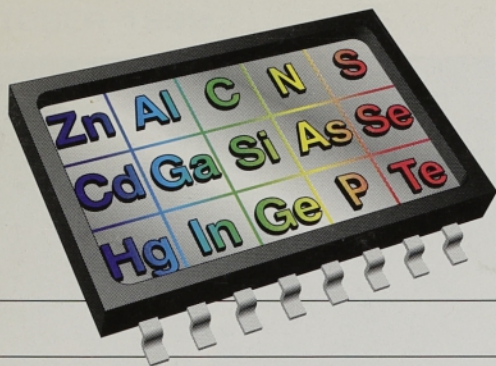




# COMPOUND

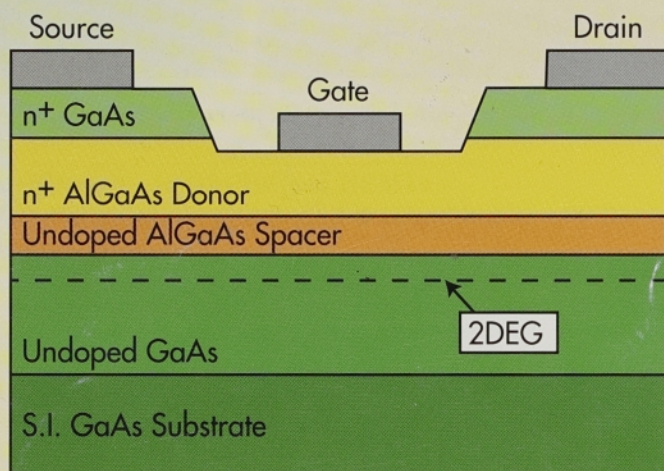
## SEMICONDUCTOR

October 1999

Volume 5 Number 8

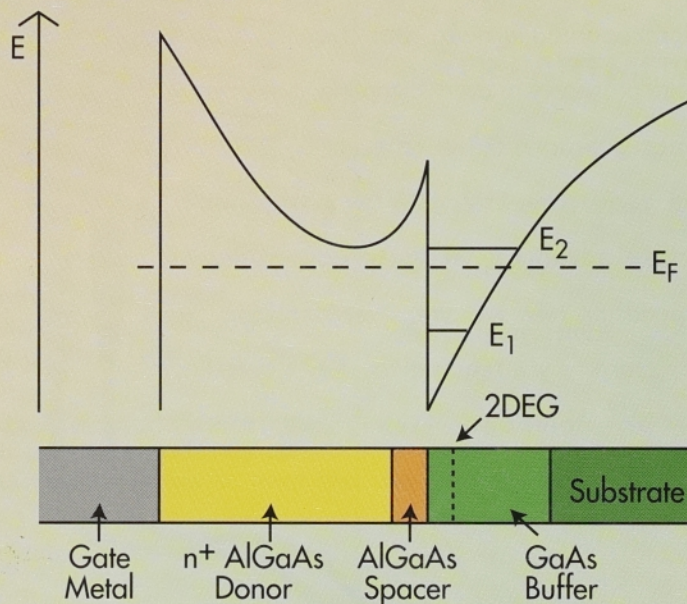
High Speed  
Metamorphic  
InAs/AlSb  
Millimeter-Wave

# HEMTs



## Also in this Issue:

- MIOMD Conference
- GaAsTEK Profile
- M/A-COM Expands





# The Key Conference

## Compound Semiconductors in Communications

Key West, Florida  
March 13-14, 2000  
[www.keyconference.com](http://www.keyconference.com)

### A Discussion of the Future Role of Compound Semiconductors in the Global Communications Industry

In the past five years the compound semiconductor industry has enjoyed unprecedented growth. But the future prosperity of every company is not guaranteed. Whether or not your company will be positioned to take advantage of these opportunities depends on how well you understand the "big picture." By attending the Key Conference on Compound Semiconductors in Communications, you will have an



opportunity to hear how the major producers and consumers of compound semiconductor devices plan to meet the challenges ahead. All of the speakers at the Key Conference will

be hand-picked by the sponsors for their knowledge about the forces that will shape the future of the compound semiconductor industry in the global communications market.



For more information visit our website at  
[www.keyconference.com](http://www.keyconference.com)

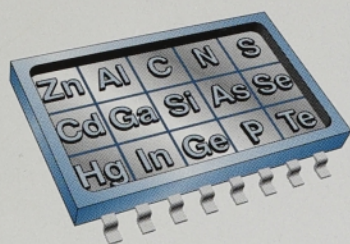
Presented by Compound Semiconductor Magazine

## The Key Conference



[www.keyconference.com](http://www.keyconference.com)





# COMPOUND

## SEMICONDUCTOR

### COVER STORY – HEMTs

#### 20 HEMTs in Handsets

Although HBTs have grabbed the headlines recently, HEMTs are still widely used in handsets, for a number of applications.

#### 22 How It Works – The HEMT

Don't know a metamorphic HEMT from a pseudomorphic HEMT? – We make it easy.

#### 24 Advances in Millimeter – Wave HEMTs

As GaAs PHEMTs and InP-based HEMTs continue to set records and as new device technologies emerge, further improvements in the performance of millimeter-wave MMICs can be expected.

#### 30 InP HEMT ICs for Lightwave Communication at 40 Gb/s and Beyond

InP HEMTs form the basis of attractive devices for ultrahigh-capacity optical communications operating at 40 Gb/s and above – some novel circuit designs and advanced packages are described.

#### 36 AlSb/InAs HEMTs with High Speed and Low Power Consumption

Improvements in the channel mobility and velocity of InP/ In<sub>x</sub>Ga<sub>1-x</sub>As HEMTs are hindered by lattice mismatch problems for  $x > 0.53$ . AlSb/InAs HEMTs featuring InAs channels have the potential for setting new standards for speed and power consumption.

#### 40 Metamorphic InAlAs/InGaAs HEMTs

Metamorphic HEMTs combine high In content channels with the processing advantages of GaAs substrates, offering several advantages for microwave and millimeter-wave applications.

### GaAs ICs

#### 9 News

M/A-COM expands fabrication facility...M/A-COM, Anadigics sign SiGe agreements...Alpha completes fab expansion, introduces HBTs...Filtronic finalizes Fujitsu fab foray...and more.

#### 50 Company Profile – GaAsTEK Offers MMIC Modules

GaAsTEK has rationalized its microelectronics manufacturing operations to supply RF, microwave and millimeter wave modules.

#### 56 Forum – GaAs ICs for ATE Applications

Rapid increases in microprocessor speeds has driven development of advanced testing equipment based on GaAs ICs, according to Alan Armstrong from Vitesse.

### OTHER FEATURES

#### 44 Conferences – Mid-Infrared Optoelectronic Materials and Devices

Results from the recent MIOMD III conference in Aachen.

#### 60 Forum – Si-on-GaAs Wafers for Monolithic Optoelectronic Integration

Wafer bonding thin Si layers onto thick GaAs substrates reduces the thermal expansion coefficient-related stresses associated with the monolithic integration of GaAs optoelectronics and Si CMOS microelectronics.

#### 62 Forum – Characterization of InP Substrates for Large-Area Focal Plane Arrays

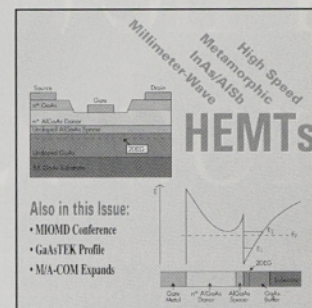
Sensors Unlimited's large-area focal plane arrays for near-infrared cameras yield chip sizes that are limited by the current 2-inch semiconducting InP wafer industry format.

#### 67 Research Review

Homoepitaxial growth of GaN with extremely high optical quality...Visible emission from GaN quantum dots on silicon...True enhancement-mode FETs from Motorola...and more.

#### 72 Portfolio

Recent developments at Kopin and Plasma-Therm.



*In the original AlGaAs/GaAs High Electron Mobility Transistor (HEMT) structure, the Schottky gate controls (modulates) the amount of carriers supplied to the channel by the n<sup>+</sup>-AlGaAs donor layer. The carriers are confined in a potential well in the GaAs layer, forming a two-dimensional electron gas, or 2DEG. For further explanation, see page 22. Our coverage of a number of HEMT-related subjects begins on page 20 with a review of the uses of HEMTs in handsets.*

### NEWS

#### 6 News Briefs

Aixtron Buys Thomas Swan...Discovery Develops High Bandwidth OEICs...Patent Awards for IMC...Spire contract for GaAsN-based HBTs...and more.

#### 14 Nitride News

First UV digital camera...Microsemi, Sterling develop SiC devices...Orders for Cree...Witech becomes Nitres.

#### 19 Materials & Equipment

AXT temporarily suspends Ge shipments...Two new MOCVD reactors for Kopin...and more.

### DEPARTMENTS

#### 4 Index

#### 65 New Products/New Literature

#### 74 Calendar

#### 76 Employment



# A new standard in GaAs production epitaxy...

VG Semicon's V150 MBE system with ThermoCell™ technology sets a new standard for high volume 4" and 6" epi processing. It offers startling advances in throughput, yield and process stability.

**High Volume** - the V150's platen design accommodates four 6", nine 4" or sixteen 3" wafers. With system control based on the industry-standard X-Gen™ automation package and a minimum 6 month scheduled cycle time, system throughput exceeds 25,000 4" or 10,000 6" wafers per year.

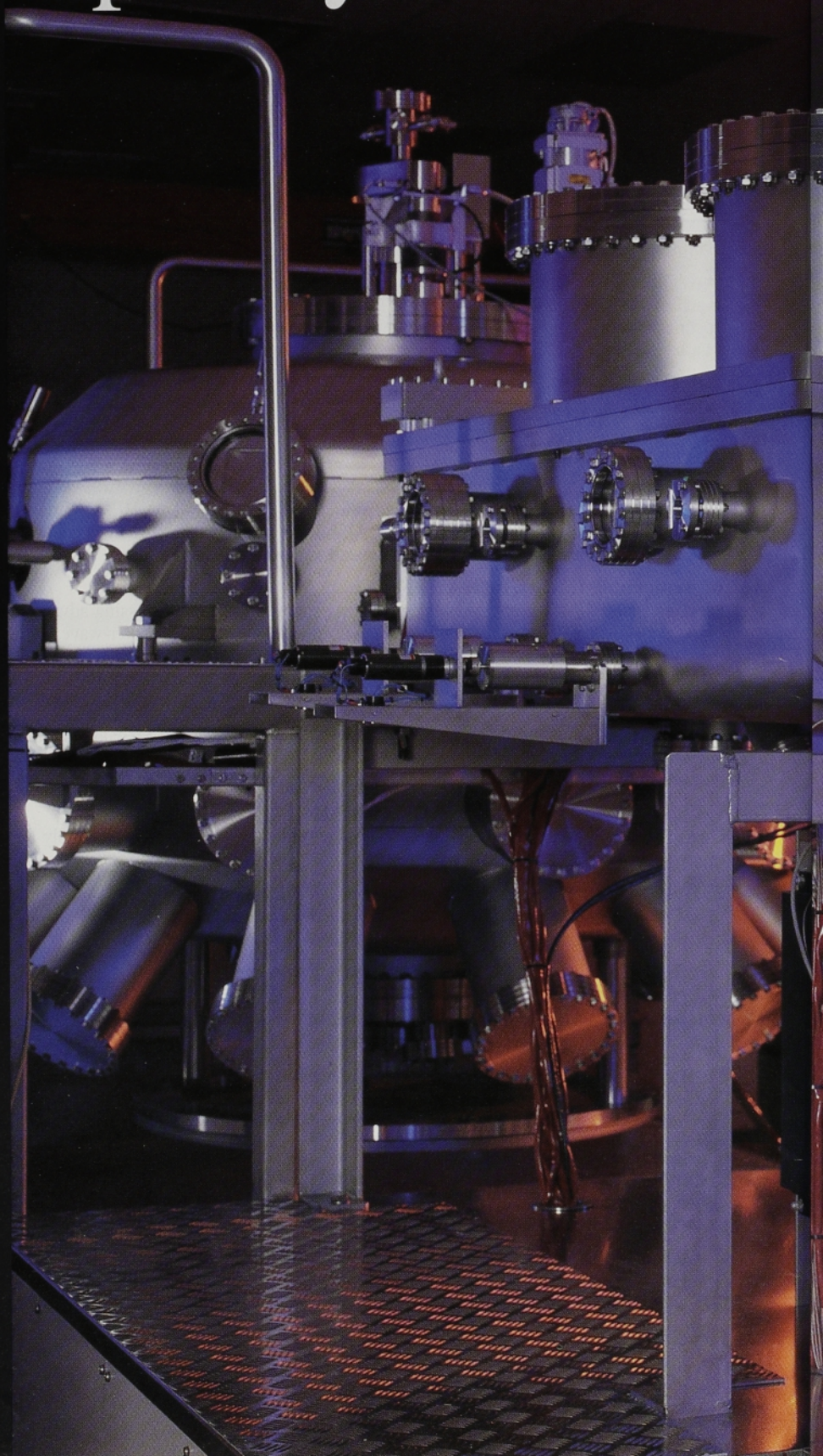
**High Yield** - VG Semicon's acclaimed ThermoCell™ technology provides process uniformity and reproducibility within 1%. But more importantly the use of ThermoCell™ effusion sources makes the V150 ten times more stable than its closest competitor, eliminating the costly requirement for daily recalibrations. And with the lowest defect levels reproducibly measured from any effusion source it's no wonder the V150 with ThermoCell™ technology has been called the most advanced MBE system available today.

