

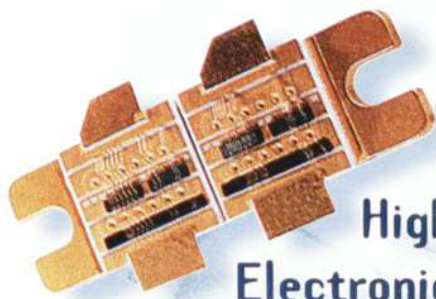
# COMPOUND

## SEMICONDUCTOR

July/August 1996

Volume 2 Number 4

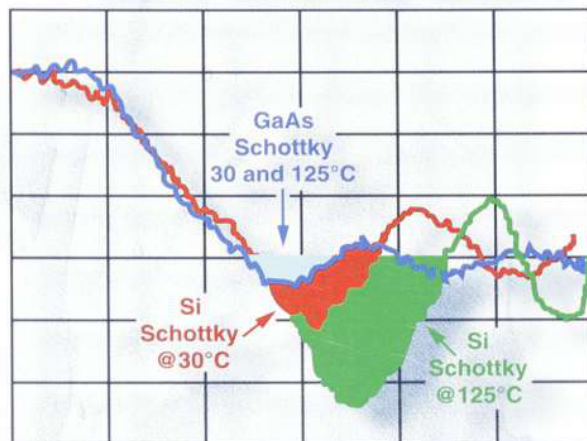
## New Applications



High Temperature  
Electronics for Wide  
Bandgap Semiconductors



Rectifiers for  
GaAs Schottky Diodes



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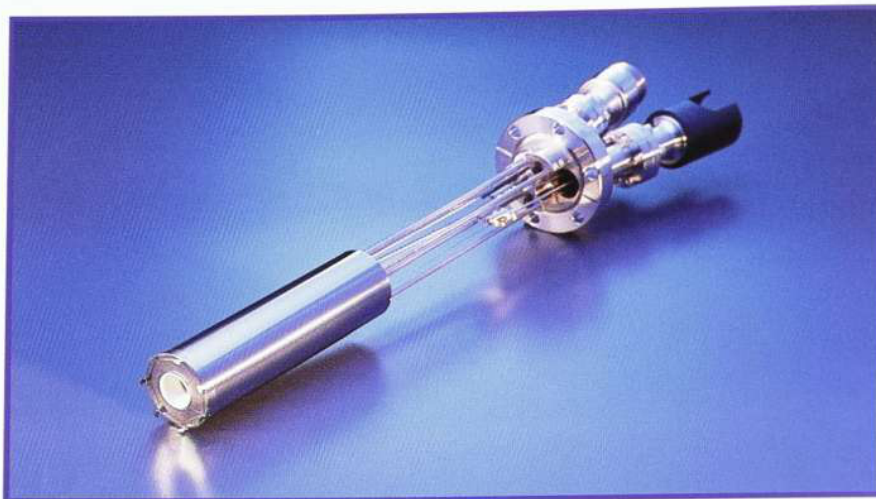
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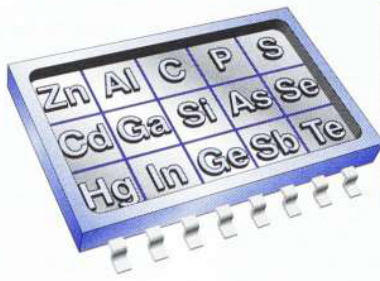
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Suite 48  
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**Editor**  
Marie Meyer  
Compound Semiconductor Magazine  
Franklin Publishing  
250 Selby Avenue  
Suite 48  
Saint Paul, MN 55102 USA  
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*On the cover: upper left - Westinghouse's high power SiC transistors (see page 4); lower right - data on Motorola's new GaAs rectifiers (see page 12); background - SiC wafer processing at Cree (see page 6) [photo by Mark Dolejs, The Herald-Sun (Durham, NC)].*



## UPCOMING EVENTS

**Mid-Infrared Optoelectronics Materials and Devices Conf.**

Sept. 17-18, 1996 at Lancaster, UK  
 TEL [44] 1524 593651 FAX [44] 1524 844037  
 Net or Web: j.hesseltine@lancaster.ac.uk

**23rd Int'l Symp. on Compound Semiconductors**

Sept. 23-27, 1996 in St. Petersburg, Russia  
 TEL [7] 812 247 6805 FAX [7] 812 247 1017  
 Net or Web: vgrig@eo.ioffe.rssi.ru or  
 http://www.ioffe.rssi.ru/ISCS-23/

**1st European Conference on SiC and Related Materials**

October 6-9, in Heraklion, Crete, Greece.  
 TEL [30] 81 239 779 FAX [30] 81 239 735  
 Net or Web: georgia@iesl.forth.gr

**Int'l Workshop on Novel Index Surfaces**

October 7-9 in Lyon, France.  
 69621 Villeurbanne Cedex France  
 TEL [33] 72 438 161 FAX [33] 72 438 531

**Symp. On Novel Device Structures**

190th Meeting of the Electrochemical Society  
 October 6-11 in San Antonio, TX, USA.  
 TEL [1] 404 894 5161 FAX [1] 404 894 0222

**43rd Nat'l Symp. Of the American Vacuum Society**

October 14-16 in Philadelphia, PA.  
 TEL [1] 212 248 0200 FAX [1] 212 248 0245  
 Net or Web: avs96@vacuum.org or  
 http://www.vacuum.org

**1996 U.S. Workshop on the Physics and Chemistry of II-VI Materials**

October 22-24, 1996 at Las Vegas, NV USA  
 TEL [1] 212 620 3544 FAX [1] 212 620 3379  
 Net or Web: lmgani@new.york.palisades.org

**2nd Int'l Symp. On Control of Semiconductor Interfaces**

October 28 - November 1 in Karuizawa, Japan.  
 TEL [81] 6 879 7702 FAX [81] 6 879 7704

**1996 IEEE GaAs IC Symposium**

November 3-6, 1996 in Orlando, FL.  
 TEL [1] 908 412 5985 FAX [1] 908 412 5986  
 Net or Web: wallacepw@aol.com

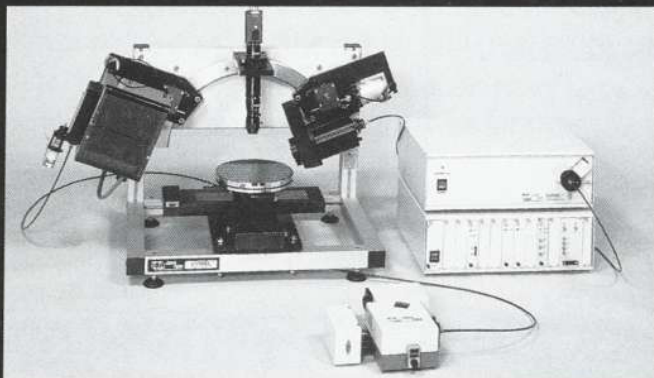
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## CALL FOR PAPERS

**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. Abstract Submission Deadline: September 2, 1996

Contact: Stravos Jezekiel  
 University of Leeds, EEE Dept.  
 Leeds LS2 9JT UK  
 TEL [44] 113 233 2000 FAX [44] 113 233 2032  
 Net or Web: s.jezekiel@elec-eng.leeds.ac.uk or  
 www.elec-eng.leeds.ac.uk/eenfsi/edmo96.html

**Gallium Arsenide VLSI '96**

A course entitled "Gallium Arsenide VLSI '96: Circuits & Systems" will be offered by the Centro Microelectronica Aplicada on November 26-29, 1996 at Maspalomas, Gran Canaria, Spain. Registration Deadline: October 1, 1996

Contact: Gallium Arsenide VLSI '96  
 Centro Microelectronica Aplicada  
 Universidad de Las Palmas de Gran Canaria  
 Campus Universitario de Tafira  
 E-35017 Las Palmas de Gran Canaria Spain  
 TEL [34] 28 45 12 32 FAX [34] 28 45 12 43  
 Net or Web: gaas96@cma.ulpgc.es or  
 http://www.cma.ulpgc.es/GaAsVLSI96/

**1996 Conference on Optoelectronic and Microelectronic Materials and Devices**

COMMAD '96 will be held December 9-11, 1996 at Canberra, Australia. The aim of this conference is to bring together industrial collaborators, scientists, engineers and students to discuss new and exciting advances in the fields of optoelectronic and microelectronic materials and devices.

Contact: C. Jagadish  
 Dept. Of Electron. Mats Eng.  
 RSPHYSSE, Australian Nat'l Univ.  
 Canberra, ACT 0200 Australia  
 TEL [61] 6 249 0363  
 FAX [61] 6 249 0511  
 Net or Web: cxj109@phys.anu.edu.au

**1997 IEEE International Solid-State Circuits Conference**

ISSCC '97 will be held February 6-8, 1997 in San Francisco, CA USA. The theme for the 1997 conference is "Multimedia".

Abstract Submission Deadline: September 6, 1996  
 Contact: Ms. Diane Suiters  
 655 - 15th Street, N.W., Suite #300  
 Washington, DC 20005 USA  
 TEL [1] 202 639 4255 FAX [1] 202 347 6109  
 Net or Web: isscc@mcimail.com

**9th European Workshop on MBE**

Euro-MBE IX will be held April 6-10, 1997 at Oxford, England. The meeting will be run on a workshop format and will cover all materials systems produced by MBE, including III-V, II-VI and elemental semiconductors, metal, oxides, insulators and organic films. The main themes will be: in-situ diagnostics, growth processes, growth on patterned and other non-planar substrates; interfaces and heterojunctions. Contributions on other topics will be welcome, but papers on devices will only be considered where a large element of growth is involved.

Abstract Submission Deadline: TBA  
 Contact: Di Pullar-Macmillan  
 Secretary to Euro-MBE IX  
 Semiconductor Materials IRC  
 The Blackett Laboratory, Imperial College  
 Prince Consort Road  
 London SW7 2BZ UK

**Eighth Biennial Workshop on Organometallic Vapor Phase Epitaxy**

The 8th OMVPE workshop will be held April 13-17, 1997 in Dana Point, CA, USA. This workshop is intended to provide an setting for the informal scientific and technical exchange of recent progress in OMVPE.

Abstract Submission Deadline: October 15, 1996  
 Contact: TMS Customer Service  
 420 Commonwealth Drive  
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 TEL [1] 412 776 9000 FAX [1] 412 776 3770  
 Net or Web: csc@tms.org

**Ninth International Conference on Indium Phosphide and Related Materials**

IPRM '97 will be held May 11-15, 1997 on Cape Cod, MA USA. Papers are requested in the following areas: Optoelectronics, Electronic Devices, Processing, Epitaxy, Bulk Growth, and Characterization. The conference will include invited and contributed oral and poster presentations. Short Courses and an Industrial Exhibit will also be offered.

Abstract Submission Deadline: November 11, 1996  
 Contact: Stephen Forrest  
 Princeton University  
 EE Dept.  
 E-Quad, Room 00301  
 Princeton, NJ 08544 USA  
 TEL [1] 609 258 3000 FAX [1] 609 258 1954  
 Net or Web: forrest@ee.princeton.edu

**7th European Workshop on Metal-Organic Vapor Phase Epitaxy**

EW MOVPE will be held June 8-11, 1997 in Berlin, Germany. This conferences aims to bring together scientists and engineers actively engaged in MOVPE, VPE and CBE/MOMBE growth of compound semiconductor materials.

Abstract Submission Deadline: February 28, 1997  
 Contact: Dr. Wolfgang Richter  
 Technische Universität Berlin  
 Hardenbergstr. 36  
 D-10623 Berlin Germany  
 TEL [49] 30 3142 2078 FAX [49] 30 3142 1769  
 Net or Web: richter@gift.physik.tu-berlin.de or  
 http://www.hhi.de

**Eight International Conference on II-VI Compounds and Devices**

II-VI '97 will be held August 25 - 29, 1997 in Grenoble, France. The conference will focus on fundamental aspects and on recent perspectives for applications of narrow and wide bandgap II-VI semiconductors. Areas of interest include: materials science, where many long-standing problems (particularly compensation) are still to be solved, low dimensional physics including semimagnetic heterostructures, and optoelectronic applications.

Abstract Submission Deadline: March 15, 1997  
 Contact: Le Si Dang  
 II-VI Conference Secretariat  
 Laboratoire de Spectrometrie Physique  
 Université J. Fourier - Grenoble 1, BP 87  
 F-38402, Saint Martin d'Heres Cedex France  
 FAX: [33] 76 51 45 44  
 Net or Web: lesidang@spectro.grenet.fr

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

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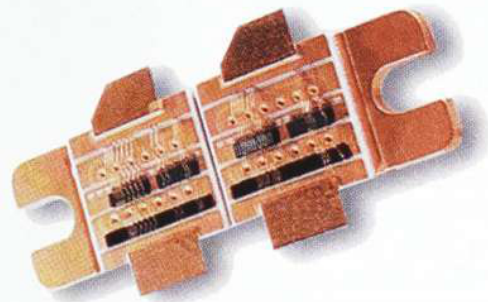
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Aachen, Germany  
AIXTRON GMBH  
Kackerstraße 15-17, 52072 Aachen  
Germany  
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Fax: +49 (241) 89 09 - 40  
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**US Headquarters**  
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# A First for Silicon Carbide

## Westinghouse Launches High Power Transistor



*Westinghouse's new silicon carbide static induction transistor (shown approximately two times actual size).*

Westinghouse Electric, through its Communication and Information Systems Division, has introduced a silicon carbide static induction transistor for use in advanced television transmission. This is believed to be the first commercial application for a SiC transistor. Westinghouse fabricates the 500 W devices (using 4H SiC wafers produced by Cree Research) and supplies them as part of a solid state 1.5 kW power amplifier module that will be sold to manufacturers of digital television transmission equipment. A complete transmitter would require 200 - 300 of the new devices.

According to Paul DeGonia, Director of HDTV Development at Westinghouse, if all goes well, the next few years might be a heyday for transmitter production. Regulatory approval for digital TV broadcasting in the US is hoped for from the FCC as early as 1997. The FCC is likely to take a "use it or lose it" approach, wherein the television stations will have

a fixed period of time - perhaps 2 or 3 years - during which they must begin digital broadcasting or else they will lose the right to do so. At the same time they must continue analog broadcasting, to service the installed base of TV sets. This means that each station that wishes to pursue digital television will need a second transmitter.

There are around 1500 television stations in the U.S., and many of them are relatively small enterprises. Therefore the cost of that second transmitter is an important consideration. Approximately two-thirds of the cost of a high power transmitter is in the power amplifiers, and a significant cost driver for the amplifiers is the power transistors. According to DeGonia, a conventional transmitter using vacuum tubes costs around \$400,000, but is not suited to advanced broadcasting. A solid-state transmitter based on Si amplifiers costs around \$1 million - more than many stations can afford. But, DeGonia says, "by using the SiC amplifier technology we can reduce the cost of the solid-state transmitter to \$500,000 - 600,000". The keys, he reports, are SiC's high temperature characteristics, allowing it to withstand junction temperatures up to 300°C, and its much higher power-density capacity - up to 500 W, compared to 124 - 140 W for standard Si products. As DeGonia puts it, "SiC transistors give us around four times more power than Si, which allows the use of far fewer devices, which in turn greatly simplifies the design of the transmitter and lowers its cost". SiC also provides excellent linearity. Some of the specifications for the Westinghouse power amplifier module are given in Table One.

Westinghouse's SiC device technology was developed at its Science & Technology Center [Pittsburgh, PA] and was originally intended for military radar. Last year, Westinghouse's Defense Electronics business was sold to Northrup-Grumman, and the two companies now jointly own this technology. Westinghouse plans to pursue further commercial opportunities, and Northrup will take responsibility for military applications.

Westinghouse is projecting a product roll-out by 1997, dependent on the transition from analog to digital television, regardless of whether the format is standard definition or high definition.

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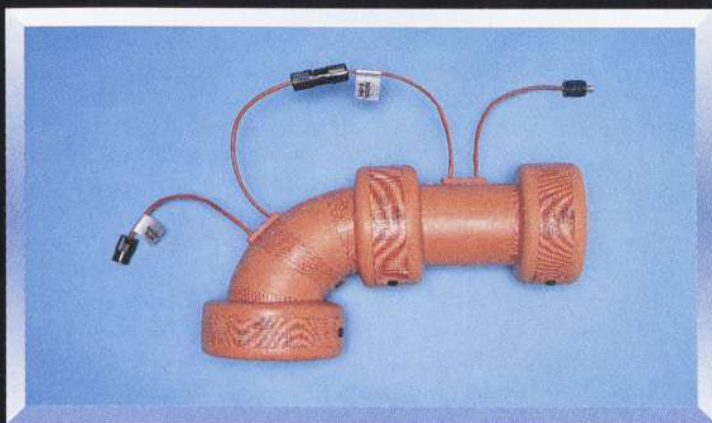
#### UHF Module Specifications

|                         |                                     |
|-------------------------|-------------------------------------|
| Nominal RF Output Power | 200 W average (approx. 1 kW peak)   |
| Frequency Range         | 470 - 806 MHz                       |
| Gain                    | 15 dB nominal                       |
| Gain Ripple             | <0.5 dB over any 6 MHz channel      |
| Phase Non-Linearity     | <5 degrees across any 6 MHz channel |
| Operating Temperature   | 0 to 45°C                           |
| Cooling                 | Air cooling with 100 CFM nominal    |

*Table One: Selected specifications for the Westinghouse Solid-State High Power UHF Advanced Television Transmitter, which features a SiC static induction transistor - the first known commercial application for a SiC microwave device.*

# Process Solutions

from HPS Division of MKS Instruments, Inc.

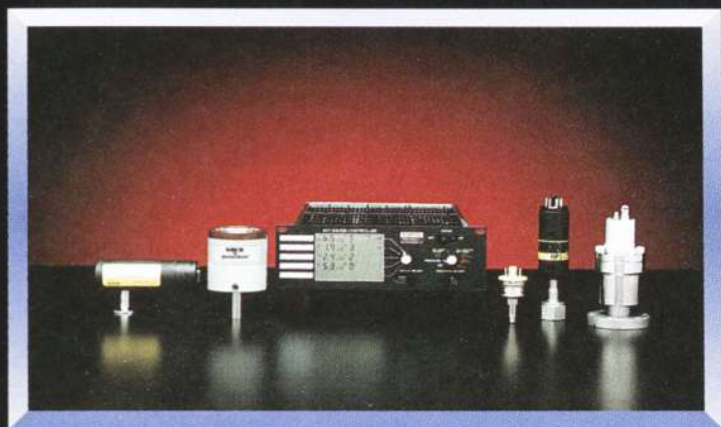


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# High Temperature Semiconductors: Evolution, not Revolution

MARIE MEYER

**H**igh temperature electronics are frequently mentioned as prospective applications for compound semiconductors. The potential for high temperature operation is inherent in the wide bandgap materials such as GaN and SiC, and even in GaAs (which is, after all, a "wide bandgap material" in comparison to Si). However, there are substantial technical and developmental issues that must be resolved before a sizable market for high temperature compound semiconductors will appear.

The following is a three-part examination of this topic. First is an overview of the high temperature materials systems. Next is discussion of the likely direction of R&D funding in this area in the U.S.A. And, finally, we provide a summary of the market for high temperature electronics.

## High Temperature Electronic Devices and Technologies

The primary types of devices under consideration for high temperature applications are sensors and their controlling electronics. Five major semiconductor materials systems are being developed for this purpose. (See Table One on page 8 for a summary of some of their most important characteristics.)

Over the next 10 years, silicon devices are expected to dominate demand for high temperature electronics. Wide bandgap semiconductors are expected to make their initial impact on the sensor market. A considerable development effort is still required before they can contribute significantly to active electronics.

### Silicon

Silicon devices can potentially operate at much higher temperatures than their current maximum temperature ratings. Si is, of course, by far the most mature and lowest cost semiconductor technology. It is, therefore, expected to dominate most of the market.

At elevated temperatures Si devices show an increase in leakage currents. However bulk Si processes such as modifications of CMOS and integrated injection logic, are being developed to address this and other issues for high temperature operation. In addition, leakage

### Summary

High temperature electronics are an interesting application for compound semiconductors, but time and effort will be needed before a sizable market can be realized. Silicon will be the dominant technology, and even in ten years time the market for GaAs and other wide bandgap semiconductors in high temperature applications will likely be less than \$200 million. Nevertheless, the need for these types of electronics as enabling technology justifies their development.

Working in conjunction with HITEN News, we present a three-part overview of high temperature electronics as an application for compound semiconductor devices. Part One: A summary of the characteristics of the five major semiconductor materials under consideration (Si, GaAs, SiC, GaN and Diamond) and the current status of efforts toward their development; Part Two: A consideration of the economic justifications for funding high temperature R&D; and Part Three: A survey of the market for high temperature electronics, including a forecast through the year 2005.

currents can be virtually eliminated by using silicon-on-insulator (SOI) technology, which is under development at many companies worldwide. SOI is especially attractive for small signal applications, but is less suited to power devices<sup>1</sup>.

### Gallium Arsenide

One of the intrinsic advantages that GaAs enjoys over Si in mainstream applications is the ready availability of a semi-insulating (SI) substrate. Unfortunately, that SI property, and hence device isolation, is reduced at higher temperatures, although GaAs MESFETs have been demonstrated up to 350°C. Heterojunction devices using wider bandgap material systems such as AlGaAs can potentially resolve the problems, although they will be more expensive. Large volumes of GaAs Hall Effect sensors are used in the automotive industry, and AlGaAs sensors have been demonstrated up to 500°C.

