufacturers are under pressure from their optoelectronics customers to improve quality and reduce costs of their 2" semi-conducting products. Consider the disparity between the alternatives: (a) InP optoelectronics, a well established and growing industry which generates steady demand for 2" semi-conducting wafers based on mature crystal growth technology requiring only incremental improvements to satisfy customer requirements; or (b) InP microelectronics, a nascent market niche with an as yet undetermined future, generating low and unpredictable demand and requiring significant investment in crystal growth technology. Is it any wonder that the substrate vendors might prefer the lower risk course described in (a)?

Actually, a surprising number of substrate vendors are already working on 3" semi-insulating InP. For the consumers - or potential consumers - the real issue seems to be the rate of progress. Elsewhere in this issue (p. 23) it was observed that InP substrate technology is 10 years behind GaAs. But since the boom in high frequency devices is here today, no one wants to wait 10 years for production-quality material. In the United States it is widely hoped that the Department of Defense might address the situation on order to lower the cost and increase the performance of its high frequency radar and communications systems.

There is clear interest in the US Air Force for an 3" InP substrate project: Laura Rea, a program manager at Wright Laboratories [Wright Patterson AFB, OH] says, "we want to desperately do something now, so that we don't have to play catch-up once the InP-based market begins to take off, and so that we can avoid the situation we had with GaAs when that occurred." Rea reports that a program to support the development of improved quality and larger diameter semi-insulating InP wafers is in the works, and may be ready as early as this summer. If such a program becomes a reality, it could be an important milestone in the development of InP microelectronics.

Thus the trends in wafer sizes in the compound semiconductor industry seem relatively clear: we should start to see the next generation in use a few facilities before the turn of the century, with the caveat that a change in direction or funding from the US government could slow down progress in the InP area. And what will come after that for our industry? 4" InP? 8" GaAs? Perhaps even metrification? Someday, undoubtedly - but for now, the samples on display, coupled with the plans in development, are impressive enough.

Directory of Substrate Suppliers (cont.)

Company	Description	Reader Service Card Number
Johnson Matthey Crystar 721 Vanaiman Ave. Victoria, BC V8Z 3B6 Canada	Sapphire substrates, CZ grown, 5" diameter capability, all orientations, custom polished, single or double sided. Contact: Fran Steed TEL [1] 604 479 9922 FAX [1] 604 479 2734	176
Johnson Matthey Electronics East 15128 Euclid Avenue Spokane, WA 99216 USA	VB and HB CdZnTe, up to 4cm x 6cm. CZ InSb, undoped or doped, up to 71mm. CZ GaSb, undoped or doped, up to 50.8mm. CdHgTe up to 15mm dia. Contact: Gerry Gruszka TEL [1] 509 922 8611 FAX [1] 509 922 8734	178
JX Crystals, Inc. 1105 12th Ave NW Suite A2 Issaquah, WA 98027 USA	GaSb wafers in several orientations (100, 111, 211, 311). 2" or 3" diameter. EPD <1000. N or P-type. Contact: Jany Fraas TEL [1] 206 392 5237 FAX [1] 206 865 0315	180
Laser Diode Products, Inc. Crystal Products 205 Liberty Street Metuchen, NJ 08840 USA	SC GaAs grown by HGF (2") and LEC (3"). Undoped GaSb polycrystal, CZ Ge up to 4". Exceptionally low EPD's. Contact: Stephen Lerner TEL [1] 908 549 9222 FAX [1] 908 549 9897	182
M/A-COM, An AMP Company 100 Chelmsford Street Lowell, MA 01810 USA	SI HPLEC GaAs in 3", 4" and 6" sizes. Email requests for brochure & tech. information to: gaas-wafers@macom.com. Look for our new Web Page coming in April. Contact: Chuck Snider TEL [1] 508 656 2675 FAX [1] 508 656 2800	184
Marketch International 5869 Beacon Street Pittsburgh, PA 15217 USA	Semiconducting and other crystals: Al ₂ O ₃ , MgO, Mg Al ₂ O ₃ , ZnO, LiAlO ₂ , InP, GaP, GaAs, NiAl, LiGaO ₂ , CdSe, sapphire and others. Contact: J. Spieckerman TEL [1] 412 421 3103 FAX [1] 412 421 1826	186
Materials Technology International 1719 Julain Court El Cerrito, CA 94530 USA	Single crystal substrates for epi wafers, including sapphire, spinel (MgAl ₂ O ₄), NdGaO ₃ , ZnO and newly developed crystals LiAlO ₂ and LiGaO ₂ . Also one side and two side polished GaSb, InAs, and InP. Contact: X.P. Jiang TEL [1] 510 234 5221 FAX [1] 510 234 5235	188
MCP Wafer Technology, Ltd. 34 Maryland Road Tongwell Milton Keynes, Bucks MK15 8HJ UK	GaAs, InP, InAs, InSb, GaSb and GaP in a wide variety of sizes and forms. Crystal growth processes include VGF, high and low pressure LEC and horizontal synthesis. Contact: Karen Lamb TEL [44] 1908 210 444 FAX [44] 1908 210 443	190
Mitsubishi Chemical Corporation Information & Electronics Company Compound Semiconductor Dept. 5-2, Marunouchi 2-Chome Chiyoda-ku, Tokyo 100 Japan	SC and SI GaAs grown by LEC and GF/VGF. Up to 4" available. Established reputation for high and consistent quality for >20 years. Contact: Katsuyuki Shimakawa TEL [81] 3 3283 4673 FAX [81] 3 3283 4485	192
Roditi International Carrington House 130 Regent Street London W1R 6BR United Kingdom	Sapphire substrates in various orientations up to 6" diameter. Contact: Christopher Kenmore TEL [44] 171 439 4390 FAX [44] 171 434 0896	194
Showa Denko K.K. 13-9 Shiba Diamon 1-Chome Minato-ku, Tokyo 105 Japan	SI and SC GaP, InP and GaAs substrates. Also GaP, GaAs, GaAlAs and AlInP epi wafers for LEDs and InP epi wafers for custom specifications. Contact: Mr. Yamamoto TEL [81] 3 5470 3503 FAX [81] 3 3435 1034 TEL [49] 211 684 035 FAX [49] 211 679 8665 In Europe: T. Chinushi Showa Denko Gmbh In N. America: Bettye Garret Showa Denko America TEL [1] 415 345 1338 FAX [1] 415 345 5403	196
Sumitomo Electric Industries, Inc. Semiconductor Division 1-1-1 Koya-Kita Itami, Hyogo 864 Japan	SI and SC GaAs, InP, InSb, InAs, GaSb and ZnSe grown by LEC, HB, VB and proprietary VCZ methods. Up to 6" GaAs and 2" and 3" InP available. ISO 9001 Certified. Contact: Atsutada Ogura TEL [81] 727 72 2281 FAX [81] 727 71 0282 In Europe: Kazuhiko Oida Sumitomo Electric Europe TEL [44] 81 905 6160 FAX [44] 81 905 6195 In N. America: Thomas Mische Sumitomo Electric USA, Inc. TEL [1] 212 308 6444 FAX [1] 212 308 6575	198
Union Carbide Crystal Products 750 S. 32nd Street Washougal, WA 98671 USA	CZ sapphire substrates. Oriented to within 0.3 degrees and polished to excellent surface finish. 2" and 3" available, also, research kits containing five small (1 cm ²) substrates. Contact: Larry Rothrock TEL [1] 360 835 2001 FAX [1] 360 835 9848	200

Material and Device Fundamentals of InP-Based Microelectronics and Optoelectronics

PALLAB BHATTACHARYA

SOLID STATE ELECTRONICS LABORATORY

DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

UNIVERSITY OF MICHIGAN, ANN ARBOR, MI 48109-2122

The III-V compound semiconductors crystallizing in the zincblende structures have energy bandgaps ranging from 0.18 to 2.42 eV. Figure 1 shows the variation of the lattice constant as a function of bandgap for a number of important binary compounds and their ternary derivatives. Six ternary alloys and an infinite number of quaternary and higher order alloys can be formed with lattice constants matching that of InP.

It is fortuitous for InP's development that alloys which lattice-match to InP have bandgaps which coincide with the 1.3 and 1.55 μm windows in optical fibers. The optical fiber communications revolution in the 1970's provided the impetus for the development of practical optoelectronic devices from alloy semiconductors whose properties were optimized with respect to fiber transmission characteristics. Although the GaAs-based GaAlAs alloys and GaAs/GaAlAs heterostructures were well-developed, they could not meet the requirements of these heterostructure devices. Attention therefore turned to the compounds and heterostructures lattice-matched to InP. Of these, the alloys formed by mixing As or P with

Sb exhibit extended miscibility gaps, which prevent growth of lattice-matched alloys under normal growth temperatures encountered in epitaxy. As a result, the GaInAs and AlInAs ternary alloys and the GaInAsP and AlGaInAs quaternary alloys have emerged as the materials of choice for 1.3 and 1.55 μm fiber optics communication by virtue of their bandgaps.

In the course of the development and characterization of the ternary and quaternary alloys for optoelectronics, it became clear that GaInAs and GaInAs/AlGaInAs heterostructures have much better transport properties compared to GaAs and GaAs/GaAlAs heterojunctions, which make them suitable for high-speed microelectronic devices. With a very low electron effective mass, very high mobilities, up to 15,000 cm^2/Vs , have been measured in undoped n-type $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ at room temperature. This is achieved in spite of limitations imposed by alloy scattering and the value is almost 100% higher than that in GaAs. Mobilities up to 4,500 cm^2/Vs have been measured at room temperature in $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$. The quaternary alloys have mobilities strongly dependent on composition, varying between 1,000 and 1,500 cm^2/Vs in pure material. The high mobility in GaInAs makes it very attractive for field effect transistors, where GaInAs/AlInAs or GaInAs/GaInAsP heterojunctions are used, or in heterojunction bipolar transistors using the same heterostructure.

In addition to the favorable low-field mobility, the large energy separation of 0.55 eV between the lowest two valleys in the conduction band of GaInAs makes the high field transport properties also very attractive. The peak and saturation drift velocities of

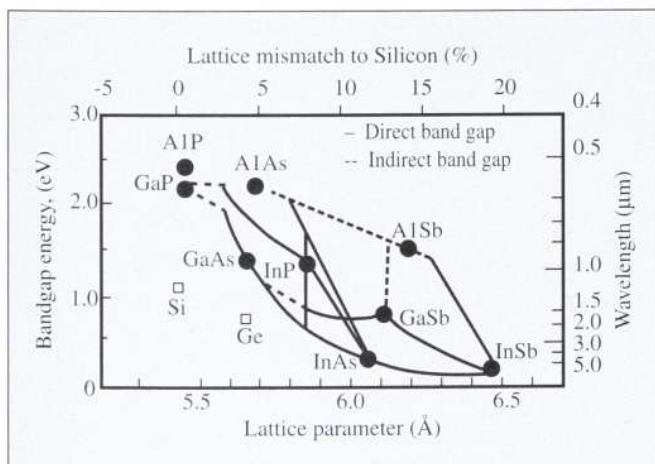


Figure 1. Bandgaps and lattice constants of III-V binary compounds crystallizing in the zincblende structure.

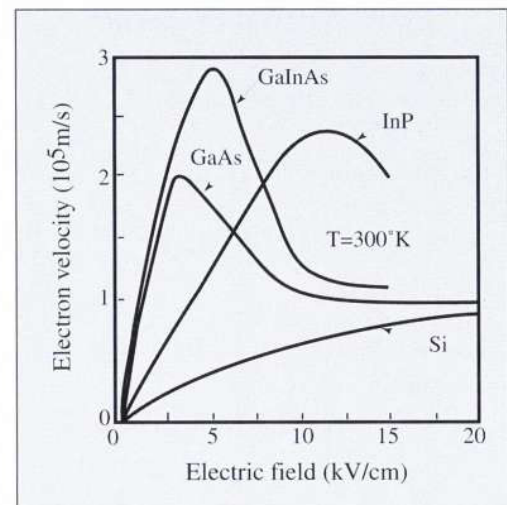


Figure 2 Velocity-field characteristics of important semiconductors.

$\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ are shown in Figure 2 and compared to those of GaAs, InP and Si. High-field transport parameters play an important role in short channel FETs. The benefits of using these compounds for high speed microelectronics are immediately obvious. Another tremendous advantage provided by InP-based devices and circuits is the higher substrate thermal conductivity (0.7 versus 0.46 W-cm/K) for GaAs.

Additional properties of InP are given in Figure 3. It is also important to mention a few disadvantages. In a small bandgap semiconductor such as GaInAs, the Auger recombination rate is much higher than that in GaAs. Leakage currents of diodes generally tend to be higher. Furthermore, GaAs does not suffer from the problems associated with alloy scattering. Fortunately, because of the light electron mass, alloy scattering does not degrade the transport properties in GaInAs. However, the photoluminescence emission linewidth is broadened by alloy scattering and this has serious implications on the performance of quantum well Stark effect modulators.

Heterostructures

Every high-performance InP-based microelectronic or optoelectronic device at the present time uses heterojunctions and quantum wells. One of the most important parameters for the design and analysis of heterostructure and quantum well devices is the heterojunction band offset, which is a consequence of the difference between the energy gaps of the two semiconductors involved. In a type I (straddling) band lineup, which holds for all the InP-based heterojunctions of interest, the bandgap difference ΔE_g is related to the conduction band offset ΔE_c and the valence band offset ΔE_v by

$$\Delta E_g = \Delta E_v + \Delta E_c.$$

Basic Material Properties

Below are some of the important properties of the InP-based compounds. InP has a bandgap of 1.35eV at room temperature.