So if your process needs high throughput, reliability, performance and reproducibility, the choice has never been easier. Talk to VG Semicon, the MBE company.

|           |                  |
|-----------|------------------|
| UK        | (44) 1342 325011 |
| USA       | (1) 800 888 7007 |
|           | (1) 978 524 1041 |
| Japan     | (81) 3 3639 9652 |
| France    | (33) 1 6092 3610 |
| Korea     | (82) 2 548 2983  |
| Taiwan    | (88) 63 535 9771 |
| Benelux   | (31) 184 490909  |
| Singapore | (65) 779 3735    |

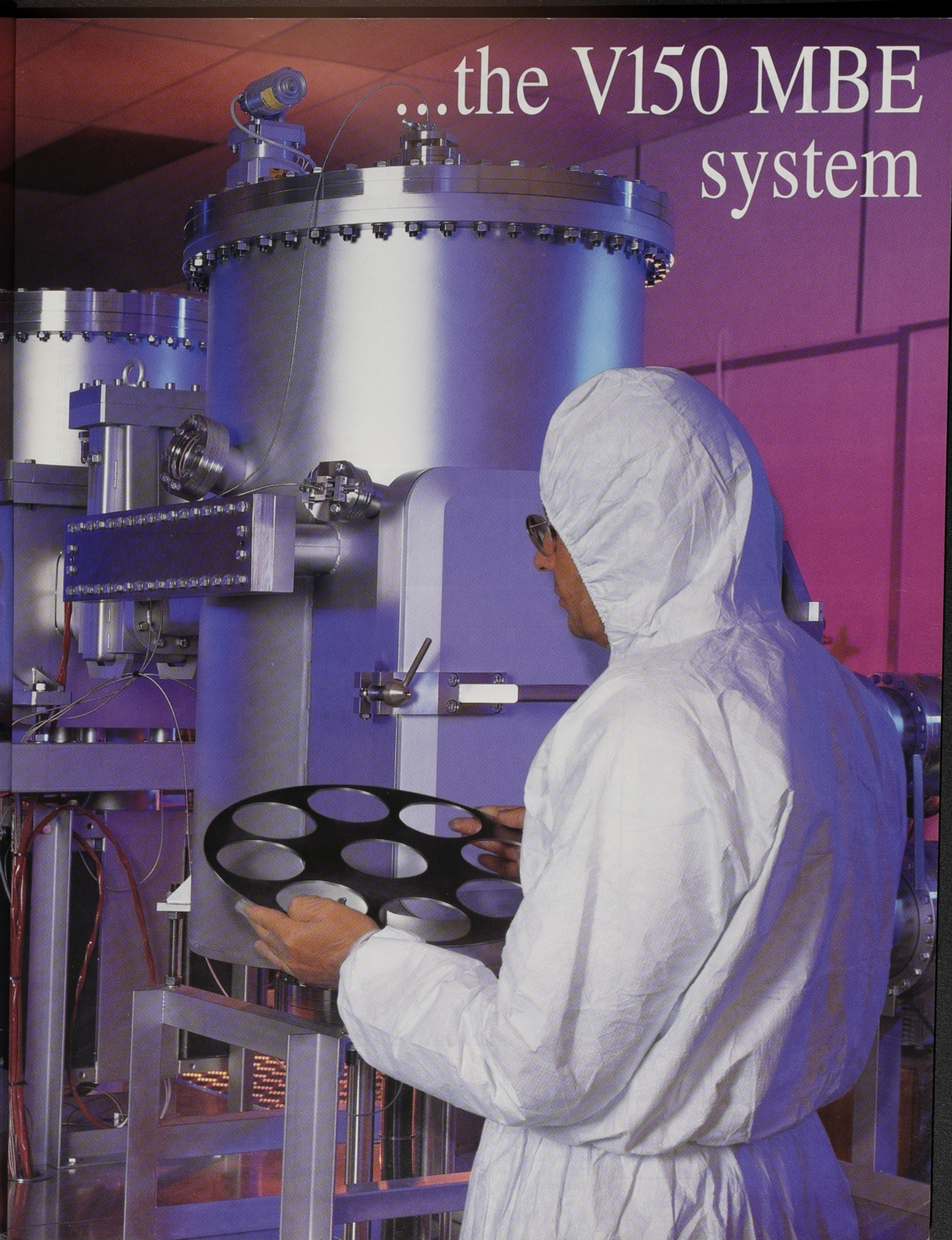
Or visit [www.vgsemicon.com](http://www.vgsemicon.com)  
and take a video tour.

 **VG Semicon**  
The MBE Company





...the V150 MBE  
system





# COMPOUND SEMICONDUCTOR

**Compound Semiconductor**  
is published nine times yearly by

Franklin Publishing  
163 Cabot Street  
Beverly, MA 01915 USA  
TEL [1] 978 927 9994  
FAX [1] 978 927 9893  
Individual annual subscription  
price: \$90 U.S., \$115 foreign.  
Library rate: \$300 U.S. and foreign.

## Editor

Tim Whitaker  
tim.whitaker@compsem.com

## Managing Editor

Marie Meyer  
mmeyer@compsem.com

## Assistant Editor

Richard Dixon  
rdixon@compsem.com

## Editorial Board

### Colombo Bolognesi

Simon Fraser University (Canada)

### Steven DenBaars

University of California at Santa Barbara (USA)

### Andrew Johnson

Defense Evaluation and Research Agency (UK)

### Robert Metzger

Georgia Institute of Technology (USA)

### Rodney Moss

Hewlett Packard Fiber Optic Components (UK)

### Shuji Nakamura

Nichia Chemical (Japan)

### Dwight Streit

TRW (USA)

### Toby Strite

Uniphase Laser Enterprise (Switzerland)

### Jacob Tarn

Epistar (Taiwan)

### Gary Tomkins

Nortel Networks (Canada)

### Andreas Waag

University of Wurzburg (Germany)

### Gary Wicks

University of Rochester (USA)

### Peter Zory

University of Florida (USA)

©Copyright 1999 by Franklin  
Publishing - all rights reserved.

## POSTMASTER

Send address changes to:  
CS Subscriptions  
163 Cabot Street  
Beverly, MA 01915 USA

# Organization Index

## Company/Organization

| Company/Organization            | Page           |
|---------------------------------|----------------|
| ACCO                            | 12             |
| A.F. Ioffe Inst. Berlin         | 69             |
| AFRL                            | 8, 17          |
| AFOSR                           | 18             |
| Aixtron                         | 6, 19, 44, 73  |
| Alpha Industries                | 11, 20, 73     |
| Anadigics                       | 10, 12, 20, 73 |
| APA Optics                      | 73             |
| Atmel                           | 10             |
| ATMI                            | 73             |
| AXT                             | 19, 73         |
| Bang and Olufson                | 50             |
| CEL                             | 8              |
| Celeritek                       | 20, 73         |
| Coherent                        | 73             |
| Conexant                        | 73             |
| Cree Research                   | 17, 73         |
| CRHEA-CNRS                      | 68             |
| Discovery Semicond.             | 6              |
| Emcore                          | 6, 68, 73      |
| Epitaxial Technologies          | 19             |
| Ericsson                        | 50             |
| Filtronics                      | 12             |
| Fraunhofer IAF                  | 25, 46         |
| Fraunhofer ISE                  | 44             |
| Fuji                            | 70             |
| Fujitsu                         | 12, 20         |
| GaAsTEK                         | 50             |
| GE Lighting                     | 18             |
| Gilfillan                       | 50             |
| Hewlett-Packard                 | 20             |
| Honeywell                       | 14             |
| HRL Labs                        | 24             |
| Hughes Electronics              | 18, 19, 52     |
| Hughes Research Labs            | 46             |
| IMA                             | 8              |
| IMC                             | 6              |
| IMEC                            | 46             |
| Infineon                        | 20             |
| IEMN                            | 40             |
| Ioffe Inst.                     | 45             |
| IQE                             | 66, 73         |
| JDS Uniphase                    | 73             |
| Johannes Kepler Univ.           | 45             |
| JPL                             | 46             |
| Kopin                           | 19, 72         |
| M/A-COM                         | 9              |
| Matsushita                      | 71             |
| Mercedes-Benz                   | 10             |
| Microsemi                       | 16             |
| MIT                             | 60             |
| MIT Lincoln Labs                | 44, 60         |
| Mitsubishi                      | 71             |
| Motorola                        | 20, 50, 71     |
| NASA                            | 8              |
| Nat'l Research Council (Canada) | 46             |
| Naval Research Labs             | 36, 48         |
| NCSU                            | 14, 64         |
| NEC                             | 8, 20, 71      |
| NIST                            | 18, 62         |
| Nitres                          | 18             |
| NTT                             | 30             |
| NVL                             | 14             |
| ONR                             | 17, 18, 38     |
| Ortel                           | 73             |
| Osram                           | 17             |
| Oxford Plasma                   | 73             |
| Philips                         | 50             |
| Picogiga                        | 73             |
| Plasma-Therm                    | 72             |
| Princeton Univ.                 | 62, 69         |
| Raytheon                        | 20, 52         |
| RF Micro Devices                | 12, 19, 73     |
| RWTH Aachen                     | 44             |
| Sarnoff Corp.                   | 70             |
| SDL                             | 70, 73         |

|                               |            |
|-------------------------------|------------|
| Sensors Unlimited             | 62, 70     |
| Siemens                       | 50         |
| Spectrolab                    | 19         |
| SpectraSensors                | 8          |
| Spire                         | 8, 73      |
| Sterling Semiconductor        | 16         |
| Sumitomo Electric             | 73         |
| Surface Technol. Sys.         | 73         |
| Tegal                         | 19         |
| Temic                         | 10         |
| Texas Instruments             | 52         |
| Thomas Swan                   | 6          |
| TriQuint                      | 12, 73     |
| TRW                           | 12, 25, 71 |
| Tyco                          | 9          |
| U.S. Army Res. Labs           | 48         |
| U.S. BMDO                     | 18         |
| U.S. Navy                     | 52         |
| UMIST                         | 46         |
| Uniroyal Technology           | 73         |
| Univ. d'Avignon               | 48         |
| Univ. Corp. Atmos. Res.       | 8          |
| Univ. of Calif. Santa Barbara | 70         |
| Univ. of Cincinnati           | 67         |
| Univ. of Iowa                 | 48         |
| Univ. of Lancaster            | 45         |
| Univ. of New Mexico           | 69         |
| Univ. of So. Ca.              | 70         |
| Univ. of Ulm                  | 19, 67     |
| Westinghouse                  | 52         |
| WiTech                        | 18         |
| Xiamen Chinese. Elec.         | 12         |

## Advertiser Index

|                                  |        |
|----------------------------------|--------|
| Aixtron                          | 5      |
| AXT                              | 55     |
| Bio-Rad Micromeritics            | 15     |
| BOC Temescal                     | 23     |
| Crystar                          | 16     |
| CS GmbH                          | 9      |
| Emcore                           | 19, 61 |
| EPI MBE Products                 | 53     |
| Epichem                          | 63     |
| Epitaxial Products International | OBC    |
| Epitaxial Technologies           | 7      |
| Freiberger                       | 39     |
| Global Communication Semi. (GCS) | 51     |
| Indium Corporation of America    | 33     |
| Insaco                           | 8      |
| IPRM                             | 69     |
| ISBLLED                          | 75     |
| Key Conference                   | IFC    |
| Loomis                           | 17     |
| MRS Spring Meeting               | 75     |
| Nordic Epitaxy                   | 45     |
| Oxford Plasma Technology         | 11     |
| Performance Materials            | 18     |
| QED                              | 35     |
| Riber                            | 27, 59 |
| Steag                            | 13     |
| Sterling Semiconductor           | IBC    |
| Strategies in Light              | 49     |
| Struers (Logitech)               | 57     |
| Super Epi                        | 20     |
| Tegal                            | 43     |
| TLC                              | 29     |
| VG Semicon                       | 2, 3   |
| Wafer Technology                 | 47     |



Web site address:  
<http://www.aixtron.com>

## IT'S A FACT

that no other MOCVD company in the world offers you the **unique**, **versatile**, and **constantly high quality** technology you're assured of from AIXTRON, whether you're producing LED's, Lasers, Detectors, HEMTs, HBTs, OEICs...