Only a few companies worldwide are known to be exploring high temperature GaAs. The American participants tend to be those with vertically integrated interests in aerospace and military systems, such as Honeywell and Hughes. Europe's main activity is at the Technische Hochschule Darmstadt (Germany), a leading center for the development of high

<sup>1</sup> For a review of SOI technology, see the "Other Materials" feature in CS 2(3), p. 44.

temperature AlGaAs and GaAs material. In addition, Siemens produces GaAs Hall effect sensors for the automotive industry. No Japanese companies are known to be putting significant resources into high temperature GaAs, although several have very strong positions in the synergistic area of high power GaAs transistors.

### Silicon Carbide

Of all of the wide bandgap semiconductors, SiC enjoys the leading position because it is the only one available both in single crystal form and in good quality heteroepitaxy, and it can easily be doped both n- and p-type. Its operating characteristics are, in theory, far superior to Si or GaAs, and devices should be able to function up to at least 600-700°C.

Although it is progressing rapidly, SiC technology today is only where GaAs electronics were roughly 25-30 years ago. Discrete power transistors fabricated on 1-inch substrates have been demonstrated by several organizations. The main driver for SiC is high power devices, and for niche high ambient temperature applications beyond 300°C. SiC electronic devices could start to be designed into systems within the next 3-4 years. (See page 4 for an early example.) Of course SiC optoelectronic devices - namely blue LEDs - are already in high volume production.

Europe has several strong centers of R&D in the SiC area, especially ABB, Daimler Benz, Siemens and Thomson CSF. The US is considered the overall leader in SiC device development, both in terms of the number of active players and the government resources being applied to the field. Most prominent are General Electric, Motorola, NASA, and Westinghouse, as well as ATMI and Cree Research, both of which supply SiC wafers commercially as well as engaging in device development. Historically, Japan's main commercial interest in SiC has been for optoelectronic devices, but corporate interest in electronic applications is beginning to increase, particularly from automotive companies such as Toyota and Nissan.

### Group III-Nitrides

The wide bandgap nitrides, especially GaN and c-BN, have outstanding characteristics, exceeding those even of SiC, and are under development for several applications including high temperature. The properties of the GaN system as an optoelectronic material are likely familiar to anyone with a current interest in the compound semiconductor industry. But as far as electronic applications are concerned, these materials are at very early stages in their development. The nitrides are expected to play only a minor commercial role in high temperature electronics over the next 10 years.

Nichia Chemical in Japan is the undisputed leader in the GaN field, but it has no current interest in electronic applications. In the US there are several efforts underway, led by APA Optics. Cree Research and ATMI are also active in the field, and General Motors is exploring c-BN for a range of automotive applications. Europe is very weakly represented in this field, with virtually no corporate activity.

### Diamond

Diamond might well be the perfect semiconductor - if only you could make something out of it. Its figures of merit are superior to all other semiconductors and diamond devices could theoretically demonstrate outstanding performance, but there are serious obstacles to realizing its potential.<sup>2</sup> Overall, diamond lags behind SiC for active electronic applications, although intensive efforts from some key groups could yet close the gap. Passive diamond devices should be the first application for this material that makes any market impact. For example, diamond thermistors with fast response times, low heat capacity and high thermal conductivity could be available shortly.

## Funding Policy and Developmental Paths

Imagine that, due to a prodigious flash of insight and technical skill, you were able to sweep away all of the device design and manufacturing issues, thereby allowing you to announce the availability of GaN and SiC semiconductor devices suitable for operation at any temperature up to 300°C with excellent functionality and reliability. Would the world beat a path to your door?

Probably not. High temperature semiconductors hold a great allure for materials scientists as an intellectual challenge, but the market forecast (see page 10) demonstrates that system designers have learned to live without them, and are likely to continue along those lines to the greatest extent possible. And in cases of absolute necessity, they can make-do with a Si solution. Undoubtedly there are many instances where system design can be improved by positioning electronic sensors or controls in extreme environments. A report issued last year by the U.S. National Academy of Sciences<sup>3</sup> offers an interesting biological analogy: just as an animal is more agile, efficient and durable when its nervous system (sensor signal processing), skeleton (physical structure) and muscular system (actuator operation) are integrated, so there are many electromechanical systems that can benefit from such a "distributed control network". However, the NAS report acknowledges that "in all the processes of our economy there are currently few in which inser-

<sup>2</sup> For a complete review, see the "Other Materials" page 30.

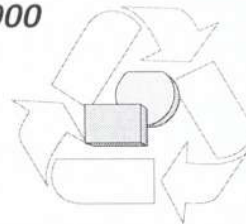
<sup>3</sup> "Materials for High-Temperature Semiconductor Devices", Copyright 1995 by the National Academy of Sciences (USA). Available in limited supply from: National Materials Advisory Board, 2101 Constitution Avenue NW, Washington DC 20418 USA, TEL [1] 202 334 3505 FAX [1] 202 334 3718 e mail nmab@nas.edu.

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tion of electronics into [high temperature] environments is absolutely required to achieve acceptable functionality." Therefore a simple economic analysis which justifies the investment required to develop high temperature semiconductors by referencing a market which can be captured is not available. Instead, the NAS advises that "the determination of whether the benefits of high temperature electronics will justify the cost [of developing them] requires the examination of how products and processes might be improved or even enabled by high temperature electronics." The report advises that the only way to increase interest and investment in widebandgap materials for electronic applications is to find "realistic, inspiring applications...that can make system designers aware of the benefits of high temperature electronics."

### System Circuits

Some applications have already been identified, and the next article demonstrates that a limited market for high temperature semiconductors already exists. However, broad-scale applications are less apparent. There are also some technical obstacles that reduce the market for our hypothetical perfect 300°C semiconductor: the technology does not exist to build a module or electronic sub-system for it. This is not a field where one can hit a "home run" with advances in semiconductor technology alone. High temperature electronics is a multi-disciplinary field which requires contributions from every technology involved in the design, production and application of electronic components and subsystems. To fully exploit the technology, sensors, active and passive semiconductors, die attachment materials, wirebonding, encapsulation, interconnection and printed circuit boards must all

### 3C Silicon Carbide Venture

A new company has been launched to commercialize sensors fabricated from 3C silicon carbide (the cubic form of SiC). The new venture, "3C Semiconductor Corporation", is located in Portland, Oregon, and its Chief Technical Officer is James Parsons, who developed a patented method for synthesizing monocrystalline 3C-SiC and forming metallized Schottky junctions and ohmic contacts to SiC while at the Oregon Graduate Institute.

The first products under development at 3C Semiconductor are devices for temperature sensing in the 200°C - 1,000°C range. The company is targeting applications in the automotive industry, as well as turbine engines and industrial processes.

be fully characterized for their high temperature capability, behavior, and reliability. The technological diversity of the field is a major barrier to progress since there is a lack of coordinated activities, and insufficient R&D funds to cover all the necessary areas.

It seems obvious, then, that system design plus semiconductor development - not just the later alone - will shape the future horizons in the high temperature electronics area. But this leaves unanswered the question of how the semiconductor research community should proceed. The most promising route for securing interest and funding is to link high temperature-oriented work to other projects related to more immediately promising markets. Quoting again from the NAS report: "the shared virtues of radiation hardness, power handling, and blue-light emission represent an important leverage for the development of high-temperature semiconductors". Or, to put it differently: if the ability to produce the perfect 300°C semiconductor had instead been turned toward producing a room temperature blue or UV laser, would the world beat a path to your door? Most definitely yes....

The NAS strongly recommends that future research be aimed at exploiting the synergistic connections between high temperature wide bandgap devices and their more marketable counterparts in the optoelectronics and power fields. As was noted earlier, Si is the

dominate high temperature semiconductor material, and funds which are earmarked specifically for high temperature research will likely go into further Si development. However, in the optoelectronics area and high power areas, there are no viable alternatives to wide bandgap materials. Thus the best strategy for creating high temperature wide bandgap semiconductors that are commercially viable is to build upon the funding for other areas which are dependent on wide bandgap materials. This should reduce the need for potential users of high temperature devices to fund the required materials development exclusively and therefore render the wide bandgap technology more cost effective.

### Conclusion

There are many instances of systems currently in use where III-V compound semiconductors play a pivotal, enabling role. The list includes wireless and satellite communications, fiber optic data transmission, and optical data storage. Various types of high temperature sensing and control electronics based on wide bandgap compound semiconductor materials may someday play a similar role. However, it seems that the developmental path in this area will be more of an evolutionary, as opposed to revolutionary, nature.

|   | High Temperature Semiconductor Materials    |                                  |   |                        |   |
|---|---|----------------------------------|---|------------------------|---|
|   | Si/SOI                                      | GaAs                             | SiC   | III-N                  | Diamond                                   |
| <b>Technical Considerations</b>         |   |                                  |   |                        |   |
| Bandgap (eV)                            | 1.1   | 1.3                              | 2.9   | 3.4-6.4                | 5.5                                       |
| Intrinsic Temperature                   | 400°C                                       | 650°C                            | >1000°C   | 600°C - 1000°C         | >1000°C                                   |
| Small Signal Devices (Tmax)             | 300°C                                       | 300°C                            | >600°C  | >550°C                 | n/a                                       |
| Power Devices (Tmax)                    | 250°C                                       | 250°C                            | >600°C  | >550°C                 | n/a                                       |
| Processing Maturity                     | Si: Very High<br>SOI: Medium                | High                             | Low   | Very Low               | Very Low                                  |
| Key Development Issues                  | Electromigration                            | Ohmics, EM                       | Substrates, Ohmics  | Substrates, Ohmics, EM | Substrates, Dopants                       |
| <b>Commercial Considerations</b>        |   |                                  |   |                        |   |
| Development Costs                       | Low   | Medium                           | High  | Very High              | Very High                                 |
| Commercial Availability*                | Now   | Now                              | 1997  | 2000                   | Sensors: 1997<br>Electronics: beyond 2000 |
| Synergistic markets / R&D opportunities | Rad hard, high speed, low voltage operation | Power, rad hard, optoelectronics | Power, optoelectronics  | Optoelectronics        | Optoelectronics, sensors                  |
| *for high temperature applications      |   |                                  | Source: HITEN News, May 1995, after Sandia National Labs Report SAN94-08501, Dreike et al |                        |   |

Table One: Summary of the characteristics and commercial status of the five major semiconductor materials systems under consideration for high temperature electronics.

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## The Market for High Temperature Semiconductors

The actual world-wide market for high temperature electronic components (meaning packaged electronic devices and sensors) in 1994 was just slightly more than \$140 million, and it is forecast to grow to \$435 million in 2000 and to reach \$1,011 million 2005 - a CAGR of 20%. See Table One. The great majority of that market will be at the 125°C to 200°C temperature range. Accordingly, the dominant semiconductor technologies in this field will be silicon and SOI, because of their superior price competitiveness. However, Simon Lande of Magus Research believes that "GaAs and wide bandgap semiconductors such as SiC, diamond and Group III-nitrides will play a critical role in applications where temperatures exceed 250°C", giving them around 16% of the market by 2005.

This data was compiled as part of a global survey on high temperature electronics conducted by Magus Research and sponsored by HITEN, the European Commission's High Temperature Electronics Network of Excellence. 175 interviews were conducted within 156 organizations in Europe, North America and Japan, covering users and produc-

ers/developers of high temperature electronics. The market evaluation was derived from a compilation of the survey responses, combined with background research.

One of the most interesting aspects of the study is the revelation of the very large difference between the Total Available Market (TAM) and the Actual Market. The TAM is the calculation of the maximum market that is theoretically available for high temperature electronics, derived from estimating the value of all the main potential applications for high temperature electronics. The Actual Market is the percentage of the TAM that is actually captured. To provide an analogy based on GaAs, one could say that the TAM for GaAs ICs is the value of all digital logic circuits plus all analog devices for RF/microwaves - but, of course, the Actual Market is significantly less, because GaAs must compete with silicon at all levels.

In the case of high temperature electronics the competition comes not from another technology but from what could be called "work-around techniques" - in other words, the avoidance of using high temperature electronics. Thus whereas the TAM is quite large (\$9.3

billion in 1994, rising to \$13.18 billion in 2000 and reaching \$17.4 billion in 2005), the percentage of it which is actually captured by high temperature electronics, i.e. the Actual Market, is very small (1.5% in 1994, rising to 3.3% in 2000 and reaching 5.8% in 2005). This reflects the strong tendency in system design to obviate the need for high temperature electronics by providing cooling or insulation, or moving the electronics to a cooler location.

Necessity is the mother of invention, and it will also be the mother of applications in this area. As the semiconductor content in all types of systems increases, the number of instances where it is desirable to insert electronic functions into extreme environments will increase until the point where the system designers have exhausted all of their work-around options. Lande points out that "the petroleum industry has been the main driving force and leading financial sponsor for the development of high temperature electronics over the past 20 years because sensors and data acquisition electronics are needed to 'log' the environment around drilling heads in wells. These measurements are critical, the application is relatively cost insensitive, and there are few alternatives that are better than placing the electronics directly into the extreme environment." This application currently accounts for around 40% of the high temperature electronics market (See Table Two), but is not expected to grow significantly. More promising in the long run are aerospace and automotive applications, which are forecast to grow by a CAGR of 34% and 22.5% respectively. In applications such as these, Lande says, "harsh environments are monitored by high temperature transducers which are controlled via long cables connecting the higher order intelligent functions. Wiring and connector count are thereby increased, resulting in electromagnetic and RF interference and high levels of measurement noise. Elaborate and expensive techniques for thermal management and cooling of densely packaged devices are an additional requirement." Given that these factors degrade system performance and efficiency (especially with regard to fuel consumption), and increase costs, high temperature electronics would seem an attractive alternative. However, Lande cautions that these applications will impose more stringent cost and reliability requirements than the well logging market, which could impede development.

For more information about HITEN, visit their web site at "<http://www.hitent.com>" or contact Simon Lande at Magus Research, Rowlandson House, 289-293 Ballards Lane, London N12 8NP, UK  
TEL [44] 181 446 2505  
FAX [44] 181 446 6483  
email lande@magus.co.uk.

### World Wide Market for High Temperature Electronic Components

|                                    | 1994     | 2000     | 2005       |
|------------------------------------|----------|----------|------------|
| <b>Actual Market</b>               | \$140.1M | \$435.0M | \$1,011.3M |
| % of TAM*                          | 1.5%     | 3.3%     | 5.8%       |
| <b>By Temperature Range</b>        |          |          |            |
| up to 200°C                        | 92%      | 88%      | 81%        |
| 200-300°C                          | 8%       | 11%      | 14%        |
| >300°C                             | 0%       | 2%       | 5%         |
| <b>By Semiconductor Technology</b> |          |          |            |
| Silicon/SOI                        | 88%      | 86%      | 84%        |
| GaAs                               | 12%      | 13%      | 11%        |
| Wide Bandgap Materials             | 0%       | 1%       | 5%         |

\*See text above for explanation of TAM.

Source: HITEN/Magus Research

Table One: The worldwide market for high temperature electronic components (packaged electronic devices and sensors), with segmentation according to temperature and semiconductor material.

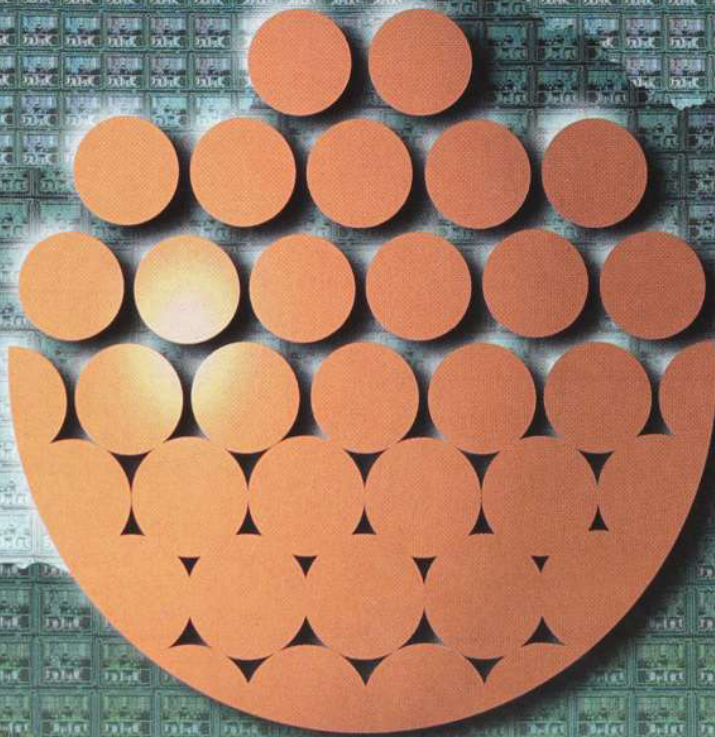
### Major Applications for High Temperature Electronics

|                     | 1994     | 2000     | 2005       | CAGR |
|---------------------|----------|----------|------------|------|
| Well Logging        | \$56.7M  | \$93.0M  | \$137.9M   | 8%   |
| Aerospace           | \$5.8M   | \$37.5M  | \$145.8M   | 34%  |
| Automotive          | \$68.6M  | \$274.0M | \$657.9M   | 22%  |
| Other*              | \$7.9M   | \$30.5M  | \$69.7M    | 22%  |
| Total Actual Market | \$140.1M | \$435.0M | \$1,011.3M | 20%  |

\*"Other" applications include military and space, consumer, industrial process control, and nuclear power.

Source: HITEN/Magus Research

Table Two: The major applications for high temperature electronics plus the value of the actual market for high temperature electronic components.



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CdTe  
HgCdTe  
Diamond  
Pd  
TiN

# Rectifiers: a New Application for GaAs

*Fast switching speeds, high voltage capabilities and high temperature operation make GaAs suitable for power processing.*

ROBERT A. METZGER and MARIE MEYER

When the non-optoelectronic applications for GaAs are discussed, there are only two categories that come up regularly: RF and microwave devices and circuits, and digital ICs. But the Motorola Semiconductor Products Sector is working to attract attention to another area where GaAs's superior properties can be put to good use: high frequency power rectifiers.

Motorola has been working on the development of GaAs rectifiers since 1991. According to Dr. Ali Salih, Program Manager for Rectifier Products at Motorola, GaAs devices working at 3 to 20 amps have been

produced over the 100 to 1000V range. A family of 10 and 20 amp, 180V and 250V GaAs rectifiers have been launched as standard products, and higher voltage (500 - 600 V) products are planned in the near future. Motorola reports that it has successfully completed OEM supply contracts with major power supply manufacturers, such as Lucent Technologies and Astec, and that Motorola's GaAs rectifiers are being used in the field today in power converters that produce 24V, 36V and 48V DC outputs.

The primary application so far has been in space-saving high frequency DC-DC convert-

ers where high efficiency is required and where silicon rectifiers are unable to provide the performance needed. Much of the demand for equipment of this type comes from telecommunications-related systems, such as central office switches, repeaters, and cellular base stations. The prices for the GaAs rectifiers range from \$6 - \$14, which is a 2-3x premium over Si rectifiers. According to Scott Delaney, Marketing Manager for Motorola's Power Products Division, that is down from an approximately 5x premium when the devices were first introduced in late 1995.

*Continued on page 14*

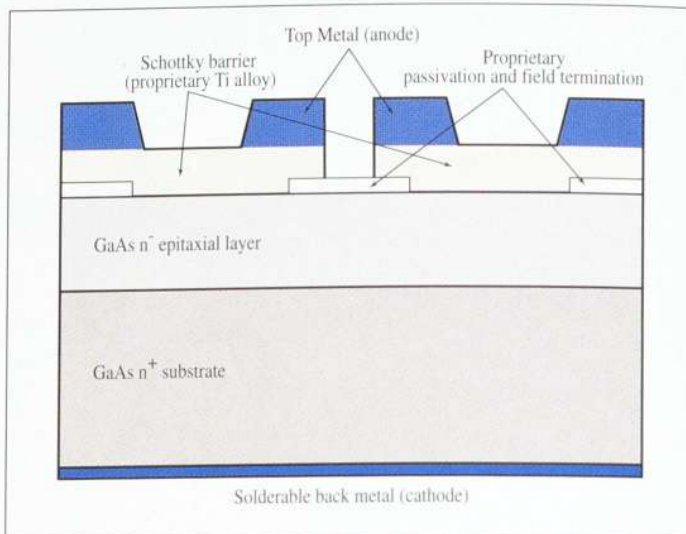


Figure One: Schematic diagram of Motorola's new GaAs Schottky diode rectifier, fabricated from n- GaAs epi grown by VPE on an n+ GaAs substrate.

## Background: Power Diodes

A **rectifier** is a two-terminal junction diode which is used in step-up and step down DC - DC voltage conversion. Rectifiers are also key components required in the conversion of AC voltage to DC voltage, and are therefore needed in virtually all non-battery operated electronic systems, where the incoming AC voltage must be converted to the DC voltage which is required to bias and operate the electronic devices within the system.

Rectifiers are commonly fabricated from silicon **p-i-n diode** structures. This is a minority carrier device in which, under forward bias conditions, electrons are injected into the p-region and holes are injected into the n-region. Large junction areas are typically used in order to reduce the current density in these devices, which in turn reduces device heating, and helps to prevent thermal breakdown. They are usually packaged as discrete devices, but can be connected in parallel to increase their power handling ability.

Standard Si p-i-n diodes are generally suitable for the vast majority of rectification applications at this time. However, a key exception to this rule is cases where input frequencies are > 10 kHz. When a high frequency

change in polarity (forward bias to reverse bias) is attempted, the reverse recovery time of the p-i-n diode is too long to keep up with the change in input frequency because of the amount of time required for the recombination of the minority carriers stored in the device. This effect can be somewhat compensated for by diffusing gold or platinum into the Si to speed up minority carrier recombination. Two classes of these special Si p-i-n rectifiers are commonly recognized: Fast Recovery devices, which can be switched in 250 - 750 ns; and Ultrafast or Super-Fast devices, with reverse recovery times between 25 and 100 ns.