(1) Lattice-Matching Compositions

- a) $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$:
 $x = 0.1896y(0.4176 - 0.0125y) - 0.47y$
 $(0 \leq y \leq 1)$
- b) $\text{Al}_x\text{Ga}_y\text{In}_{1-x-y}\text{As}$:
 $y = 0.468 - 0.983x$
 $(0 \leq x \leq 0.476, 0 \leq y \leq 0.468)$
- c) $\text{Ga}_x\text{In}_{1-x}\text{As}$: $x = 0.468$
- d) $\text{Al}_x\text{In}_{1-x}\text{As}$: $x = 0.476$

(2) Direct Bandgaps

- a) $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$:
 $E_g = 1.35 - 0.775y + 0.149y^2$ (298K)
- b) $\text{Al}_x\text{Ga}_y\text{In}_{1-x-y}\text{As}$:
 $E_g = 0.75 + 1.0496x + 1.0645x^2 - 0.033x^3$
 $(0 \leq x \leq 0.48)$ (298K)
- c) $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$:
 $E_g = 0.74 \pm 0.01$ eV (298K)
- d) $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$:
 $E_g = 1.49 \pm 0.1$ eV (298K)

(3) Electron and Hole Effective Masses

electron effective mass - m_e/m_0
 light hole effective mass - m_{lh}/m_0
 heavy hole effective mass m_{hh}/m_0

- a) $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$:
 $m_e/m_0 = 0.079 - 0.038y$
 $m_{lh}/m_0 = 0.120 - 0.0999y + 0.030y^2$
 $m_{hh}/m_0 = 0.46$
- b) $\text{Al}_x\text{Ga}_y\text{In}_{1-x-y}\text{As}$:
 Very little experimental data are available and therefore values are calculated by interpolation from the constituent binaries.
- c) $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$:
 $m_e/m_0 = 0.041$
 $m_{lh}/m_0 = 0.051$
 $m_{hh}/m_0 = 0.46$
- d) $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$:
 $m_e/m_0 = 0.075$
 $m_{lh}/m_0 = 0.096$
 $m_{hh}/m_0 = 0.41$

The study of band offsets, both by theory and experiment, has been long and arduous and often there are disagreements. The disagreements in experimental values occur partly from material/interface quality and partly from the technique used. I will list here some well-accepted (average) values of the band offsets of important InP-based heterojunctions.

(a) $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}/\text{InP}$: There is considerable disagreement and $\Delta E_c/\Delta E_v$ ranges from 67:33 to 37:63.

(b) $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}/\text{InP}$: $\Delta E_c : \Delta E_v$ is $\sim 40 : 60$, with $\Delta E_c \cong 220$ meV and $\Delta E_v = 400$ meV.

(c) $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}/\text{Al}_{0.48}\text{In}_{0.52}\text{As}$: $\Delta E_c : \Delta E_v$ is $\sim 70 : 30$ with $\Delta E_c \cong 520$ meV.

(d) $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}/(\text{Al}_x\text{Ga}_{1-x})_{0.48}\text{In}_{0.52}\text{As}$: For this heterostructure system it has been found that $\Delta E_c : \Delta E_v \cong 73 : 27$.

Two features are immediately obvious. For the $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}/\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ heterostructures ΔE_c is much larger than ΔE_v and ΔE_c has a large value of ~ 520 meV. Therefore very efficient electron transfer and modulation doping takes place in modulation-doped heterostructures and very high sheet carrier densities ($\sim 10^{13}$ cm $^{-2}$) are obtained. Coupled with the large intervalley separation in GaInAs and resulting favorable high-field transport properties, we have all the ingredients for high-performance, modulation-doped FETs (MODFETs), also known as High Electron Mobility Transistors (HEMTs). In comparison, GaAs has a much lower Γ -L intervalley separation (280 meV) and ΔE_c for GaAs/ $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}$ heterostructures is only 210 meV. Another area where a large band offset ΔE_c becomes useful is the tailoring of the impact ionization coefficient ratio, α/β , in GaInAs/AlInAs quantum wells. It is desirable to have $\alpha/\beta \gg 1$ or $\ll 1$ for low-noise 1.55 μm avalanche photodiodes. Finally, quantum wells with large ΔE_c are used in the active region of 1.55 μm lasers to reduce the temperature dependence of the threshold current, arising (partly) due to electron leakage over the barriers.

The second important feature is that for the GaInAs/InP heterostructure $\Delta E_v > \Delta E_c$. This feature is extremely attractive for the design of high performance n-p-n heterojunction bipolar transistors (HBTs), wherein the injection of holes from the base to the emitter is minimized. In contrast, it may be remembered that for GaAs/GaAlAs, $\Delta E_c : \Delta E_v = 57:43$.

Electronic Devices

InP-based heterostructures are used in the design and fabrication of high-performance HBTs and HEMTs. Advances in materials

technology and processing techniques have helped in the realization of extraordinary performance characteristics of these transistors and their circuits, such as amplifiers and oscillators. As a consequence, great strides have been made in InP-based microwave monolithic integrated circuits (MMICs) and OEICs.

(a) HEMTs

In lattice-matched and pseudomorphic HEMT devices a two-dimensional channel of electrons is formed by transfer doping from a wide bandgap doped layer to a narrow bandgap undoped layer across a heterojunction. A thin (30 - 50 Å) spacer layer is usually inserted in between. The efficiency of transfer doping depends on the conduction band offset. The channel conductance is modulated by a voltage applied across a gate electrode, formed on the wide bandgap doping layer, which shifts the Fermi level in energy in the 2-D channel. The typical heterostructure used is $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}/\text{Al}_{0.48}\text{In}_{0.52}\text{As}$. Although very impressive results have been obtained in GaAs-based pseudomorphic HEMTs in terms of gain, microwave performance, and noise performance, far superior results have been obtained with InP-based GaInAs/AlInAs heterostructures. The main advantages, and the reasons for these, are the following:

(i) Much larger conduction band offset results in a higher channel carrier density. This leads to larger output current and power, larger gain, and lower noise figure at high frequencies;

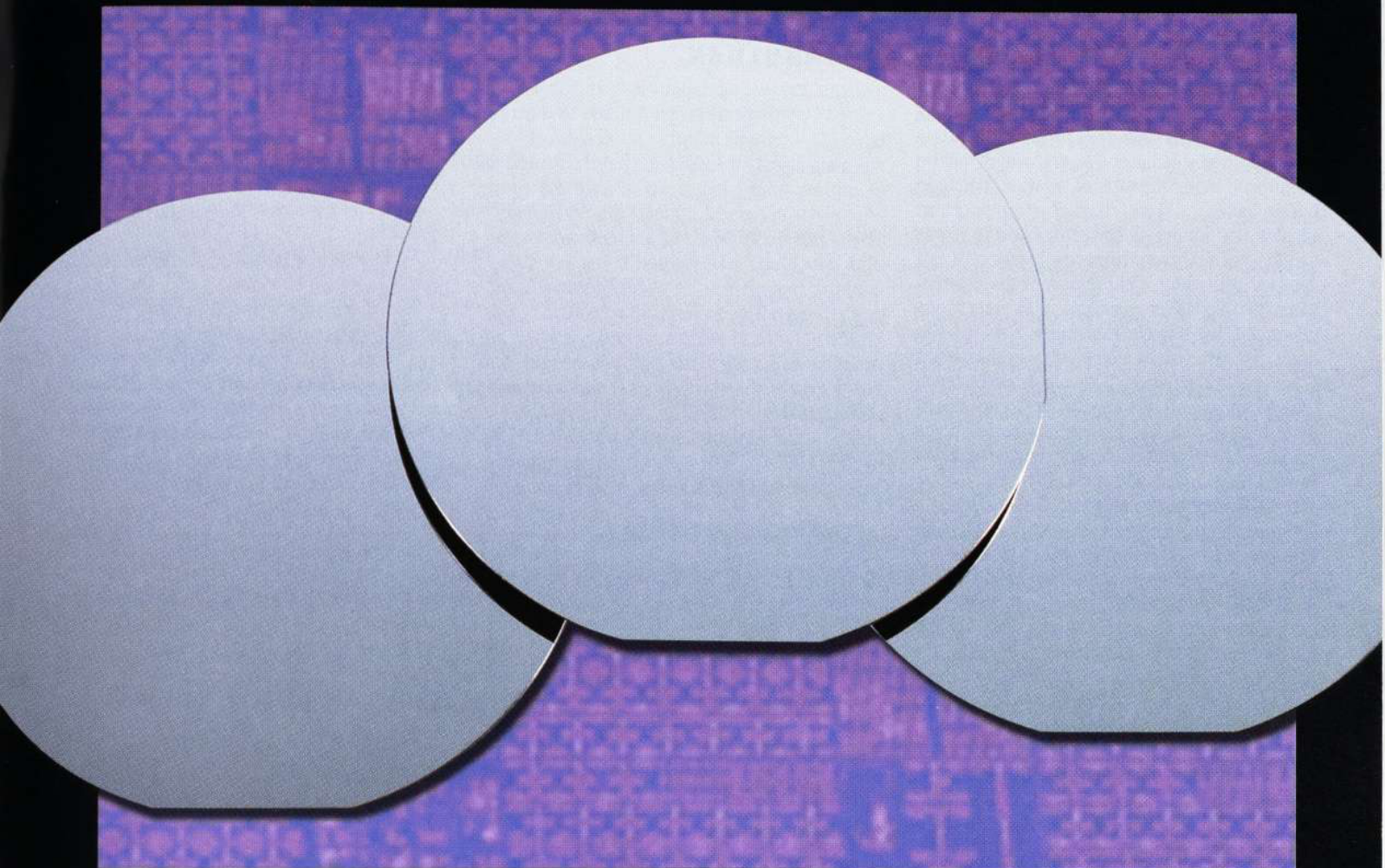
(ii) higher mobilities and peak velocities in GaInAs and GaInAs/AlInAs modulation-doped heterostructures lead to higher cut-off frequencies;

(iii) absence of D-X centers (present in GaAlAs) in lattice-matched $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ eliminates problems such as I - V collapse, threshold voltage shift, and persistent photoconductivity during operation at cryogenic temperatures.

In pseudomorphic HEMTs (PHEMTs), the channel material is usually (biaxially) compressively strained and therefore the band offset is increased further. This leads to even better performances, principally due to two reasons: higher sheet carrier density and a wider energy separation of the subbands in the 2D channel, leading to more carriers remaining in the ground state. However, there is a trade-off with material and heterointerface quality as one increases the amount of In in the channel material and thereby the misfit. For misfits larger than 2%, the growth modes of strained layers are altered from a layer-by-layer 2D

Figure 3. Basic material properties of InP.

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.

M/A-COM
an AMP company

Circle 6 on Reader Service Card

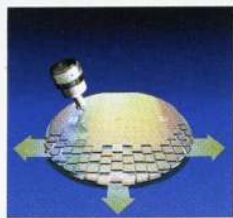
mode to an island 3D mode. Consequently interface roughness increases at the heterointerface, degrading the carrier transport properties and device performance. In fact, the best results in InP-based pseudomorphic HEMTs are obtained with a $Ga_{0.3}In_{0.7}As/Al_{0.48}In_{0.52}As$ heterostructure.

There are, however, some materials-related problems that are inherited in using InP-based heterostructures for HEMTs. GaInAs/AlInAs HEMTs exhibit high output conductance compared to GaAs/GaAlAs devices. This is due to energetic electrons being emitted to adjacent layers, which can be minimized with the use of a wide bandgap buffer layer. The channel (source-drain) breakdown voltage is lower due to the lower bandgap of GaInAs. Impact ionization of hot carriers in the high field region of the channel leads to two adverse effects. The electrons generated by impact ionization flow to the drain and give rise to a *kink effect* in the output $I_{ds} - V_{ds}$ characteristics. The excess holes reach the source as well as the gate and contribute to increased gate leakage. The number of holes reaching the gate will depend on the valence band discontinuity, and we know $\Delta E_c : \Delta E_v = 70 : 30$ for the lattice matched GaInAs/AlInAs heterojunction. Techniques such as insertion of a thin AlAs layer in the spacer layer of the device have greatly reduced gate leakage.

After years of intense materials and device research and development, InP-based lattice-matched and pseudomorphic HEMTs have emerged as leading candidates for ultra-low noise and high frequency applications. These are the best transistors ever realized. Transconductances of $\sim 1000\text{mS/mm}$ are realized with $0.1\mu\text{m}$ gate devices and recently a PHEMT with f_{max} of 600GHz and a noise figure of 1.4dB at 94GHz was reported. These devices are critical components for advanced satellite communications, radio astronomy, and wideband instrumentation.

(b) HBTs

The same material benefits, which help the achievement of higher levels of performance in InP-Based HEMTs, also improves the performance characteristics of InP-based HBTs. Thus the larger band offset in the GaInAs/AlInAs emitter junction improves the injection efficiency. Better transport properties in the GaInAs base region improves the current gain cut-off frequency f_T . Low bandgap materials also ensure low specific contact resistivity in the base and a higher value of the maximum oscillation frequency f_{max} . There are several other advantages. The surface recombination velocity of $Ga_{0.47}In_{0.53}As$ is much smaller than that of GaAs (10^3 compared to 10^6 cm/s), which implies that the injection efficiency is further improved. Since the intervalley separa-



Scribe & Break TECHNOLOGY

chip free kerfs

non-contact breaking

0.1 degree diamond adjustment

small die processing

5 times faster than sawing

yield increases

higher die density on the wafer

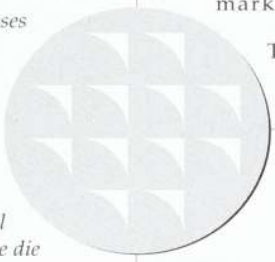
less residual stress on the die

wafer edge detection

multiple die sizes

pick & place compatible

ideal for processing lasers



DYNATEX INTERNATIONAL™

5577 Skylane Boulevard
Santa Rosa, CA 95403

Phone: 707-542-4227

Fax: 707-579-8599

Still Sawing Your Wafers?

{ Your Competition Isn't }

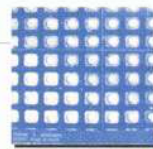
INCREASE YOUR MARGIN:

SPEED	120,000 die per hour 250μ x 300μ
MEMORY	Fully programmable
VERSATILITY	Multiple die size capability
ENVIRONMENTAL	No D.I. or toxic waste water
YIELD	Superior yield & improved efficiency

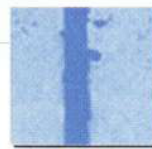
Dynatex is your source for this revolutionary generation of patented scribe and break technology for processing a wide variety of crystalline materials from GaAs and Silicon to Quartz, Lithium Niobate, Ceramic and Glass.

The DX-III has the versatility for placement in any production market where yields and an investment return are critical.

The DX-III is the *SAW* alternative.



DX-III Screen (800X)



Saw (800X)



DX-III (800X)



DX-III

Circle 65 on Reader Service Card

DYNATEX INTERNATIONAL

tion in GaInAs is larger, hot electrons can be launched at the emitter junction and these can quickly transit the base region, increasing f_T and f_{max} further. Double heterojunction devices are used, in which a wide bandgap collector is also incorporated. This increases the collector breakdown voltage, reduces the output conductance and enables high-power operation. High frequency transistors are being scaled down in size and the scaling properties of high-gain submicrometer HBTs are excellent. They have low power dissipation and can be easily integrated with optoelectronic devices in OEICs for optical communication systems. Values of f_T and f_{max} of ~ 250 GHz have been reported for InP-based HBTs.