...And we can prove it!

## FACT!

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

## FACT!

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

## FACT!

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



WHAT BETTER GUARANTEE OF OUR

*Commitment to AIXcellence*

# AIXTRON®

### European Headquarters

Aachen, Germany

AIXTRON AG

Kackertstraße 15-17, 52072 Aachen  
Germany

Phone: +49 (241) 89 09 - 0

Fax: +49 (241) 89 09 - 40

### Customer Service Line

Phone: +49 (241) 89 09 - 91

e-mail: [info@aixtron.com](mailto:info@aixtron.com)

### US Headquarters

Chicago, IL

AIXTRON Inc.

1670 Barclay Blvd.

Buffalo Grove

IL 60089 USA

Phone: +1 (847) 215 73 35

Fax: +1 (847) 215 73 41

e-mail: [info@aixtron.com](mailto:info@aixtron.com)

### Sales and Service

Tokyo, Japan

Moritani & Co., Ltd/AIXTRON

4th Section, 12th Machinery Dept.

Industrial Machinery Division

1-4-22 Yaesu, Chuo -ku

Tokyo 103-8680, Japan

Phone: +81 (3) 32 78 - 61 31

Fax: +81 (3) 32 78 - 61 21

e-mail: [KYP00751@niftyserve.or.jp](mailto:KYP00751@niftyserve.or.jp)





## Aixtron Buys Thomas Swan

In a move that consolidates the MOCVD equipment market, Aixtron (Aachen, Germany) has purchased Thomas Swan's Scientific Equipment Division. The division, which manufactures MOCVD reactors at its plant in near Cambridge, England had sales of £6.6 million (~\$10 million) in the year ending March 1999. The assets of the former Thomas Swan Division will be acquired by Thomas Swan Scientific Equipment Ltd., a newly formed company owned 100% by Aixtron AG and registered in England. The company will operate independently within the Aixtron Group, and equipment manufactured in England will continue to be distributed on a world-wide basis under the established trade name "Thomas Swan".

According to VSLI Research Inc., Aixtron enjoyed a 44% share of the MOCVD equipment market in 1998. The second largest supplier was Emcore, with a 20% share, while Thomas Swan accounted for just over 7% of sales.

"The acquisition is a strategic move designed to strengthen our technological leadership," says Claus Ehrenbeck, Aixtron's

investor relations manager. "The purchase will significantly extend our range of products and offer the potential for synergy between the two groups in R&D, purchasing and other areas."

Aixtron's MOCVD reactors are based around horizontal tube designs and utilise the planetary concept, in which rotating substrates (up to 95 in some systems) are placed on a platen that also rotates. Thomas Swan's major production MOCVD system is the CCS reactor, which has a capacity of up to 18 two-inch wafers for the growth of InP- and GaAs-based materials. This reactor has a vertical design, in which precursors enter from the top through a close-coupled showerhead (CCS) delivery system that is unique to Thomas Swan. In recent marketing efforts, Thomas Swan has focused on promoting a version of the CCS reactor for the nitride market that has a capacity of up to six 2-inch wafers.

## Discovery Develops High Bandwidth OEICs

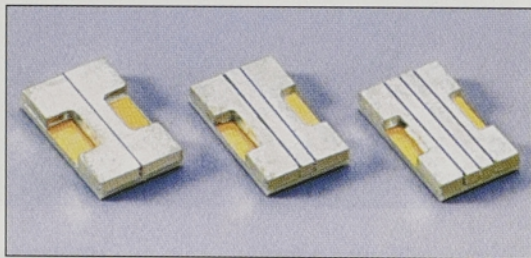
Discovery Semiconductors (Princeton, NJ) has received two contracts to develop ultra wideband PIN photodiodes and receivers. A \$736,000 contract was awarded by the US Army to target the development of multilevel photonic modules. The modules will contain optoelectronic integrated circuits (OEICs) consisting of a monolithic InGaAs PIN photodetector and PHEMT-based power amplifier. The attainment of target performance of 44 GHz bandwidth and a power output of 100 mW will allow phased array antenna designers to reduce the payload of communication satellites by up to 100 pounds, equivalent to a saving of 1.5 to 3 million dollars.

In a separate award, Discovery received \$65,000 from the Ballistic Missile Defense Organization (BMDO) to develop a 100 GHz photodetector/ amplifier OEIC. These OEICs will be designed into 100 GHz emitter and receiver modules, for potential applications such as free space RF data links.

## Patent Awards for IMC

Industrial Microphotonics Company (IMC) has announced receipt of two US patents for high power laser diode bar packages. The patents relate to IMC's Silver Bullet and MicroStack packages. Both provide low thermal resistance between the junction of the diode bar and the heat sink for either CW or pulsed operation. The Silver Bullet is a low cost high average power bar and array package that can easily be soldered to a heat exchanger. It can accommodate from one to three 1 cm long bars per module (see figure).

"We have worked for several years to develop the Silver Bullet as a high performance, low cost package," says Ed Stephens, IMC's Director of Product Development. "We believe that this device is an excellent option for customers developing new laser diode bar applications and for retrofit for older, higher cost packages." The Silver Bullet family consists of 20 W CW, 40 W CW and 50 W QCW 1-bar arrays; 40 W CW, 70 W CW and 100 W QCW 2-bar arrays; and 60 W CW, 90 W CW, and 150 W CW 3-bar arrays.



*IMC's patented Silver Bullet high power laser diode packages can incorporate from one (left) to three (right) 1 cm long laser diode bars.*

The MicroStack is a high density package with a pitch of less than 400  $\mu$ m, which is useful for high duty factor (>20%) quasi-CW diode stacks. The packaging system provides the ability to test the diode bars prior to assembly of the laser array stack, a feature that is particularly important to production yield when fabricating large diode stacks.



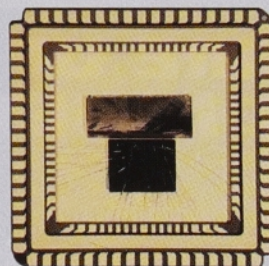
# INTRODUCING THE NEW GENERATION OF WAFER TECHNOLOGY



*In an exciting, rapidly expanding industry* where the electronic, microwave or optical device is key to success, having the right starting material is imperative.

Epitaxial Technologies, LLC, offers epitaxial wafer foundry services, value-added wafer products and wafer technology support that enables rapid, low-cost development and production of wireless and fiber-optic components for telecommunications applications. We are committed to providing the highest level of quality, responsiveness and innovation to satisfy your wafer needs for:

- Wireless RFICs and MMICs
- Advanced Device Technologies
- Wafer Engineering
- Sensors and Optoelectronics



In addition to our reputation for delivering products on time and within budget, we are recognized for superior expertise in research, design and fabrication of wafers, as well as extensive knowledge of customer applications.



Our commitment is to your success - to help your business grow, achieve optimum capability and profitability. At Epitaxial Technologies, we are setting a new standard and ushering in a new generation of wafer technology.



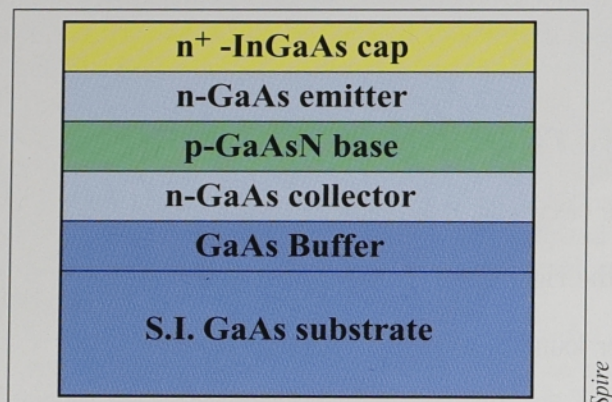
**Epitaxial Technologies LLC**  
*The Epitaxial Wafer Technology Experts*

(410) 455-5594 • 1450 South Rolling Road • Baltimore, MD 21227 • e-mail: [epiwafers@erols.com](mailto:epiwafers@erols.com)



## Spire Contract for GaAsN-based HBTs

Spire Corp. (Bedford, MA) has received a two-year contract to continue development of a promising new approach to make next-generation HBTs for military and commercial applications.



*Basic schematic of Spire's advanced HBT structure, which contains a highly carbon-doped GaAsN base layer. Indium co-doping in the base eliminates lattice mismatch and improves device performance.*

The contract from the Air Force Research Laboratory at Wright-Patterson Air Force Base is worth \$700,000. Using a low bandgap GaAsN base region, the new HBT structure (see figure) will offer lower operating voltage and longer life than current HBT designs. After completion of development, Spire plans to offer these wafers on a commercial basis to device customers as a complement to its current line of standard GaAs/AlGaAs-based HBT wafers.

GaAsN with 3 percent nitrogen has a bandgap of approximately 1.0 eV and will provide the large emitter-base bandgap difference needed to assure high device gain. The absence of aluminum (compared to, for example, an AlGaAs/GaAs emitter-base pair) will contribute to longer device life by reducing interface defect centers. Spire's patented MOCVD process will employ high carbon doping of the GaAsN base region coupled with indium co-doping. The introduction of In compensates for the strain induced by adding carbon and nitrogen to the base layer, thereby eliminating lattice mismatch and improving device performance.

## SpectraSensors Sells Laser-Based Measurement Systems

SpectraSensors, a manufacturer of tunable laser diode gas sensors and systems, recently received two separate purchase orders for research aircraft hygrometers. A hygrometer is an instrument that measures humidity. One system will be flown aboard a NASA high-altitude aircraft to study rocket and shuttle exhaust plumes, while the other, provided to the University Corporation for Atmospheric Research, will study cloud formation and dynamics. SpectraSensors has also appointed International Moisture Analyzers Ltd (IMA) of the UK as a distributor for laser-based moisture measurement equipment for industrial process monitoring.

## CEL Sells NEC's Fiber-Optic Products

NEC Electronics Inc. is to transfer all marketing, sales, technical support and distribution responsibilities in North America for NEC fiber optic components to California Eastern Labs (CEL), beginning October 1, 1999. NEC's components for the fiber-optic market in North America, including laser diodes, avalanche photodiodes and optical modules, are manufactured at a state-of-the-art facility in Roseville, CA. CEL, a privately held company with a partnership with NEC dating back to the 1960s, is already the exclusive North American source for NEC's RF, microwave and optoelectronic products.