Another alternative is to use a **Schottky diode** structure instead of the p-i-n structure. In a Schottky diode the electrical barrier is formed between metal and semiconductor regions, not n- and p-regions. In the absence of p-n junctions there is no appreciable storage of minority carriers. As a result, the reverse recovery time of Schottky diodes is much less than those of p-i-n diodes. Schottky diodes are also capable of providing lower turn-on voltages than p-i-n diodes, and as a result will dissipate less power and run at higher efficiencies.

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## The Advantages of GaAs

Motorola has been manufacturing Si rectifiers for more than 40 years, and it is their firm belief that Si is reaching its physical limits in meeting the basic performance requirements at high frequencies, including fast switching speed, low forward voltage drop, and high temperature capability. According to Delaney, Motorola's new rectifier line benefits from two advantages: the use of GaAs, and the use of Schottky diode technology. Conventional rectifiers made from Si p-i-n diodes are suitable for the majority of applications, but their switching speed at high frequencies is limited due to minority carrier charge storage. Silicon Schottky diodes can overcome this problem; however, they have limited usefulness above 150 - 200V because they suffer from large leakage current and switching losses. But GaAs, with its larger bandgap, allows the fabrication of Schottky diodes with breakdown voltages in excess of 1000V. In addition, in a GaAs Schottky the surface Fermi level is pinned due to a high density of surface states, resulting less surface leakage and higher operating voltages.

A schematic of the basic Motorola device is shown in Figure One. Despite its deceptive simplicity, Delaney reports that a great deal of developmental effort was required to produce a manufactureable product, especially with regard to the termination, passivation and titanium barrier metal processes. However, the effort is expected to pay-off, because the ability to use Schottky devices for high voltage applications provides faster switching capability to a voltage range not previously well served by p-i-n diodes. In Si, the switching speed becomes slower as breakdown voltage increases

es. In addition, GaAs can endure much higher temperatures than Si, again because of its larger bandgap. One possible negative attribute of that larger bandgap is the fact that it also causes the forward voltage drop,  $V_f$ , of GaAs to be large, but this fact is mitigated by the fact that GaAs has a carrier mobility that is five times larger than that of Si. The voltage level for which the  $V_f$  of GaAs is similar to Si is about 200V; above 200V, GaAs runs lower. This is a fortuitous circumstance, since Si Schottky performance deteriorates at ~150-200V.

## Benefits at the System Level

The argument for using GaAs in rectifier applications is that the features described above allow the customer to more than recover the added cost of the component by reaping the benefits of a more efficient power supply. The most outstanding characteristic of the GaAs diodes is their reverse recovery time. Figure Two illustrates the reverse recovery waveform for Motorola GaAs and Si Schottky rectifiers operating under identical forward biased conditions of 6 amps. The amplitude of the peak reverse current and duration is much less for the GaAs device. The recovery time,  $t_r$  (defined as the time that it takes for the current to damp back to zero after it initially crosses the zero current level) is typically 15 ns for GaAs and 30 ns for Si at room temperature. However, it should be noted that these devices usually operate well above room temperature. Figure Three shows the leakage current comparison of 200V Si and GaAs rectifiers. In the case of the GaAs rectifier, the leakage current doubles every time the temperature increases by 16°C for temperatures up to 100°C and every 12°C for temperatures between 100°C

and 150°C. In comparison, the Si Schottky rectifier shows leakage current doubling every 7-8 °C up to 150°C. Not only does leakage current increase at these higher operating temperatures, but so does the  $t_r$ . Figure Two shows that for GaAs and Si rectifiers operating at 125°C  $t_r$  increases from 15 to 17 ns for the GaAs device, whereas the Si device shows a much larger increase, from 30 to 52 ns. Motorola's Salih attributes this to a factor of three increase in the charge stored in the Si diode, while there is no significant change in charge storage in the GaAs device. Another effect which is illustrated in Figure Two is that the reverse recovery current fall time of the Si Schottky rectifier is very steep compared to that of the GaAs rectifiers. When this high rate of change in current (di/dt) is coupled with stray inductances, it causes voltage transients, as well as ringing in the circuit.

In the final analysis, the most important characteristic of the GaAs Schottky rectifiers is how well they improve the performance of power conversion systems. Motorola has compared the performance of 600V GaAs rectifiers in DC-DC converters to those using both Si Schottky rectifiers and Ultrafast Si p-i-n diodes. The frequency limit for the Si Schottky device was 100 kHz, while at this level the GaAs Schottky device was still improving in efficiency, reaching a maximum efficiency of 94.2% at 300 kHz. In the case of the Si Schottky rectifier the efficiency was 87.8%, while that of the Ultrafast p-i-n diode was 81%. At first glance it may appear that the difference in efficiency between the GaAs and Si Schottky devices is not all that great at 6.4%. However, when operating at 400 W, this means that the GaAs Schottky converter dissipated only 23.2 W, as compared to the 48.8 W dissipation

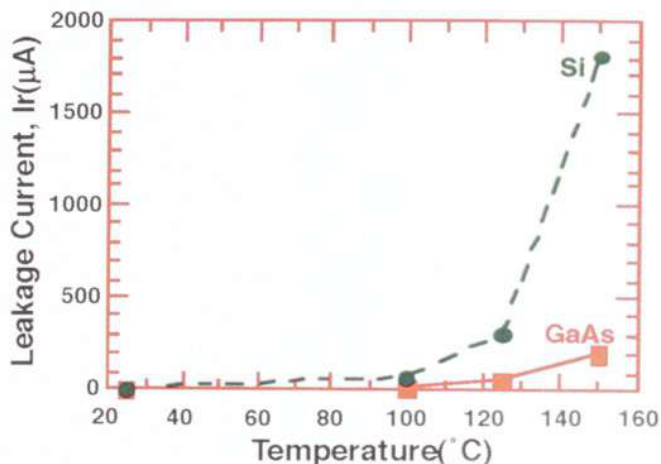
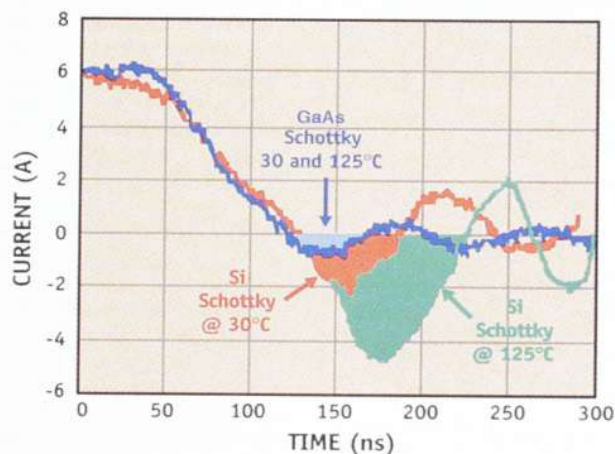


Figure Two and Three: Figure Two (left) shows the reverse recovery characteristics for a GaAs Schottky diode in comparison to a Si Schottky diode at room temperature and 125°C. Figure Three (right) shows the leakage current as a function of temperature for GaAs and Si diodes.

pated by the Si Schottky - nearly twice as much. This means that using the GaAs device allows twice the power to be converted for the same amount of loss - a significant difference. Also, in compact DC to DC converters, the power loss has a significant impact on the amount of heat sink area which is required. In the current example the heat sink temperature rose by 50°C in the case of the Si rectifier, but only 30°C when the GaAs rectifier was used.

### GaAs Niche

Motorola's new GaAs rectifiers are currently being used primarily in one niche - telecommunications networks. According to Delaney, "the initial early acceptance has been in the high performance end, with Lucent and Astec featuring the diode in some of their high end power supplies. Entry into the market via such a niche is to be expected, because of the premium that must be paid for the product." However, Delaney also reports that volume manufacturing has been launched<sup>1</sup>, and this fact, coupled with increasing yields, is bringing

<sup>1</sup> The epi for the devices is grown at Motorola using VPE on 2" and 3" wafers. Plans for scaling up to 4" are in the works.

prices down. He doubts whether GaAs diodes will be competitive with Si at much less than 200V, but he is optimistic that the lower price points will bring broader market acceptance at the higher voltage ranges.

### Don't Rule Out the p-i-n Diodes

While Motorola is clearly far ahead in the GaAs rectifier field, there are several other companies which are believed to be exploring it as well, including Texas Instruments, ABB, SGS-Thomson, and Fuji. The most unique entrant into this field is International Semiconductor Corporation [Santa Monica, CA], a developmental stage company that owns a majority interest in GAD Semiconductors Ltd. [Migdal Ha' Emek, Israel]. GAD is an 11-employee spin-off from the Ramot University of Tel Aviv, formed in 1993 for the purpose of developing GaAs p-i-n diodes as a commercial product. The company reports that in 1995 it developed a series of 10 amp GaAs p-i-n diodes with switching times approaching 14 ns. This product is ready to go into production for Power Factor Correction (PFC) applications. Earlier this year GAD introduced a 20 amp model. International Semiconductor claims to have received a firm

production order for GAD's GaAs p-i-n diodes from Motorola, and reports that it recently received an order for test quantities from SGS-Thomson. One interesting aspect of the company's marketing plan is that they apparently have their eye on the European home appliance market. A new European standard proposed for 1997 would require all appliances to have PFC capabilities - not a bad idea, given that the standard European power supply is 220V, compared to the 115V standard found in North America. The company lists European appliance giant Braun among its prospects, and reports that it is in discussions with at least one European distributor about this application.

In the long run, International Semiconductor and GAD hope that they can not only find a market for mass-produced GaAs p-i-n diode rectifiers, but also find other applications for their core technology as well. Possibilities they are exploring include switching transistors, thermosensors, x-ray sensors, neutron detectors, ultra-low capacitance capacitors, and novel controlled semiconductor capacitors (varactors). But for now, their primary challenge is demonstrating that the seemingly simple GaAs p-i-n diode can both find a market niche and be mass-produced in an economical fashion.

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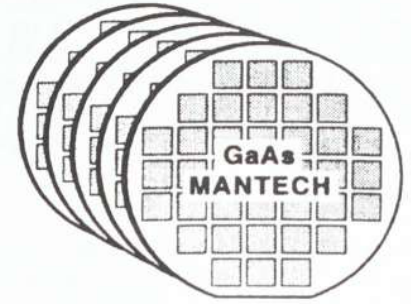
# 1996 GaAs MANTECH Conference

April 28-May 2, 1996

San Diego, California

*To fully exploit the material and device advantages of GaAs, manufacturable process techniques must be established*

ROBERT A. METZGER



It has been apparent for several decades now that III-V-based materials and the devices that can be fabricated from them possess performance characteristics superior to what can be obtained with Si-based materials and devices. However, in order to establish a manufacturable product which can compete in the "real world", much more is needed than just the blazing performance which can be obtained in a research or university environment. Above all else, a stable, manufacturable device process is required in order to produce a commercially viable product. The realization of the importance of process development was recognized at the 1996 International Conference on GaAs Manufacturing Technology ("GaAs MANTECH"), the tenth in a series of conferences aimed at improving the manufacturability of GaAs ICs. This was the first year that the conference was organized as an international meeting.

## Etching

Etch rates, selectivities between different compounds, and the profile of the resultant etched material, are all critical factors in the establishment of a manufacturable semiconductor etch process. Undoubtedly, one of the most important issues in etching is the ability to etch to a specific depth in a controllable and reproducible manner, whether this is during recess gate etching for a MESFET or HEMT, or to expose the base or collector regions of an HBT. Traditionally, etch depth control has relied on either calibrated etch rates, or on the use of etch stop layers. However, several new methods of controlling etch depths were presented at this years MANTECH.

As described by G. DeSalvo and coworkers from Wright-Patterson Air Force Base [WPAFB, OH], normal III-V semiconductor wet etching occurs at the semiconductor-etchant interface, where several chemical reactions are occurring in parallel - the formation of new surface compounds, and the removal of those compounds. DeSalvo described a method referred to as digital etching, which separates the parallel chemical reactions which are occurring at the surface into two distinct processes. The first process step forms a thin surface layer compound, where the thickness of this compound is fixed due to the self limiting nature of

the chemical reaction used. After the establishment of this layer, the surface is then cleaned to prevent mixing of the chemicals present in the first process with those which will be used in the second process. The second chemical reaction then selectively removes the newly formed surface film compound but does not affect the unreacted layer beneath it. In the etching of GaAs, a standard wet chemical etching process consists of using  $H_2O_2$  and HCl, in which the  $H_2O_2$  oxidizes the GaAs, and the HCl etches away the oxidized GaAs. By separating the oxidizing and the etching processes by using the digital etching technique, the  $H_2O_2$  is first used to form an oxide layer (this is a diffusion limited process, and therefore self limiting), the surface then cleaned with DI water, and the oxidized GaAs is then removed with HCL. This process is done on a slightly modified photoresist spinner (modifications required to handle the caustic nature of the etch). This process is repeated as many times as necessary to etch to a total desired depth. With this technique, an etch resolution of 16 Å is obtained. Used in the fabrication of a AlGaAs/InGaAs/GaAs PHEMT, it was shown that the gate recess etch using this technique produced the same device characteristics as a device using a selectively etched gate recess process, and therefore opens the way for highly controllable etching without the need of etch stop layers.

Also relying on the nature of self-limiting reactions is work performed by Daniel Dobkin of Enigmatics [Sunnyvale, CA] and coinvestigators from Watkins-Johnson Company [Palo Alto, CA], in which an electrochemical based selective etching scheme is developed in a commercially available electrochemical profiler using solutions of citric acid and potassium citrate. This technique relies on the electrochemical formation of a passivating oxide on Al containing layers in order to stop the etching process. Almost perfect selectivity for GaAs over thin layers (9-12 Å) of AlAs were obtained with this technique.

The nitride-based material system has received wide attention for its optical properties, but L.S. Klingbeil and coworkers at Motorola [Tempe, AZ] report on the use of sputtered AlN for preventing surface damage and minimizing surface state densities of GaAs-based devices during Reaction Ion Etching (RIE). Because AlN shows

high selectivity to fluorine-based dry etches, this material is an ideal candidate as an etch stop during fluorine-based RIE etching of oxides and silicon nitrides. It was found that the use of AlN within the spacer formation process prevented RIE exposure of the channel surface and resulted in almost complete elimination (>93%) of transient behavior, where this is characterized as the time required for currents to stabilize after the application of a gate voltage. In addition, Schottky barrier characteristics improved with the use of AlN etch stop layers, and the across wafer variation in threshold voltage was reduced by 50%.

## Lithography

Lithography can be quite demanding in the definition of gate dimensions for FET devices, where in some research environments, gate lengths are entering into the sub-0.1 µm regime. However, it is not just small gate lengths which are required for high speed FET-based devices. In addition, the specific profile of the gate metal (mushroom, gamma and T profiles) is of critical importance in order to reduce stray capacitance and decrease gate resistance, where it is typically required that a combination of small gate lengths at the point of the metal-semiconductor interface (0.1 to 0.25 µm) must be coupled with wider structures at the top of the metal gate (0.5 to 1.5 µm). These two, often conflicting requirements, typically require multiple layers of resist, multiple exposures, and multiple metalizations in order to obtain the desired gate profile - a process which is critical to control if high yields are to be obtained.

Because of the smaller wafer sizes used by GaAs manufacturers (3-4 inch) as compared to Si manufacturers (6-8 inch), GaAs manufacturers are often faced with the prospects of using an older generation optical lithography tool (not only from the perspective that some of the newer tools are not 3-4 inch compatible, but also from the economics perspective that an older generation lithography system can be much less expensive). Lawrence Studebaker of Hewlett-Packard [Santa Rosa, CA] compared the capabilities of an older lithography tool with advanced mask techniques to a newer lithography tool with conventional mask techniques, by contrasting a G-line (436 nm) stepper

process utilizing a chromeless phase-shift mask (PSM) and AZ6200 resist to a deep UV I-line (365 nm) stepper process using a conventional chrome photomask and APEX-E resist, for the fabrication of 0.2  $\mu\text{m}$  mushroom gates. Studebaker demonstrated that both processes are capable of producing 0.2  $\mu\text{m}$  gates, where the G-line process takes advantage of existing older capital equipment, but does have lower throughput due to the requirement for double exposure (needed for the PSM process) and also requires a more expensive phase-shift mask. In contrast, the I-line process requires greater capital investment, but has higher throughput, and uses less expensive conventional masks. Studebaker points out that by combining deep UV with PSM that optical lithography is capable of 0.1  $\mu\text{m}$  gate lengths, thereby pushing optical lithography into the realm which had been the exclusive domain of E-beam lithography.

K.M. Renaldo and coworkers at Westinghouse Electric [Baltimore, MD] reported on a Design of Experiments (DOE) approach in the optimization of processing parameters for a three resist layer multiple E-beam exposure, selective develop process, for recessed PHEMT T-gates. Using a three layer PMMA, P(MMA-MMA) copolymer, PMMA resist stack and examining 12 different processing parameters (including resist thicknesses, E-beam dose, and develop times), a research-type process was refined into a manufacturable tolerant process through the optimization of gate lithography processing parameters. It was

determined that if the slope of the resist on either side of the base of the "T" gate structure was too vertical, that the crossbar attachment of the top of the gate structure became marginal, resulting in wafers with missing crossbars. Using these PHEMTs in the fabrication of a 0.25  $\mu\text{m}$  gate length Ka-band power MMIC (total gate periphery of 6  $\mu\text{m}$  consisting of 120 50  $\mu\text{m}$  wide gates), 1.1 W of power and 25 dB gain at 31.33 GHz was obtained. Using this power MMIC to benchmark the improvements in the gate lithography process, MIMIC yields climbed from less than 5% before the DOE approach was initiated to nearly 50% with the implementation of the DOE results.

Another method to obtain small gate lengths is the use of angle-evaporation techniques, in which gate metal deposition is done with wafers mounted in a non-normal orientation, so that the metal purposely covers the sidewalls of existing structures on the wafer. C.Y. Lee and coworkers at Watkins-Johnson [Palo Alto, CA] describe a 0.2  $\mu\text{m}$  gamma-gate process FET process. The technique uses a multiple layer resist structure and two angle evaporations to define an aluminum mask above the wafer surface to control the width of the gamma-gate head, along with a Ge plug on the wafer surface in order to define the gamma-gate footprint. As a result, the gate length is well controlled by the evaporation angle and resist thickness. Using this approach, 0.2  $\mu\text{m}$  gamma-gates with less than  $\pm 0.01 \mu\text{m}$  (1  $\sigma$ ) gate length variation across a 2 inch wafer were obtained.

Unlike the case for FET-based devices, where critical gate dimensions are approaching 0.1  $\mu\text{m}$ , HBTs have much larger geometries, with only the most experimental of structures approaching the 1.0  $\mu\text{m}$  regime. However, in order to optimize HBT performance, self aligned emitter-base structures are needed, where minimum spacing between base-metalization and the exposed emitter sidewall is highly dependent on lithography. J. Sewell and coworkers at Wright Patterson Air Force Base [WPAFB, OH] describe a self aligned HBT process for thermally shunted GaAs/AlGaAs structures in which the emitter elements are thermally coupled to each other in order to reduce temperature nonuniformity and prevent current channeling which limits device power performance. The key to this process is in the use of electroplated gold on the exposed emitters, which provide a retrograde profile due to the sidewall slope of the resist openings to the emitter. This retrograde emitter metalization profile is then exploited in the self aligned metalization of the base shunt. Using this process, HBTs exhibiting  $f_t$  of 60 GHz,  $f_{max}$  of 100 GHz and power densities of 5 mW/cm<sup>2</sup> have been obtained.

As evidenced by the work presented at this years MANTECH, the commercial viability of GaAs will not be due to any intrinsic material/device characteristics but by combining those superior characteristics with mature, stable and highly controllable processes.

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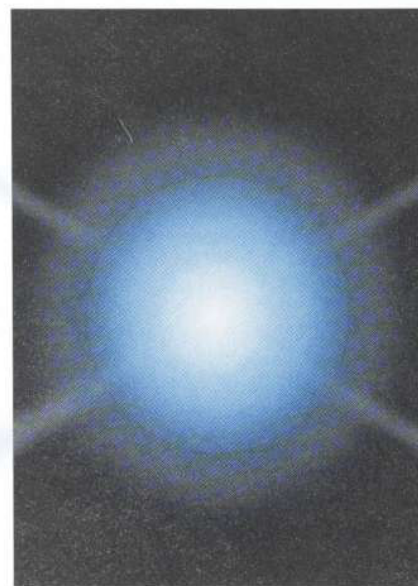
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| Oxygen           | < 100 | ppb |
| THC (as Methane) | < 50  | ppb |
| Water            | < 200 | ppb |

# Celebrating Our First Year of Publishing

This issue of *Compound Semiconductor* marks the successful completion of our first full year of publishing. We've decided to mark the occasion by using these two pages to update a selection of the most interesting stories and themes that we have covered over the past twelve months.

We'd like to take this opportunity to say "Thank You" to all of our subscribers for supporting our publication. We hope that you enjoy reading it as much as we enjoy producing it!

## Nitrides, Naturally



The easiest decision we made in our first year was picking the topic the cover of our premier issue: short wavelength light emitting devices. Blue LEDs were the hottest topic around last summer; this summer, blue lasers are the most interesting subject for discussion. Anyone familiar with the field knows that Nichia Chemical and its head of R&D, Shuji Nakamura, are the vanguard of progress for these devices. As we reported in our last issue (CS 2(3) 22), Nakamura has recently announced some important updates on his

GaN blue laser, including the fabrication of cleaved facets for a structure grown on sapphire and successful growth on a spinel ( $MgAl_2O_4$ ) substrate. This issue brings news of further expansion of Nichia's LED manufacturing capability (see page 25). Thus we thought it appropriate to mark our first anniversary by soliciting Nakamura's opinions about some topics that will likely effect future progress in the nitride field:

**CS:** What is the forecast for commercializing your GaN laser?

**Nakamura:** "We are very close to CW operation of the laser diodes. We want to start selling the blue LDs in 1997 or 1998."