Optoelectronic Devices

The important optoelectronic devices using InP-based heterostructures are detectors and lasers. Photodetectors of various types (junction diodes, MSM detectors, avalanche photodiodes and phototransistors) are made with GaInAs, GaInAlAs, or GaInAsP as the active region, simply to absorb the incoming light of 1.3 or 1.55 μm wavelength.

GaAs/GaAlAs heterostructures would just not do the job. A slight disadvantage of using these low bandgap materials in photodiodes is the large reverse leakage current and associated noise. This problem is solved by using heterojunctions and advanced structures such as separate absorption and multiplication (SAM) avalanche photodiodes. It may be noted that SiGe photodiodes would also work at these wavelengths. However for fast response and high speed, the InP-based devices are superior because of better transport properties.

GaInAsP quaternaries and GaInAs/GaInAsP or GaInAs/AlInAs quantum wells are used as the active (gain) regions in 1.3 and 1.55 μm lasers. Again, GaAs/GaAlAs heterostructures are not suitable in this wavelength range. Compared to GaAs, the InP-based materials have lower gain and differential gain, due to differences in the band structure. As a consequence, the threshold currents are higher and the small-signal modulation bandwidth is slightly lower. Nonetheless, ~ 1 mA edge emitting lasers are being made with InP-based heterostructures and a small-signal modulation bandwidth of ~ 30 GHz has been reported. Another materials related prob-

lem is the increased rate of Auger recombination in lasers made with small bandgap materials. Auger recombination is dominant in the presence of hot carriers. Hot carriers, gain compression, and leakage over heterobarriers contribute to increased temperature dependence of the threshold currents in InP-based lasers ($T_0 \sim 45^\circ\text{C}$ compared to 125°C in GaAs-based lasers, where $I_{th}(T) = I_{th}(0) e^{T/T_0}$). The effects related to hot carriers are greatly alleviated in the tunneling injection laser recently developed by the author and co-workers. Some of these problems are offset by better substrate conductivity in this material system.

In vertical cavity surface-emitting lasers, which use quarter-wave stacks of hi-lo index layers as end reflectors, a special problem is encountered. Since the index difference between GaInAs and AlInAs is very small, a large number of periods of the two layers are required for high reflectivity. This makes growth difficult and devices operation far from ideal. A fusion technique is currently being used to bond GaAs/AlAs quarter-wave stacks to a InP-based active region to form 1.55 μm VCSELs.

Invitation to Contribute to *Compound Semiconductor*

Introduction and Mission Statement

The mission statement for our magazine is "to provide a focal point for the global compound semiconductor industry". To help achieve that goal we are instituting a new feature, to be called the *Compound Semiconductor* Forum. It is designed to allow our readers to share their unique viewpoints or specialized knowledge about compound semiconductor science and technology by analyzing, summarizing or explaining recent work or developments. We are soliciting contributions from qualified individuals who wish to make a contribution to the general understanding of compound semiconductor technology or the industry which is based upon it.

Instructions

1) Almost any compound semiconductor-related topic is acceptable, provided that it is not too narrowly focused. Our primary selection criteria will be the article's level of interest or usefulness to our readers.

2) We will be particularly interested in certain topics by the dates given below, but we would welcome other items as well:

High Temperature Semiconductors	June 1
GaAs ICs	August 1
Nitride Technology	October 1
Epitaxial Growth	December 1

3) Remember that you are writing for a magazine, not a technical journal. The familiar structure used in technical papers - abstract, introduction, experimental detail, etc. - does not apply here. Instead, you should focus on a lively discussion of the chosen topic. Space is limited, so please pay attention to the Technical Specifications given at right, especially regarding word counts.

3) Whenever appropriate, the author should review/describe not only his/her own recent work but also significant reports from other leading workers in the field. The reader will benefit from receiving a more complete picture.

4) When in doubt, contact us - we'll be happy to provide help along the way.

Technical Specifications

1) Maximum word count = 1100.

2) Provide a succinct and descriptive title, and try to incorporate at least two sub-headings in the main body of the text. Provide the author's name and brief discussion of affiliation and background - not more than 25 words.

3) One figure is desirable. Up to two are acceptable. Subtract 200 words from the maximum word count for each figure used. Include a descriptive caption for each figure.

4) Due to space constraints, we cannot accommodate more than 3 bibliographic references.

5) FAX or mail the completed manuscript to us. Please: no email submissions. Include the figures and captions, and an exact word count. We will notify you of acceptance or rejection, or suggest appropriate revisions, as soon as possible.

Address contributions or questions to:

Editor, *Compound Semiconductor Magazine*
Franklin Publishing, 250 Selby Avenue,
Saint Paul, MN 55102 USA,
TEL [1] 612 227 5397; FAX [1] 612 227 5499
email: editor@compsem.com

Electronic Circuits and Devices

GaAs-Based pHEMT C-Band Power Amplifier

High efficiency power transistors are a critical component of solid-state power amplifiers (SSPAs) needed in satellite communications systems. At lower microwave frequencies (< 10 GHz), the GaAs-based MESFET has been considered the baseline power device for SSPA applications. However, higher efficiencies should be possible with heterojunction-based FETs, such as the pseudomorphic high electron mobility transistor (pHEMT). An MBE-grown C-band (4.0-8.0 GHz) pHEMT utilizing AlGaAs/InGaAs/GaAs with 15% In in the channel, and gate-drain breakdowns in excess of -20 V, is reported. At 4.5 GHz, a $0.25 \mu\text{m} \times 1.2 \text{ mm}$ pHEMT, with a drain-source voltage of 5V, exhibited an output power of 0.35 W and power added efficiency (PAE) of 79%, which is the highest reported efficiency for a GaAs-based pHEMT at this frequency. A power amplifier fabricated with these pHEMTs exhibited an output power of 1.2W with a PAE of 74% at 4 GHz operation. Work performed at the Hughes Research Laboratories [Malibu, CA]. See "High-Efficiency GaAs-Based pHEMT C-Band Power Amplifier," J.J. Brown et al, IEEE Microwave and Guided Wave Letters, 6(2), 91 [February 1996].

GaN/P/GaAs HBT Power Amplifiers for 10 GHz Operation

The relative ease of fabricating the emitter-base mesa structure of GaInP/GaAs-based HBTs is due to the availability of highly selective wet etches, making the GaInP/GaAs HBT an excellent candidate for reliable and reproducible manufacturing. A single stage GaInP/GaAs HBT MMIC power amplifier was fabricated which consisted of 128 emitter fingers, each having an area of $2 \times 30 \mu\text{m}^2$. Operating under pulsed conditions (pulse width 100 μs , duty cycle 10%) and at the relatively moderate current density of $2 \times 10^4 \text{ A/cm}^2$, this MMIC produced a maximum output power of 9 W with a power added efficiency of 42% at 10 GHz operation, representing the best performance of any GaInP/GaAs HBT MMIC power amplifier at this frequency and pulse conditions. Work performed at Daimler-Benz AG, Research Center [Ulm, Germany]. See "High Efficiency GaInP/GaAs HBT MMIC Power Amplifier with up to 9 W Output Power at 10 GHz," K. Riepe et al, IEEE Microwave and Guided Wave Letters, 6(1), 22 [January 1996].

High Temperature RF Performance of MESFETs with AlAs Buffers

High temperature operation of electronics (100-300°C) are required for a wide range of aircraft, automotive and space applications. Semi-insulating GaAs substrates experience a resistivity degradation under high temperature operation, resulting in a leakage path which degrades FET dc performance. AlGaAs buffers have been used to alleviate this problem, but in turn can introduce RF degradation due to deep centers which act as electron traps (DX-centers). However, it is shown in this work that for temperatures up to 200°C, MBE grown MESFETs using AlAs buffers (thickness from 250 to 400 nm) showed that f_t was unaffected, and f_{max} actually improved as compared to devices which used no buffers. Work performed at the Northeastern Consortium for Engineering Education [Port Royal, VA] and Wright Laboratory [Wright-Patterson AFB, OH]. See "High-Temperature Microwave Characteristics of GaAs MESFET Devices with AlAs Buffer Layers," C. Ito et al, IEEE Electron Device Letters, 17(1), 16 [January 1996].

High Transconductance AlGaIn/GaN FETs

Due to the almost 2 eV conduction band discontinuity at the AlN/GaN heterojunction, extremely high two dimensional gas concentrations (2DEG) of up to $2 \times 10^{13} \text{ cm}^{-2}$ may be possible, making devices based on this heterostructure a potential candidate for high transconductance, g_m , devices. Using a $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}/\text{GaN}$ HFET structure (and therefore a much reduced conduction band discontinuity as compared to the AlN/GaN heterojunction), a transconductance of 64 mS/mm was obtained, representing an improvement by a factor of three over previously reported results. This improved g_m occurs when the device is placed under UV illumination, which is believed to produce trapped positive charge and conduction electrons in the channel, which enhances the surface density of the 2DEG in the device channel up to $2 \times 10^{12} \text{ cm}^{-2}$, while decreasing the source series resistance. Work performed at APA Optics [Blaine, MN] and University of Virginia [Charlottesville, VA]. See "High Transconductance AlGaIn/GaN Optoelectronic Heterostructure Field Effect Transistor," M. Asif Khan et al, Electron. Lett., 31(24), 2130 [23 November 1995].

Ballistic Transport in AlGaAs/GaAs MODFETs

The transconductance of a FET will increase under the operating conditions of ballistic transport, during which no carrier scattering takes place. Because the transconductance of a FET reflects the saturation velocity of the electron transferred under the gate, the observation of temperature independency of the transconductance would indicate that electrons had been transported without scattering. Using this criteria to determine the presence of ballistic transport, AlGaAs/GaAs MODFETs with an applied drain voltage of 3 V were found to display a temperature independent transconductance for $0.05 \mu\text{m}$ gate length devices. For this short gate length device the electron transit time was less than 0.15 ps, and the electron velocity was determined to be $8.2 \times 10^7 \text{ cm/sec}$. Work performed at Matsushita Electronics Corporation [Osaka, Japan]. See "Temperature-Independent Transconductance in $0.05 \mu\text{m}$ -Gate AlGaAs/GaAs MODFET," T. Ueda et al, Solid-State Electronics, 39(1), 21 [January 1996].

Buried-Channel Charge-Coupled Device in 6H SiC

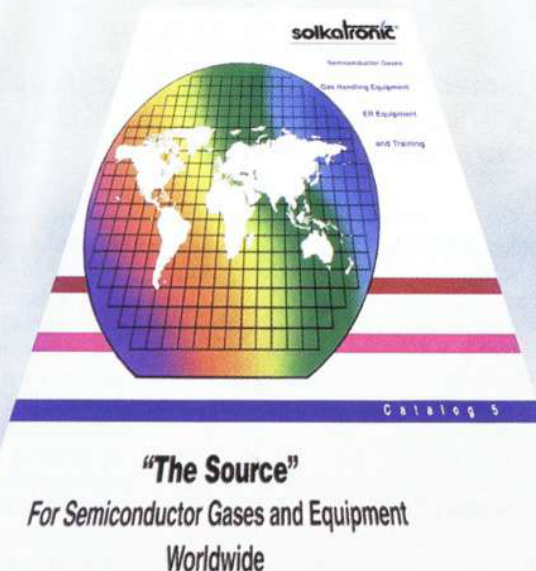
Until recently, SiC research and development efforts have focused primarily on discrete devices which have been capable of high power, high frequency, and elevated temperature operation. However, due to SiC's wide bandgap and low generation rate, this material should be well suited for UV imaging in the presence of an intense background of visible and infrared radiation - enabling the fabrication of a so called "solar blind" detector.

Taking advantage of the native SiO_2 which can be grown on SiC, researchers at Purdue University [West Lafayette, IN] have fabricated the first reported SiC MOS-based CCD (charge coupled device) image sensor. The process begins with a lightly doped p-type epilayer ($1-2 \times 10^{16} \text{ cm}^{-3}$) of 6H-SiC grown 3-5 μm thick onto a highly doped p-type (0001) substrate. Selective implantation of nitrogen through a Ti mask was performed at 650°C to form the source/drain regions, while a second lithography and nitrogen implantation was used to form a near-rectangular ion-buried channel. This channel exhibited a peak donor concentration of $1.2 \times 10^{17} \text{ cm}^{-3}$ and a junction depth of 190 nm, which resulted in an electron mobility of $200 \text{ cm}^2/\text{Vs}$. A double-level overlapping polysilicon-gate process was used to transfer charge between adjacent CCD wells, in which the oxide thickness under the first level gate is 70.8 nm, while the oxide under the second level gate is 64.5 nm. The buried channel CCD (BCCD) was configured as a four-phase, eight stage linear shift register, consisting of 32 transfer gates plus two input gates and one output transfer gate. Running at a speed of 5.5 kHz, the observed output voltage swing during charge transfer corresponded to a charge packet of 2.9×10^7 electrons. After 17 elemental transfers along the shift register, the charge in the leading packet, as compared to the charge of subsequent packets, is about 90.4%, corresponding to a charge transfer efficiency of about 99.4% per transfer. It is believed that this charge transfer efficiency may be limited by charge trapping in bulk states along the length of the CCD, and that this inefficiency may be improved by maintaining a bias charge in each potential well.

See "Experimental Demonstration of a Buried-Channel Charge-Coupled Device in 6H Silicon Carbide," S.T. Sheppard et al, IEEE Electron Device Letters, 17(1), 4 [January 1996].

MEGABIT® II

The Next Generation



Solkatronic Chemicals introduces Megabit® II, the next generation of High Purity Semiconductor Grade Gases.

Megabit® gases ensure the purity and performance consistency that maximize yield. The purity of long-term storage is guaranteed by using microPure® cylinders.