# SAPPHIRE UP TO 8" DIAMETER

**Any/all crystal orientations!**

- Wafer carriers for III/V materials
- Unlimited life against most reagents
- Custom produced to your specific dimensions and features

**CALL: 800.959.0264**



INSACO, INC.  
P.O. Box 9006  
Quakertown, PA 18951-9006  
Fax: (215) 536-7750  
[www.insaco.com](http://www.insaco.com)



## M/A-COM Expands Fabrication Capacity

**M**/A-COM, a leading supplier of RF, microwave and millimeter-wave semiconductors and components, recently completed a significant expansion of its GaAs production facilities at Lowell, MA and Colorado Springs, CO. In addition to adding equipment at both locations, the company also increased its workforce and moved to multiple shifts, as Rick Hess, President of M/A-COM, explains. "Both operations now operate 24 hours a day, 7 days a week," says Hess. "Previously, we were running an average of 1½ shifts on 5 days. We have already attained a 4-fold increase in capacity this year, and by the end of this calendar year we will probably have attained a 6-fold increase over the level prior to the expansion. Clearly, this represents a very substantial increase in the number of wafers run."

Changes were made to M/A-COM's existing 4-inch lines, although the company intends to move to larger diameter wafers within a year. "We do have plans in place to move to 6-inch, and the effort will begin in 2000," says Hess. "The conversion will occur first at our Colorado Springs operation, since this is set up to run fewer processes at higher volumes, and also has more room for expansion. The Lowell fab will also be converted to 6-inch in due course."

With its headquarters in Lowell, M/A-COM is a unit of Tyco Electronics, Inc. The Colorado Springs fab was acquired from Cray when that company went bankrupt in 1995.

### Wireless, Automotive Applications Drive Growth

The expansion in capacity has been driven primarily by the wireless communications market and in particular the rapid growth in demand for wireless handsets. "We have done very well with leading handset manufacturers in developing GaAs products," says Hess. "There has been substantial growth in this market, especially on the digital side. The

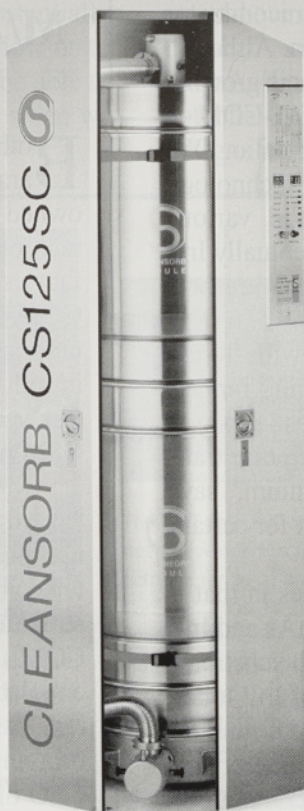
high linearity requirements of PCS applications in particular are strongly matched with the capabilities and qualities of GaAs. This has clearly been our main driver from a volume point of view."

Switches are a traditionally strong area for M/A-COM, and the company has

been the market leader for many years. More recently, a second area of strength has emerged in highly integrated ICs incorporating the up- and down-converter functions in handsets. "We also supply power amplifier products for handsets, although we are not the market leader,"

### Removal of Hazardous Gases Passive Dry Bed Chemisorption

## CLEANSORB Series for R&D- and Process Equipment



- Unmatched Safety for MOVPE Waste Gases
- No Consumption of Process Facilities
- Simple to Operate, Long Column Lifetimes
- Unique Local Waste Management Service
- System of Choice for MOVPE Users

#### Headquarters

CS Clean Systems  
D-85732 Ismaning  
Germany  
Tel. +49-89-9624 00-0  
Fax. +49-89-9624 00-22

#### United Kingdom

Tel. +44-1203-712 555  
Fax. +44-1203-712-666

#### Italy

Tel. +39-11-910 5200  
Fax. +39-11-917 2132

#### Netherlands

Tel. +31-72-5 72 18 00  
Fax. +31-72-5 72 18 18

### Your partner worldwide



#### France

Tel. +33-1-4649 7969  
Fax. +33-1-4780 7183

#### Israel

Tel. +972-3-574-5917  
Fax. +972-3-677-1280

#### Japan

Tel. +81-3-57 44 75 81  
Fax. +81-3-57 44 75 91

#### Scandinavia

Tel. +46-08-570 20863  
Fax. +46-08-570 21245

#### USA

CS Clean Systems  
Fremont CA 94539  
Tel. +1-510-770-9595  
Fax. +1-510-770-8879

#### South Korea

Tel. +82-342-7 81 37 61  
Fax. +82-342-7 81 37 68

#### Taiwan / China

Tel. +886-3-5783340  
Fax. +886-3-5770438

#### Singapore

Tel. +65-298-28 80  
Fax. +65-298-92 21



says Hess. "However, we do have a lead position in other power amplifier markets such as VSAT." Hess reports that M/A-COM is looking at HBT-based ICs for power amplifier and other applications. In addition to developing an HBT process internally, M/A-COM is also evaluating potential relationships with outside sources.

There are also a number of large markets in the millimeter-wave region, such as LMDS and related communication systems. "There are many big opportunities out there," says Hess. "In particular, automotive applications will create a very large, long term market for millimeter-wave products. At the system level, M/A-COM is already manufacturing radars for automotive applications, and we see growth in this market for both sensors and communications devices." M/A-COM's radar systems are currently in use on Mercedes-Benz cars [See CS 5(1), p. 28].

The volume and cost requirements of the automotive market will also drive manufacturers of radar systems to use MMICs. "Today's product is not totally MMIC-based," notes Hess. "However, as radar systems move to high-volume production, MMICs will definitely be required."

## A Portfolio of Technologies

The mix of products from M/A-COM's Semiconductor Division is currently around 60% GaAs, 40% silicon. Although Rick Hess notes that the GaAs portion of the business is growing faster than the silicon piece, he points out that M/A-COM is committed to maintaining a balanced technology portfolio. "We do not believe that there will be one semiconductor technology for all applications," he says. "We think that the various semiconductor technologies - Si, SiGe, GaAs, and eventually InP - will each have specific opportunities for which they are best suited."

M/A-COM recently announced an agreement with Temic Semiconductor (see box, right) to develop products using Temic's SiGe process. In addition, M/A-COM already has a power process for SiGe that is intended to replace silicon bipolar transistors. "We will take an active role in silicon germanium," says Hess. "We believe that it's a good technology, and that for certain applications it's the best choice."

M/A-COM is unique among US GaAs companies in that it has a division that makes and sells semi-insulating GaAs and InP wafers. For InP, M/A-COM has been working on both substrates and InP-based devices. "One of the big drawbacks of InP today is the base material cost," says Hess. "With government funding we are working on a program to develop 4-inch diameter InP boules. We decided that if InP was going to be a competitive technology, we had to run the processes on 4-inch wafers, because most fabs including our own operate 4-inch lines." In addition, M/A-COM has an ongoing effort to develop InP devices and process technology.

## Automation and Packaging

The new fabrication facilities rely heavily on automated processing and testing. "One of our goals has always been to keep handling down as much as we possibly can," says Rick Hess.

"The requirements of the handset market are very demanding, and automation helps us to attain high levels of reproducibility." M/A-COM has also developed expertise in very fast automated test in order to meet the cost requirements of high volume commercial markets.

Hess believes that packaging is the area where some of the most important advances will be made in the coming years. "I think that packaging will evolve to the point that you can use mixed technologies - GaAs, SiGe, InP - in the same package, and really exploit the full capabilities of the different devices," he explains. "That's also why we believe that you need to have a balanced portfolio of all the semiconductor technologies. The people who are successful will be those who figure out how to incorporate the different technologies in small packages at low cost."

Ball grid array (BGA) is an emerging packaging technology that is very good from the performance point of view and also has the potential to reduce costs dramatically. M/A-COM has an automated BGA assembly line in Lowell, as well as using off-shore capabilities for high volume applications. "We see packaging as driving the business to new levels and changing the way we operate," concludes Hess.

## M/A-COM, Anadigics Sign SiGe Agreements with Temic

Both M/A-COM and Anadigics recently announced separate agreements with Temic Semiconductor, a wholly owned subsidiary of Atmel Corp., to develop RFIC products based on SiGe. Temic operates a 6-inch SiGe wafer fabrication facility with foundry services in Heilbronn, Germany, and has been shipping SiGe products in high volume since the beginning of 1999. In 1998, the company introduced the world's first SiGe RF DECT chip set, and this year it introduced the first SiGe power amplifier for GSM phones.

M/A-COM's agreement with Temic was described as "an alliance to jointly design and manufacture SiGe products for the high-volume, commercial applications in the telecommunications marketplace." These will include infrastructure, wireless telephony, WLAN and WLL. "M/A-COM's extensive experience in RF & Microwave products coupled with its 'world-class' ASIC modeling and on-die test capability complements our long-term strategy of bringing SiGe to the marketplace," says Frank Heinrich, CEO of Temic.

Anadigics and Temic have agreed to share information about SiGe process technology and RFIC design. "Having access to Temic's SiGe facility and technology provides us with an opportunity to complement our existing GaAs and silicon programs," says Charles Huang, Anadigics' chief technical officer. "Anadigics is a major player in RFICs for the communications market," says Frank Heinrich. "Working with Anadigics on SiGe technology will be a win-win situation for both our companies."



# Alpha Completes Major GaAs IC Fab Expansion, Introduces HBT Products

Alpha Industries recently announced the completion of the first phase of a major expansion program that has upgraded and expanded the available clean room space at its GaAs IC fabrication facility in Woburn, MA. This will allow Alpha to increase the fab's production capacity to four times the level of one year ago. The new equipment is now in use and producing GaAs RFICs in high volume for major wireless handset manufacturers. The second phase of the expansion program has been accelerated as the company has observed continued strong growth in demand from its wireless OEM customers above the level of its original projections. This second phase will involve installation of additional production equipment in a portion of the existing clean room space, and is expected to be complete by the summer of 2000, at a cost of approximately \$12 million.

"We have planned the first two phases of this expansion process carefully to provide for even greater capacity in the future," says Bruce Nonnemaker, Alpha's Director of Operations. "All of the new equipment, and much of the existing equipment, is 6-inch wafer compatible; we have moved to a substantially higher level of automation; and new equipment will allow us to reduce our line width to 0.4 microns or lower. We will be able to convert the fab to high-volume 6-inch wafer operation when we choose, with limited capital expenditures."

## HBT Power Amplifiers for CDMA Phones

Alpha has introduced its first GaAs HBT product, a low-voltage, high-efficiency linear PA for use in PCS CDMA digital wireless handsets. This is the first commercial product from Alpha's GaAs HBT technology alliance with Network Device, Inc. (NDI), an independent GaAs foundry based in Sunnyvale, CA and Infinesse, a fabless design and development house [see CS 5(3), p. 4].

"This new power amplifier, the AP 126-89, is a major step forward for Alpha," says Jean-Pierre Gillard, Alpha's VP of business development. "The development process has been completed on schedule, in little more than six months, and the amplifier is now being sampled to our wireless customers world-wide." With the addition of HBT-based ICs to Alpha's existing MES-FET- and PHEMT-based products, the company now has the full range of high-efficiency and low cost GaAs process technologies available today.

"The addition of HBT process devices will allow us to expand our customer base into additional major wireless handset OEMs," continues Gillard. "This first product is an AlGaAs/GaAs device, but in response to a clear reaction from potential customers we will also be introducing InGaP-emitter designs in the future."

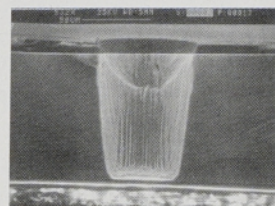


A global network of offices, providing world-wide sales and customer service, gives Oxford Instruments Plasma Technology the ideal platform to fully support our systems in even the most demanding of manufacturing environments.

With production-proven performance, the OIPT through-wafer via-hole process surpasses all current industry requirements on anisotropy and via-hole roughness.