**CS:** In your opinion, when will the manufacturers of CD and DVD players be ready for the "blue laser format" for optical data storage?

**Nakamura:** "Between 1998 - 2000."

**CS:** Last year you demonstrated that you could achieve yellow and even red emission from InGaN/AlGaIn SQW structures - although the output at the longer wavelengths was rather weak. (See CS 1(3) 8). Are you working on improving these devices? Do you think that a monolithic red-green-blue (RGB) chip can be fabricated from the GaN system?

**Nakamura:** "At present, we have no plans to develop commercial yellow and red nitride LEDs, because cheap AlInGaP models are already available. We can fabricate a monolithic RGB chip any time using nitrides for indoor display use. However, the yield would be small, and the brightness is probably not high enough for outdoor use due to poor performance of the red nitride LEDs."

**CS:** What are the biggest technical challenges that you face in the further development of nitride LEDs and lasers?

**Nakamura:** "For LEDs, the biggest challenge is how to grow high In content InGaN layers for red LEDs. For lasers, the biggest technical challenges are high operating current density and high voltages, which must be reduced for CW operation."

**CS:** Do you think that sapphire is the best long term choice for a substrate?

**Nakamura:** "For the long term, GaN bulk crystal would be the best substrate. However, it is unlikely that it would become feasible in the near future considering the size and the price."

**CS:** Do you have any plans to work on nitride-based microelectronics?

**Nakamura:** "No, I don't. I'm interested only in optoelectronic devices."

## Vitesse and D

When thinking about ICs, it is easy to equate "digital" with "computing". Therefore, when two GaAs supercomputer manufacturers (Convex and Cray) disappeared last year it seemed the harbinger of bad times for digital GaAs. Thus it has been a very pleasant surprise to see how well Vitesse Semiconductor, the world's largest GaAs IC fab, has done since then. Production revenue for the first half of the current fiscal year is up nearly 70% with 15-20% profit margins, which is driving share prices to remarkable levels.

The key to Vitesse's success has been communications, not computing, applications. In the early 1990's the majority of Vitesse's revenue did come from the computer sector, but, according to Vitesse's President and CEO Lou Tomesetta, most of that work was custom projects, whereas the company's standard products, developed using internal investment, have always been aimed at the communications market. As the volume of computer business has shrunk until it is virtually zero, Vitesse's telecommunications business has grown 70% a year. Vitesse plans to be active in all of the three big applications for serial communications: SONET currently accounts for around 50% of revenues; Fibre Channel brings in around 10%, and is expected to grow rapidly; and production in the ATM area is expected to debut in 1998. Fueled by the growth in telecommunications, Vitesse has been growing at around 10% per quarter - results that make the GaAs microprocessor seem like a relic from a by-gone era.

## DVD's are Just Around the Corner

CD-players, both audio and ROM, are very big business, currently selling at a rate of nearly 100 million units a year. This makes the launch of the higher data-density follow-up product, the digital versatile disk (DVD), big news. In Japan the DVD is considered to be the most important new consumer-electronics product since the introduction of the VCR in the 1970's. The electronics giants who are leading the DVD field have frequently seemed on the verge of falling out with each other, an event which would upset standardization of the format and delay introduction. However, it now appears that a consensus has been achieved that nothing should be allowed to prevent the first products from being launched this fall. Estimates for market penetration are hard to pin down - on the low side, the forecast is for 50 million players annually by 2000; the high estimate is roughly twice that.

All of which means demand for semiconductor lasers. The new DVD standard will require 635 - 650 nm AlGaInP diodes, in contrast to the 780 nm AlGaAs lasers used in the CD format. Output power for the read-only version will be ~5 mW. Erasable DVD systems are planned for introduction in 1 - 2 years time, but observers say progress in this area may be held up by lack of a high-yielding process for producing the higher power (35 mW) versions of the lasers that would be required.

And who will be manufacturing all of this new equipment? At this point it appears that the top three manufacturers of DVD players will be Matsushita (which owns the National, Panasonic, Technics and Quasar brands), Sony and Toshiba. Sony plans to begin producing 100,000 systems per month in August. They are known to have substantial captive laser manufacturing capability, and recently installed a new processing line to meet demand from the DVD application (see CS 2(2) 15). Toshiba is also believed to be planning to use captive laser manufacturing. *The Economist* recently reported that Matsushita is planning to outsource the optical pickups. Among the potential merchant laser manufacturers, Sanyo has been the most visible in the early stages. Elsewhere in this issue (page 22) we report their aggressive forecast for DVD laser manufacturing: 300,000 units per month by September, and 1 million units per month by the end of FY 1997. If they can meet these goals, they will be able to meet roughly one-half of the total demand for DVD lasers.

## al GaAs Doing Well



## What About Silicon Germanium?

There are reams of evidence that suggest that SiGe can produce high-performance circuits for both analog and digital applications, but a vital question has remained unanswered: can SiGe compete in the marketplace? At present the question is academic, because there are no SiGe devices in production. But that technology may have recently moved one step closer to becoming a reality.

In mid-May IBM and Hughes Electronics announced a collaborative effort to create high-speed communication products based on IBM's SiGe HBT process. The two companies have been cooperating on SiGe research for some time, but this new agreement marks the transition from the research to the development phase, according to a Hughes spokesperson. An ambitious time-table has been set-out under which Hughes would be using SiGe-based circuits in consumer products sometime in 1997.

Under the new agreement IBM will supply Hughes with fully processed SiGe HBT wafers which Hughes will use to build prototype devices for testing in potential applications in several divisions, including Hughes Network Systems, Hughes Aircraft, Hughes Telecommunications & Space, and Delco Electronics. It appears that analog applications will be explored first. Details about applications were not available, but the *New York Times* carried a story in its May 13 edition which speculates that one of the first products would be an automotive collision avoidance system.

According to IBM's Bernie Meyerson, the SiGe production process at IBM will be fully qualified for standard manufacturing before the end of this year. No "catalog products" are planned, but he expects that their foundry service will have multiple customers drawn from the ranks of companies which have partnered with IBM in developing the technology. Hughes is now the most visible prospect, but Meyerson reports that there are others as well, although their names cannot be revealed for reasons of confidentiality. All of which suggests that the 1997-1998 period should be a very interesting phase in the development of the GaAs industry, in that it appears that the debate between SiGe and GaAs may finally move off paper and into the system design arena.

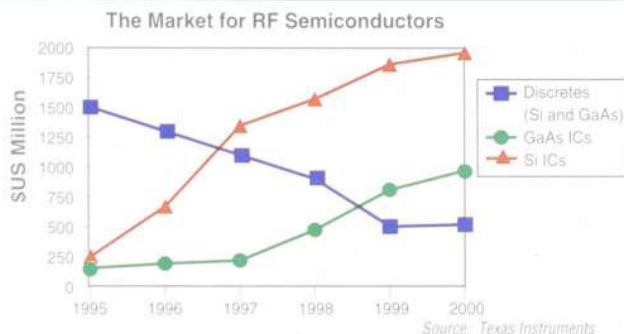


Figure One: Texas Instrument's forecast for increasing integration in RF semiconductors.

## Greater Integration in Cell Phones: Fabs Lay-Out Their Strategies at '96 MTTs

One of the re-occurring topics of discussion in this magazine over the past twelve months has been the status of integration in GaAs analog devices for use in wireless handsets. Portable phones have provided, at last, the high volume markets that GaAs fabs have been seeking for years. However, until recently there has been surprisingly little demand for high levels of RF integration, due in large part to the fragmentation of the market caused by the large number of competing standards and technologies. Discretes, made from either Si or GaAs, have predominated.

All of that is now changing. Tim McCaffrey, Manager of New Product Development for Texas Instrument's RF/Mixed-Signal Products, believes that Si and GaAs ICs will very quickly overrun the position held by discretes in today's wireless handset market. His forecast for the next five years is summarized in Figure One. He notes two primary reasons for this shift: greater integration will provide significant cost reductions for the handset manufacturers; and more integrated RF front ends will result in reduced power consumption, thereby extending talk-time.

With all this in mind, TI and others rolled out their new, more highly integrated cell phone chips at the 1996 Microwave Theory and Techniques Symposium (MTT-S), held in June in San Francisco. TI is planning to release a total of 25 new Si and GaAs RF products within the next year. The company favors Si on a cost/performance basis for analog and 900 MHz applications, and plans to transition its RFIC technology from BiCMOS to CMOS, and leave BiCMOS to dominate in the intermediate frequency (IF) and broadband territories. But GaAs is favored for CDMA applications and the higher frequency (1.9 GHz) PCS standard.

Another company which is clearly hedging its bets with respect to semiconductor technology is Philips, which introduced two Si front-end devices for 900 MHz analog cellular that the company claims reach new lows in power consumption and cost while increasing performance. By putting more features onto the Si and using fewer discrete components, the company believes these chips are a step toward what it sees as the ultimate goal: a one or two chip-radio. But the company is keeping its GaAs options open as well. As we reported in our last issue (*CS* 2(3) 18), Philips has teamed up with TriQuint to gain access to the latter's high volume GaAs fab. "It's important to offer customers a buffet of technologies," said Todd Antes, Philips' marketing manager for wireless communications.

And TriQuint itself took advantage of the occasion to host a press conference to introduce two new products - a pair of dual-mode RF power amplifiers - and to argue the case for GaAs. With RF integration an eventual reality, and GaAs being the only solution that makes sense for power amplifiers - as the company is wagering - then GaAs is the future of RF technology, concluded Chris O'Connor, marketing and applications manager for TriQuint. He firmly asserts that GaAs integrated circuit power amps will re-define cell phone technology, and that silicon will not win the RF component battle. Readers of this magazine are likely to hope that he is correct.

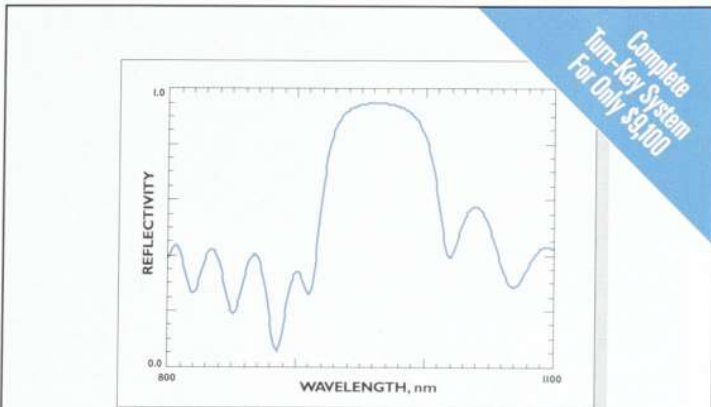
## IEEE Urges Demo of Laser Satellites

The IEEE has issued a report urging the U.S. Government to fund demonstrations of laser-based satellite communication (satcom) systems, with the aim of proving that they offer several cost and performance advantages over conventional microwave technology. The major advantages of laser satcom are said to be smaller mass, power and volume requirements resulting from reduced transmit/receive apertures and lower divergence beams arising from the use of wavelengths which are three orders of magnitude shorter than microwaves. As summarized in Table One, the report holds that laser satcom mass and cost should be about 33% that of microwave systems, and power consumption should be ~50%. Recurring costs per terminal should also be lower in laser satcom systems, so that existing microwave systems could benefit from converting if three or more new terminals are required. Additional performance advantages are also said to be available with laser satcom, including better security and better protection against jamming (both attractive for military applications) and the use of "an essentially unlimited and unregulated spectrum with virtually no interference".

The Jet Propulsion Laboratory (JPL) at CalTech is the lead center within NASA for satellite laser communications. According to Tim Krabach, Program Manager for Small Satellite Technology at JPL, there are two competing views of regarding the components that should be used to build laser satcom networks. One camp advocates using the 1.55 micron wavelength to allow direct feed from the satellite into fiber optic long-haul telephone transmission lines. In this case the transmission sources would likely be laser diodes with Er fiber amplifiers to boost transmission power. The alternate proposal is to transmit at 0.86 microns, using solid-state lasers. This

camp argues that the direct feed concept is too technologically challenging to be practical, and that the 0.86 micron system allows for a much simpler architecture, especially on the satellites. Krabach reports that the determination of the operating wavelength "is a matter of intense discussion", and is, at this time, unresolved. In either case the receivers would likely be based on InGaAs or InGaAsP avalanche photodiodes.

Laser satcom is not a new idea. The technology has in fact been under development in the USA for 30 years, and for more than 15 years in Japan and Europe. The report argues that all of the pieces which are necessary to implement laser satcom are now available, or will be soon, but the cost of performing the final demonstration of the viability of the idea is too high for industry to bear alone. (The report also attempts to raise the specter of the USA losing technological leadership to the Japanese or Europeans.) The final recommendation is that the U.S. Department of Defense and NASA should team up to "conduct the necessary space flight demonstrations to establish the viability and characterize the performance of laser satellite communication systems". NASA is said to be in the process of preparing a response.



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### Data Rate and Communications Technology

| Feature                     | 225 Mbps   |           | 750 Mbps   |           |
|-----------------------------|------------|-----------|------------|-----------|
|                             | Laser      | Ku-Band   | Laser      | 60 GHz    |
| Mass                        | <50 kg     | ~180 kg   | <55 kg     | ~215 kg   |
| Power Consumption           | <125 W     | ~250 W    | <220 W     | ~300 W    |
| Antenna Size (LEO*)         | <35 cm     | ~250 cm   | <35 cm     | ~250 cm   |
| Antenna Size (GEO**)        | <35 cm     | ~250 cm   | <35 cm     | ~400 cm   |
| Development Cost            | <\$US 100M | ~\$US 40M | <\$US 100M | \$US 60M  |
| Recurring Cost per terminal | <\$US 20M  | ~\$US 50M | <\$US 25M  | ~\$US 70M |

\*Low Earth Orbit

\*\*Geosynchronous Orbit

Table One: Comparison of laser and microwave satcom systems. From "Laser Satellite Communications, Programs, Technology and Applications", a report of the IEEE-USA Aerospace Policy Committee, April, 1996.

## Phillips Demonstrates Green Laser DVD Playback

Philips Research [Briarcliff Manor, NY] reports that it has demonstrated playback using a blue-green semiconductor laser to read data from a DVD (digital versatile disk). The laser used was a ZnSe-based diode emitting at 520 nm which was jointly developed by Philips and 3M's Photonics Research Laboratories [Saint Paul, MN]. The laser lifetime at room temperature is still only 3.5 hours, but performance was sufficient to perform the demonstration. Diego Olego, group leader for the Philips effort, said "we've illustrated the real-world applicability of blue-green semiconductor lasers by demonstrating there are no inherent problems to using them with advanced electronic products."

According to Olego, the next task is to improve the laser lifetimes. He foresees that functioning blue-laser diodes for storage products might be available "by the end of the century", at least in low-power, read-only models. He does not say whether they will be ZnSe or GaN - and Philips' continued investment in GaN research (see page 25) demonstrates that the company is keeping both of its options open.

## LEDs Stop Traffic in New Jersey

The Department of Transportation for the State of New Jersey has awarded Dialight Corporation [Manasquan, NJ] a contract for \$1.47 million to provide more than 12,000 red LED traffic signals. Dialight believes that this is the largest LED traffic signal order placed in the United States to date. The LEDs used to construct the signals are AlInGaP devices manufactured by Hewlett-Packard. Around 200 - 300 individual LEDs are used in each signal.

The investment in LED signals is justified because they use up to 90% less energy and are more reliable than incandescent lights. "We project energy savings of about \$450 per intersection per year", said NJ DOT Commissioner Frank Wilson. "For the 970 intersections in which they will be installed, that adds up to more than \$400,000 a year." The state also hopes to reduce its maintenance bill. The new signals will be installed in the southern part of the state, and the NJ DOT is said to be planning to convert to LED traffic signals along all state roadways sometime in 1997. According to Dialight's Michael Mayer, several other states and municipalities are moving toward LEDs as well.

## Details on Thomson/Daimler GaAs Venture

As we reported in our previous issue (CS 2(3) 18), Thomson-CSF of France and Daimler-Benz of Germany are teaming up for a GaAs joint venture. The new company will be known as "United Monolithic Semiconductors" (UMS) and will be owned 50% by Thomson and 50% by two Daimler subsidiaries - Daimler-Benz Aerospace (DASA) and TEMIC Telefunken Microelectronic. As a result of this new joint venture the former

GaAs production activities of Thomson-CSF Semiconductors Specifiques in Orsay and the Daimler-Benz GaAs Foundry in Ulm will be merged. The "front-end" processing activities will be concentrated in Ulm, where a 4" line will be added to the existing 3" line. Back-end processing will be concentrated in Orsay, as well as the design activities, product line coordination, and marketing and sales. The respective basic research activities of both partners is not part of the joint venture, as was originally reported, and R&D will be continued at the parent companies.

According to Heinrich Dambkes, President and C.E.O. of UMS, the objective of the joint venture is to create a stronger position in the GaAs microelectronics area, a technology which is of strategic importance for both of the mother companies. GaAs components will be produced for mobile communications, radio links, traffic and automotive applications as well as defense and space use. Technologies already available at UMS cover applications from 900 MHz to 90 GHz, based on PMHFETs, MESFETs and HBTs. Dr. Dambkes cites as a special highlight a 4" silicon-like process specifically for consumer and commercial applications. It features enhancement and depletion modes as well as power profile transistors, thus enabling mixed function circuits.

The core activities of UMS will focus on standard products, ranging from GSM power amplifiers to a 38 GHz microwave link family up to a complete and very compact set of chips for collision avoidance radar. UMS will also continue to offer foundry services for MESFET and HEMT technologies.

In addition to UMS, there are five other GaAs fabs in Europe: Alcatel Telettra (Italy), Alenia (Italy), GEC (England), Philips Microwave (France), and Siemens (Germany). Thomson formerly operated a second GaAs fab in Grenoble primarily for digital circuits, but that activity was put on hold in 1995, and is now merged with with the new joint venture.

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InP  
AlGaAs  
GaN  
GaP  
InAs  
GaSb

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# News from Japan

## NEW DEVICES

### Mitsubishi Electric GaAs MMIC for Analog Cellular Phones

Mitsubishi Electric has begun sample shipments of a GaAs 2-stage amplifier MMIC for analog cellular phones. The MGF7113P is housed in a newly-developed low-thermal-resistance plastic package that measures 6.0x9.9x1.75mm and weighs 0.15g, helping reduce the size and weight of application systems. It provides an output of 1.1W when operating from 4.7V and is sample-priced at 1,500 yen (\$14.29). The company plans to produce 50,000 units monthly. The new MMIC is intended for use in analog phones for the AMPS standard, and can be adapted for E-TACS.

### Toshiba Develops New Series of Power-Saving LEDs

Toshiba has developed a new series of power-saving InGaAlP LEDs which are intended to be lost-cost components which provide the proper luminance range for portable devices. The company claims that their new "TLxU Series" features 1/10 the power consumption of conventional LEDs. A 612nm orange LED in the series features a current of 20mA at the luminous intensity of 2600mcd and 2mA at 260mcd. The company attributes the reduction in power consumption to the use of the quaternary materials and a proprietary optical simulation technique. The company will ship samples from July, at 20-30 yen (18-28¢), and start volume production at 5 million units per month in September.

### Sanyo Electric to Sample-Ship LNA MMIC

Sanyo Electric has developed and will sample-ship from July a GaAs low-noise amplifier MMIC. Designed for use in the front end of mobile communications equipment, the SPM0103A achieves a noise factor of 1.1dB and a linear gain of 12db. It operates on 3V and at 20mA, is housed in a 2.9x1.5mm<sup>2</sup> mini mold package, and sample-priced at 500 yen (\$4.59). Sanyo will be producing 50,000 units monthly at the end of this year, targeting high-end cellular phones and PHS phones.

### NEC develops GaAs CATV Power Amplifier ICs

Sample shipments of GaAs CATV power amplifier ICs have been launched by NEC. The company is believed to be the first Japanese supplier to enter this market. The gain-stage pre-amp IC, sample-priced at 15,000 yen (\$137.61), and the power-stage post-amp IC, sample-priced at 20,000 yen (\$183.49), are 770MHz CATV power amplifiers able to transmit 110 channels of TV programs. NEC also markets Si bipolar CATV power amplifier ICs. It will produce about 10,000 units of the new GaAs chip per month from August.

## RESEARCH & DEVELOPMENT

### Matsushita Electronics Develops Self-Excitation DVD Laser

Matsushita Electronics has developed a 650nm self-pulsating semiconductor laser for DVD applications. The company will start mass production of a DVD-ROM semiconductor laser with an output of 5mW this summer and a 30mW-output DVD-RAM semiconductor laser later this year in order to meet demand for DVD equipment which will reach the market this fall. Stored in a 5.6mm-diameter package, 1/10 the size of conventional units, the red semiconductor laser has a proprietary structure which contains a GaInP saturable absorption layer slightly above its disordered multiple quantum-well active layer made of GaInP and AlGaInP, which helps it achieve a super-low noise level.

### Matsushita Electric Develops Pump Laser for 1.55 micron

Matsushita Electric has developed what it describes as a high-output semiconductor laser for amplification of 1.55 micron optical signals used in CATV and video-on-demand services. The 1.48-micron pump laser generates 260mW at 25°C and has a lifespan of 100,000 hours. A module integrating the laser as well as lens and optical fiber achieves an output of about 180mw, which the company says is nearly twice the optical output of conventional modules. Sample shipments are expected to begin soon.