For your next generation of high purity semiconductor gases and gas handling equipment, Solkatronic has a new source of information on:

- ◆ Megabit® II Gases - Analyzed for Trace Metal Impurities
- ◆ microPure® Gas Handling Equipment
- ◆ ER Equipment and Training

SOLKATRONIC... "The Source" for:

- ◆ Megabit® Grade Gases
- ◆ microPure® Cylinders
- ◆ Metals Analysis
- ◆ Basic Manufacturer of:
 - Arsine Hydrogen Selenide
 - Phosphine Silicon Tetrafluoride

Solkatronic's new Catalog 5: It's brand new, it's comprehensive, it's simple to understand, and it's **FREE**. Call today for your copy.

solkatronic®



Solkatronic Chemicals
30 Two Bridges Rd. Fairfield, NJ 07004-1530
Tel: 201-882-7900 Fax: 201-882-7967 Toll Free: 800-521-3981
A Division of Solvay Specialty Chemicals, Inc.

Solkatronic... "The Source" for Semiconductor Gases and Equipment Worldwide.



Est. 1989

Eighth International Conference on Indium Phosphide and Related Materials

IPRM'96

April 21-25, 1996

Convention Center "Stadtgarten", Schwäbisch-Gmünd, Germany

Sponsors: Information Technology Society within VDE (ITG), IEEE Lasers and Electro-Optics Society (LEOS) and IEEE Electron Device Society (EDS).

Topics:

- **Bulk and Semi-insulating Materials** technical sessions will highlight advances in crystal growth technology, including semi-insulating substrates. Methods for in-situ and post growth defect and doping control. Wafer thermal stability and characteristics. New non-destructive characterization methods for bulk impurity identification, improvements in homogeneity and purity in doped and semi-insulating crystals.
- **EPITAXY** - sessions will deal with improvements in growth methods, the enrichment of crystal physics and selective growth as well as strained quantum well structures now being used in real devices, such as PICs and DFB lasers. Topics on low dimensional structures are also included where substantial improvements in quality will be reported by various techniques including self-organization.
- **Processing** - sessions include innovation in nanostructure fabrication for realization of quantum wires and boxes, in-situ processing and novel dry and wet etching methods for highly controlled selective processing, and fabrication techniques. Advances include progress in ohmic and Schottky contacts, passivation, reliability, thin film deposition, interface control and stabilization and functional hybrid integration.
- **Electron Devices** - papers show strong on-going improvements in HEMT and HBT performance as well as performance of JFETs and HFETs. Pseudomorphic and lattice matched devices are compared and sessions on HFETs, HEMTs and HBTs will review microwave low noise and high power performance. Further subjects include development of electronic integration techniques using HEMTs, HBTs and RTDs, quantum effect and mesoscopic devices.
- **Optoelectronics** - submissions highlight new levels of performance improvements in traditional edge-emitting and VCSEL lasers. Advances in optical modulators and amplifiers, waveguide based devices, quantum structures and photodetectors will be presented. Photonic and optoelectronic integration is widely applied to discrete devices such as lasers for application to WDM, enhanced optical coupling, high performance modulators/lasers and high speed receivers. Other topics in optoelectronics include solar cells, new device approaches such as inter-subband transition lasers and superlattice APDs. New devices for optical switching, networking and signal processing.
- **CHARACTERIZATION and CONTROL** sessions will focus on novel methods and new results on the characterization of materials (bulk and epi) and devices, in-situ control of growing layers and of processing steps with emphasis on quality control and reproducibility.
- **Industrial Exhibition:** IPRM'96 provides an opportunity for our internationally based industrial vendors to exhibit their latest technology in Germany. Limited space requires us to contract booths on a first come first serve basis. Contact one of the following individuals.
Post Deadline Papers: Authors should submit a two-page camera-ready abstract plus 10 copies to IPRM96 Program Chair Professor Klaus Heime, RWTH Aachen, Templergraben 55, D-52056 Aachen, Germany. **Papers must be received by March 19, 1996.**
Contacts: Conference Chair, Olaf Hildebrand, Alcatel, Stuttgart, Germany (F: +49 711 821 46355); Exhibition Chair, Holger Jürgensen, AIXTRON, Aachen, Germany (F: +49 241 890925); Publicity Chair, Joe Lorenzo, Rome Laboratory, Bedford MA, USA (F: 617-377-6765).

RF GaAs at the 1995 GaAs IC Symposium

RF GaAs Demonstrates a Wide Range of Applications from Personal Communications Through Millimeterwave

ROBERT A. METZGER

Digital GaAs results from the 1995 GaAs IC Symposium were covered in our previous issue. (See CS 2(1), p. 44.) In this issue we review the outstanding analog reports from that conference.

At times, it appears that RF has become synonymous with the frequency range of 900 MHz to 2.4 GHz - those bands allocated for personal communication systems. While it is undoubtedly true that GaAs-based ICs targeting that frequency range are now experiencing large market successes, and are generating sales that are expected to reach the \$1 billion level in the next few years, significant activity is also taking place at higher frequencies - those all the way up to the 100 GHz range, driven both by military applications, as well as by the potential for future commercial systems. This wide range of activity was in ample evidence at the 1995 GaAs IC Symposium, where as much attention was focused on the explosion in personal communications applications over the 900 MHz to 2.4 GHz range, as was devoted to higher frequency microwave and millimeterwave circuits and applications.

ICs for Personal Communications

In the personal communications bands from 900 MHz to 2.4 GHz, GaAs continues to take advantage of its unique material characteristics to produce low noise, high power, and high power added efficiency (PAE) products, particularly in the areas of low noise amplifiers (LNAs) and power amplifiers (PAs).

C.H. Kim and coworkers from ETRI [Taejon, Korea] reported on a front end receiver for CDMA/AMPS dual mode applications at 3.3 V operation. The receiver, which is fabricated with 1.0 μm all ion implanted MESFET technology, consists of an LNA with gain control, a cascode mixer with an LO buffer amplifier, and two IF amplifiers with a mode selection switch to operate in either the CDMA (digital) or AMPS (analog) mode. Operating in either the CDMA or AMPS mode, the receiver exhibits a gain of 33 dB and a noise figure of 2.8 dB.

Due to superior PAE characteristics, which directly result in longer battery lifetimes, GaAs has found one of its greatest successes in the personal communications market place in the area of power amplifiers (PAs). This was reflected at the symposium, with the details of several new GaAs-based PAs. N. Kasai and coworkers from Mitsubishi Electric [Hyogo, Japan] reported on a buried p-layer lightly doped drain self aligned gate FET (BPLDD SAGFET) for power amplification at 1.9 GHz, which exhibits a power density of 240 mW/mm and a power-added efficiency of 54% at 3.3 V operation - this being the highest reported power density for a SAGFET at this frequency. The Mitsubishi researchers believe that using a nonrecessed gate approach (SAGFET) leads to a higher level of reproducibility and manufacturability as compared

to the wet etching processes used during gate recess processing of MESFETs. The SAGFET exhibits an extremely high gate-to-drain breakdown voltage of -20 V and a transconductance of 210 mS/mm. At a 1.0 μm gate length and 1.2 mm gate-width, the FET exhibits an output power of 24.7 dBm (300 mW), making it suitable for low to moderate power Japanese PHS applications. Mitsubishi plans to use this technology in the formation of single chip transceiver (LNA, PA, Switch and up/down converter) for PHS applications.

Y. Hasegawa and coworkers from NEC [Kawasaki, Japan] reported on what they believe to be the first use of Heterojunction FETs (HJFETs) for commercial power amplifier applications over the frequency range of 0.9 and 1.5 GHz, which is suitable for Japanese digital phone applications. Grown by MBE, the HJFETs use a double doped AlGaAs/InGaAs structure. It has been felt by many manufacturers that MBE grown heterostructure-based devices can not compete on a cost basis with ion implanted MESFETs, but NEC has found that due to the HJFETs superior power generating abilities, that HJFET-based devices can be fabricated with significantly smaller chips, thereby yielding more chips per wafer and therefore reducing the cost per chip. A 2-stage PA was fabricated and encapsulated in a package of 14.2 x 11.2 x 2.4 mm³ - half the volume of what is normally required for MESFET-based multichip ICs performing the same function. Power added efficiency of the PA is 45%, and an adjacent channel interference level of -50 dBc at an output power of 31.2 dBm (1.33 W) was demonstrated for 3.4 V operation in the frequency range of 0.9 GHz to 1.5 GHz.

Preparing to meet the needs for the new North American PCS band at 1.8 to 1.9 GHz, P. Walters and coworkers at Rockwell International [Newbury Park, CA] have fabricated a dual RF input high linearity power amplifier for TDMA/CDMA applications for operation from 1.85 to 1.91 GHz. Using Rockwell's power HBT process which utilizes 4 inch GaAs and MOCVD epitaxial layers, an HBT with an emitter area of 1792 μm^2 was shown to be capable of 2W output power at 70% efficiency. Due to the HBTs high power density capabilities, the device is approximately 80 to 90% smaller than a MESFET delivering the same power. In digital operation, adjacent channel power rejection is better than 30 dBc at a power level of 800 mW and gain of 22 dB. Packaged in relatively inexpensive plastic SSOP-16 packages, the maximum output power of the PA is 2W with a PAE of 40%.

23rd International Symposium on Compound Semiconductors St. Petersburg, Russia

September 23-27, 1996

ISCS-23

Successor to the International Symposium on GaAs and Related Compounds

ISCS-23

Organized by the Ioffe Physico-Technical Institute
and the St. Petersburg Scientific Center of the Russian Academy of Sciences

First Announcement and Call for Papers

The 23rd International Symposium on Compound Semiconductors (ISCS-23) will be held in St. Petersburg, Russia - a city which has a long history of excellence in sciences and, specifically, in physics of semiconductors. This Symposium continues a series started in 1966. The first 20 events bore another name, the Symposium on GaAs and Related Compounds. The present name reflects the emergence of many other compound semiconductors as vital materials for modern electronic and optoelectronic devices. ISCS-23 will be held on September 23-27, 1996 at the Astoria Hotel where the majority of participants will be accommodated. The Hotel is located in the downtown, near St. Isaac's Cathedral and Mariinskii Palace. The opening session is scheduled to be held in the building of the Russian Academy of Sciences, founded in St. Petersburg in the mid-18th century.

Scope and Format

In the spirit of the preceding meetings, the Symposium is to be a forum for papers on all aspects of compound semiconductors, including growth, processing, devices, and ICs. The main materials are III-V compounds, SiC and wide band gap II-VI compounds such as ZnSe, ZnS, etc. Specific areas will include, but not be limited to:

1. Nanoelectronics and Nanophotonics
2. Epitaxy and in-situ Processing
3. Visible Emitters
4. Heterostructure Photocells
5. Heterostructure Transistors
6. OEICs
7. High Power, High Temperature Devices
8. Simulation and Modeling
9. Quantum Effects
10. Quantum Dots
11. Characterization

The Symposium program will be comprised of invited and contributed papers. The contributed papers will be refereed by the members of the Program Committee on the basis of submitted abstracts. The authors will be given 30-40 and 20 minutes for oral presentations of invited and contributed papers, respectively. A part of contributed papers will be presented in poster sessions. The list of invited speakers will be announced in due time.

Submission of Contributions

Authors are requested to submit their contributions by April 30, 1996. The papers should be submitted in both forms listed below. The forms should include: title, authors' names (capitalize the name of a principal author who will present the paper), authors' affiliations, body text, and the number(s) of related area(s) (listed above in "Scope and Format") in priority order.

Extended Abstract Form

The Extended Abstract may consist of one-page text and, if necessary, one optional page with up to 4 figures, and should be submitted on paper (6 copies). It should be clear on the originality and the relevancy to the scope of the Symposium. The Extended Abstract will be only a subject for consideration of the Program Committee and will not be published.

Short Summary Form

The Short Summary (text only, no more than 100 words) should be submitted both on paper (6 copies) and electronically as an ASCII file. Electronic files may be sent to the Secretary of the Organizing Committee by e-mail (Subject: ISCS-23, <name of the principal author >) or on IBM PC compatible disk. The first way is preferable. The Short Summary will be published in the program booklet prior to the Symposium.

The decision of the Program Committee will be notified to the principal author by early June 1996. A limited number of papers reporting very recent results of special importance will be accepted as Late News Papers. The abstract may be submitted before June 30, 1996. The acceptance of papers will be notified prior to the Symposium.

Submissions should be sent to:

Secretary of the Organizing Committee

Dr. V. Grigor'yants
Ioffe Institute
26 Polytechnicheskaya
St Petersburg, 194021, Russia
Phone: [7] (812) 247 6805
Fax: [7] (812) 247 2135 or 247 1017
E-mail: vgrig@eo.ioffe.rssi.ru
Telex: 121453 FTIAN SU

As in the past, the Proceedings of the Symposium will be published as part of the long-standing series of these meetings. For accepted papers, authors will be asked to submit the manuscripts to facilitate refereeing. The format and instructions will be forwarded at the time of acceptance notification.

For More Information

Anyone requiring more information about ISCS-23 is encouraged to visit our WWW site at <http://www.ioffe.rssi.ru/ISCS-23/> or contact one of the following:

Secretary of the Organizaing Committee:

Dr. V. Grigor'yants
Ioffe Institute
26 Polytechnicheskaya
St Petersburg, 194021, Russia
Phone: [7] (812) 247 6805
Fax: [7] (812) 247 2135, 247 1017
E-mail: vgrig@eo.ioffe.rssi.ru
Telex: 121453 FTIAN SU

US Co-Secretary of the Organizaing Committee:

Prof. M. Shur
University of Virginia
Department of Electrical Engineering
Charlottesville, VA 22903-2443
USA
Phone: [1] 804 924 6109
Fax: [1] 804 924 8818
E-mail: shur@virginia.edu

Exhibits

The Symposium will again feature a table top exhibition. This is an opportunity for companies to display their latest products, technologies, and services. If interested in exhibiting, please contact:

Member of the Organizing Committee responsible for exhibition
Dr. M. Mizerov, Scientific & Engineering Center for Microelectronics
26 Polytechnicheskaya, St Petersburg, 194021, Russia
Phone: [7] (812) 2474059
Fax: [7] (812) 247 8640
E-mail: mizerov@mec.pti.spb.su

Millimeterwave

Millimeterwave (> 30 GHz) operation is seeing more and more demand in a wide range of applications, including phased array radars, satellite communications, smart munitions, collision avoidance systems, indoor WLAN and radiometry. For these applications to be realized, improvements in performance, as well as increased levels of integration will be required. In this frequency range, the question is no longer one of silicon versus GaAs, but more often as to which GaAs-based device best serves a given application, or in some circumstances, one of GaAs vs InP.