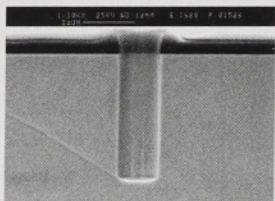
**Uniformity** < 5%  $3\sigma$  over 150mm  
**Reproducibility** < 5%  $3\sigma$   
**Throughput** > 2 wfrs/hr

...hole shape and roughness can be tailored to meet individual customer requirements...



Through wafer  
GaAs based via  
feature formed  
by RIE

The OIPT through wafer via hole process has been developed to provide maximum versatility across a range of process results and hardware configurations. Both RIE and ICP processes are available for GaAs and InP based devices, where via hole shape and roughness can be tailored to meet the individual customer requirements. Options include batch processing of x4 4" wafers by RIE, or single wafer 4" and 6", high rate processing by ICP.



Through wafer  
GaAs based via  
feature formed  
by ICP-RIE

Please contact your local sales office for further details on our through-wafer via-hole process and to request your free copy of our **Compound Semiconductor Solutions** brochure, produced specifically for the compound semiconductor industry.

### UK (Manufacturing)

Tel : +44 (0)1934 837000

Fax : +44 (0)1934 837001

E-mail:

plasma.technology@oxinst.co.uk

www.oxfordplasma.com

### Germany

Tel : +49 (0)6122 9370

Fax : +49 (0)6122 937100

E-mail: plasma@oxford.de

### France

Tel : +33 169 85 25 22

Fax : +33 169 41 86 80

E-mail:

oxford.instruments@wanadoo.fr

### USA East Coast

Tel : +1 978 369-7321

Fax : +1 978 371 7595

E-mail: optsales@oxford.usa.com

### USA West Coast

Tel : +1 510 656 8820

Fax : +1 510 656 8944

E-mail: optsales@oxford.usa.com

### Japan

Tel : +81 (0)3 5245 3591

Fax : +81 (0)3 5245 4466

### People's Republic of China

Tel : +86 10 6833 0334/5/6

Fax : +86 10 6833 0337

### Singapore

Tel : +65 337 6848

Fax : +65 337 6286

E-mail: oxfirst@pacific.net.sg

OXFORD

Oxford Instruments  
Plasma Technology



## Filtronic Finalizes Fujitsu Fab Foray

Filtronic plc has completed the acquisition of Fujitsu's former DRAM fab in Newton Aycliffe, County Durham, England. The 310,000 sq. ft. facility was purchased for £13 million (~\$20 million) with financial assistance from the UK government. An estimated £22 million (~\$35 million) will be spent to turn the facility into one of the world's largest 6-inch fabs, which should be operational by late spring 2000.

The facility will be used to produce GaAs PHEMT-based ICs, including LNAs and PAs that will be incorporated into integrated RF front-end modules for cellular handsets. Filtronic plans to supply the module, which will replace up to 24 components currently found in dual band handsets, as a pre-tested and tuned product. When fully operational, the Newton Aycliffe facility will have an estimated capacity of over 350 million GaAs devices per annum. The company expects to purchase up to six production MBE systems with 6-inch growth capability over the next several years.

### "The Lighter Side of Fabrication"

A closer look inside a 72" wafer fab



*Equipment maintenance can prove to be quite a chore in a 72" wafer fab. This equipment engineer is inspecting just one of the many massive vacuum chambers used in the evaporation process*

Ron Smith

## TriQuint Allies with ACCO

TriQuint Semiconductor has signed a design service agreement with ACCO, a major independent European RF design center based in France. The agreement will utilize ACCO's third party design resources in conjunction with TriQuint's GaAs IC foundry service to provide European customers with a local turnkey presence for custom RFICs. TriQuint is developing a worldwide network of independent, certified Design Centers to support its GaAs foundry services. Founded in 1994, ACCO focuses on developing leading edge RF and microwave ICs for the semiconductor and system manufacturing industry.

## Palm VII Slot and Design Center for Anadigics

Anadigics' DC/DC converter has been designed into the Palm VII connected organizer, the first handheld organizer equipped with a wireless antenna that allows users to access the Internet, conduct e-commerce transactions, and send and receive instant messages. The GaAs MESFET-based DC/DC converter provides the Palm VII with a small, highly efficient power management IC.

Anadigics also announced recently that it has opened an RFIC design center in Dallas, Texas. This will support the company's efforts to develop new products for RF applications and allow further penetration into the wireless communications market. "This new design center presents a focused expansion that will aid us in achieving our aggressive product development goals to dominate the RF deck in the handset market," says Bami Bastani, President and CEO of Anadigics. The center will provide RFIC designs based on GaAs and silicon-based RF processes.

## TRW Installs New MBE System

TRW has released details of its new high volume production MBE system. The company has installed the industry's first Riber 6000 system at its facility in Redondo Beach, CA and will utilize the machine's capacity of 9 four-inch wafers to grow HBT epilayers. "TRW led the industry in establishing MBE as a reliable process for volume production of GaAs microwave and millimeter-wave ICs," says Dwight Streit, director of TRW Telecom Products. "This new machine greatly increases TRW's MBE capacity, enabling us to keep pace with the rapid growth of our chip business." At full production rates, TRW states that the fully automated system will process more than twice the number of four-inch GaAs wafers per day compared to its current MBE systems.

## RFMD Ships Chips to China

RFMD has received its first major order from China for RFICs for dual band GSM cellular handsets. The company will supply PAs to Xiamen Overseas Chinese Electronic Co., Ltd., which expects to produce one million handsets in 2000. There are currently around 23 million cellular subscribers in China, a number expected to grow by 10 million per year. The Chinese Ministry of Information Technology has allowed foreign manufacturers to produce base stations and handsets to serve this market, but is also funding domestic scientific research and encouraging Chinese manufacturers to make foreign-designed phones. Eventually, Chinese manufacturers will produce domestically designed phones and sell them under Chinese brands.



## When it comes to RTA, we have a MMIC, MESFET, HEMT, HBT, LED, GaAs, GaN, InP, SiC and a PhD.

Annealing furnaces are a technology that works, but they have problems that engineers must overcome. And yes, they have served you well in the past, but we are talking about the future. You will need tighter control of the process as the industry moves towards tougher applications. And that's why there's a new alternative.

Rapid Thermal Annealing (RTA) results in better control due to RTA's much shorter heating and cooling times. In contrast to conventional annealing furnaces, RTA suppresses undesired side reactions during cooling or heating, such as thermal decomposition, haze or spiking. Dual-side heating with independently controlled halogen lamps gives RTA a lower thermal budget and improved control of thermal reaction kinetics compared to conventional furnaces.

STEAG is a leader in RTP Technology. Now, we are conducting research for the various applications of RTA in order to create the latest technology for the future. For example, we have already delivered 6" tools to the industry. For more information about RTA or to see if we can help you with your processes, contact a STEAG sales representative. Email us at [rta@steag.com](mailto:rta@steag.com), or visit our web-site at [www.steag.com](http://www.steag.com).



**steag**

RTP Systems

LED

Laser Diodes

Solar Cells

MMIC

MESFET

HEMT

HBT

GaAs

GaN

InP

SiC

Europe  
+49.7348.981.0

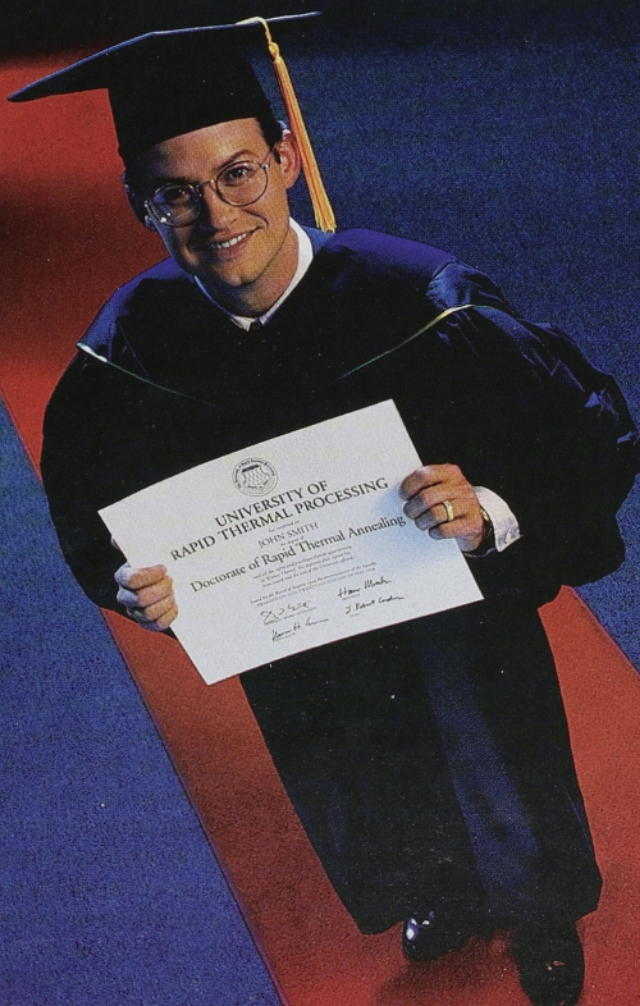
United States  
+1.512.438.1300

Japan  
+81.44.812.6955

Korea  
+82.342.718.5121

Singapore  
+65.35+66.893

Taiwan  
+886.35.770651



SHAPING  
the  
FUTURE



## First UV Digital Camera Based On GaN/AlGaN Photodiode Array

A UV camera sensitive to the 320-365 nm spectral region and based on a 32x32 array of backside-illuminated GaN/AlGaN p-i-n photodiodes has been successfully demonstrated. The work<sup>1</sup> was carried out by a team comprising Jan Schetzina's group at North Carolina State University (NCSU), together with Honeywell Technology Center and the Army's Night Vision Laboratory (NVL) at Ft. Belvoir. Large-format UV photodiode arrays of this type have a number of potential applications, including biological agent detection, missile detection, atmospheric ozone-level detection, welding imagery, flame sensing and astronomy.

The 1024-element photodiode array was fabricated from an MOVPE-grown heterostructure using standard photolithographic, etching, and metallization procedures, and was hybridized to a silicon readout IC using In bump bonds. The hybridized array was back-illuminated through the transparent sapphire substrate.

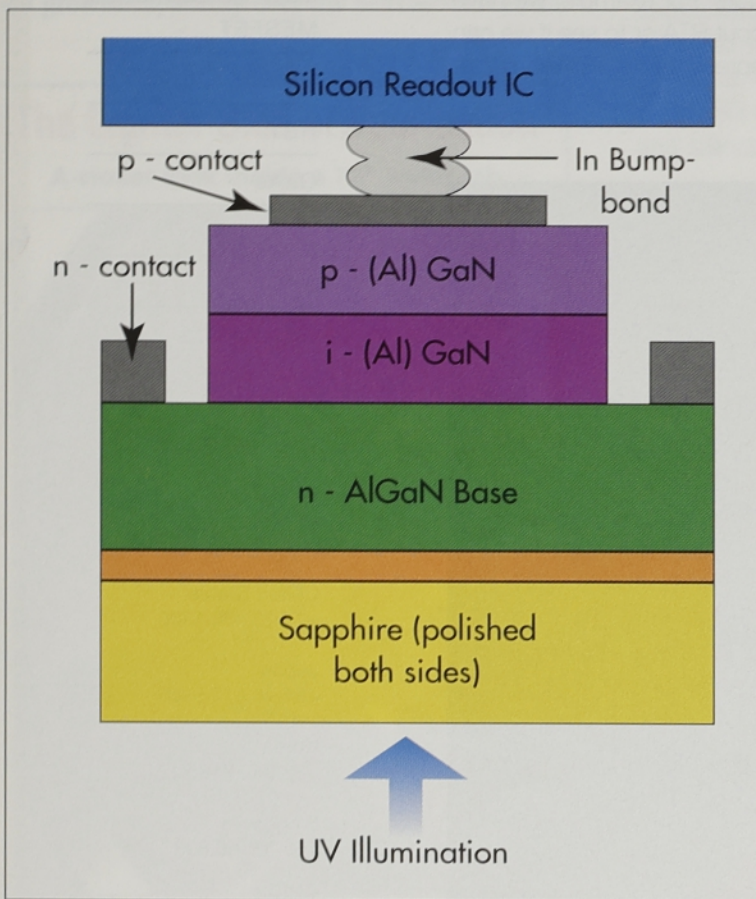


Figure 1. Schematic of the GaN/AlGaN photodiode structure, and the bonding scheme to form the hybridized focal plane array. With 18% Al in the base and no Al in the other layers, the UV responsivity window of the diode is 320-365 nm. This window can be adjusted by changing the Al content in the layers.