### Hitachi Develops 1Tbit Optical Storage Technique

Hitachi has developed a technique to store 1Tbit of data on optical disk using a scanning near optical microscope (SNOM). The SNOM uses an optical fiber probe, which is 50nm in diameter at its tip, much narrower than visible light wavelengths, to emit light from 10nm away on a 60nm-diameter area on a phase-shift optical disk based on GeSbTe alloy. The amorphous alloy becomes crystallized when heated, thus changing reflectivity. The SNOM can write 170Gbit of data per square inch, about 170 times larger than DVDs. The technique uses an optical detector to catch reflected light and achieves a read speed of about 10Mbps.

### Si Resonance Tunnelling Effect Device Reported

The Matsushita Electric Semiconductor Research Center has developed a silicon resonance tunnel effect device - a feat previously possible only in compound semiconductors. The company hopes that the low power consumption of such devices - up to 1/10 that of conventional devices - will allow the fabrication of advanced memory and logic chips. The company reports that the new device will be investigated to help increase the level of SRAM integration three to five times compared to devices made using the same design rule. When used for logic circuits, the device will be used to create multi-valued signal processing circuits, which can process multiple values, unlike conventional digital circuits which handles only "0" and "1." Matsushita plans to commercialize the new device by 2010.

## INDUSTRY

### Sanyo Electric to Raise DVD Laser Production

Sanyo Electric has announced that it is ramping up its production of red semiconductor lasers for use in Digital Versatile Disc (DVD) players. The company plans to achieve a monthly production target of 300,000 units by September and raise output to 500,000 units by March 1997 and 1 million units in fiscal 1997, when it expects that the market for the new DVD players will begin to take off. Tottori Sanyo is sample-shipping a 635nm, 5mW self-excited red semiconductor for use in DVD players and is scheduled to begin shipping a 635nm, 30mW sample for use in recorders in July.

### Stanley Electric to Expand IrDA Module Production

Stanley Electric will triple its IrDA (Infrared Data Association) standard-compliant module production to 300,000 units per month in the second half of this year. The company reports that this move is in response to forecasted increases in demand from both home and abroad. In April Stanley began shipping samples of the HRM100S module that conforms to the IrDA version 1.0 (2.4-115.2Kbps) and the SHARP-proposed DASK format, and the company now plans to release an IrDA version 1.1 model for 4 Mbps operation in August. Stanley is one of the world's largest manufacturers of LEDs, and ranked 8th in *Compound Semiconductor's* 1996 list of the world's largest compound semiconductor device manufacturers. According to a *Dempa Shimbun* article, the world IrDA module market is expected to grow to 2 million units per month by the end of this year.

### Sumitomo Announces Plans for 4" and 6" GaAs

Sumitomo Electric plans to increase 4" compound semiconductor wafer output at its Itami plant by 25% from the current 5,000 units monthly and begin mass production of 6" wafers as early as fiscal 1997. The company will invest about 1 billion yen (\$9.3 mil) to install new equipment at the plant within this fiscal year and is considering making an additional investment in the next fiscal year if demand picks up. Investment in 6" wafer production will reach 3 billion yen (\$28.0 mil), and output is expected to total 2,000-3,000 units monthly by 1998. The company reports that the new 6" wafers are intended for both the domestic and export markets, with the U.S.A. accounting for the large majority of export sales.

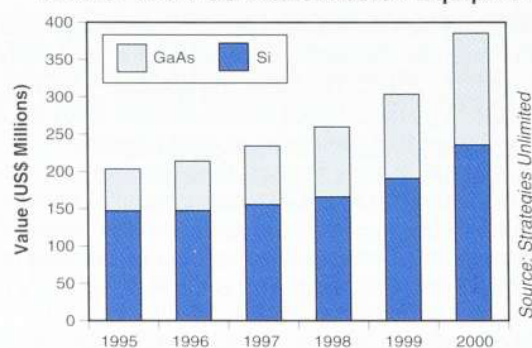
## GaAs in the Cellular and PCS Infrastructure

Strategies Unlimited (Mountain View, CA) has released a new report (see box, right) which forecasts that the market for cellular and PCS transmission equipment will grow from its current value of \$5.9 billion to more than \$10.2 billion by the year 2000. The growth, which equates to a CAGR of 11.75%, will be driven by large increases in the worldwide subscriber base, which is forecast to grow to 343 million in 2000 from 52 million in 1994, a 36% CAGR. In the next two years subscribers are expected to begin to move from the analog systems which predominate today (currently 81% of the total market) to digital cellular, so that digital will have ~45% of the market by 2000. PCS is expected to have an excellent long-term growth potential, but Strategies Unlimited forecasts that it will hold < 1% of the global wireless telephone market by 2000.

New base station installations are forecast to increase from 74,000 per year in 1995 to more than 220,000 per year in 2000. In turn, the use of microwave radio is growing rapidly for the interconnection of cell sites. The use of microwave radio is forecast to grow at a rate of 36% as microwave links become the primary means of base station interconnection.

All of this infrastructure building will create demand for RF and microwave components. Strategies Unlimited forecasts that Si technology will dominate the base station market, but GaAs FETs and RFICs will find more usage in the higher frequency PCS equipment at 1.8 - 1.9 GHz, and GaAs FETs and MMICs will be widely used in microwave radio equipment, especially for power amplifiers. The forecast for Si and GaAs RF and microwave devices in these applications is summarized in Figure One.

RF and Microwave Conents for Cellular and PCS Transmission Equipment



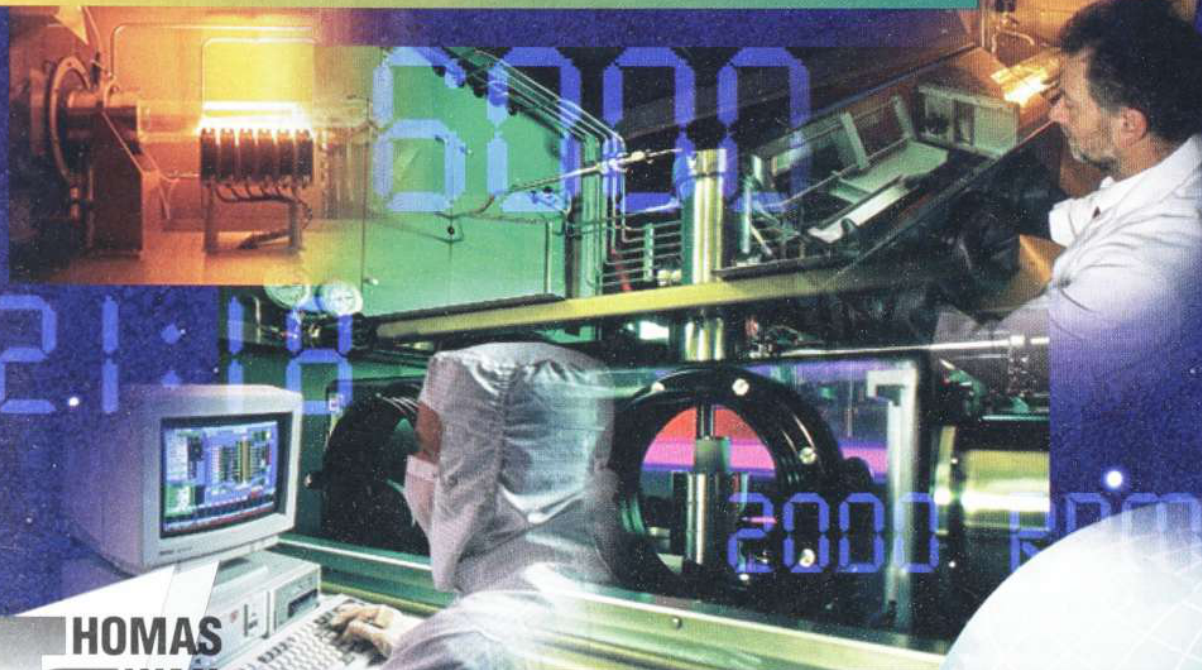
Source: Strategies Unlimited

Figure One: Strategies Unlimited's five-year forecast for Si and GaAs RF and microwave devices in cellular and PCS transmission equipment.

"RF Components for PCS Base Stations and Links - A Market Review and Forecast 1995-2000", published by Strategies Unlimited, 201 San Antonio Circle, Suite 205, Mountain View, CA 94040 USA, TEL [1] 415 941 3438, FAX [1] 415 941 5120, E-mail: strultld@ix.netcom.com. 348 pages, 300 illustrations, 140 tables, \$3,450. Provides an in-depth analysis and five-year forecast of worldwide cellular and PCS services by region and technology. Annual market estimates for analog cellular, digital cellular and PCS are provided for six world regions from 1996 through 2000. The study also profiles the world's leading manufacturers of cellular and PCS technology.

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## Discrete Inquiry into the Transistor Market

Motorola and Hewlett-Packard are the leading suppliers of Si and GaAs discrete transistors, according to a new study recently released by Allied Business Intelligence (see box, below). Motorola tops the Si market, while Hewlett-Packard leads in GaAs. See Figure One for the top five companies in each category.

According to ABI's Andy Fuertes, the greatest incidence of use of GaAs transistors is in the 0.5 - 2 GHz range, closely followed by products for the 2 - 8 GHz range. He also notes that "although HEMT and HBT technologies receive an inordinate amount of attention in the trade press, the most common GaAs transistor is the FET, by a very large margin".

The report demonstrates that the most important application for both GaAs & Si transistors is communications, which accounts for 41% of the market. See Figure Two. GaAs has a 22% share of the communications market, a 28% share of the military market, and enjoys a 50% share in the satellite application. See Figure Three. Fuertes says "GaAs is most popular in the satellite application due to its high operating frequency and linearity". He also points out that discretely will likely remain viable in the satellite field for some time due to the low levels of integration found there. In contrast, ABI forecasts increasing competition for discretely from both Si and GaAs ICs in the other major applications, which will slow the growth in the discrete transistor area. The combined market for Si and GaAs discrete transistors is forecast to exceed \$1.2 billion by 2000.

*"Semiconductors and Amps: Global Markets, Applications and Competitors: 1995 to 2000 Analysis", published by Allied Business Intelligence, Inc., 202 Townsend Square, Oyster Bay, NY 11771-2339 USA, TEL [1] 516 624 3113, FAX [1] 516 624 3115, Web www.alliedworld.com. Published April, 1996, 229 pages, 97 figures, \$2,800. Chapters include: Si Transistors, Si Amplifiers, Si MMICs, GaAs Transistors, GaAs Amplifiers, GaAs MMICs, End Use Overview (15 different markets) and Selected Producer Profiles (>40 companies). Coverage includes analysis of each segment as well as market forecasts for 1995-2000. Circle 5 on Reader Service Card*

| Leading GaAs & Si Transistor Producers |                           |  |                  |                 |
|--|---------------------------|--|------------------|-----------------|
| Si Transistors                         |                           |  | GaAs Transistors |                 |
| Rank                                   | Company                   |  | Rank             | Company         |
| 1                                      | Motorola                  |  | 1                | Hewlett-Packard |
| 2                                      | Philips                   |  | 2                | NEC             |
| 3                                      | Hewlett-Packard           |  | 3                | Mitsubishi      |
| 4                                      | NEC                       |  | 4                | Hitachi         |
| 5                                      | Thomson SGS/Siemens (tie) |  | 5                | Toshiba         |

Source: ABI

Figure One: ABI's rankings of the leading manufacturers of Si & GaAs discrete transistors in 1995.

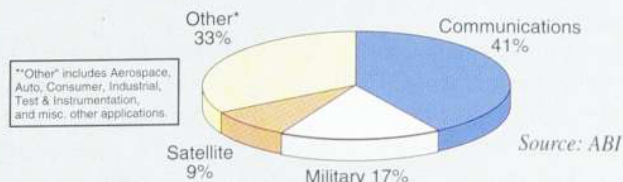


Figure Two: The market for discrete transistors by application.

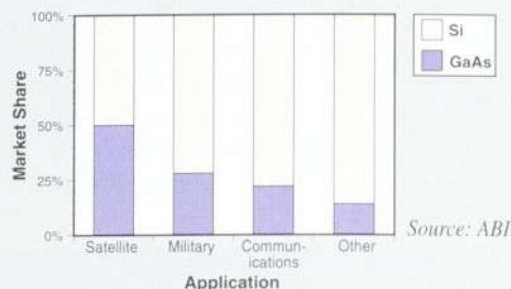


Figure Three: Segmentation of the major applications for discrete transistors by material type.

## VENDOR NEWS

### Epichem, Air Products Re-Align

Epichem Limited [Wirral, Merseyside, UK] and Air Products & Chemicals [Allentown, PA USA] have announced a substantial re-organization of their relationship. Effective May 1st, Epichem has taken worldwide responsibility for the sales and marketing of the organometallics used in the compound semiconductor industry. The new arrangement will include the formation of a wholly owned subsidiary Epichem, Inc. which will assume full responsibilities for all aspects of the organometallics business from Air Products covering North and South America and the Pacific Rim. Air Products will continue to manufacture organometallics, including TBA and TBP, on behalf of Epichem under a long term tolling agreement. Manufacturing will also continue at Epichem in the UK.

### E.P.I. Completes MBO

The management of Epitaxial Products International Ltd. [Cardiff, Wales, UK] have completed a management buyout (MBO) of the company from Shell Ventures UK Ltd. The sale by Shell was conducted as part of its drive to dispose of non-core businesses. According to the co-founders and executive directors of E.P.I., Drew Nelson and Mike Scott, the MBO will allow the company to further improve and extend product ranges with increased focus.

### Emcore Reorganizes, Increases Epi Wafer Services

Emcore Corporation [Somerset, NJ] has announced a reorganization of the company, including the formation of a new division providing epi wafer services. The "Echelon Electronic Materials Division" is intended to assist Emcore's equipment customers by providing "a back-up second source" to their in-house capabilities. The new division will use five production scale MOCVD reactors at Emcore, and the company reports that it has committed \$5 million in capital to install a new cleanroom with computerized wafer mapping characterization equipment. The new wafer foundry expansion is scheduled to be completed in the third quarter of 1996.

The reorganization at Emcore will also result in the company's existing operation being regrouped into four divisions. Equipment manufacturing will be concentrated in the TurboDisc™ MOCVD Systems Division. The new Technology Division, which will focus on materials research and process development, will be headed by Dr. Richard Stall, one of the company's co-founders. The Business Development Division, which encompasses sales and marketing and service and technical applications, will be headed by William Kroll. An Administration and Finance Division has also been created.

Emcore is the largest MOCVD equipment manufacturer in North America, with a staff of more than 170 and annual revenues reportedly in excess of \$30 million.

## Picogiga Goes Public

Picogiga S.A. [Les Ulis, France] successfully completed its initial public offering (IPO) of stock on June 5. The company is now traded on the Nouveau Marche, the French equivalent of the NASDAQ exchange. Trading opened at FFR 100 (~\$20) and is currently around FFR 130 (~\$26).

Picogiga, the first commercial GaAs epiwafer vendor, was founded in 1985 by Linh T. Nuyen, Chairman of the Board and CEO. He was previously head of the ultra-high speed IC integrated circuit group at Thomson CSF's central research laboratory. While at Thomson he co-invented the HEMT, and the core of Picogiga's business today is the MBE growth of epiwafers for HEMT fabrication. The company claims around 42% of the worldwide merchant market for MBE wafers.

Both by plan and by necessity, Picogiga has made itself into an export-oriented company. Last year the United States and Japan accounted for 50% and 30% of sales, respectively. Five years ago the figures would have been reversed. The company attributes this change to a new ascendancy of American companies in the RF & microwave semiconductor business.

One of the first niches that Picogiga found for its HEMT wafers was the manufacture of receivers for satellite television broadcasting. This area currently accounts for ~15% of annual sales. The biggest application sec-

tor is wireless telecommunications, an area which has expanded rapidly until it is now approximately one-half of the company's business. Growth in these commercial areas has meant a declining reliance upon defense applications, which currently account for 34% of sales, down from 41% two years ago.

Picogiga's forecast for the next few years is optimistic. They predict growth in the satellite receiver business, due to the increasing popularity of DBS in the United States, and the enormous growth potential for satellite TV services in the Asia Pacific region. The prospectus estimates that dish production and Picogiga's sales in this area will both experience a CAGR of around 35% over the next 2 - 3 years. Wireless telecommunications are also identified as a growth area for the company, as GaAs gains a greater share of the market due to migration to digital systems and higher frequencies. The company forecasts that between 1995 and 1998 wireless handset production will grow at a CAGR of 25%, and company sales into this area will grow at a CAGR of 47.5%. The company also reports that its products have recently found use as Hall effect sensors for electricity meters, and that this segment constitutes a "reserve" market with the potential to fuel future growth.

| Picogiga: Results & Forecast |      |            |            |            |            |            |            |             |
|------------------------------|------|------------|------------|------------|------------|------------|------------|-------------|
|                              | 1995 |            | 1996 (est) |            | 1997 (est) |            | 1998 (est) |             |
| Total Revenue                | FFR  | 39,177,000 | FFR        | 51,812,000 | FFR        | 78,639,000 | FFR        | 110,333,000 |
|                              | US\$ | 7,835,000  | US\$       | 10,362,000 | US\$       | 15,728,000 | US\$       | 22,067,000  |
| Income before Tax            | FFR  | 6,847,000  | FFR        | 10,506,000 | FFR        | 17,347,000 | FFR        | 35,281,000  |
|                              | US\$ | 1,369,000  | US\$       | 2,101,000  | US\$       | 3,469,000  | US\$       | 7,056,000   |
| Net Income after Tax         | FFR  | 4,399,000  | FFR        | 5,268,000  | FFR        | 10,923,000 | FFR        | 22,281,000  |
|                              | US\$ | 879,000    | US\$       | 1,053,000  | US\$       | 2,185,000  | US\$       | 4,456,000   |

Source: Picogiga Prospectus, May 1996

## NITRIDE NEWS

### Nichia Chemical to Double LED Production

Nichia Chemical reports that it will double its LED production by this fall in response to growing demand for LED units for full-color displays. The company attributes the increasing demand to its introduction of a high-brightness green LED last fall. Nichia, which currently produces 5 million green, blue and blue-green LEDs per month, will raise output to 10 million units per month by September or October. Nichia reported company-wide sales of ¥28 billion (\$257 million) for the 1996 calendar year, up 36% over 1995. LEDs account for approximately 20% of the total, or ¥5.6 billion (\$51 million). About 40% of LED production output is exported to Taiwan, Korea, the U.S., and Europe for display applications.

### More Funding for Cree/Philips Blue Laser Development

Cree Research and Philips Research have received an \$5.2 million contract from the Defense Advanced Research Projects Agency (DARPA) for the development of a GaN blue laser. The contract will include DARPA funding of \$4.3 million and Cree and Philips cost sharing of approximately \$1 million. The contract will be administered over three years, and is in addition to a \$8 million joint agreement which the same three parties entered into in April, 1995. That contract, a two year effort, involved \$4 million in DARPA funding and \$4 million in cost sharing between Cree and Philips. In May, 1995, Cree also received a \$5.8 million contract from DARPA which was aimed at improving SiC wafers for electronic applications. With regard to the new award, Neal Hunter, President of Cree, stated "This program will build on the substrate and GaN thin-film work that has been the focus of the initial program. The new award will enable the team to work on the actual fabrication of laser devices, leading to the stated goal of an operational blue laser."

### HP and Temic Planning for Blue LEDs

Hewlett-Packard has confirmed that it plans to enter the blue LED market with its own product line sometime next year. HP has been offering SiC blue LEDs manufactured by Cree Research since 1993, but will likely discontinue this activity once its own product line is ready. The company plans to use GaN technology. Additional details are not available at this time. Temic Telefunken GmbH [Heilbronn, Germany], a subsidiary of Daimler-Benz, has also announced that it will be entering the blue LED market with a GaN on SiC product. The company plans to offer 3mm and 5mm packages, as well as surface-mount devices. They declined to offer a timetable for introducing the new products.

### ONR May Expand Wide BandGap Program

The U.S. Office of Naval Research (ONR), Electronics Division, anticipates that it may receive \$10 million or more of additional funding for FY 1997, pending congressional approval. These funds, if allocated, would allow ONR to significantly expand its wide bandgap development program, perhaps by 3x, and would allow consideration of new proposals for wide bandgap semiconductor device and circuit development. According to Max Yoder, Acting Director for Electronics at ONR, the primary areas of interest would be 1) microwave and millimeter wave power amplifier devices; 2) high power switches; and 3) UV emitters and detectors. The bidding is currently envisioned as being open to worldwide competition. If the program does expand, the official channel for inviting proposals will be a BAA (broad agency announcement) appearing in *Commerce Business Daily* sometime after the appropriations bills are signed into law. However, if this occurs after October 1, the deadlines for the proposals may be as little as 45 days. Therefore an e-mail distribution list has been established to provide updates. Interested parties who wish to be included should contact [yoder@snap.org](mailto:yoder@snap.org).

# HgCdTe for Cooled and Uncooled IRFPAs: Dual-Band Detectors and Beyond

OWEN K. WU  
HUGHES RESEARCH LABORATORIES  
MALIBU CA 90265 USA

**H**gCdTe infrared detector technology has progressed from photoconductive devices based on bulk materials in the early 1980s to epitaxial thin film photovoltaic (P-V) devices for the present second generation infrared focal plane arrays (IRFPAs). The P-V devices are usually double-layer heterojunction structures (e.g. p-on-n) grown by liquid phase epitaxy (LPE). The use of epitaxial HgCdTe has enabled IRFPAs to increase from 32 x 32 elements in the early 1980s to the present state-of-the-art 480 x 640. Over the last few years the sophistication of these arrays has evolved still further as more powerful epitaxial techniques and other advanced processing technologies have become available. Many DoD mission requirements project the need for more advanced detector concepts requiring smaller pixel dimensions (< 25  $\mu\text{m}$ ) and larger array sizes (> 480 x 640) operated at higher temperatures and with multi-spectral detection capability. At the same time, the IR industry is demanding a low-volume, fast cycle time and flexible manufacturing technique for high performance IRFPAs with affordable costs. Recent progress suggests that both of these often contradictory sets of requirements can be met, which will mean that more applications are available to HgCdTe devices.