Due to what many consider superior noise performance, the PHEMT, whether GaAs- or InP-based, is typically the device of choice for LNA applications at millimeterwave frequencies. However, M. Feng and coworkers from University of Illinois [Urbana IL] and Raytheon Company [Andover, MA] report on using an ion implanted MESFET process for the fabrication of a five stage LNA at 27-34 GHz operation. Using Raytheon's 0.25 μm T-gate MESFET production process, transistors were fabricated which exhibited peak transconductances of 280 mS/mm with f_t values of 60 GHz. The best fixtured noise performance obtained for the LNA was 2.3 dB with 31.4 dB gain at 33 GHz operation. This noise figure is comparable to those obtained by PHEMTs at this frequency range, and does not require the epitaxial growth required for PHEMTs. At a somewhat higher frequency of 43 GHz, is work reported by T. Kashiwa and coworkers from Mitsubishi Electric [Hyogo, Japan] on using a dual-gate PHEMT with 0.15 μm gate lengths in the fabrication of a low noise variable gain amplifier. The amplifier exhibits a minimum noise figure of 1.8 dB, an associated gain of 22 dB, and a gain control range of 30 dB. This performance is comparable to the best reported PHEMT performance at this frequency using either GaAs or InP.

Using a PHEMT structure, in which the AlGaAs Schottky layer has been replaced with GaInP, T. Saito and coworkers at Fujitsu [Kawasaki, Japan] reported on the performance of a 60-GHz image rejection downconverter. A GaInP/InGaAs heterostructure grown by MOCVD is used in this structure, which results in a thinner electron supply layer and better carrier confinement than is possible with AlGaAs/InGaAs, and therefore should produce a higher gain and lower noise device. The downconverter consists of a four-stage low noise amplifier and a single-balanced active-drain mixer utilizing 0.1 μm gates. The circuit exhibits a maximum conversion gain of 22.9 dB at 61 GHz and a minimum noise figure of

3.16 dB at 58.5 GHz for a 5 dBm LO power input and a 140 MHz IF output. These are the best results to date of circuit of this type at 60 GHz.

Operating at even higher frequencies, M. Camiade and coworkers at Thomson CSF [Orsay, France] reported on a W-Band front end receiver for radiometry applications, which includes a three stage LNA, a sub-harmonically pumped mixer, and a LO amplifier. The receiver is fabricated using two commercially available HEMT processes in which the LNA uses 0.15 μm PHEMTs, and the IF amplifier uses 0.2 μm HEMTs. The receiver exhibits more than 20 dB conversion gain and less than 6.5 dB noise figure for RF operation at 93.5 GHz and IF operation over 100 to 600 MHz. Also reporting on circuits at W-Band are researchers at TRW [Redondo Beach, CA]. E.W. Lin and coworkers used InP-based HBTs to fabricate a 94 GHz Schottky-diode singly-balanced mixer chip. InP-based materials were used to take advantage of its superior electronic transport properties which result in higher f_t and f_{max} values. Using a self aligned 1.0 μm InAlAs/InGaAs HBT process, and an IF of 1 MHz, the InP-based HBT diode mixer achieved a noise figure of 16 dB, which is an improvement of 17 dB over a GaAs HEMT diode mixer using the same process. This improvement in noise performance is attributed to the lower $1/f$ noise of the InP HBT vertical-diode compared to the GaAs PHEMT planar diode.

Power

GaAs-based power amplifiers, whether MESFET-, PHEMT-, or HBT-based have been a major insertion point for GaAs technology into wireless applications over the commercial bands from 900 MHz to 2.4 GHz, offering low voltage, high PAE operation and competing head to head for market share with Si-based bipolar, CMOS and BiCMOS. However, at higher frequencies, where Si substrate losses make Si-based power amplifiers impractical, GaAs approaches dominate, and the competition is no longer between material types, but between which device structure (often PHEMT versus MESFET) best meets an applications needs. Output power from these devices is proportional to the product of the maximum drain current, I_{max} and the breakdown voltage. Traditionally, PHEMTs have exhibited higher I_{max} values due to high channel carrier densities because of the use of heterostructures, while MESFETs have exhibited high breakdown voltages.

P. White and coworkers at Raytheon Company [Andover, MA], fabricated a two

stage amplifier for operation over 4.3-5.1 GHz (C-band) utilizing a fully monolithic PHEMT approach. The two stage amplifier was fabricated using a 0.25 μm T-gate production process, which exhibits gate to drain breakdowns of 13 to 14 V, transconductances of 375 mS/mm, I_{max} of 550 mA/mm, and a PAE in excess of 75% at 5 GHz for tuned discrete devices. With a total gate periphery of 8.2 mm, the amplifier produced 9.3 W of power at a PAE of 59% for operation at 4.7 GHz and 7 V operation. Also reporting on PHEMT power were Y.C. Chen and coworkers at Hughes Aircraft Company [Torrance, CA]. Using a 0.25 μm PHEMT process which utilized planar doping above and below the channel, and a double recess etch process, they were able to obtain breakdown voltages in excess of 20 V. It is believed that this high breakdown voltage was the result of the reduction in total delta doping by 15% (improved breakdown voltage by 5 V), and by decreasing the cap doping by a factor of 2.5 (improved breakdown voltage by an additional 4 V). The fabricated 2-stage amplifier produced 6.7 W of power at a PAE of 40% for 8.5 GHz operation. Lastly, J.M. Schellenberg of Schellenberg Associates [Huntington Beach, CA] used TRW's power PHEMT foundry process which utilizes double delta doped structures with 22% In in the channel and 0.2 μm gate lengths in the fabrication of a power PHEMT for 32 to 34.5 GHz operation. The TRW process results in an I_{max} of 600 mA/mm and a transconductance of 527 mS/mm, with a gate to drain breakdown of 9.5 V. A novel bias scheme is used, in which a two-stage PHEMT amplifier is biased in series (normally biased in parallel), so that higher bias voltages can be used with a correspondingly lower bias current. When biased at 20 V, the power amplifier produced .66 W output power, at a PAE of 41.1% - some 10-15% higher than the best PAEs at this power level and frequency.

Demonstrating that not all new work on power devices is taking place with PHEMTs, S. Arai and coworkers at Toshiba [Kawasaki, Japan] used a heterojunction MESFET structure for power generation, feeling that although the PHEMT is superior in high gain and operating frequency, that it is inferior to the FET in breakdown characteristics, and therefore reliability. The Heterojunction MESFET (H-FET) process utilizes MBE grown AlGaAs Schottky layers and GaAs channels, a double recess etch, and 0.3 μm gate lengths. The resulting H-FETs performance at 42 GHz consisted of 1 W output power at a 30.1% PAE. Using accelerated lifetesting over a temperature range of 175 to 250°C, lifetimes in excess of 10^6 hours were estimated.

What's new in the "other" semiconductor materials, like silicon? From time to time we take a look. This time we focus on two major mainly-silicon conferences held the past few months.

Silicon Devices and ICs with GaAs-like Performance Reported

ROBERT A. METZGER

The 1995 International Electron Device Meeting (IEDM, Washington DC, Dec. 10-13, 1995) offered the silicon industry an opportunity to present their latest speed records. Several examples of Si bipolars were presented which demonstrated both f_t and f_{max} values in excess of 50 GHz - making these devices comparable to the best SiGe HBTs reported to date, as well as being competitive with GaAs-based MESFETs and HBTs. M. Ugajin and coworkers at NTT LSI Laboratories [Kanagawa, Japan] presented the results of their Ultra-high-performance Super Self-aligned process Technology (USST). The base-poly contact region used in this approach is formed by a newly developed self aligned process, which results in a reduction of base resistance, R_B , by 40%, as well as a reduction in the base-collector capacitance, C_{JC} , by 50%. As a result, f_{max} becomes about twice as large as it had been for NTT's previous super self aligned technology. At a V_{CE} of 2.5 V, the f_t and f_{max} are 50 and 70 GHz, respectively, while at a V_{CE} of 1 V, the f_t and f_{max} are 44 and 55 GHz, respectively. Using these transistors, a minimum ECL gate delay of 16.5 ps was obtained. Takahiro Onai and coworkers of Hitachi [Tokyo, Japan], also reported on reducing both base resistance and base-collector capacitance in order to improve the RF performance of their Si bipolars. In their process, base electrodes are made using a self-aligned metal/*in-situ* doped poly Si technology, to produce a low resistance base region, as well as producing a link base which is shallower than the intrinsic base, thereby providing smaller collector capacitance without using a selectively implanted collector. At a V_{CE} of 2.0 V, the f_t and f_{max} are 60 and 50 GHz, respectively. Using these transistors, a minimum ECL gate delay of 16.2 ps was obtained, while a delay time of 14.3 ps was obtained in a differential ECL ring oscillator. Even Si-CMOS, a much

poorer RF performance technology than Si-bipolar, is making significant RF improvements. S.P. Voinigescu and coworkers at Bell-Northern Research [Ottawa, Ontario, Canada] reported on a 0.5 μm bulk CMOS process, in which a salicided n-MOSFET exhibited a transconductance of 160 mS/mm, f_t of 20 GHz and a record f_{max} of 37 GHz, making these devices potentially competitive for wireless applications over the 900-2400 MHz region.

An intrinsic advantage that GaAs MMICs have over Si is a semi-insulating substrate, which allows for the fabrication of high Q inductors (where Q is a measure of the ratio between the energy stored to energy dissipated in the inductor). In the case of a Si substrate, which is much more conductive (there is no equivalent semi-insulating Si substrate), Q's are degraded due to losses in the substrate. Because of this, inductors for Si MMICs often must be placed off chip. GaAs-based MMICs with on-chip inductors can achieve higher packing density, lower parasitics (no contacting to and from an off chip component), and higher reliability. However, progress is being made on improving Q's in Si-based MMICs. Joachim N. Burghartz and coworkers at IBM T.J. Watson Research Center [Yorktown Heights, NY], reported on Q's of up to 24 for inductors fabricated on silicon substrates, the highest values yet reported by using standard silicon technology with multi-level interconnects. By using a 5 level interconnect process, and oxide-based insulation between layers, a three turn inductor was fabricated which exhibited an inductance of 1.45 nH, a Q of 24, and a self resonance frequency of greater than 20 GHz. Using this technology, a fully integrated power amplifier was fabricated with an input matching section using a 0.8 μm BiCMOS process. The input matching section used a 5.1 nH 6 turn inductor with a Q of 11.5, while the bipolar transistors exhibited an f_t and f_{max} of 12

and 14 GHz, respectively. The resulting power amplifier, designed to operate at 675 MHz, exhibited a maximum power gain of 18.5 dB, output power of 24 dBm (250 mW), and a PAE of 52%.

ISSCC

While the IEDM focuses on device performance, the International Solid-State Circuits Conference (ISSCC, San Francisco, CA, Feb. 8-10, 1996) is the traditional showcase where the best circuit performance is presented. In the areas of wireless and telecommunications, new silicon-based circuits were presented which displayed performance that had previously been demonstrated only by GaAs-based circuits.

VCOs

Voltage controlled oscillators (VCOs) are critical elements for both wireless and telecommunications applications, used for clock generation, data rate calibration and mixing. M. Soyuer, and coworkers from IBM [Yorktown Heights, NY], who reported on improved Q's in inductors at the IEDM [see above], reported at the ISSCC on fully monolithic VCOs, required for up and down converters in receivers. Implemented in IBM's 5-level metal 0.5 μm BiCMOS process, and utilizing only NMOS transistors (f_t of 12 GHz), the VCOs are designed to operate at 4 GHz with a 3 V supply. MIM capacitors with a Q of 30, and inductors with a Q of 8 are fabricated on 10-12 ohm-cm Si substrates. The resulting VCO exhibits a 9% tuning range with an on-chip varactor-tuned resonator over a control voltage range of 0 to 3 V. An oscillator phase noise of -85 dBc/Hz is achieved at a 100 kHz offset. Low phase noise is critical in the performance of a VCO being used as a local oscillator (LO) for mixing applications, since phase noise appears

as additive noise in the received signal, while in the transmitter, it produces spurious sidebands on the output signal which may overwhelm other weak signals situated nearby in frequency. At even higher frequencies, Larry Larson and coworkers from the Hughes Research Laboratories [Malibu, CA], and IBM [Yorktown Heights, NY], using high speed SiGe with f_i and f_{max} values in excess of 40 GHz, have produced VCOs at 7.52 GHz and 12 GHz, with phase noise of -103 dBc/Hz, and -80 dBc/Hz at 100 kHz offsets, respectively, values which are comparable to GaAs-based VCOs. In the commercial wireless range, at frequencies of 900 MHz, A. Rofougaran and coworkers at UCLA [Los Angeles, CA] have fabricated a 900 MHz CMOS LC-Oscillator with Quadrature Outputs using 1.0 μ m CMOS. Using a novel process, the Si under the inductors is selectively removed by gaseous etching, thereby eliminating much of the parasitic capacitance, and extending the inductor self-resonance to several GHz. Run from a 3 V power supply, a phase noise of -96 dBc/Hz at an offset of 100 kHz is obtained. A. Ali and coworkers at Rockwell International [Newport Beach, CA] also report on a VCO operating at 900 MHz, which uses a 25 GHz f_i bipolar process, operates over 2.7 to 5V, and exhibits a phase noise of 101 dBc/Hz at a 100 kHz offset.

Wireless

Two of the key elements in any wireless system are the LNA and mixer. A. Karanicolas and coworkers from AT&T Bell Laboratories [Holmdel, NJ] presented a CMOS LNA and mixer for 900 MHz applications, operating at 2.7 V. Using a 0.5 μ m CMOS process, the LNA exhibits a minimum noise figure of 1.9 dB and gain of 15.6 dB, and the mixer (using a LO of 1 GHz) shows a minimum noise figure of 5.8 dB. The LNA dissipates 20 mW, and the mixer 7 mW. GaAs MESFETs certainly offer lower noise and better gain at 900 MHz than these devices, but for many 900 MHz applications, better gain and noise are not needed. As a result, the important comparison is not that of performance, but price, which is a great challenge for GaAs MESFETs competing with Si CMOS. GPS receivers operating at the civilian L1 band (1.575 GHz) represent a potentially interesting commercial area. F. Piazza and coworkers from Swiss Federal Institute of Technology [Zurich, Switzerland] reported on a GPS 1.6 GHz front end receiver fabricated in a 13 GHz f_i BiCMOS process. The receiver which shows a gain of 22 dB, consumes only 12 mA at 3 V - which is a decrease by a factor of 10 from commercially available receivers, and will result in a major savings of battery power.