<sup>1</sup> See MRS Internet J. Nitride Semi. Res. at <http://nsr.mij.mrs.org/4/9/>

### Photodiode Structure

The epitaxial structure employed in the demonstration consists of an n-type AlGaN base layer, an undoped GaN layer and a p-type GaN layer (see Figure 1). The base layer contains about 18% Al, and absorbs radiation at wavelengths shorter than around 320 nm. Likewise, the diode does not respond to wavelengths greater than 365 nm, since this corresponds to the optical absorption edge of GaN at 300 K. This photodiode has a narrow responsivity band (320-365 nm) within the UV region, and is therefore termed a "visible-blind" detector. A peak responsivity of 0.20 A/W was recorded at 358 nm, corresponding to an internal quantum efficiency of 80%.

If the Al content of the base is increased to around 35%, the device becomes responsive to wavelengths as short as 270 nm. In addition, Al can be added to the top GaN layers to reduce the upper wavelength limit. In this way, the response band of the diode can be tuned for different UV applications [also see CS 4(5), p. 22].

The 300 K dynamic resistance at zero-bias ( $R_0$ ) was measured for selected GaN/AlGaN photodiodes. The product of  $R_0$  and the device area  $A$  is a widely used figure of merit for detectors. The  $R_0A$  product was  $1.5 \times 10^9 \Omega\text{-cm}^2$ , corresponding to a device detectivity ( $D^*$ ) of  $6.1 \times 10^{13} \text{ cm Hz}^{1/2}\text{W}^{-1}$ . This  $D^*$  value, obtained at room temperature, is one of the largest ever obtained for any semiconductor photodetector, and is within a factor of five of  $D^*$  values associated with UV-enhanced photomultiplier tubes.

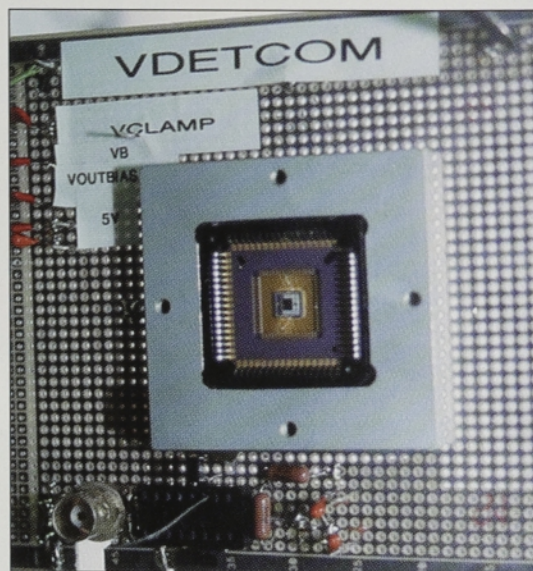
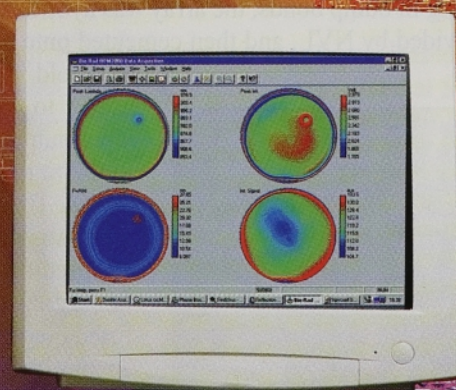
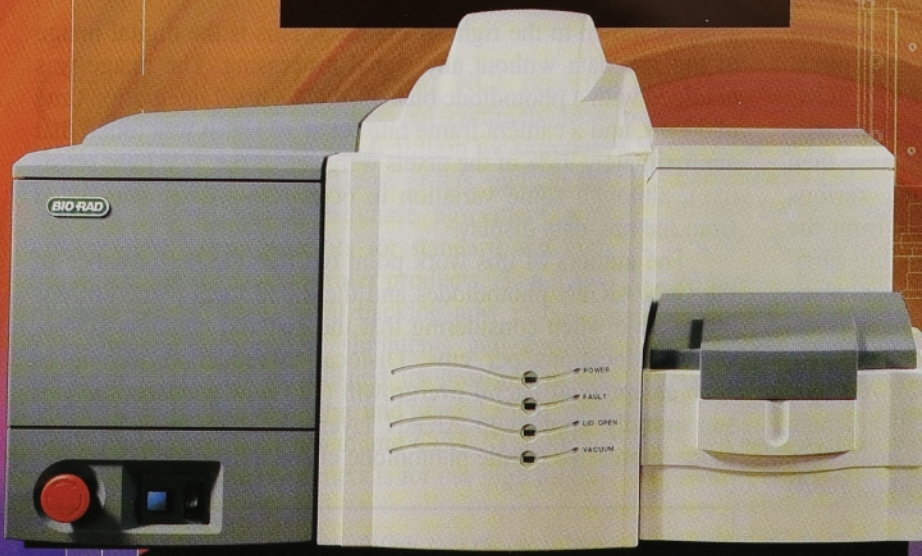


Figure 2. Hybridized GaN/AlGaN UV photodiode array mounted on a PC board prior to testing.



# rpm2000

RAPID PHOTOLUMINESCENCE MAPPER

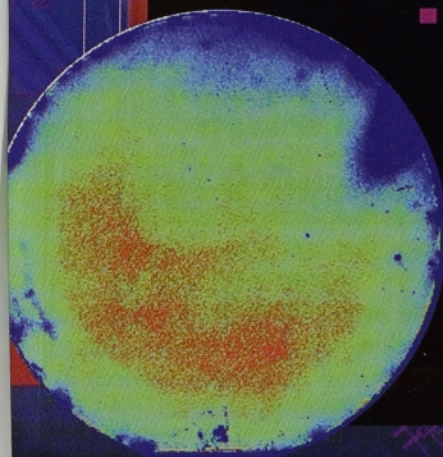
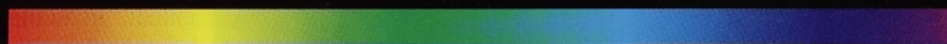


## Time & money wait for no-one

With the new **RPM2000** you don't have to wait. In 30 seconds you could be viewing the analysed spectral results of more than 2000 points on your wafer. Modular in design and with a footprint not much larger than a desktop PC the **RPM2000** is an ultra rapid, reliable and easy to use tool for full production control / inspection / analysis.

- Laser & Detector options to cover 350nm - 1700nm
- Upto 3 Lasers & 3 Detectors without module changes
- Full VCSEL & BRAGG Reflector Analysis
- 2" - 6" Capability

For further information and detailed brochure  
please contact our sales team on the numbers below.



**BIO-RAD**

www.bio-rad.com

**Semiconductor  
Systems Division**

**USA**

Bio-Rad Micromeritics, 520 Clyde Avenue, Mountain View, CA 94043-2212  
Phone 650-934-8800 Fax 650-934-8810

**Europe**

Bio-Rad Micromeritics Ltd, Bio-Rad House, Maylands Avenue, Hemel Hempstead, HP2 7TD, UK  
Phone +44 181 328 2290 Fax +44 181 328 2580

**Japan**

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

**Pacific Rim**

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



sales\_sms@bio-rad.com



## Array Fabrication and Performance

The 32 x 32 array used in the camera demonstration consisted of a 44  $\mu\text{m}$  x 44  $\mu\text{m}$  mesa diode, fabricated on a 53.4  $\mu\text{m}$  pitch. Using In bump bonds, the array was hybridized to a silicon ROIC provided by NVL, and then cemented onto a leadless chip carrier.

Gold wire bonds were then used to link the various input/output channels from the ROIC to the leadless chip carrier. The finished UV focal plane array was mounted onto a printed circuit board in preparation for testing (Figure 2). A single fused quartz lens of focal length 25 mm was used to image UV scenes onto the photodiode array.

The test scene was a brass sheet with the letters "NCSU" milled out, which was rear-illuminated with a UV source centered at about 350 nm with a FWHM of ~40 nm (see Figure 3). The scene as imaged by the AlGaIn-based photodetector



Figure 3. The UV source used to test the GaN/AlGaIn array (left), and the digital image without signal processing.

array is shown to the right of Figure 3. This is the digital image of the raw data without any signal processing. The image was obtained with a photodiode bias of -0.1 V, a pixel integration time of 32 ms, and a camera frame rate set at 30 Hz. It was found that approximately 95% of the pixels were active (i.e. UV light sensitive), although some variation in pixel responsivity was noted from the raw-data display.

The authors of this work point out that the performance of the GaN/AlGaIn photodiodes and the diode focal plane array is remarkable when considering that the material contains  $10^{10}$  or more dislocations per  $\text{cm}^2$ . Dislocation reduction techniques such as epitaxial lateral overgrowth (ELO) or pendeoepitaxy, if successfully applied to AlGaIn layers, hold promise for even more impressive nitride photodiode characteristics in the future.

## Microsemi, Sterling Semiconductor to Develop SiC Devices

Microsemi Corp., a manufacturer of discrete semiconductor products based in Santa Ana, CA has entered into an alliance with Sterling Semiconductor, Inc. (Sterling, VA) to design and develop silicon carbide-based devices for a variety of applications.

Microsemi plans to use SiC technology to create devices for high-speed modems, implantable cardio defibrillators, military radar, space applications, MRI equipment and other applications that can benefit from the high-temperature and high-frequency properties of SiC. The first product under development is a 480 V Schottky diode to be packaged in Microsemi's patented Powermite surface mount package. It has been scheduled for initial demonstration in the first quarter of next year.

"As a leading supplier of semiconductor devices for niche market applications, Microsemi can identify opportunities to develop value-added solutions based on SiC," says Manuel Lynch, Microsemi's marketing director. "Thus, we've developed a strategy that joins our market focus with the SiC substrate and epitaxy technology that has been developed at Sterling."

Sterling Semiconductor's president, James LeMunyon, commented: "In addition to selling SiC substrates, an important element of our business strategy is to make devices in partnership with an established discrete semiconductor device manufacturer."

The physical and electronic properties of SiC are superior to those of Si and GaAs for. "SiC properties lend themselves to certain high-temperature, radiation resistant, and high-power/high-frequency applications," notes Lynch. "These would benefit from the efficiency of a Schottky diode, combined with the performance characteristics of a conventional silicon rectifier. For example, SiC brings Microsemi a unique advantage by allowing us to quadruple the voltage of the highest-rated Schottky diodes available today."



## Crystar Sapphire Substrates for Gallium Nitride Applications

Setting the standards for flatness  
and surface finish...

- Wafers oriented to within  $\pm 0.25^\circ$
- Primary flat tolerances to  $\pm 0.5^\circ$
- Extensive wafer characterization to ensure substrate quality
- Laser Marking available
- Competitive lead times

As a member of the Johnson Matthey Group, Crystar is committed to providing the industry's highest standard products and services

721 Vanalman Avenue, Victoria, BC, Canada V8Z 3B6  
Tel (250) 479-9922 Fax (250) 479-2734  
www.jmcrystar.com



## Product Orders and Contracts for Cree

Cree Research, Inc. (Durham, NC) recently announced that it has received contracts from several customers totaling \$66.6 million for shipment through September 2000. These orders include the one-year renewal of its purchase agreement with Osram Opto Semiconductors for standard and high brightness SiC LEDs and wafer products. As a result of these orders, Cree's total backlog now stands at \$111 million for product shipments and contract research. "Cree has established its position as the world's low cost leader of blue and green LEDs," says Neal Hunter, Cree's chairman and CEO. "The greatest demand from our customers is for our high brightness chips."