## HgCdTe Consortium

Both MOCVD and MBE have been pursued worldwide for the growth of HgCdTe during the last decade. In Japan, Fujitsu has been focusing on MOCVD, and NEC has been betting on MBE since the beginning. On the other hand, in the United States several companies - principally Hughes and Rockwell - had been pursuing both technologies, but from 1992 on both companies have emphasized the MBE and abandoned MOCVD because of lack of funding and slow progress in MOCVD. Specifically, this was because the growth temperature was less than 200°C for MBE but around 350°C for MOCVD, making it more difficult to control the p-type doping in the MOCVD due to the formation of Hg vacancies at higher growth temperatures.

In 1991 Hughes announced the breakthrough of p-type doping technology for MBE. Subsequently Rockwell reported the use of the ion implantation technique for fabricating p-n junctions. As a result, in late 1993 DARPA awarded a multi-year contract to support a HgCdTe MBE consortium including Hughes, Rockwell, Texas Instruments, University of Illinois at Chicago, and Georgia Institute of Technology. Both approaches - ion implantation

and in-situ doping - are being pursued by the consortium, led by Rockwell and Hughes, respectively. The ion implantation approach has the advantage that it is a planar process and only requires a simple surface passivation. Its disadvantages are that it is difficult to entirely repair damage created by the process, and it is almost impossible to use the process to build multi-layer structures for advanced detectors. On the other hand, the advantage of the in-situ doping approach - and it is an important one - is that it is a simple layer-by-layer growth process and so it is relatively easier to use to build multi-layer structures. It is true that it is difficult to achieve p-type doping reproducibly with low defect density, and it requires a very stringent passivation for mesa structures. However, Hughes has already perfected these processes and as a result has been able to demonstrate a functioning 128 x 128 long wavelength IR (LWIR) FPA. It should be noted that these accomplishments in HgCdTe MBE technology were greatly accelerated by the collaboration and competition among the members of the consortium. Indeed, it is the stimulation of the consortium interaction which has made such significant progress possible in HgCdTe technology over the last three years.

Starting even earlier, and as a result of

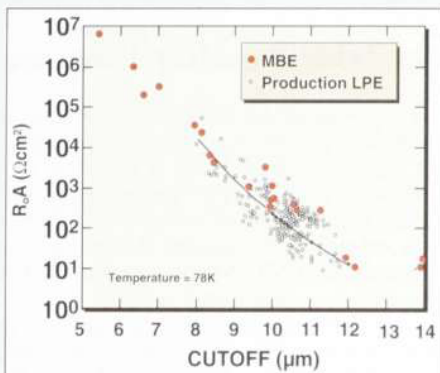


Figure 1: Plot of  $R_0A$  for MBE-based IRFPAs showing performance comparison to the LPE production trend line.

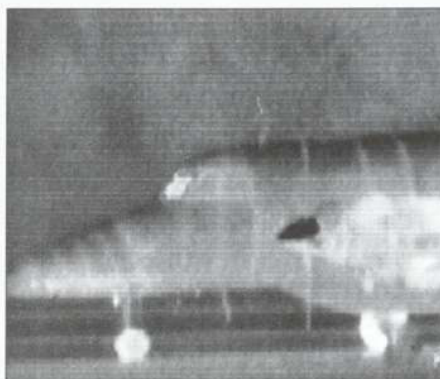


Figure 2: IR image of just-landed airplane showing structure and heat-arcs on wheels due to landing friction. Obtained with MBE-grown 128 x 128 LWIR FPA

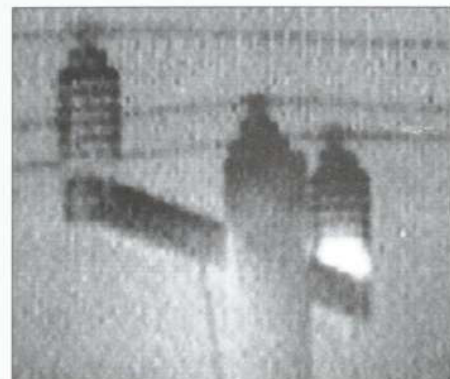
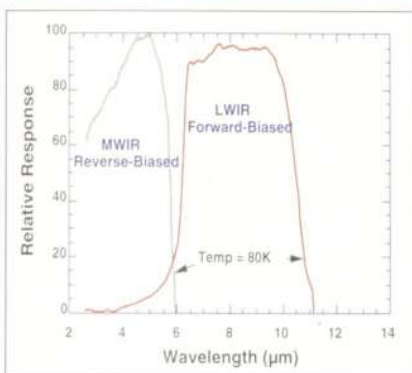


Figure 3: IR image of overheated power pole. Obtained with MBE-grown 128 x 128 LWIR FPA

intense effort over a ten-year period, the Hughes Research Laboratories developed a HgCdTe MBE capability that now provides a versatile and robust technology for the development of advanced IR detector device structures for future systems applications. A long-term strategy at Hughes has been to develop basic MBE growth techniques that will extend the technology to more advanced device architectures than are possible with LPE. That strategy has culminated in a well-developed technology for the direct growth of both n- and p-type  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  alloys that demonstrate classical electrical behavior and Auger-limited minority carrier lifetime over the entire range of  $x$ -values from 0 to 1. The composition of HgCdTe alloys can be varied readily by choosing appropriate beam flux ratios and tailoring the composition to the wavelengths in the short wavelength IR (SWIR) to very long wavelength IR (VLWIR) range (meaning  $1.3\mu\text{m}$  -  $20\mu\text{m}$ ). These basic building blocks, when coupled with the advanced device modeling and fabrication processes at Santa Barbara Research Center (SBRC, a subsidiary of Hughes) have provided a pathway to high performance IRFPAs and complex multi-layer IR detector device structures for dual-band FPAs, large staring arrays on Si substrates, and novel avalanche photo-diode detectors operating at room temperature.

The broad applicability of MBE technology is demonstrated by the routine growth of device-quality material in a single system for the p-on-n double layer heterojunction (DLHJ) structures used to produce SWIR to VLWIR detector arrays. Under the DARPA consortium, Hughes has demonstrated high performance HgCdTe  $64 \times 64$ ,  $128 \times 128$  and  $488 \times 4$  focal plane arrays (FPAs) for medium (MWIR) and LWIR detection using HgCdTe DLHJs were based on a p-on-n structure grown on (211) CdZnTe substrates. These devices had cutoff wavelengths for detection of  $4\text{--}10\mu\text{m}$  at 77K, and their performance compares very well to the SBRC LPE-based production process, as shown in Figure 1.



**Figure 4:** Relative spectral response vs. wavelength for dual-band (MWIR and LWIR) detectors operating at reverse and forward bias modes.

## HgCdTe After Dark

In 1994 an MBE-grown LWIR  $128 \times 128$  array was hybridized to a Si readout circuit to form a sensor chip assembly, and a high performance LWIR camera was constructed for the first time using the in-situ MBE-grown DLHJ technology. Two of the high resolution IR images obtained are shown in Figures 2 & 3. Figure 2 shows the structure of an airplane where the heat arcs are also observed on the wheels due to the heat generated during the landing. Figure 3 shows the overheated spot of an electrical power pole in need of the Edison company's attention! The after-dark clarity and definition of these images are a visual testimony to the efficacy and promise of MBE-based HgCdTe detector arrays and indicate that HgCdTe MBE technology is capable of producing high performance IRFPAs. In addition, these MBE-based HgCdTe IRFPAs have an average quantum efficiency greater than 60% without anti-reflection coating at 78K, which is one order of magnitude greater than that for the GaAs/AlGaAs quantum well infrared detectors (QWIP). Similarly, the operational temperatures for HgCdTe-based IRFPA range from above liquid nitrogen and up to room temperature, while those for QWIP are mostly below liquid nitrogen temperatures. Theoretical calculations suggest that the Sb-based superlattice may be able to operate at higher temperatures still, but more concrete evidence needs to be presented. At the same time, the compositional uniformity of the MBE-grown HgCdTe layer is comparable to the composition of the III-V MBE technology which can be achieved today. In short, were it not for the broad manufacturing experience and know-how of QWIP - its maturity - an objective comparison of QWIP and MBE-based HgCdTe IRFPA would show that the latter is a clearly superior technology.

As the infrared technology continues to advance, there is a growing demand for multi-spectral detectors for advanced infrared systems. For example, multi-spectral infrared sensors are an important component of the LANDSAT earth resources system. They also have considerable potential for atmospheric physics instruments such as those used in NASA's Earth Observation System for better environment sensing and monitoring. For military applications, multi-spectral detectors are needed for better target discrimination and identification. The highly successful MBE technology has now been applied to the growth of n-p-p-n four-layer double heterojunction structures used to produce sequential mode dual-band detectors having sensitivities in any chosen combination of SWIR, MWIR and LWIR bands. These dual-band detectors basically consist of two p-n junctions, one for each spectral band (for example MWIR & LWIR). The top and bottom n-type layers are the LW and MWIR absorbers with the middle two layers being transparent. In one bias mode, the MWIR junction is reverse-biased, producing a signal for the MWIR; and the LWIR junction is forward-biased, producing no signal. Reversing the bias polarity

activates the LWIR junction but not the MWIR junction. Several sequential dual-band detectors have been demonstrated and excellent MWIR-LWIR detector results have been obtained with LWIR  $R_0A > 100\text{ ohm-cm}^2$  ( $10.5\mu\text{m}$  cutoff) and MWIR  $R_0A > 105\text{ ohm-cm}^2$  at 78K ( $5.7\mu\text{m}$  cutoff). The relative spectral response of this kind of dual-band detector is shown in Figure 4. This preliminary demonstration indicates that HgCdTe MBE in-situ doping technology is now capable of growing multi-layer structures for advanced IRFPAs. Current work on dual-band detectors is being actively pursued and rapid progress is expected in the near future.

As the size of the hybrid infrared focal-plane array increases, achieving long-term thermal cycle reliability of the array hybrid becomes more difficult because of the thermal expansion mismatch between the Si readout electronics chip and the bulk CdZnTe substrate on which the HgCdTe array is fabricated. We have made a significant advance towards eliminating the mismatch and producing reliable, large-area FPA's by using MBE deposition of high quality films of CdTe(211) and HgCdTe(211) directly on Si(211) substrates without GaAs initiation layers. This has allowed the fabrication of LWIR  $256 \times 256$  arrays and MWIR arrays based on Si substrates with near trendline performance comparable to that obtained on bulk CdZnTe at 77K. Further reduction in the HgCdTe defect density ( $< 10^6/\text{cm}^2$ ) should improve the detector performance. This first demonstration of all-MBE-grown HgCdTe IR detector structures on Si substrates represents a significant advance towards the goal of producing reliable large-area FPAs directly on Si.

The most complex device produced to date by HgCdTe MBE is a multilayer SWIR avalanche photo-diode operating at room temperature having a gain of 10 at 1 GHz. (The details on this uncooled detector will be reported in the upcoming US Workshop on the Physics and Chemistry of II-VI Materials in Las Vegas, October 22-24, 1996.) This device structure, comprising various n, n<sup>+</sup>, p and p<sup>+</sup> layers, is made possible by the recent significant advances in MBE technology. Other novel devices such as IR-lasers may likewise soon be realized using HgCdTe-based superlattice and quantum well structures.

Thus HgCdTe MBE technology can be utilized for uncooled, as well as cooled, IRFPAs. Its maturity has led to the dual-band detector technology and opens a wide variety of applications beyond the purely military, such as medical diagnostics of tumors and clogged arteries, and many automotive and other industrial uses.

*Owen K. Wu has pioneered and led the HgCdTe MBE research and development at Hughes Research Laboratories since 1985. Previously, he managed the development of III-V MBE technology at Gould Research Center in Chicago. He invented the p-type doping technology and is the principal investigator for several ongoing HgCdTe MBE projects at HRL.*

# IV-VI Compound Semiconductor Diode Lasers: Still Going Strong!

*The author argues that lead salt lasers will retain an important position in the future, despite recent progress in competing systems.*

ZHISHENG SHI

ETH, INSTITUTE OF QUANTUM ELECTRONICS  
ETH-TEIL TECHNOPARK, PFINGSTWEIDSTR. 30  
CH-8005, ZURICH, SWITZERLAND  
e mail: shi@iqu.phys.ethz.ch

The IV-VI lead-salt materials system (PbSe, PbTe, and related materials) provided the first laser diodes for operation in the mid- and far-infrared region (3-12 micron). Today, IV-VI materials are facing a great challenge: the invasion of their "home field" by III-V's. Researchers have now demonstrated that Group III-antimonide heterostructure diode lasers can access wavelengths shorter than 5 micron (see CS 1(2), p. 12). Furthermore, the new quantum cascade (QC) lasers, which employ Group III-arsenide materials (see CS 2(1), p. 26), have achieved wavelengths up to 8.6 micron and pulsed operating temperature up to 260K. Browsing recent overviews of the topic, someone said "IV-VI lasers, if not dead, are dying"!

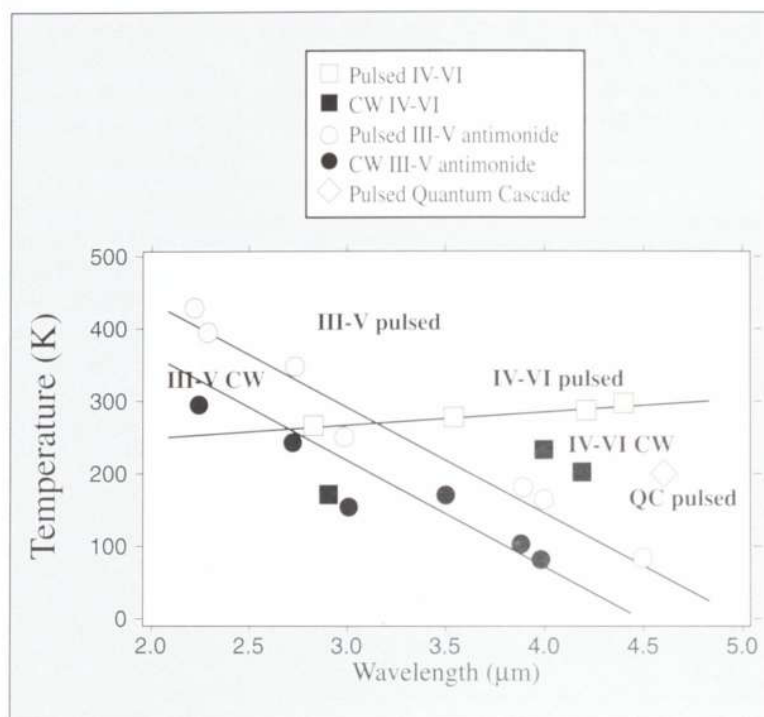
Are the days of IV-VI compounds really numbered? Current activity in the world of IV-VI lasers suggests otherwise. All of the commercial mid-IR diode lasers that are currently available are made exclusively from the IV-VI's. Companies such as Laser Components [Olching, Germany] and Laser Photonics, Analytic Division [Andover, MA USA] produce and supply IV-VI lasers on a commercial basis. The market for such devices is currently around \$2 million per year, with a total consumption of approximately 750 units; however, their significance is greater than these numbers indicate, because the diodes play an enabling role for several types of high resolution spectroscopy. In the research field, the Fraunhofer Institute of Physical Measurement Technique (IPM) in Germany, Shizouka University in Japan and the Lebedev Physical Institute in Russia are continuing their IV-VI laser efforts. A IV-VI group in University of Oklahoma is also actively pushing their theoretical and experimental results into laser emission. And, encouragingly, in Japan, Hamamatsu Photonics are co-operating with the IV-VI group at Shizouka University on a ¥550 million (\$5 million) project

to commercialise their IV-VI quantum well (QW) lasers. Besides laser activities, other IV-VI researchers such as the group in Zurich, Switzerland with their promising results of IV-VI infrared detectors on Si and the group in Linz, Austria with their basic research into IV-VI materials, provide new ideas and opportunities for IV-VI diode lasers. In sum, IV-VI laser development is successfully continuing, be it with much lower investment than goes into III-V's.

## IV-VI State of Art

The main present market for mid infrared diode lasers is dominated by trace-gas-sensing systems based on laser absorption spectroscopy. CW lasers are preferred to achieve selectivity and sensitivity. Potential applications include long distance wireless communication using mid-infrared laser pulses, medical diagnostics, explosive detection and differential absorption light detection and ranging systems. Which material system will win the competition to supply laser diodes for these future applications will depend upon which can meet the requirements of high CW operating temperature (ultimately room temperature), reasonable output power, and, in some cases, single mode operation. Among these factors operating temperature is economically important since it influences both price and complexity.

For operating temperature at wavelengths larger than 3 micron, IV-VI diode lasers have a good position as compared to their III-V counterparts. As shown in Figure One, IV-VI lasers have demonstrated the highest operating temperature both at CW and pulse in this area. Nonradiative recombination, principally from material defects and Auger recombination, essentially limits the present operating temperature in nearly all mid-infrared lasers. IV-VI lead salt semiconductors, with their minimum gap at the L-point of the Brillouin zone, have nearly mirror symmetric conduction and valence bands, thus similar effective masses of both electron and holes. Theoretical calculations predict much smaller Auger recombination rates as compared to III-V's. Auger recombination rates can be further reduced by making QW structures. (The carrier densities ( $n$ ) required to achieve threshold in QW lasers are



Reported maximum operating temperatures of mid IR diode lasers.



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lower, and Auger recombination is proportional to  $n^3$ .) A remaining problem is that of gain saturation caused by high material losses and the lower saturation gain in QW. Aiming to overcome this problem, multiple QW (MQW) lasers have been made. IPM (Germany) showed pulsed laser emissions at 9°C of PbSe/PbSrSe MQW lasers. Recently Laser Photonics Analytic division reported their results of over 220 K laser emission at CW mode using PbEuTe/PbTe separate confinement buried heterostructures. On the whole, there is a promising picture for IV-VI lasers, that at present seem to keep their III-V counterparts at arm's length, especially at wavelengths in excess of 3 microns.

### What Will the Future Bring?

Future efforts to improve IV-VI lasers should be fruitful.[1] Epitaxial growth of IV-VI materials needs to be improved since diffused homojunction lasers using bulk material still provide the highest output power (100mW). Carrier concentrations caused by non-stoichiometry are still high and mobility decreases exponentially as the band gap of the confinement materials increases - giving a maximum total band offset limitation of about 100meV.[2] The thermal conductivity of IV-VI materials is relatively low, which means a higher chance to get into a thermal-run-away situation. It also is the reason for the large difference between the present CW and pulsed operating temperatures. Any efforts towards reducing the volume joule heating or the whole thickness to improve the heat transport will increase the maximum CW operating temperature and probably also the output power.[3] Although it seems ideal to grow PbTe (PbSe) based lasers on PbTe (PbSe) substrates, the quality of IV-VI substrates is still very poor compared with the present commercial III-V or Si substrates. Attempts to use other than IV-VI substrates also seem to be worthwhile trying.

So, there is ample room for major improvements.

In the foreseeable future of mid infrared lasers, QC lasers might see the best chance to meet the application requirements, but there are still no theoretical predictions that allow a sound judgement. III-V antimonide-based lasers may share the market with IV-VI's in the 3-4 micron range. Nonetheless, there is no doubt that, despite losing part of their traditional markets, IV-VI lasers covering from 3-12 micron will still be active - making the mid infrared laser family rich and diverse, to the benefit of those that want (or need) to apply mid IR diode lasers.

### References

1. Z. Shi, M. Tacke, A. Lambrecht, and H. Bottner, Appl. Phys. Lett. 66, 2537(1995).
2. Z. Feit, M. McDonald, R.J. Woods, V. Archambault, and P. Mak, Appl. Phys. Lett., 68, 738(1996).
3. M. Tacke, Infrared Phys., 36, 447(1995).

*Zhisheng Shi received the M.S. degree from Jilin University in China in 1987. From 1987 to 1991 he worked in Changchun Institute of Physics, Chinese Academy of Science, on IV-VI laser R&D. From 1992 to 1995 he worked as a visiting scholar in the Fraunhofer Institute of Physical Measurement Techniques in Germany on IV-VI quantum well lasers. In parallel he received the Ph.D. degree from Freiburg University in 1995. He is presently doing postdoctoral research at Swiss Federal Institute of Technology (ETH).*

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### Contributions Welcome

The mission statement for our magazine is "to provide a focal point for the global compound semiconductor industry". To help achieve that goal we have instituted the "Forum" section 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. Almost any compound semiconductor-related topic is acceptable, provided that it is not too narrowly focused. Our primary selection criteria is the article's level of interest or usefulness to our readers.

If you are interested in contributing an article, please contact the editor at the address given on page 1 for guidelines.

# Progress and Challenges in the Diamond Semiconductor Field

ROBERT A. METZGER

The most commonly discussed wide bandgap materials are GaN, SiC, and ZnSe. However, there is a fourth material: diamond (carbon), which not only offers the intrinsic advantages inherent to a wide bandgap material, but in addition exhibits unique thermal and field emission characteristics which widens the range of its potential applications beyond the realm of a conventional wide bandgap material. In many respects diamond may be the "ultimate" wide bandgap material, but it is extremely difficult to process, and the technology behind it is immature.