Telecommunications

As the market continues to grow for high data rate telecommunications (622 Mb/s and beyond), so does the circuit technology competition. J. Hauenschild and coworkers at Philips Kommunikations Industrie [Nurnberg, Germany] reported on a chip that uses Philips Semiconductor's QUBIC2 BiCMOS process to perform demultiplexing and clock and data recovery (CDR) functions at data rates of 2.5 to 10 Gb/s. The QUBIC2 process uses 24 GHz f_i npns and 0.7 μ m gate length CMOS (the initial results reported here were for npns with an f_i of 16 GHz). A 1:4 DEMUX was fabricated which consisted of a 1:2 DMUX including a divider, and a 2:4 DMUX, plus another divider driving output stages at 2.5 Gb/s and 1.25 GHz. The upper frequency limit for the divider function was measured to be 6.5 GHz for 11 dBm input power. The circuit dissipates 450 mW from a 3.6 V supply. O. Kromat and coworkers at Ruhr Universitat [Bochum, Germany] reported a silicon bipolar circuit that generates all functions required for the PRBS (Pseudo Random Binary Sequence) testing to be used as a telecommunications circuit diagnostic. This chip, fabricated in Hewlett Packard's 25 GHz f_i silicon bipolar production process, incorporates two 4:1 multiplexers generating two PRBS's up to 10 Gb/s. Operating at 5 V and dissipating 6.2 W, this circuit can handle a maximum data rate of 11.5 Gb/s.

Your Best Source for PBN—Worldwide



Advanced Ceramics developed Boralloy® and is the original patent holder and innovator of PBN products for MBE. No other company can match our experience, production capacity and customer service.

Our technical expertise and commitment to product development have resulted in several industry innovations which have increased crucible life and MBE yields:

- double-walled crucibles that improve aluminum deposition
- "hot lipped" crucibles that reduce defects during gallium deposition
- Boralectric® heaters that improve thermal uniformity and provide increased durability
- custom surface textures

**ISO9002
CERTIFIED**

Most of the world's leading companies involved in MBE and crystal growth rely on Advanced Ceramics Corp. Find out how Boralloy PBN products can improve your operation.

Advanced Ceramics
CORPORATION

11907 Madison Ave.
Cleveland, OH 44107 USA
Tel: 800-822-4322 or
216-529-3900
Fax: 216-529-3975

See ACC on the Internet: <http://www.advceramics.com>

The Portfolio Stumbles Out of the Gate, Draws Even at the Post

MARIE MEYER

The winter of 1996 proved that technology stocks are no place for the faint-hearted investor. Technology was *the* hot sector on Wall Street last fall. But, inevitably, the need for price corrections arose, and they came with a vengeance in early January, with a particularly big sell-off of semiconductor stocks in the first two weeks of the year.

The seven stocks in the Compound Semiconductor Portfolio were also generally lower in January, but strong performance by SDL and Vitesse in February returned the group's value back to its starting point by the end of February. See Table One. Although the Portfolio failed to register any significant gain, it did keep pace with the rate of change in the NASDAQ composite, and it outperformed the semiconductor sector index.

Concerns about over-supply in the silicon industry and price erosion in the memory markets prevented a rally in mainstream semiconductor stocks. In contrast, case-by-case performance results appear to have been more significant than large-scale trends for the stocks in our portfolio. However, some spill-over effect from the silicon industry is to be expected.

Case-by-Case

Shares in **SDL** posted a gain of 22% in the first two months of 1996 on the strength of good sales and margin figures, and its very healthy backlog. **ATMI** was largely neutral for the period, as was **Cree Research**, although the latter experienced a bit of a rollercoaster ride along the way. Despite the fact that it is more consistently profitable now than it has been in the past, Cree cannot shake the appearance of instability in its SiC/GaN manufacturing process. In addition, although the company did post 4th quarter profits of \$822,000, revenues for the quarter included recognition of a one-time licensee fee of \$1,423,000 from Siemens (see CS 2(1), p. 14).

The four GaAs manufacturers in our portfolio turned in mixed results. Shares in **Alpha Industries** were down 31% on the basis of a cautionary forecast from management. The company predicts a slowing of growth over the next 1-2 quarters because of capacity problems in its ceramics business; activity in the GaAs MMIC business appears to be good, but not spectacular. Also down was **Anadigics**, which is performing well but still struggling to regain the share price levels it enjoyed in 1995 (>\$30 in September). It finished the period down a surprising 15%, perhaps because the company has suggested it will post lower gross margins in the short term due to price competition and new product launches. Investors may also be signaling concerns about a slowdown in cellular equipment. Weakness in the Japanese PHP market and production problems were blamed for the period's most surprising result: despite a 75% increase in revenues, **TriQuint Semiconductor** missed its fourth quarter profit projection by 75%. But the company weathered the fallout - including a downgrade by a few analysts - and managed to end February at almost the same price as the first of the year.

The brightest spot so far in 1996 has been **Vitesse Semiconductor**, which set records for revenue and profit in the 4th quarter. Perhaps even better yet, they received a huge endorsement: *Smart Money*, a widely-read investment magazine, picked them as one of the ten best American stocks under \$20. The editors seemed to like Vitesse's claim to a 60% share of the market for digital GaAs (no need to worry about a silicon glut or cellular phone weakness here), as well as analysts' predictions of a 200% earnings growth. Shares in Vitesse rose to the \$25 level shortly after the story was published; they ended the period just below \$20, up 48% from the first of the year.

Briefly

Throughout the next several issues we will provide a brief profile of each of the seven companies in our Portfolio. In this issue we take a look at Alpha Industries and ATMI. We also provide some of the highlights from the quarterly earnings reports for our other five selections.

Alpha Industries

The end of the Cold War signaled the need for change at Alpha Industries, away from the defense-related electronics which produced approximately 75% of the company's revenues. Consumer-driven wireless communications offered an opportunity for the company to reinvent itself, and today less than 25% of their business is defense-related. Although the transition period was painful at times, the company has pulled through in good shape, with 1995 sales of \$93.3 million and net income of \$4.4 million, or \$0.53 cents per share.

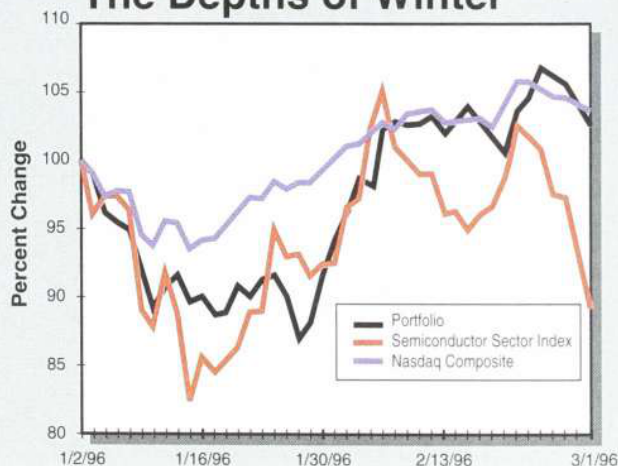
Alpha is divided into the Microwave Group [Woburn, MA] and Trans-Tech, Inc. [Adamstown, MD], a subsidiary which manufactures ceramics

The Compound Semiconductor Portfolio

Company	Symbol*	1/2/96	3/1/96	Change
Alpha Industries	AHA	13.625	9.375	-4.25
Anadigics, Inc.	ANAD	21.25	18.0	-3.250
Advanced Technology Materials	ATMI	10.375	10.0	-.375
Cree Research	CREE	14.75	15.125	+0.375
SDL Inc.	SDLI	25.375	31.0	+5.625
TriQuint Semiconductor	TQNT	14.25	13.625	-.625
Vitesse Semiconductor	VTSS	13.125	19.375	+6.25

Portfolio Value, 3/1/96 (100 shares of each) \$11,650
Change since 1/2/96 +3%

The Depths of Winter



used in handsets and transmission systems. The Microwave Group offers both Si and GaAs semiconductor products. A full range of discrete devices for microwave systems are offered, as well as MMICs for frequencies ranging from 900 MHz up to 94 GHz. The semiconductor business accounts for around two-thirds of the company's revenues. Further segmentation according to material type is not available. However, Alpha's Vice President and CFO, David Aldrich, confirms that they are committed to GaAs as the cornerstone of their strategic planning. "We believe that both our Si and GaAs businesses will grow, but our GaAs business will grow more rapidly, because GaAs is going to continue to displace Si in microwave and millimeterwave communications." The company pursues both the transmission system and handset markets.

Alpha's most recent earnings reports revealed some operational problems (see previous page), but the company has shown growth in orders, sales and earnings. For example, nine-month results for sales and income are up 27% and 78% respectively, and the company reports that sales of GaAs MMICs to the top four wireless OEMs (AT&T, Ericson, Motorola, Nokia) are up 75% over last year. M.J. Reid, Alpha's President and CEO, reports that a recent secondary stock offering has left the company "virtually debt-free", with sufficient cash to fund future growth. The current period of readjustment will mean slow growth for the next quarters and will certainly depress share prices. However, it also looks like the company will be well positioned to take advantage of the future opportunities that the wireless market may create.

ATMI

ATMI [Danbury, CT] is unique among the companies in our portfolio because it is not primarily a semiconductor company - its main focus is on semiconductor materials and processing equipment. Both ATMI and Alpha share another unique characteristic which sets them apart: both have a significant level of activities which are not related to compound semiconductors. In the case of ATMI, these "other" activities constitute the majority of the company's business. The Diamond Electronics Division, which includes a large number of wide bandgap materials technologies, at present accounts for less than 15% of ATMI's revenues. (The rest comes from the EcoSys and NovaMos divisions, which supply gases, environmental equipment, and delivery systems to the silicon semiconductor and flat panel display industries.) Nevertheless, ATMI is included in the portfolio because the company's long term strategic plan is to build the Diamond Electronics business into a position of prominence.

Despite its name, the Diamond Electronics Division actually focuses only one-fourth to one-third of its efforts on diamond-related activities. The remainder comes from what is termed "wafer products". These include SiC wafers and GaN on SiC epi wafers; conventional III-V epiwafers (arsenides and phosphides) which are produced by the recently acquired Epitronics operation (see CS 2(1), p. 12), as well as distribution agreements involving SOI and SIMOX produced by Nippon Steel, and GaAs and InP wafers produced by MCP. According to Tim Murray, Director of Marketing for Wafer

Products, the common threads uniting all these items are a bandgap which is "wider than silicon", and common end-users, i.e. companies or R&D groups who are researching alternatives to conventional silicon. ATMI plans to capitalize on these similarities and become a "one-stop-shop" for materials for advanced semiconductors. ATMI's near-term future is determined largely by the other divisions; however, the Diamond Electronics Division may in time provide the company with a unique position in advanced semiconductor field.

The Others, In Their Own Words

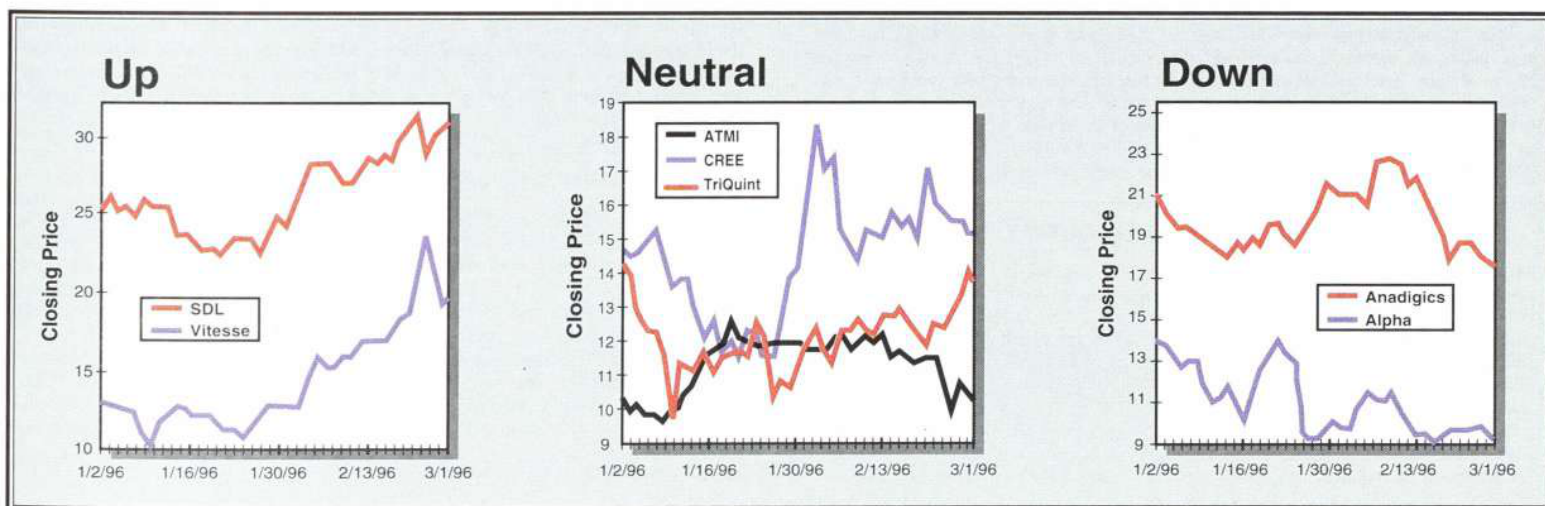
Anadigics: Net sales for 1995 were \$51.5 million, up 48% over 1994. Sales to the DBS market were down, but a very large increase was recorded for sales of cellular ICs (\$15.1M vs. \$1.6M for 1994). Fiberoptic ICs were up 55%; CATV ICs were up 33%.

Cree: A direct quote from their quarterly report: "The Company is striving to significantly increase its production of blue LED chips over the coming quarters but is currently addressing repeatability issues in the manufacturing process that continue to limit production...[Neal Hunter, President and CEO, stated] We believe that we will manufacture over 1.5 million superbright chips during the current quarter and six million chips in the [subsequent] quarter. The certainty with which we meet these targets depends on our ability to decrease the volatility of our epitaxial process." On a more positive note, Mr. Hunter also stated that Cree would likely make an announcement regarding "the first significant microwave device in SiC" sometime in March.