Cree has also received contract awards to develop 4-inch SiC substrates, and to fund microwave and power switching R&D efforts. A Title III contract has been awarded to Cree by the United States Air Force with a total value of \$4 million, including a 50% cost share that will be funded by Cree. The award covers the period through August 2001 with the primary focus on quality improvement and cost reduction of production quantities of 3-inch SiC substrates and for the development of 4-inch SiC substrates.

### Microwave and Power Switching R&D

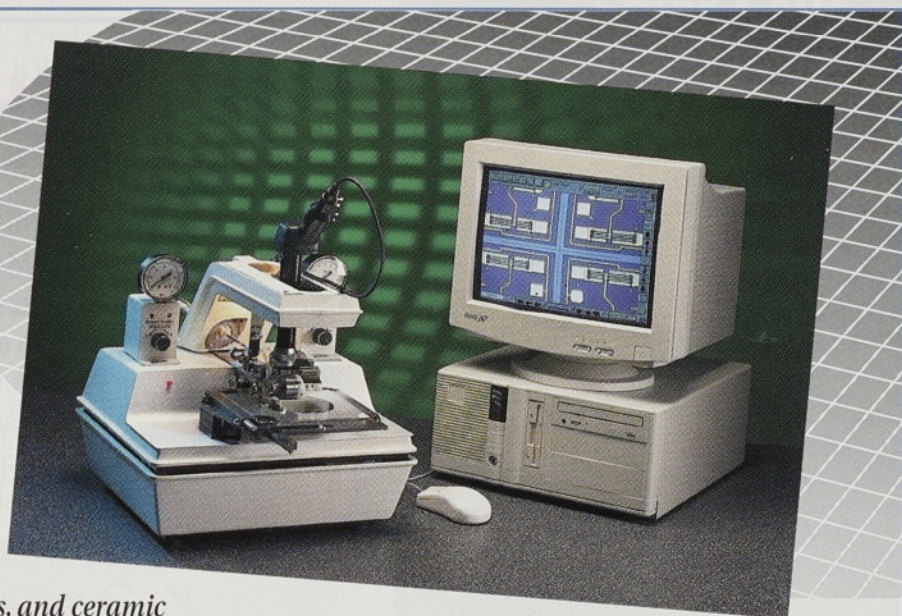
The Office of Naval Research (ONR) and the Air Force Research Laboratories (AFRL) have awarded Cree research contracts valued at \$6.8 million for the development of wide bandgap microwave and power switching devices. Around \$1.5 million will be funded by Cree under cost share programs. \$3.5 million is directed toward the development of component technologies to enable future generation Advanced Multifunctional Radio Frequency Systems (AMRFS). The U.S. Navy has reported that they intend to invest millions of dollars into new radar technology in coming years to develop a more capable radar that can search, detect, and track smaller and faster targets. However, R&D will be required to enable SiC- and GaN-based amplifiers to perform very wide bandwidth radar functions.

"Future generation advanced radar systems will require higher power levels that we believe are attainable from SiC and GaN devices," says John Palmour, Cree's Director of Advanced Devices. "Power levels required for these systems are not possible with current silicon or gallium arsenide technologies."

AFRL has funded an additional award focused on high power GaN microwave devices for airborne radar and space-based military systems, as well as a variety of commercial applications. Other programs from Defense Advanced Research Projects Agency (DARPA), through ONR and AFRL are focused on power switching devices for motor control and power conditioning applications.

## INTEGRATED SCRIBE & BREAK WAFER DICING SYSTEM GIVES 98-99% YIELD. DAY AFTER DAY.

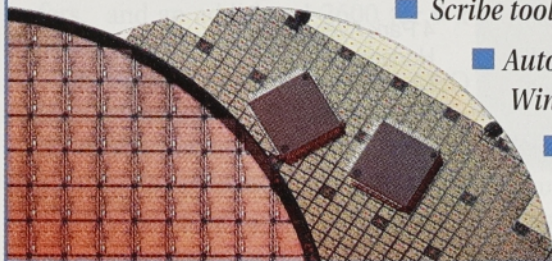
- Dice III-V material, thin silicon, sapphire, glass, and ceramic
- Sawframe or hoop presentation for pick and place operation
- Proprietary scribe tools perform repeatedly in rote fashion on all materials
- Scribe tool change requires only three minutes
- Automatic computer control utilizes Windows 95® and Starflight Vision System
- Clean, cosmetically perfect dice
- Unequalled throughput



Scribe and break the new Loomis way.  
Call or write today for complete details...

### LOOMIS

1204 Church St.  
St. Helena, CA 94574  
Phone: 707-963-4111  
Fax: 707-963-3753  
[www.loomisinc.com](http://www.loomisinc.com)





## WiTech Becomes Nitres, Receives White LED Funding

**W**iTech (Widegap Technology, LLC), a California-based company set up in 1997 to develop and commercialize GaN-based devices, has changed its name to Nitres, Inc. The company's investors and business remain the same. Nitres is a leader in the development of wide bandgap semiconductor devices such as LEDs, microwave power transistors, and ultraviolet photodetectors. The company has developed prototype blue, green, white and ultraviolet light emitter products, and plans to launch a line of high brightness LEDs early next year. Its R&D technologies include microwave transistors such as HEMTs and HBTs, UV photodetectors and blue lasers.

The corporate offices of Nitres are located in Westlake Village, CA, and its R&D operations are in Goleta, CA, near the University of California at Santa Barbara (UCSB). The company is privately financed and has R&D contracts funded by the U.S. Commerce Department (NIST), Air Force, AFOSR, BMDO, Office of Naval Research, and Hughes Electronics. Nitres has partnerships with GE Lighting for the development of LED-based lighting technology, and with Hughes Electronics to develop GaN microwave power transistors.

### \$1.5 Million Contract for White LEDs

Nitres was recently awarded a contract worth almost \$1.5 million by the Ballistic Missile Defense Organization (BMDO) to continue to develop white LEDs. These devices combine blue GaN-based LEDs with polymer downconversion media. Most existing white LED products use phosphors; light emitted by the phosphor combines with radiation from the blue LED to give white light by additive mixing. "The use of polymer downconversion media is a novel and useful alternative to phosphors," says Fred Blum, CEO of Nitres. "The principle of producing white light is the same, but we expect the polymer to result in a better color temperature."

Solid-state white lamps are an emerging new technology that could revolutionize specialty lighting with high efficiency, long-life light sources. Lifetimes of 5-10 years and predicted efficiencies of over 10% for LEDs far exceed those of incandescent bulbs. The life cycle cost of ownership of solid state lamps will also be lower because of electrical energy and change-out labor cost savings. Applications for such lamps include automotive and aircraft interior lighting, electronic display backlights, and building exit and pathway lighting.



## WHAT WILL YOU PUT IN YOUR PERFORMANCE MATERIALS?

At Performance Materials, we put everything we've got into our technical ceramics, so you can put your trust in them.

- 24-hour turnaround on stock orders.
- Custom designs of PerformancePBN™ in as little as 3 weeks.
- PerformanceSiC™ products of silicon carbide.
- Clean packaging.
- Technical troubleshooting any day, any hour.
- Unique shapes.

For more, talk to the experts in chemical vapor deposition: Performance Materials.

**Performance Materials, Inc.**  
*A material advantage.*

4 Park Avenue  
Hudson  
New Hampshire 03051 U.S.A.  
603-598-9122  
fax 603-598-9126

info@performancematerial.com www.performancematerial.com



### AXT Temporarily Suspends Ge Shipments

American Xtal Technology (AXT) has announced that it will suspend the shipment of Ge wafers to Spectrolab (a division of Hughes Electronics Corporation) at its request for approximately two months. This is in response to continued softness in the satellite market. The agreement to suspend shipments, scheduled to take effect in mid-September, will adversely impact AXT's revenues by approximately \$1 million per month.

"Our overall substrate business remains healthy," said Morris Young, AXT's president and CEO. "We continue to see strong market growth in both GaAs and InP. Despite some short-term softness in the satellite industry, we continue to believe that satellite technology is a very viable solution to the ever-increasing need for higher bandwidth in communications." Young added that AXT has the capacity, resources and technology to meet the strong demand when it returns.

### Kopin Adds Two New Reactors for HBTs

Kopin has completed the initial stage of a \$15 million expansion of its Taunton (Massachusetts) transistor fab with the order of two Aixtron production reactors, bringing its total of systems bought recently to six. Matthew Micci, VP of Sales and Marketing said: "We began our expansion with three AIX 2400s and one AIX 2600 machine, but due to the strong market demand, added an additional 2400 for 5 x 4-inch wafers, and an additional 2600 for 9 x 4-inch or 5 x 6-inch wafers."

Dr. John Fan, president and CEO added: "Customer demand for our GaAs HBTs has been very strong, and we have an option on three more machines next year."

### RFMD Orders Tegal Plasma Etcher

Tegal has announced that RF Micro Devices (RFMD) has placed a follow-on order for a Tegal 901G diode plasma etcher. The tool will be used for etching devices on GaAs substrates at RFMD's North Carolina manufacturing facility. The Tegal 901 is a diode plasma etcher intended for pad, zero layer, non-selective nitride, backside and planarization, in addition to oxide, nitride, poly- and III-V materials such as GaAs. The platform is designed around a transport system that can accommodate 3-inch (75 mm) to 6-inch (150 mm) round substrates, as well as square and rectangular substrates.

### EPI orders MOCVD Reactor for AlGaInN

Epitaxial Products International (a part of IQE Group) has placed an order for an Aixtron multiwafer reactor with a capacity of 6 x 2-inch wafers for the growth of AlGaInN materials. The expected delivery date of the new reactor is before the end of Q4 1999. Initially, EPI will use the system for the growth of InGaInN-based epiwafers for green and blue LEDs. Subsequent developments will include the supply of epiwafers for blue/violet laser diodes and electronic devices for high frequency or high-power applications.

### Ulm Buys HVPE System for GaN

A growth of GaN has been installed by Aixtron at the University of Ulm in Germany. The AIX VPE system, which has a capacity of 1 x 2 inch or 1 x 3 inch wafers, will be used to grow thick GaN layers (at temperatures up to 1100°C) that are suitable as templates for subsequent growth of high-quality laser structures.

EMCORE Electronic Materials

**E<sup>2</sup>M<sup>TM</sup>**

**Offering the device manufacturing community the most reliable, cost-effective solutions in the industry**

### *Our Solutions*

***Epitaxial Materials for:***

**Blue, Red, Orange, Yellow LEDs**

**pHEMTs**

**HBTs**

**FETs**

**Solar Cells**



EMCORE Electronic Materials

394 Elizabeth Avenue, Somerset, NJ 08873 USA

Tel: + 1 (732) 271-9090 • Fax: + 1 (732) 271-9686

WEB: [www.emcore.com](http://www.emcore.com) • E-mail: [info@emcore.com](mailto:info@emcore.com)



## HEMTs in Handsets

*Although HBTs have been grabbing the headlines recently, HEMTs are widely used in a number of roles in wireless handsets.*

**H**EMTs were originally developed as a high performance military technology, and are firmly established as the predominant technology for millimeter-wave applications. The first GaAs devices to penetrate the lucrative wireless handset market were MESFETs, while epi-based HEMT and HBT processes have enjoyed growing success in recent years. These device types offer intrinsic performance advantages, in terms of linearity and efficiency, and superior die area costs compared to MESFETs.

### PHEMTs for Power

While HBT suppliers such as RF MicroDevices have been

extremely successful in getting their power amplifier products into handsets, PHEMTs are also widely used.

"A couple of trends are driving the use of PHEMTs for power amplifiers," says Mark Wilson of Motorola's Semiconductor Product Sector. "These are significantly better performance than implanted parts, and the availability of a true enhancement-mode technology which requires no drain switch and which offers similar performance to HBTs."

Depletion-mode HEMTs and MESFETs require a negative voltage generating circuit to turn off the transistor and a drain switch to eliminate the standby current. These additional components, which are not required by E-mode devices or HBTs, increase system cost, take up valuable board-space and require extra design and engineering effort. "Several of our customers have a system-level specification for power amplifiers that they not require a drain switch, and require only a single operating voltage," says Wilson, adding that Motorola's recently introduced E-mode HFET technology is now in full production (see page 71).