## Characteristics

Natural diamond has a bandgap of 5.45 eV, exhibits large hole ( $1600 \text{ cm}^2/\text{V}\cdot\text{s}$ ) and electron ( $2200 \text{ cm}^2/\text{V}\cdot\text{s}$ ) mobilities, saturation velocities of both carriers in excess of  $10^7 \text{ cm}/\text{sec}$ , as well as an extremely large thermal conductivity of  $2000 \text{ W}/\text{mK}$  (13 times greater than Si and 40 times greater than GaAs). In addition, diamond can exhibit a negative electron affinity (NEA - in which the conduction band minimum lies below the vacuum level), which allows electrons to be emitted from the surface under relatively low field conditions, making the material quite suitable for cold cathode applications and field emission displays. It is these intrinsic characteristics which are driving current research and development efforts in an attempt to exploit these impressive properties for the fabrication of electronic and optoelectronic devices.

Thin film CVD-grown diamond films are currently limited to only p-type layers, with the dopant being used that of boron, which has a relatively deep acceptor level of 365 meV.

There is currently no suitable n-type dopant for diamond, which limits the types of electronic devices which can be fabricated with diamond to FET-type structures or Schottky-based diodes. The high acceptor activation energy for boron in diamond means that full electrical hole activation does not occur until a temperature of approximately  $500^\circ\text{C}$  is reached, which means that low resistivity layers are difficult to obtain at lower operating temperatures. Even though high temperature operation improves dopant activation, under these conditions, hole mobility degrades, exhibiting a value of approximately  $125 \text{ cm}^2/\text{V}\cdot\text{s}$  at  $500^\circ\text{C}$ , as com-

**Summary: Diamond, with its many attractive characteristics, and despite its host of technical problems, is in many ways the ultimate wide bandgap material. Some commercialization (for heat sink applications) has occurred, and there is ongoing interest in capitalizing upon its negative electron affinity for use in low power field emitters. UV detectors and FET-type devices for high temperature operation are also under investigation. The future prospects for diamond will require the resolution of several challenges, including the lack of n-type doping and shallow p-type doping, and the availability of practical substrate materials.**

pared to the best room temperature of  $1600 \text{ cm}^2/\text{V}\cdot\text{s}$ . The pursuit of n-type dopants, as well as that of shallow p-type dopants is an ongoing critical area of diamond research.

Three distinct categories of diamond films are currently being produced, determined by the type of substrate that is being utilized: diamond; textured/highly oriented diamond; and non-lattice matched substrates (Si, metals, insulators). When used for CVD growth these substrates produce films which are either homoepitaxial, highly oriented crystalline, or polycrystalline, respectively. These three dif-

ferent types of diamond films typically exhibit hole mobilities of 1500, 230, and  $70 \text{ cm}^2/\text{V}\cdot\text{s}$  respectively. As a consequence of these characteristics, the substrate of choice is highly dependent on the specific application, and is a tradeoff between crystalline perfection and cost.

## Material Applications

The large thermal conductivity of diamond makes it ideally suited as a thermal management material in applications that would include those of heat sinks, packaging and in multichip modules. DARPA is currently starting a diamond program to address thermal management issues in defense systems focusing in the areas of power electronics and T/R (transmit/receive) modules. The use of diamond for these applications have already reached the commercial market place, an example of which is a product offered by Diamonix [Allentown, PA], a unit of Monsanto, which is selling diamond heat sinks with thermal conductivities  $> 1300 \text{ W}/\text{mK}$ . The area of thermal management should continue to be a growth area for diamond, requiring only polycrystalline material which can be grown on relatively inexpensive substrates, and is not constrained by doping requirements.

A great deal of the interest currently being generated in diamond work is due to its NEA capabilities. ATMI [Danbury, CT] and Si Diamond Technology [Austin, TX], are actively working in this area, where diamond's NEA characteristics can be utilized for low power field emitters used either in flat panel displays, or as discrete emitters. In typical operation, the diamond is used as the cathode material of an emitter, in which the electrons can be extracted from the diamond's surface through a field applied by an anode placed several microns above it, and the electrons then used to strike a phosphor which excite it, and in turn cause it to emit a photon. The work in field emitters can be characterized as being in the experimental/early development stage, with NEA characteristics being evaluated and modified as a function of the diamond field emitter shape, dopant within the field emitter, as well as altering the surface emission properties by coating the diamond surface with such materials as H<sub>2</sub>, Ti, Ni, Co and Cu. One of the challenges for this application is the need to inject electrons back into NEA devices so that high current density emission can be maintained. This has been attempted by introducing both phosphorus and nitro-

gen into diamond emitters. As recently reported in *Nature* (Vol 381, 9 May 1996, pg. 140), by Ken Okano, a group from Tokai University [Kanagawa, Japan], the Japanese National Institute for Research in Inorganic Materials [Ibaraki, Japan], University of Surrey [Surrey, UK] and the University of Liverpool [Liverpool, UK] used a saturated solution of urea ((NH<sub>2</sub>)<sub>2</sub>CO) to obtain N concentrations in diamond films of  $3.5 \times 10^{20}$  as determined by Rutherford Backscattering (the degree of electrical activation of the N was not reported). Field emitters fabricated from these heavily nitrogen doped diamond films exhibited a threshold voltage as low as 0.5 V/ $\mu\text{m}$  - a value significantly lower than that previously reported for either boron or phosphorous doped polycrystalline diamond films. If this material were used in the cathode of an emitter, driven by a commercial battery of 1.5 V, and utilizing a gap between the anode and gate of 3  $\mu\text{m}$ , it would provide a current density of more than  $10^6$  A/cm<sup>2</sup>, a value suitable for use with existing phosphors.

### Device Applications

Besides taking advantage of its intrinsic conductivity and NEA characteristics in the pursuit of applications, diamond is starting to find its way into many other devices. The wide bandgap of diamond means that intrinsic diamond is highly insulating ( $> 10^{16}$  ohm-cm, which is 8-10 orders of magnitude greater than semi-insulating GaAs), making it well suited for detectors operating in the UV ( $> 5.5$  eV) to X-ray range, as well as being suitable for detecting ionizing particles such as alphas, electrons, neutrons and pions. Researchers at the University College London [London, UK], have fabricated both metal-diamond-metal structures used as photoconductive devices, as well as Schottky-based photodetectors using p-type diamond. The photoconductors show a maximum responsivity peak at 200 nm, with a responsivity  $10^6$  times higher at this wavelength than in the visible region, making this material a good candidate for a solar-blind UV detector (see CS 2(3), pg. 29).

In the area of diamond-based electronics, workers at Kobe Steel's Electronic Materials Center [Research Triangle Park, NC] have fabricated FET-type diamond thin films structures using a microwave plasma deposition system with metal/insulating diamond/semiconducting diamond structures and metal/oxide/semiconducting diamond structures. Both these structures showed interface-state densities of approximately  $10^{12}$  /cm<sup>2</sup>-eV (some 2 orders of magnitude greater than that observed in silicon MOS devices). Due to diamond's large bandgap, these FETs exhibited saturation and pinch-off at temperatures as high as 500°C, with the best transconductance measured at 1.3 mS/mm, with drain-to-source currents of 10 mA. These FETs were used to fabricate a common-source amplifier circuit which was char-

acterized using input signals from 20 Hz to 1 MHz and exhibited DC gain of 5 at 250°C. In addition, a pair of MOSFETs were configured as NAND and NOR digital logic gates which operated at 400°C.

Other device efforts include those of AEA Technology [Oxfordshire, UK] which has fabricated diamond-based thermistors which show a temperature coefficient of resistance of 70 kohm/K over a range of 20-300°C, as well as using an insulated diamond gate structure in the fabrication of a MISFET similar in concept to those fabricated by Kobe Steel. Taking advantage of diamond's large bandgap, and the high breakdown voltages associated with it, Sandia [Albuquerque NM] and Alameda Applied Sciences [San Leandro, CA] have demonstrated diamond switches which can operate at 1 kV and 18 A, with future goals for operation of up to 10 kV and at currents of up to 100 amp. In addition, diamond has been utilized in the fabrication of surface acoustic wave (SAW) filters, taking advantage of its fast phase velocities (10 km/s as compared to the 4.5 km/s in LiNbO<sub>3</sub> and LiTaO<sub>3</sub> which are typically used in SAW devices) with researchers at Sumitomo Electric [Yokohama, Japan] having fabricated ZnO/Diamond SAW devices with 0.75  $\mu\text{m}$  interdigitated transducers operating at frequencies of 3.5 GHz, which if having been made on the more conventional LiNbO<sub>3</sub> or LiTaO<sub>3</sub> substrates, would have required 0.25  $\mu\text{m}$  IDTs to operate at 3.5 GHz.

Lastly, the issue of the inability of forming p-n junctions in diamond due to the lack of a method for n-type doping is being investigated in a novel fashion by workers at Osaka University [Osaka, Japan]. They have formed p-n junctions by using a n-type GaAs layer obtained by lift-off, and wafer bonding it to a p-type diamond substrate through Van der Waals bonding, to form a p-n junction. The electrical junction formed by this technique displayed a photovoltaic effect, exhibiting a photovoltage in excess of 0.1 V under illumination from a 789 nm laser, indicating that a p-n junction had been formed.

As these applications have shown, diamond has many of the intrinsic characteristics that make it an outstanding candidate for many wide bandgap applications. However, as also illustrated by these examples, a great deal of research and development work remains to be done before this material is ready to compete with the more conventional wide bandgap materials. The most critical issues which must be overcome before diamond can effectively compete with the other wide bandgap materials is the lack of a n-type dopant, and the challenge of improving the crystalline quality of thin films without having to resort to growth on diamond substrates.

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## 0.86 eV Platinum Schottky Barriers on InP by Electroplating

A major obstacle to the development of an InP MESFET/HEMT technology has been the lack of a suitable gate metallization technology. Experimentally, InP surfaces are generally characterized by metal-independent Schottky barrier heights (SBHs) of approximately 0.4 eV. Such low SBHs values result in high gate leakage currents.

Japanese researchers investigating low-energy Schottky barrier fabrication methods have recently demonstrated an *in-situ* electroplating process that leads to the formation of nearly ideal Schottky metal-semiconductor junctions characterized by a SBH of 0.86 eV. This process delivers only hundreds of milli-electronvolts to the semiconductor surface at room temperature; a result which should be contrasted to the high temperatures involved in the electron beam evaporation of refractories like Pt. The low energy formation process prevents the formation of a disordered layer that pins the Fermi level at the semiconductor surface, and the resulting electroplated gate SBHs do show a metal work function dependence.

The Pt electroplating process consists of two steps: an InP anodic etching step is first carried out and is followed by the Pt electroplating cycle. Both steps are carried out in an  $H_2Cl_6/Pt$  electrolyte. The anodic etching depth can be controlled by the number of electrical pulses applied to the electrolyte bath. After several hundred angstroms of InP are etched to provide a clean, defect free InP surface, Pt is deposited onto the InP substrate by simply reversing the polarity of the potential supply, thereby allowing an *in-situ* transition between the anodic etching and gate metallization modes.

Schottky diodes were fabricated by patterning photoresist on InP substrates, and by using the resist mask to delineate the gate electrode patterns. Schottky barriers were compared to similar devices fabricated with a conventional vacuum deposition process: the electroplated Pt gates were characterized by a SBH of 0.86 eV and ideality factors of  $n = 1.13$ , whereas the vacuum deposited Pt gates displayed a SBH of 0.44 eV with a large ideality factor of  $n = 1.70$ . The room temperature I-V characteristics of the electroplated gates featured a five order of magnitude reduction in the gate leakage current in comparison to the electron-beam deposited gates.

InP MESFETs with micron scale Pt gate metallizations were also fabricated with the new electroplating process (separate experiments have shown that the electroplating process can even be used with 0.2  $\mu m$  geometries defined by electron-beam lithography). The plated-gate MESFETs displayed kink-free drain characteristics, good drain current saturation and channel pinch-off, and low gate leakage currents. A maximum transconductance of 24 mS/mm was obtained for a MESFET with a gate length of 3.5  $\mu m$ . The electroplating process therefore appears to be promising for the development of high-power InP-based devices and circuits.

Work done at Hokkaido University, Sapporo (Japan). See "0.86 eV Platinum Schottky Barrier on Indium Phosphide by In Situ Electrochemical Process and Its Application to MESFETs", S. Uno et al., *Jpn. J. Appl. Phys.*, Vol. 35, Part 1, No. 2B, 1258 [February 1996].

# 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

### Heterojunction Laser Based on Vertically Coupled InAs Quantum Dots in a GaAs Matrix

The prediction of low threshold current density lasers has motivated much work aiming at the formation of high-quality quantum dot and wire structures. Recent research has shown that quantum dots can be formed by the nucleation of growth islands associated with the Stranski-Krastanov epitaxial growth mode in highly mismatched hetero-epitaxial systems. To improve the performance of quantum dot based lasers, it is advantageous to make use of vertically coupled quantum dots in order to maximize the overlap of the light wave and the laser active region; the potential increase in laser cavity gain is then expected to reduce the lasing threshold current density.

Russian and German researchers have recently implemented heterojunction lasers with active regions consisting of vertically coupled quantum dots (VCQDs) formed by depositing several InAs and GaAs cycles. Each cycle consists of 1.7 monolayer of InAs and of a 4 nm thick GaAs layer grown at a temperature of 485°C. The growth temperature for the cladding and contact layers was set to 600°C. Each vertically coupled quantum dot was composed of three vertically ordered InAs regions separated by GaAs layers 2-4 monolayers in thickness. At room temperature, an intense PL line arises due to the electron and hole ground states in the tunnel-coupled dots.

The electroluminescent characteristics of the lasers were measured with pulsed pumping (100 ns pulses with a 5 kHz repetition rate) between 80 and 300 K. With moderate excitation levels, the lasing energy was found to match the peak of the PL spectrum all the way to room temperature, indicating that lasing proceeds through the ground state of the VCQDs. In the range between 80-150 K, the lasing threshold remains  $\sim 40 A/cm^2$ . Over the temperature range 80-300 K, the lasing threshold remains significantly lower than that of QD lasers with only one layer of quantum dots. Work performed at the A. F. Ioffe Physicotechnical Institute (St. Petersburg, Russia) and the Technische Universität (Berlin, Germany). See "An Injection Heterojunction Laser Based on Arrays of Vertically Coupled InAs Quantum Dots in a GaAs Matrix", Zh. I. Alferov et al, *Semiconductors* 30 (2), 194 [February 1996].

### Polarization Dependent Output in LEDs with Ordered GaInP Active Regions

The GaInP alloy tends to spontaneously form ordered alloys under certain MOCVD growth conditions. The ordered phases consist of a monolayer superlattice of GaP/InP layers arranged in the  $[1\bar{1}1]$  and the  $[11\bar{1}]$  crystal directions. Alloy ordering can decrease the measured energy gap value in comparison to that of a completely random alloy. Alloy ordering also modifies the crystal symmetry. Group theoretical considerations show that the alloy ordering lifts the valence band degeneracy; as a result, optical transitions with polarizations parallel to the  $[1\bar{1}1]$  and the  $[11\bar{1}]$  directions turn out to be forbidden in a completely ordered alloy.

Surface emitting LEDs based on p-i-n AlGaInP/GaInP double heterostructures with ordered GaInP active regions were recently grown by MOCVD on exactly-oriented (100)  $n^+$  GaAs substrates. To suppress ordering, cladding layers were grown at 710°C, while the ordered  $Ga_{0.52}In_{0.48}P$  active layer was grown at 650°C. Ordered and disordered active layer samples were prepared from the same "ordered" epitaxial layers by using a rapid thermal annealing step to disorder the active region in some devices in order to provide a direct comparison for the effect of ordering on the LED characteristics.

The LED electroluminescent spectra showed a peak at 673 and 650 nm for the ordered and disordered devices, respectively. The ordered LEDs showed a 60% higher electroluminescent efficiency compared to the disordered LEDs, a discrepancy which can be explained by the annealing damage in the RTA-disordered LEDs. The polarization dependent output power of the ordered LEDs shows a contrast of 1.4 dB between polarizations parallel to the  $[01\bar{1}]$  and  $[011]$  directions. The polarization dependence was found to be nearly independent of diode current and mesa geometry while no such polarization dependence was observed for the RTA disordered LEDs. A maximum theoretical polarization contrast of 1.8 dB could be expected for a perfectly ordered active region. Work performed at the Paul Scherrer Institut (Zurich, Switzerland) and the Institut für Technische Physik I (Erlangen, Germany). See "Polarization Effect in Light Emitting Diodes with Ordered GaInP Active Layers", E. Greger et al, *Appl. Phys. Lett.* 68 (17), 2383 [April 1996].

### Depletion-Mode $ZnS_{0.07}Se_{0.93}$ MESFET

ZnSe-based wide bandgap materials have attracted much interest in view of their application to blue-green light emitting diodes and lasers. In an optoelectronic integration context, the development of ZnSe-based transistors may become technologically attractive. Researchers from the State University of New York at Buffalo and their colleagues from 3M have recently demonstrated  $ZnS_{0.07}Se_{0.93}$  depletion mode MESFETs grown by MBE on a lattice-matched GaAs semi-insulating substrate. The thickness of the MESFET Cl-doped channel was approximately 0.4  $\mu m$ , with a net doping of  $10^{16} - 10^{17} cm^{-3}$ , and an electron mobility of 350-400  $cm^2/Vs$ . Ohmic contacts were formed by Cr/In/Cr evaporation and rapid thermal annealing, while a self-aligned gate was formed by channel recessing and Au evaporation. The electrical parameters for a  $W/L = 200 \mu m / 2 \mu m$  gate device were a pinch-off voltage of -13 V, a drain breakdown voltage of 28 V, and an average transconductance of 8.73 mS/mm. Work performed at the State University of New York at Buffalo (Amherst, NY). See "Fabrication and Characterization of a Depletion-Mode  $ZnS_{0.07}Se_{0.93}$  MESFET", A. Wang et al, *IEEE Elect. Dev. Lett.* 17 (5), 217 [May 1996].

# Electronic Circuits and Devices

## 3V L-Band Power HEMTs

GaAs MESFETs have experienced large market penetration for power amplifier applications in cellular phones due to their high power added efficiencies. However, as operating voltage is reduced, the output power of MESFETs can quickly decrease, thereby requiring MESFETs with large peripheries (10-20 mm) in order to produce sufficient output powers. PHEMTs offer a possible solution to this problem. Utilizing a 1.0  $\mu\text{m}$  gate-length GaAs-based PHEMT with 21% In in the channel and delta-doped structures both above and below the channel, this device exhibited a current density of 425 mA/mm at  $V_{gs}$  of 0.5 V and a maximum transconductance of 270 mS/mm. For class AB operation at 900 MHz and 3 V, this 5 mm gate-width HEMT demonstrated an output power density of 200 mW/mm, a 64% PAE, 18.2 dB linear gain, and over 1 W output power - this being the highest power density for this type structure reported to date. Work performed at the National Chiao Tung University [Hsinchu, Taiwan, ROC]. See "5 mm High-Power-Density Dual-Delta-Doped Power HEMT's for 3 V L-Band Applications," Y.L. Lai et al, IEEE Electron Device Letters, 17(5), 229 [May 1996].

## 40 Gbit/s MUX/DEMUX operation with InAlAs/InGaAs/InP HEMTs

High speed MUX and DEMUX circuits are key components in optical fiber communication systems. Demonstrations of these circuits for 40 Gbit/s operation have been obtained on wafer for both AlGaAs/GaAs HBTs and Si bipolar technologies, but not for FET-based approaches. For the first time, both MUX and DEMUX IC modules have been fabricated using InAlAs/InGaAs/InP HEMTs which operate in excess of 40 Gbit/s. Using 0.1  $\mu\text{m}$  gate-lengths, these HEMTs exhibit average transconductance,  $f_t$  and  $f_{max}$  values of 1.0 S/mm, 169 GHz, and 264 GHz, respectively. A 2:1 MUX which uses a SCFL series gated selector circuitry with source followers at the output stage operates up to 46 Gbit/s while consuming 1.7 W, and the DEMUX which utilizes HLO-type D-flip flops operates at 40 Gbit/s and consumes 1.9 W. A power supply voltage of 5.2 V is required and the chip size is 2x2 mm<sup>2</sup>. Work performed at NTT LSI Laboratories [Kanagawa, Japan]. See "46 Gbit/s Multiplexer and 40 Gbit/s Demultiplexer IC Modules Using InAlAs/InGaAs/InP HEMTs," T. Otsuji et al, Electronics Letters, 32(7), 685 [28 March, 1996].

## Collector-Up Ge/GaAs HBTs

Small bandgap Ge (0.75 eV) is lattice matched to GaAs, thereby making it a suitable base material in the fabrication of GaAs/Ge-based HBTs. The narrow bandgap Ge should allow low power operation due to an emitter-base turn-on voltage which has been shown to be 0.7 V less than that of AlGaAs/GaAs HBTs. Using a collector up structure, which enables the fabrication of small collector-base junction areas and thereby reduces the collector-base resistance which helps to improve  $f_{max}$ , a MBE grown Ge/GaAs HBT was fabricated. The GaAs emitter is first grown in a GaAs-based growth chamber, and then the sample is transferred into a Ge-growth chamber where the Ge base and collector are grown. Utilizing boron doping from a high temperature Knudsen cell, the 1800 Å Ge base region is p-type doped at  $2 \times 10^{20} \text{ cm}^{-3}$ , where this high doping level produces an intrinsic base resistance of 50 ohm/sq - the lowest value reported for bipolar transistors. The resulting device showed an  $f_t$  of 25 GHz (limited by the wide base), and a  $f_{max}$  of 112 GHz (enhanced by the collector-up structure and the heavy base doping). Work performed at NEC Corporation [Ibaraki, Japan]. See "112 GHz Collector-Up Ge/GaAs Heterojunction Bipolar Transistors with Low Turn-On Voltage," M. Kawanaka et al, IEEE Transactions on Electron Devices, 43(5), 670 [May 1996].