SDL: Revenues for 1995 were \$53.9 million, up 63% over 1994. 4th quarter results included a one-time write-off of in-process R&D related to the acquisition of Seastar Optics (see CS 2(1), p. 12). Without that write-off, *pro forma* net income for the year was \$5.7 million, more than double 1994 results.

TriQuint: A direct quote from a company press release: "During the fourth quarter, TriQuint ran into manufacturing yield problems, equipment problems, and vendor problems all contributing to an inability to meet demand for our products as well as causing us to scrap a large number of wafers, and finished parts." The company reports that many of the problems have been uncovered and fixed and yields are improving, but are not yet at record highs. They also report that "TriQuint has been shipping to PCSI (Cirrus Logic) chips to be used in the Personal Handy Phone in Japan. The phones have not sold as our customers expected and significant inventory is building in the channel of manufacturing and distribution...we have chosen to take a more conservative view and take the Personal Handy Phone out of our booking plans for the remainder of 1996."

Vitesse: Revenue for the quarter equaled \$14 million, up 44% over the same period last year. Income was \$1.8 million, or 10 cents a share, compared to \$562,000, or 4 cents a share, in the same period in 1994. Bookings for the quarter were a record \$16.9 million on the strength of the communications and test equipment markets. The company also reported improved production revenue, gross margins, and cash on hand.



Compound Semiconductor
is now accepting ads
from organizations and individuals
regarding employment opportunities.

Rates & Specifications for Standard Ads. Standard ads with minimum formatting (as shown below) are available at \$25.00 per line or fraction thereof (88 characters per line), with a \$100.00 minimum. To submit your ad by mail send the ad copy as a text-only file (<filename>.txt) on a 3.5" DOS formatted diskette to: CS Employment, Franklin Publishing, 250 Selby Avenue, Suite 48, Saint Paul, MN 55102 USA. You may also submit your ad copy by E mail by sending it as an plain text file (no encoding) to: jobs@compsem.com.

Orders & Deadline. Check or purchase order must accompany order/ad copy. No agency discounts. *Compound Semiconductor* is published bi-monthly. Orders and copy are due on the 15th day of the month which precedes the cover date.

Display Ads

Black and white display ads are available for companies wishing to use their own formatting style. Sizes and rates are given below. Send camera-ready art to: CS Employment, Franklin Publishing, 250 Selby Avenue, Suite 48, Saint Paul, MN 55102 USA.

Size	Dimensions	Rate
1/4 page	5"H x 3 3/8"W	\$1,350
1/2 page	5"H x 8 3/8"W	\$2,600
1 page	10 7/8"H x 8 3/8"W	\$3,350

Orders & Deadline. Check or purchase order must accompany ad. No agency discounts. *Compound Semiconductor* is published bi-monthly. Orders and copy are due on the 15th day of the month which precedes the cover date. For example: ads for our July/August issue are due on June 15. The magazine is normally mailed in the third week of the first month of the cover date.

Engineering Positions at Vitesse Semiconductor

Vitesse Semiconductor Corporation is the world's leader in the design, development, manufacture and marketing of digital GaAs integrated circuits. Our ICs are used in a wide variety of products in the high performance communications, test and instrumentation, computing and defense markets. We offer a unique group culture based on individual voices in a success-driven environment. Our company president, an engineer himself, takes a personal interest in individual achievements as well as group accomplishments. Our career opportunities include: **Design and Test Engineers** - BSEE/MSEE, C++, 2-5 years experience in VLSI, ATE timing circuit design; **Product Engineers** - BSEE/MSEE, 3 years experience, VLSI fabrication techniques, materials and equipment. Qualified candidates mail/fax your resume to Vitesse Semiconductor Corporation, Human Resources, Department CS296, 741 Calle Plano, Camarillo, CA 93012. FAX: (805) 389-7188. EOE M/F/D/V.

Rockwell: III-V Circuit Design and Processing

The Science Center, Rockwell's corporate research and development laboratory in beautiful Thousand Oaks, CA has **multiple openings for talented circuit design and processing professionals in GaAs, InP and GaN related areas.** We are advancing high frequency semiconductor and packaging technologies for mixed signal device/circuit applications which will produce greater performance at reduced cost. Join us in one of the best working environments available. Experienced candidates with a PhD or MS should forward resumes via fax: (805) 373-4797; e-mail: resumes@scimail.risc.rockwell.com or mail: Professional Staffing EDL, Rockwell Science Center, PO Box 1085, Thousand Oaks, CA 91358. Equal Opportunity Employer: - M/F/H/V.

Technical Positions at SDL

SDL is the world's leading manufacturer of high power semiconductor lasers. We offer a professional yet casual working atmosphere with many opportunities for creative technical contributions. SDL's products are used in communications, data storage, medicine, printing, science and materials processing. SDL has opportunities for technical contributions in many areas including: **advanced materials development (such as GaN), semiconductor laser device design, semiconductor laser manufacturing, opto-electronic packaging and system development.** SDL offers competitive salaries and an excellent benefits package including employee stock options, 401(k) and stock purchase plan. Please send your resume to: SDL, Inc., Human Resources, 80 Rose Orchard Way, San Jose, CA 95134, FAX to (408) 943-9389 or e-mail to HRSDDL@aol.com. In your resume please refer to listing #CS-100.

Scientists and Engineers at TRW

TRW has openings for scientists and engineers with education and experience in heterojunction materials and devices. Specific positions include: **senior materials engineer** - PhD EE, Physics, or Materials Science with 5 years experience in MBE growth and characterization of compound semiconductor material; **entry level materials engineer** - BS or MS EE, Physics, or Materials Science with interest in compound semiconductor materials; **heterojunction device engineers** - MS or PhD EE or Physics. Research & development positions and MMIC production positions available for engineers with experience in HEMT or HBT devices, processing, and test. Contact Dwight Streit, TRW D1-1302, One Space Park, Redondo Beach, CA 90278. Fax 310.812.7011, email dwight.streit@trw.com. USA Citizenship or PR required.

Researchers at Hughes Research Laboratories

Hughes Research Laboratories seeks researchers with advanced degrees, excellent communications abilities and experience in: **compound semiconductor devices and circuits**, including characterization, fabrication, design, & microfabrication techniques; **advanced microwave and millimeter wave device and IC technologies**, including antenna design, test and fabrication, C and C++, computer systems/software; **MMIC, Digital, Analog and OEIC Designers**, including SiGe & InP HBTs, GaAs PHEMTs and InP HEMTs - LNAs, SSPAs, VCOs, A/D & D/A Converters, DDS and Transimpedance Amplifiers - mixed-signal & mixed device ICs; **computational electromagnetics**, including radar cross section prediction, antenna modeling, electromagnetic simulation of circuits and packaging. HRL offers an ideal location, competitive salary and benefits package. Send your resume: Department #3031-CSM, Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, CA 90265, FAX 310-317-5651, E-mail: lross@msmail4.hac.com. WebPage at: <http://www.hrl.com/> Proof of legal right to work in US required. EOE.

Engineering Positions at M/A-COM

At M/A-COM, our expertise in providing high-volume, high-performance gallium arsenide (GaAs) and silicon semiconductors as well as other core wireless technologies is used in a wide range of portable communications applications across a broad and growing frequency spectrum. We've become the driving force behind many of today's leading cellular products through the development of components used by the cellular industry's leading manufacturers. Having also introduced the market's only two-chip WLAN solution for spread spectrum applications, we've become a leading supplier to cellular base stations. In the future, we'll continue to play a major role in the PCS revolution as well as advanced automotive electronics, interactive television, satellite and navigation systems. Now M/A-COM can be the force behind your progress. Increased technology, resources and a commitment to both research and development continue to take M/A-COM further into the world of wireless and wired communications. Imagine where you could go as part of the team that's driving the cutting-edge in RF/microwave technology. We are currently recruiting **ENGINEERS for the following areas: Design, Manufacturing, Quality, Process, Sales, Reliability, and GaAs Materials.** Send/Fax resume or letter of interest to: M/A-COM, Inc., Employment and College Relations, 1011 Pawtucket Boulevard, Lowell, MA 01853, FAX: (508) 442-4443. EOE.

Join the Leader in GaAs Technology for Wireless Communications

Combine progressive technology with exceptional talent and the result is Microelectronics, a division of Raytheon Electronics and developer of today's most innovative GaAs-based ICs for wireless communication markets. **MMIC Design Engineers/Scientists, Entry to Mid-Level.** Working in a team environment, you'll be responsible for amplifier, upconverter, downconverter or fully integrated transceiver IC designs used in a range of commercial applications including cellular telephones, wireless LANs, Direct Broadcast TV Receivers and VSAT Tx/Rx module. Designs will be progressions from previous generations and radically new designs. We offer outstanding benefits and compensation, paid higher education and an atmosphere close to Boston, the seacoast and the mountains of New England. If working for the leader in advanced GaAs technology is where you want to be, please send your resume to Microelectronics, Human Resources, 362 Lowell Street, Andover, MA 01810. FAX (508) 470-9211.

UPCOMING EVENTS

8th Int'l Conf. On InP and Related Materials

April 21-25, 1996
See ad, page 42

1996 Int'l Conf. On GaAs Manufacturing Technology

April 28 - May 2, 1996
See ad, page 14

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

May 12-15, 1996 at Freiburg, Germany
Contact: Dr. W. Jantz
Fraunhofer IAF
Tullastrasse 72
D-79108 Freiburg I. Br. Germany
TEL [49] 761 5159 510
FAX [49] 761 5159 423
Net or Web: jantz@iaf.fhg.de or
http://www.fhg.de/events.html

20th Workshop on Compound Semiconductor Devices and Integrated Circuits

May 19-22, 1996 at Vilnius, Lithuania
Contact: Iona Matulioniene
Semiconductor Physics Institute
A. Gostauto 11
LT-2600 Vilnius, Lithuania
TEL [370] 2618 101 FAX [370] 2627 123
Net or Web: matulionis@uj.pfi.lt or
http://uj.pfi.lt/conf/wocsdice/woc96.htm

1st European GaN Workshop

June 2-4, 1996 at Rigi, Switzerland
Contact: Toby Strite
IBM Zurich Research Laboratory
Saumerstrasse 4
Ruschlikon CH-8803 Switzerland
TEL [41] 01 724 8355 FAX [41] 01 724 1789
Net or Web: str@zurich.ibm.com

1996 European GaAs and Related III-V Compounds Applications Symposium

June 5-7, 1996 in Paris, France
Contact: GAAS '96
ENSEA, 6 avenue du Ponceau
95014 Cergy Cedex, France
FAX [33] 1 30 73 6627

8th Int'l Conf. On MOVPE

June 9-13, 1996 in Cardiff, Wales, UK
Contact: Glenda Bland
Global Meeting Planning
GMP 22 Plas Tahiesin
Portway Village Marina, Penarth
South Glamorgan CF64 1TN Wales, UK
TEL [44] 1222 700 053 FAX [44] 1222 700 685
E-mail 100416.1402@compuserve.com

1996 Device Research Conference

June 24-26, 1996 at Santa Barbara, CA USA
Contact: Jim Sturm
Princeton University
EE Dept., Olden Street
Princeton, 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

1996 Electronic Materials Conference

June 26-28, 1996 at Santa Barbara, CA USA
Contact: Customer Service, TMS
420 Commonwealth Drive
Warrendale, PA 15086 USA
TEL [1] 412 776 9000 FAX [1] 412 776 37700

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

July 21-26, 1996 in Berlin, Germany
Contact: Dr. Axel Hoffmann, Secretary
Institut für Festkörperphysik
PN 5-1, TU Berlin
Hardenbergstr. 36
10623 Berlin, Germany

Ninth Int'l Conference 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.
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@ceq.uiu.edu

Ninth International Conference 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.
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

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

26th European Microwave Conference

The 26th European Microwave Conference will be held September 9-12, 1996 at the Hilton Hotel, Prague, Czech Republic. This international conference is designed for the microwave industry, and is intended to allow participants to investigate and verify new research and development trends in the field of microwaves.
Contact: Nexus Media Limited
Nexus House, Swanley, Kent BR8 8HY UK
TEL [44] 1322 660070
FAX [44] 1322 661 257

CALL FOR PAPERS

23rd International 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: April 28, 1996
Contact: See ad on page 44 for more information.

International Workshop on Growth, Characterization and Exploitation of Epitaxial Compound Semiconductors on Novel Index Surfaces

NIS '96 will be held October 7-9, 1996 in Lyon, France. The use of substrates oriented on non-(100) surfaces has rapidly grown during the last years due to the novel physical properties that structures grown on these substrates exhibit (e.g. piezoelectricity, dopant incorporation, etc.). In addition, regrowth on patterned substrates to achieve low dimensional structures is accomplished on high index surfaces. The aim of this workshop is to discuss these aspects and to systematically emphasize new directions a prospects in this rapidly growing field. The workshop will provide a context of interdisciplinary discussions about the material, technical, device and theoretical aspects between delegates from academia and industry.
Abstract Submission Deadline: May 15, 1996
Contact: Prof. G. Guillot
INSA Lyon, LPM, Bat 502
69621 Villeurbanne Cedex, France
TEL [33] 72 438 161 FAX [33] 72 438 531
Email guillot@insa.insa-lyon.fr

Symposium On Novel Device Structures 190th Meeting of the Electrochemical Society

The 190th Meeting of the Electrochemical Society will be held October 6-11, 1996 in San Antonio, TX USA. Symposium L3, "Novel Device Structures", is devoted to recent developments in novel devices which utilize new materials, processing approaches and/or transport mechanisms.
Abstract Submission Deadline: June 3, 1996
Contact: April Brown or Kevin Brennan
Georgia Institute of Technology
ECE Department, Atlanta, GA 30332-0250
TEL [1] 404 894 5161 FAX [1] 404 894 0222

Microwaves & RF Conference and Exhibition

The 1996 Microwaves & RF Conference and Exhibition will be held October 8-10, 1996 at the Wembley Conference and Exhibition Center, London, UK. This is an annual event for companies involved in RF, microwave and millimetre wave components and application technologies.
Contact: Nexus Media Limited
Nexus House
Swanley, Kent BR8 8HY UK
TEL [44] 1322 660070 FAX [44] 1322 661 257

43rd National Symposium of the American Vacuum Society

The 1996 AVS National Symposium will be held October 14-18, 1996 at the Pennsylvania Convention Center in Philadelphia, PA. Papers are solicited in several areas, including Electronic Materials and Processing, Surface Science, and Magnetic Surfaces, Interfaces and Nanostructures.
Abstract Submission Deadline: May 10, 1996
Contact: AVS
120 Wall Street, 32nd Floor
New York, NY 10005 USA
TEL [1] 212 248 0200 FAX [1] 212 248 0245
Net or Web: avs96@vacuum.org or
http://www.vacuum.org

2nd International Symposium On Control of Semiconductor Interfaces

ISCSI-II will be held October 28-November 1, 1996 in Karuizawa, Japan. This symposium will cover all the fields concerning solid-solid interfaces between semiconductor and metal, insulator or semiconductor. The scope includes but is not limited to formation and control of interfaces, characterization, and device related phenomena.
Abstract Submission Deadline: May 31, 1996
Contact: Prof. T. Ito
Secretary, ISCSI-II
Osaka Univ., EE Dept.
2-1 Yamada-oka, Suita
Osaka 565, Japan
TEL [81] 6 879 7702 FAX [81] 6 879 7704

1996 IEEE GaAs IC Symposium

The 1996 GaAs IC Symposium will be held November 3-6, 1996 in Orlando, FL USA. The focus of this conference is on recent developments in integrated circuits using GaAs, InP, and other compound semiconductor devices. Coverage embraces all aspects of the technology, from materials issues and device fabrication through IC design and testing, high volume manufacturing and systems applications.
Abstract Submission Deadline: May 10, 1996
Contact: Phil Wallace
Anadigics
Box 4915, 35 Technology Drive
Warren, NJ 07060 USA
TEL [1] 908 412 5985 FAX [1] 908 412 5986
Net or Web: wallacepw@aol.com

4th IEEE International Workshop on High Performance Devices for Microwave and Optoelectronic Applications

EDMO '96 will be held November 25-26, 1996 at the University of Leeds, Leeds, UK. The purpose of EDMO '96 is to provide a forum for microwave and optoelectronic device fabricators, modelers, designers and users to discuss the interaction between system needs and advanced devices and circuits. There will be three main underlying themes to the workshop: 1) electronic devices for mobile radio and wireless LANs; 2) electronic and photonic devices for optical communications, especially in the local loop; and 3) the convergence of microwave and optoelectronics technologies.
Abstract Submission Deadline: September 2, 1996
Contact: Stravos Lezekiel
University of Leeds, EEE Dept.
Leeds LS2 9JT UK
TEL [44] 113 233 2000 FAX [44] 113 233 2032
Net or Web: s.lezekiel@elec-eng.leeds.ac.uk or
www.elec-eng.leeds.ac.uk/en6nsi/edmo96.html

Advertiser Index

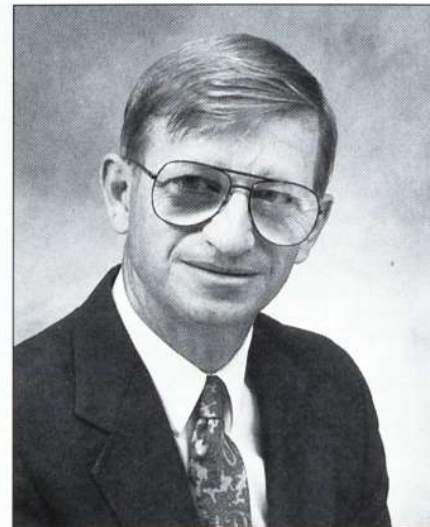
Company	Page
Advanced Ceramics	47
Aixtron GmbH	3
Bio-Rad Micromesurments	IBC
Bio-Rad Micromesurments	19
CVD Products	16
Dynatex International	38
Emcore Corporation	31
EPI MBE Products Group	11
GaAs MANTECH Conf.	14
IPRM Conf.	42
ISCS Conf.	44
Litton Airtron	21
M/A-COM	37
MCP	OBC
Morton International	23
MR Semicon	13
Oxford Instruments	8
Solkatronic	41
Struers/Logitech	10
Sumitomo Electric	IFC
VG Semicon	5

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

Contributions must be received by April 15 to appear in our next issue.

Opportunities and Challenges for InP-Based Microelectronics in Military and Commercial Applications

PAUL T. GREILING MANAGER, MICROELECTRONICS LABORATORY
HUGHES RESEARCH LABORATORIES
MALIBU, CA USA



The Hughes Microelectronics Laboratory has a broad-based InP microelectronics research and development program. We enjoy the benefit of having an in-house customer which requires advanced high frequency devices and circuits - namely, the Hughes Satellite Company. We are currently delivering low-noise InP HEMTs for satellite communications, and next year we will begin delivery of InP MMICs and HBT analog and digital ICs for the same application.

When we began our InP microelectronics development program in 1987, the decision to switch from GaAs to InP was easy. At that time the market was almost 100% military. As such, it was driven by performance considerations - in those days, a 0.1 dB lower noise figure was extremely significant. But now the military market has gone soft, and cost-conscious commercial markets are more important. Therefore we have been called upon to develop an InP technology which is capable of providing high performance but at the same time meets the commercial system cost goals.

The performance advantages of InP HEMTs and HBTs over competing Si or GaAs devices is well established. Consider low noise amplifiers (LNAs). In this area InP HEMTs provide better performance, i.e. lower noise figures and higher gain, than other semiconductor device over the entire frequency range from 1 to 100 GHz. In fact, for all small signal RF applications, the InP-based HEMT has the best performance. The performance advantage is small at the lower end of the frequency band, but it increases significantly with increasing frequency. Therefore it seems likely that GaAs MESFETs and PHEMTs will likely remain the LNA technologies of choice for the high-volume, cost-sensitive applications at the lower end of spectrum. However, at around 20 GHz and above, the InP HEMT LNA begins to have an increasingly significant performance advantage with a decreasing cost penalty. Therefore InP HEMTs are the best technology for millimeterwave LNA applications such as military communications and radar, or commercial, automobile-based radar and WLANs. But, it should be noted that for millimeterwave power applications, InP has not yet demonstrated the requisite levels of reliability. This leaves the GaAs PHEMT as the device of choice for power applications up to 60 GHz.

For IC applications, whether digital, analog, or optoelectronics, the InP HBT provides superior performance with respect to higher speed and lower power dissipation than either SiGe or GaAs. Presently, we are developing a 100 GHz InP HBT IC technology for high performance requirements in our radar, missiles and satellite business units. In the near future, this capability will be extended to 200 GHz. It is our view that a combination of our InP HBT technology with a high performance Si bipolar technology will provide the best solution for high speed IC applications. The advantage of InP becomes significant for clock frequencies of 5 to 10 GHz and above depending on the circuit

complexity and its function. But, in the area of microwave power applications, the InP HBT is struggling to replace the well-entrenched GaAs PHEMT. The final decision, however, as to the best power technology for microwave frequencies is still being argued since new technologies are emerging and may displace all existing ones.

Devices for millimeter wave applications must be fabricated on epitaxial wafers, using E-beam defined gates. In this arena, both GaAs and InP have similar costs, although GaAs currently enjoys the advantage of larger wafer sizes. However, both GaAs and InP MMICs are too expensive for most commercial markets. A previous editorial in this magazine (CS 1(3), p. 48) noted that high levels of integration are not always the best solution for RF applications. This may be fortuitous for InP's development for commercial applications, because reducing the circuit complexity, in some cases down to discretized, allows both GaAs and InP to become more cost competitive. This same strategy applies to the InP HBT IC technology, in which circuit complexity is traded off with yield to achieve both the required performance and cost goals.

The future of the InP program at Hughes is driven by the military applications within our business units. Military applications, which used to support virtually the entire III-V microelectronics effort in the US, have become less prominent in recent years as commercial applications such as cellular phones have become more important. But the military applications provide us with insertions for our InP technology, and allow us to develop a base from which we can build cost-competitive automotive, wireless and satellite millimeterwave products. The growing millimeterwave digital radio and collision warning radars are potential products for a combination of Si/GaAs/InP-based technologies. By the beginning of the next century, data links will be requiring 40 Gbit/s bandwidths and higher. A combination of high performance, small complexity InP HBT ICs combined with Si-based technologies will meet these needs. At Hughes, as both military and commercial millimeterwave markets grow, InP will become more and more an enabling technology which is critical to our success.

When we began our InP microelectronics development program in 1987, the decision to switch from GaAs to InP was easy. At that time the market was almost 100% military. As such, it was driven by performance considerations - in those days, a 0.1 dB lower noise figure was extremely significant. But now the military market has gone soft, and cost-conscious commercial markets are more important. Therefore we have been called upon to develop an InP technology which is capable of providing high performance but at the same time meets the commercial system cost goals.

Dr. Paul T. Greiling is Manager of the Microelectronics Laboratory of Hughes Research Laboratories in Malibu, CA. Dr. Greiling, who received his BSEE, MSEE and Ph.D. from the University of Michigan, has 26 years of professional experience developing microwave/millimeterwave solid-state devices and ICs. Presently, Dr. Greiling's laboratory is responsible for research, development and modest volume production of high performance microwave/millimeterwave devices and ICs for utilization in low noise, power, digital and analog applications within Hughes Electronics.

Every Hall System you'll
ever want!



MODULAR Resistivity & Transport Properties of Semiconductors & Thin Films

With many years experience of building Hall Effect Systems we know that your requirements often change with time. With the HL5500PC Hall Effect System, this is no longer a problem.

As your needs change the System changes with you.

We offer a two temperature stage for rapid QA measurements, a choice of cryostats, a wafer mapping stage and a buffer amplifier module that extends the measurement range to 10^{12} ohms.



RC2400

Other products in the range include the RC2400 Alloying Furnace and the HL5900PC Hall Profiler.

Call for details



HL5900PC

BIO-RAD

Semiconductor
Systems Division

USA

Bio-Rad Micromeritics, 520 Clyde Avenue, Mountain View, CA 94043-2212
Phone 415-961-6900 Fax 415-961-6715

Europe

Bio-Rad Micromeritics Ltd, Bio-Rad House, Maylands Avenue, Hemel Hempstead, Herts, HP2 7TD, UK
Phone +44 (0) 1442 232552 Fax +44 (0) 1442 234434

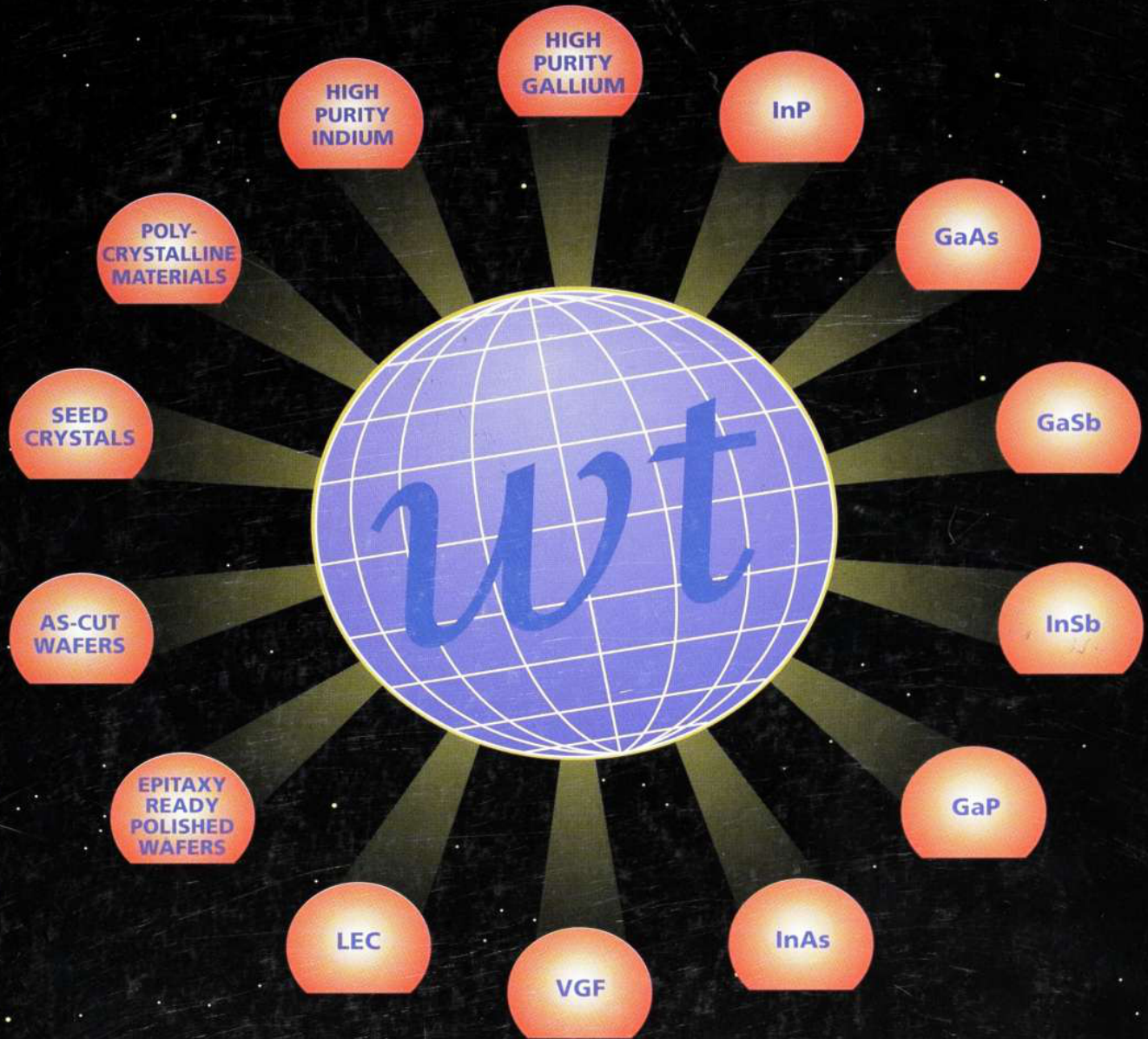
Japan

Nippon Bio-Rad Laboratories KK, Cowing Park Bldg, 5-7-18 Higashinippon, Anagawa-ku, Tokyo 116
Phone 03-5811-6288 Fax 03-5811-6273

Pacific Rim

Bio-Rad Pacific Ltd, Unit 1111, 11/Floor, New Kowloon Plaza, 38 Tai Kok Tsui Road, Kowloon, Hong Kong
Phone 852 2789 3300 Fax 852 2789 1257

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



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

Circle 130 on Reader Service Card

**Quality system
approved to
BS EN ISO
9002:1994**