## 220 GHz $f_t$ GaAs-Based PHEMTs

InP-based HEMTs show the highest  $f_t$  and  $f_{max}$  values of any transistor structures, but GaAs-based PHEMTs continue to improve in performance, challenging InP-based performance. AlGaAs/InGaAs HEMTs with 20% In in a 120 Å channel and a 120 Å Al<sub>0.2</sub>Ga<sub>0.8</sub>As Schottky layer were used in the fabrication of 0.1  $\mu\text{m}$  PHEMTs with 2-DEG concentrations of  $2.3 \times 10^{12} \text{ cm}^{-2}$  with mobilities of 6500 cm<sup>2</sup>/V-sec. The devices exhibited an extrinsic and intrinsic transconductance of 1070 and 1510 mS/mm respectively, a maximum current density of 550 mA/mm and a peak  $f_t$  of 220 GHz, these results being the highest ever reported for HEMTs fabricated on GaAs substrates. Work performed at the University of Lille [Villeneuve D'Ascq, France]. See "1510 mS/mm 0.1  $\mu\text{m}$  Gate Length Pseudomorphic HEMTs with Intrinsic Current Gain Cutoff Frequency of 220 GHz," F. Diette et al, Electronics Letters, 32(9), 848 [25 April 1996].

## 800 GHz Solid State Local Oscillators

The need for higher frequency operation continues, with local oscillators operating in the submillimeter wavelength range (300 GHz-3 THz) being a critical component for any RF system. Utilizing Schottky Barrier based multiplier technology, optimized diodes were fabricated utilizing a combination of thin epitaxial layers (240 nm) and doping levels of  $2.3 \times 10^{17} \text{ cm}^{-3}$ , such that the epitaxial layer which makes up the diode is fully depleted, just before the onset of avalanche breakdown. Using this approach, a varactor tripler operating up to 800 GHz with 250 mW output power was fabricated - this being the highest output power ever reported at this frequency. Work performed at the University of Virginia [Charlottesville, VA] and Radiometer Physics GmbH [Meckenheim, Germany]. See "Progress Toward Solid-State Local Oscillators at 1 THz," T.W. Crowe et al, IEEE Microwave and Guided Wave Letters, 1(6), 207 [May 1996].

# A new era: SiC high-frequency electronics



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## Quantum Cascade Lasers Operate Above Room Temperature

Diode lasers operating between 2 and 12 micron wavelengths are needed for gas detection, IR spectroscopy, laser surgery and military applications. Competition in the field of mid-IR lasers has increased over recent years, with four basic technologies under investigation: IV-VI ("lead salt") interband lasers, III-V (antimonide) interband lasers, III-V type II quantum well lasers, and III-V quantum cascade lasers. Elsewhere in this issue (see page 28) evidence is given that the IV-VI lead salt lasers are in many respects the most mature of these four technologies, and the only one which is currently in production. But a recent report from Bell Laboratories demonstrates that quantum cascade lasers are progressing rapidly.

The quantum cascade laser is a new mid-infrared light source which is based on one type of carrier (electrons) making transitions between energy levels created by quantum confinement. As compared to the competing technologies, quantum cascade lasers should have the advantage of a large  $T_0$ , which characterizes the temperature sensitivity of the lasing threshold, and higher temperature operation, since the main nonradiative channel is optical phonon emission rather than the Auger effect. The later parameter is especially important. Room temperature or even thermoelectrically cooled mid-IR laser diodes are not currently available, which places some rather obvious limits on their commercial potential.

The situation has now changed somewhat, as Bell Labs have demonstrated quantum cascade lasers which operate at or above room temperature. The device consisted of a GaInAs/AlInAs heterostructure grown lattice matched to an n+ InP substrate by MBE. An InP top cladding layer is used to optimize heat dissipation. The lasing wavelength of these devices is 5 microns. Operating temperatures up to 320K were achieved in a pulsed mode, and 140K operation was achieved in continuous wave mode. The  $T_0$  is 114K, which is much larger than the  $T_0$ 's of other similar wavelength laser diodes (<50K). This indicates a reduced temperature sensitivity of the thresholds of the quantum cascade lasers. A peak pulsed optical power of 200 mW and average power of 6 mW were obtained at 300 K.

See "High power mid-infrared quantum cascade lasers operating above room temperature", J. Faist et al, Appl. Phys. Lett. 68, 3680 [1996].

## Optoelectronic Devices

### Record Performance for 1.55 Micron Laser Diodes Grown Using TBA and TBP

Laser diodes operating at 1.55 micron wavelengths are key components of long haul optical fiber data transmission systems because of the low loss of the fibers and the existence of erbium doped fiber amplifiers for this wavelength. Record performance 1.55 micron laser diodes were recently reported. A  $93 \text{ A/cm}^2$  threshold current density, 91% internal quantum efficiency result was obtained in a strained single quantum well MOCVD-grown GaInAsP laser. Tensile-strained, compressively-strained and unstrained quantum wells were investigated in this study. The best results were obtained with compressive strain. A second significant point of this work concerns the MOCVD growth. Typically MOCVD uses the highly toxic gases, arsine and phosphine, as its group V sources. In the present work, the alternative group V sources, tertiarybutylphosphine (TBP) and tertiarybutylarsine (TBA), were used. These alternative sources are less hazardous than arsine and phosphine since they are liquid with low vapor pressures. The success with TBA and TBP clearly demonstrates that the use of these less toxic, alternative group V sources in MOCVD does not compromise the quality of the material. Work performed at the University of Southern California [Los Angeles, CA]. See "Fabrication, Characterization and Analysis of Low Threshold Current Density 1.55 micron Strain Quantum-Well Lasers", A. Mathur, et al, IEEE J. Quantum Electron. 32(2), 222 [February, 1996].

### High Bit Rate, Long Wavelength Monolithic Photoreceiver

The integration of photodetectors and preamplifier circuits to produce monolithic photoreceivers would be advantageous for high speed data transmission systems because of compactness, ruggedness and packaging ease. Several laboratories have reported single channel integrated photoreceivers operating at bit rates above 10 Gb/s. For such applications as wavelength division multiplexing, multichannel photoreceivers are needed. A significant step toward achieving a multichannel, high speed, integrated photoreceiver was recently accomplished with the construction of a two channel receiver array. Each channel consisted of a waveguide p-i-n photodiode and a HEMT preamplifier. The epitaxial layers were deposited on a semi-insulating InP substrate by MOCVD in a single growth run. The HEMT layers, consisting of AlInAs and GaInAs, were deposited first, followed by the InP/GaInAsP/GaInAs photodiode layers. The photoreceiver exhibited sensitivities of -16.1 dBm and -15.3 dBm for each channel for a 10 Gb/s pseudorandom NRZ signal at a wavelength of 1.55 micron. Crosstalk was better than -20 dB. Work performed at the NTT Opto-Electronics Laboratories [Atsugi, Japan]. See "10-Gb/s Two-Channel Monolithic Photoreceiver Array Using Waveguide p-i-n PD's and HEMT's", K. Takahata, et al, IEEE Photon. Tech. Lett. 8(4), 563 [April, 1996].

### Tunable Resonant Cavity Photodetector

A novel photodetector was recently described, which consists of a p-i-n photodiode inside a voltage tunable resonant cavity. The resonant cavity was constructed in the AlGaAs material system with distributed Bragg reflector (DBR) stacks. The upper DBR consisted of an n-type, freely suspended cantilever section above a fixed, p-type section. The air gap between the two sections can be varied by the applied voltage between the two sections, thereby tuning the cavity. The lower DBR is fixed and is n-type. The p-i-n photodiode is formed by the p-type section of the upper DBR, an intrinsic region containing InGaAs strained quantum wells, and the n-type lower DBR. The resonant cavity causes the detector to respond to a narrow bandwidth only 3.5 nm wide. The center wavelength can be continuously tuned over 30 nm by varying the bias on the cantilever over a 7 volt range. The detector exhibited a peak responsivity of 0.093 A/W. The device can also be operated in a mode that enables wavelength tracking. In this mode, as the wavelength of the source drifts away from the center wavelength of the resonant cavity, the output of the photodetector will decrease and the bias on the cantilever is automatically adjusted to bring the cavity back on resonance with the source wavelength. The device can also be operated in a mode that enables its use as a wavelength meter. Work performed at Stanford University [Stanford, CA]. See "Widely and Continuously tunable Micromachined Resonant Cavity Detector with Wavelength Tracking", M.S. Wu, et al, IEEE Photon. Tech. Lett. 8(1), 98 [January, 1996].

### Wavelength Shifting of a Quantum Well Laser by Ion Implantation

Many applications of laser diodes would benefit from the availability of different wavelength devices on the same chip. Epitaxial regrowth is an obvious method to accomplish this goal, but has the disadvantages of complicated processing and epitaxy, and problems with the quality of the regrown material. An alternative scheme is the selective area, partial intermixing of the quantum well active region. In a recent work, the intermixing was accomplished by ion implantation and annealing. The as-grown laser structure, which lased at 1.5 microns, consisted of InP clads, an InGaAsP core and 5 InGaAs quantum wells. Phosphorus ions were implanted at a dose of  $2.5 \times 10^{13} \text{ cm}^{-2}$  and an energy of 1 MeV. The expected mean range of the implant was less than half of the distance down to the active region. The lasers were subjected to post-implant anneals, which cause implant-created defects to diffuse through the core, clad and active region. The movement of the defects through the active region causes partial intermixing of the quantum well and barrier layers, producing a blue shift of the emission wavelength. The observed post-anneal blue shift was as large as 60 nm. A crucial part of this work is the fact that the wavelength shifting was not accompanied by any increase in threshold current. This 60 nm wavelength shift is sufficient to make the structure transparent to the original lasing wavelength, enabling the future integration of lasers with low loss waveguides. Work performed at the National Research Council [Ottawa, ON Canada] and University of Western Ontario [London, ON Canada]. See "Demonstration of an Ion-Implanted, Wavelength-Shifted Quantum-Well Laser", IEEE Photon. Tech. Lett. 8(1), 16 [January, 1996].

# Summer Slip

MARIE MEYER

There was not much "hard news" from the seven companies in the Compound Semiconductor Portfolio, and, as a result, there was little overall change during the May - June period, which ended the period down 7% from the previous issue, but up 36% for the year.

The hardest hit stock was **Vitesse Semiconductor**, which ended the period down over 5.5 points. However, the company still looks fundamentally solid, so the downturn is most likely the result of profit-taking. However, the same cannot be said for the other two losers for the period., **Alpha Industries** was down by more than two points for May - June, and is down 4.75 for this year. Company performance has been lack-luster for the past few quarters, as management had predicted, and the company has warned that it will report a loss for the quarter ended June 30, due to "overall softness in the North American cellular market and the delayed roll-out of the Personal Communications System (PCS)".

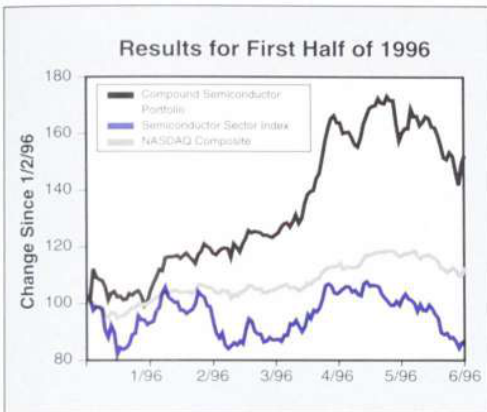
After that, Alpha's management hopes that the worst will be behind them. M.J. Reid, President and CEO, said "We remain focused on the wireless market, and our long-term view is that this will be the main area of strong growth for the

company...we anticipate break-even to positive results in the second quarter [which will end in September] and that the rest of our 1997 fiscal year will be profitable, with a ramp up of demand starting late in our second quarter." Reid also reports the receipt of a number of "small but significant" design wins, including MMICs for analog and digital cellular, PCS and GSM pre-production and qualification orders from AT&T and Motorola, and initial production orders for interactive set-top cable converters from Scientific Atlanta and General Instruments. To increase focus on the wireless markets, Alpha is decreasing its investments in its non-wireless subsystems business, which develops transceivers and other more highly integrated products for OEMs. This activity is likely to contribute to the loss which is anticipated for the quarter just ended.

Alpha is currently trading at a price/earnings (P/E) ratio of ~19. See box. If they can deliver the goods - actually secure the production orders when business picks up - then they look like the best "buy" of the group.

The other stock that was down significantly for the May-June period was **Cree Research**, which lost 3.25 points to reach roughly a break-even point for the year. A continued slide seems likely. On July 2 the company announced that it expects to report a loss for the quarter just completed, due to LED manufacturing troubles. The company reports that it doubled its LED output in comparison to the previous quarter, but "epi productivity in June was lower than necessary to offset costs". It appears, then, that the company has not yet conquered the "volatility" of its epitaxial process that it reported earlier (see CS 2(2) 49). Cree was able to report the receipt of additional government funding for its blue laser program (see page 25). The company reports that "a portion of this funding will be specifically used to achieve epitaxial process stability and consistent repeatability that is critical for the formation of the blue laser and for the production of blue diodes." Cree president Neal Hunter said "1996 has been a critical transition period for Cree as we moved from a research and development company to one that is driven by product revenue. This transition has moved slower than we had hoped, however, we are certain, as are our corporate technology partners (Siemens and Philips), that the

fundamentals of our core technology will continue to drive us forward and enable Cree to lead the development of the blue LED market." Cree's LED shipments for the quarter just completed were 3 million units; in comparison, Nichia reports that it is getting ready for production runs of 10 million LEDs per month (see page 25). Obviously, Cree is going to face quite a challenge if they are serious about attaining that leadership position.



## The Compound Semiconductor Portfolio

| Company                       | Symbol* | 1/2/96 | 6/28/96  | Change | P/E Ratio |
|-------------------------------|---------|--------|----------|--------|-----------|
| Alpha Industries              | AHA     | 13.625 | 8.875    | -4.75  | 19        |
| Anadigics, Inc.               | ANAD    | 21.25  | 29.125   | +7.875 | 29        |
| Advanced Technology Materials | ATMI    | 10.375 | 13.50    | +3.125 | 94        |
| Cree Research                 | CREE    | 14.75  | 15.00    | +0.25  | 91        |
| SDL Inc.                      | SDLI    | 25.375 | 41.625** | +16.25 | -         |
| TriQuint Semiconductor        | TQNT    | 14.25  | 20.75    | +6.5   | 45        |
| Vitesse Semiconductor         | VTSS    | 13.125 | 24.125   | +11.0  | 58        |

Portfolio Value, 6/28/96 (100 shares of each) \$15,300  
Change since 1/2/96 +36%

\*AHA traded on AMEX, all others traded on NASDAQ

\*\*SDL split three-for-two on June 12. Prices listed adjusted to reflect pre-split value.

# PROMECEME

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Circle 180 on Reader Service Card

*Compound Semiconductor*  
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**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    |
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| 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 |

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### 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.

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### Engineering Positions at Epitaxial Products International Ltd (UK).

Epitaxial Products International Ltd was founded in 1988 and has quickly established itself as a World Leader in the supply of custom III-V epitaxial material structures. In order to meet the anticipated growth in demand for III-V products, EPI aims to recruit professional engineers of the highest calibre from electronic engineering, materials science or physics disciplines. If your degree or post graduate experience has encompassed semiconductor theory and you have an understanding of III-V devices, epitaxial processes or material characterisation techniques such as x-ray diffraction, photoluminescence spectroscopy and other electrical/optical processes, then we want to hear from you. If you are interested in joining our team at EPI, please forward a copy of your current CV, quoting reference CS/96062 to Chris Meadows, HR/QA Manager, Epitaxial Products International Ltd., Cypress Drive, St.Mellons, Cardiff, CF3 0EG, UK. FAX: +44 1222 779929.

### Research Opportunities in Wide Bandgap Semiconductors

The Semiconductor Research Group at the Materials Division of the Electrotechnical Laboratory (Tsukuba, Japan, 60 km from Tokyo) is looking for post-doctoral fellows or sub-bachelor researchers working in our group for 4 or 5 months. Called researchers will be expected to work on the characterization of III-V nitride epitaxial films or band calculation for III-V nitrides.

The requirements for candidates are as follows: Doctor's degree or equivalent; good communication skills in English or Japanese; experience in the research on semiconductor physics or semiconductor engineering (with experience of CVD or MBE preferable, but not mandatory), and interest in nitride semiconductors and their application. The fellowship award is a monthly living allowance of about ¥270,000; travel fee between the fellow's home country and Tsukuba, and a housing fee. The desirable beginning of the fellowship is between October, 1996 and February, 1997.

Interested applicants should send CV, name and contact information (address, telephone number, fax number, e-mail address etc.), and references. In the selection process, a publications list and a recommendation letter will be necessary.

**Address information or inquires to:** Dr. Sadafumi Yoshida, Chief, Quantum Materials Section, Materials Science Division, Electrotechnical Laboratory, 1-1-4, Umezono, Tsukuba, Ibaraki 305, Japan. TEL [81] 298 54 5222 FAX [81] 298 58 5434 E mail: e8101@etrlps.etl.go.jp

### Postgraduate Research Opportunities at NEWI

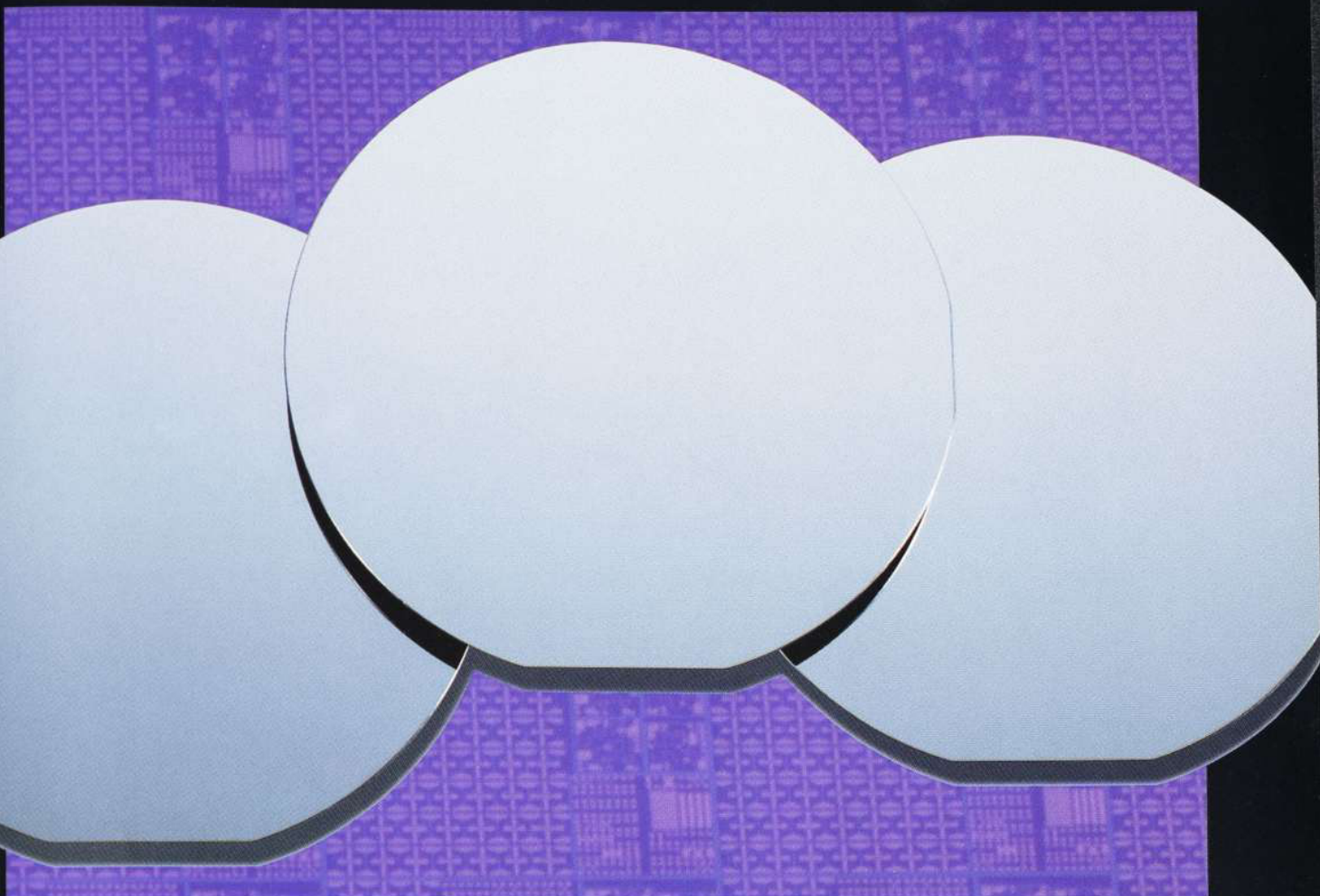
Excellent opportunities currently exist for postgraduate research in the Advanced Materials Research Laboratory in Wrexham. This laboratory is a recognised Centre of Expertise in the growth of compound II-VI semiconductors by the MOCVD process. In addition to three dedicated MOCVD reactors, the laboratory possesses a comprehensive range of optical, electrical & structural material characterisation equipment. Current research activities include:

- MOCVD growth & characterisation of wide band gap II-VI optoelectronic semiconductors
- In situ studies of MOCVD growth mechanisms via novel optical (RAS) & structural (STM) techniques
- Novel thin film, flat panel display materials
- Fabrication of self-organising low-dimensional quantum dots by MOCVD.
- Computer modelling of MOCVD reaction chemistry

Generous postgraduate student funding is available for research in these increasingly commercially important areas. Two M.Phil studentships are now available starting this fall and would suit individuals with a background in chemistry and an interest in thin film growth mechanisms.

For further information, please contact: Dr Andy C. Wright, Advanced Materials Research Laboratory, North East Wales Institute for Higher Education, Mold Rd., Wrexham LL11 2AW UK. Tel: [44] 1978 293 001 Fax: [44] 1978 290 008 email: wrighta@newi.ac.uk

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