Fujitsu, NEC and others have also developed E-mode HFET technology and Alpha is also currently sampling E-mode devices. "There is a certain level of enthusiasm for E-mode processes," says Gary Carr, marketing manager in Hewlett-Packard's wireless semiconductors division. "The data is there to show that these processes might do as well or in some cases better than HBTs." Carr also notes that HP will continue to evaluate HBT and E-PHEMT technology to see how they fit with the company's portfolio.

### The Challenge of HBTs

Of course, HBTs also operate from a single positive supply and do not require a drain switch. "These two features are advantages in terms of cost and ease of use over HEMTs for wireless power amplifier applications," says Barak Maoz, VP of Wireless Power Amplifiers at Anadigics. The company plans to introduce HBT-based PAs later this year.

Along with Alpha, Raytheon RF Components recently launched HBT-based products for the handset market. According to Sanjiv Shah, marketing manager for handset products at Raytheon, HBTs offer the best solution for single supply PA modules. "We believe that HBTs offer competitive solutions to market needs," says Shah. "However, our main products are PHEMT-based and we will continue to develop and offer these for as long

### SUPER EPI

Super Epitaxial Products, Inc.

~ a devoted MOCVD products supplier ~

**Super EPI provides the best quality MOCVD epitaxial wafers**

(Multi-wafer MOCVD reactors, 2", 4" and 6" wafers capability)

- AlGaInP/GaInP
- AlGaAs
- GaInAsP
- GaN

for high performance devices:

- Light Emitting Diodes
- Laser Diodes
- Photo-Detectors
- HBTs
- high brightness



Tel: (410) 772-0078

Fax: (410) 772-0079

<http://www.superepi.com>

e-mail: [info@superepi.com](mailto:info@superepi.com)



as the market requires them." For example, Raytheon's new base station products are PHEMT-based, since this technology offers better backed-off performance and PAE for higher output powers. Shah notes that products based on HBTs or wide bandgap devices may be introduced for these applications in the future.

Mark Wilson of Motorola believes that HBTs and PHEMTs each have their own benefits. "There are trade-offs for each type of device," he says. "We are in the process of adding HBT technology to our portfolio, as it is well suited to certain applications." HBT supporters often quote the cost advantage of smaller die size, however according to Wilson the difference is not as significant once the area of bond pads and other circuit features are taken into account. "PHEMTs are very cost-competitive with HBTs," he says.

The cost of epitaxy is a major factor when comparing PHEMTs with MESFETs. "No-one is willing to pay for the performance advantages of PHEMTs, they expect them at the same price as implanted technologies," says Wilson. "For PHEMTs, the die size is smaller compared to MESFETs, the wafers are more expensive, and the processing is simpler in terms of the number of steps. When you lump all of this together, I think that the price of 4-inch epiwafers from commercial vendors has to fall below the \$500 mark to keep the manufacturing die cost of PHEMTs the same as ion-implanted parts." Another factor in the cost equation is wafer size, and Motorola has started to process 6-inch GaAs wafers. "We have already completed 6-inch ion-implanted wafers through final assembly and they look beautiful, we expect the same shortly from epitaxial devices," says Wilson.

## The Complete Portfolio

A clear trend is emerging among GaAs IC suppliers to offer a full range of processes and to let the customer decide, depending on the performance requirements of the handset platform. "By having a complete portfolio of technologies I think you can have the best of all worlds," says Mark Wilson, "provided of course that you can manufacture all those technologies simultaneously."

Alpha has also recently added HBT-based ICs to its range of power amplifier products (see page 11). "We are not in a technology contest," explains Jean-Pierre Gillard, VP of business development at Alpha. "It is our strategy to present our customers with all GaAs process technology options, and let them choose the one they feel is most appropriate for their product." Gillard adds that Alpha's PHEMT-based PAs will shortly enter high volume production, joining the existing MESFET-based products and the new HBT PAs. Both Anadigics and Infineon also intend to run all three GaAs processes - MESFET, PHEMT and HBT - in their new 6-inch GaAs fabrication facilities, although Anadigics does not intend to produce PHEMT-based power amplifiers.

## Switching Over to PHEMTs

With the numerous modulation formats in use at different frequencies, manufacturers continue to build dual-band and multi-mode handsets, and these require components to switch between the different amplification chains. GaAs-based switch products are dominated by MESFETs, although PHEMTs offer

distinct advantages for RF power switching applications and are rapidly gaining market share. M/A-COM and Alpha have PHEMT-based switch products, and Anadigics has plans to introduce them.

Alpha announced its first production order for PHEMT-based switches in April. The switch ICs will be used in Motorola's V3688 dual-band handset, and other design wins will be announced shortly, according to Jean-Pierre Gillard. "We still have MESFET switches in production, but all of our design effort is now focused on PHEMT-based devices, as these offer both cost and performance advantages," he says. "PHEMT technology offers lower loss, higher isolation, and also performs better from a linearity point of view. In addition, PHEMTs allow us to make smaller die, which translates directly in to lower cost. This situation arises because Alpha has its own internal source of epitaxial material - we are one of the largest producers of material grown by MBE - and does not have to pay high costs for purchasing PHEMT epiwafers."

Anadigics recently announced production of MESFET-based switches, and plans to introduce PHEMT-based in the future. "PHEMT was chosen for next generation switches because it provides lower loss and higher linearity compared with MESFET, when low control voltage is used," says Barak Maoz. "Also, it provides a superior solution for switches for GSM applications because of the high power transmitted by GSM handsets."

## Receiver Functions

Hewlett-Packard recently announced new products, including a switched-LNA RFIC for CDMA handsets, based on its second-generation PHEMT process. "These products provide a performance, size and cost combination that is not found elsewhere in the market," says HP's Gary Carr. "Our new PHEMT process has been optimized for high volume consumer applications, particularly handsets. The original process was targeted on very high performance, high frequency military applications, as well as the commercial DBS market at around 12 GHz. We have detuned the high frequency performance and focused on a more consistent, higher yielding process for wireless."

The CDMA handset RFIC features a built-in switch to bypass the amplifier in receive chains, which reduces system current needs and also provides a higher dynamic range. "For the receiver functions, demands for greater dynamic range are increasing with each new standard," explains HP's Robert Myers. "Dynamic range is limited on the low end by noise figure and on the high end by distortion and intercept point. The second-generation PHEMT process provides a higher mobility than MESFETs, which results in higher gain and lower receiver noise figure. Discretes have a minimum noise figure of 0.5 dB, while the noise figure of the switched-LNA RFIC is only 1.4 dB, with associated gain of 14 dB. Another benefit of the new process is improved consistency compared to both the previous generation of PHEMTs and to MESFET devices."

These examples clearly illustrate that HEMTs have an important role to play as commercial products for high volume applications.



## How It Works...

The High Electron Mobility Transistor (HEMT) uses modulation doping to increase the carrier mobility in the channel. In the original AlGaAs/GaAs HEMT structure (see Front Cover), the Schottky gate controls (modulates) the amount of carriers supplied to the channel by the  $n^+$ -AlGaAs donor layer. The carriers are confined in a potential well in the GaAs layer, forming a two-dimensional electron gas, or 2DEG. The undoped AlGaAs spacer separates the ionized donors in the  $n^+$ -AlGaAs layer from the free electrons in the 2DEG, ensuring a high mobility in the channel.

HEMTs are sometimes termed MODFETs (or modulation-doped FETs) and are also referred to by the more generic name HFET, or heterojunction FET. The HFET label is widely used in Japan because Fujitsu trade-marked the name HEMT.

Modern, high performance HEMTs have an InGaAs channel layer, in order to take advantage of the superior electron transport properties of this material compared to GaAs. The figure below shows schematic structures of three common types of InGaAs channel HEMT. Typically, electrons are supplied by a delta-doped region within the AlGaAs or InGaAs layer. As in the conventional AlGaAs/GaAs structure, an

## ...The HEMT

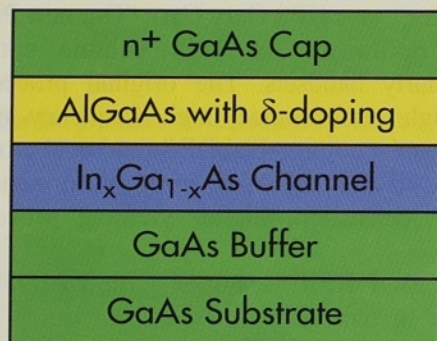
undoped spacer is placed between the donor layer and the channel. Some HEMT structures have doped layers on both sides of the channel.

However, InGaAs cannot be grown lattice-matched to GaAs. In a pseudomorphic GaAs-based HEMT, or PHEMT, the InGaAs channel is strained due to the mismatch between the substrate and the thin channel layer. The maximum In content of the channel is limited by the need to prevent relaxation of the InGaAs layer, which would be accompanied by the formation of dislocations.

Growth on InP substrates permits higher InAs mole fractions in the InGaAs channel. Lattice matched InP HEMTs (sometimes referred to as LM-HEMTs) have  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  channels, while a higher In content results in a strained-channel, pseudomorphic device.

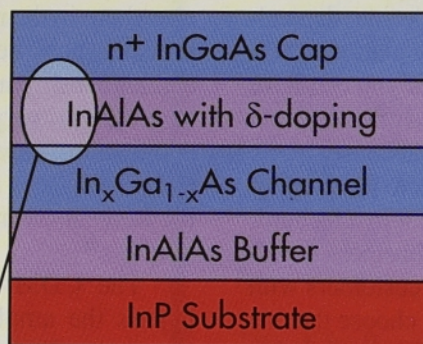
In a metamorphic HEMT (MM-HEMT), the large lattice mismatch between the GaAs substrate and the InGaAs channel is accommodated by the formation of misfit dislocations in a thick metamorphic buffer layer grown directly on the substrate. The buffer layer also traps these dislocations and prevents their propagation into the active layer.

### Pseudomorphic HEMT (PHEMT)



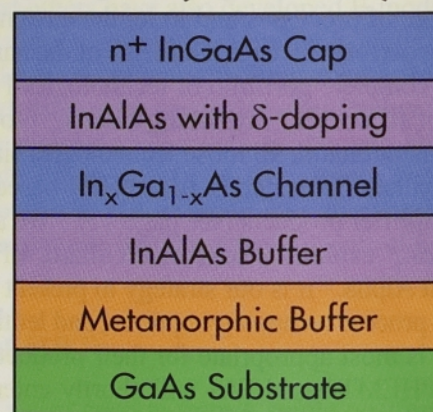
In Composition  
in Channel:  
 $0.15 < x < 0.30$

### InP HEMT

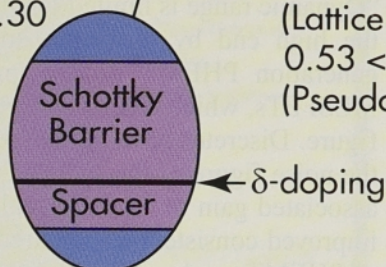


In Composition:  
 $x = 0.53$   
(Lattice matched)  
 $0.53 < x < 0.80$   
(Pseudomorphic)

### Metamorphic HEMT (MM-HEMT)



In Composition:  
 $0.30 < x < 0.80$



*Typical cross-sections of different types of HEMT. The donor layer (AlGaAs or InAlAs) generally consists of an undoped spacer adjacent to the channel, a delta-doped layer and an undoped Schottky layer. A recess etch through the cap allows the Schottky gate contact to be placed on the donor layer.*



# FOR HIGH-PRECISION COATING...

## Ultra-reliable thin-film deposition – why Temescal stands apart.

Why do more thin-film professionals prefer Temescal?  
Because over the decades, the name *Temescal* has come to mean “absolutely, positively reliable coating.”

Temescal systems of today offer conveniences like touch-screens and recipe-controlled automation.

Handling a range of source materials. State-of-the-art capabilities and flexibility...

But always the same Temescal *reliability*.

## Deposition systems to cover you, whatever your application.

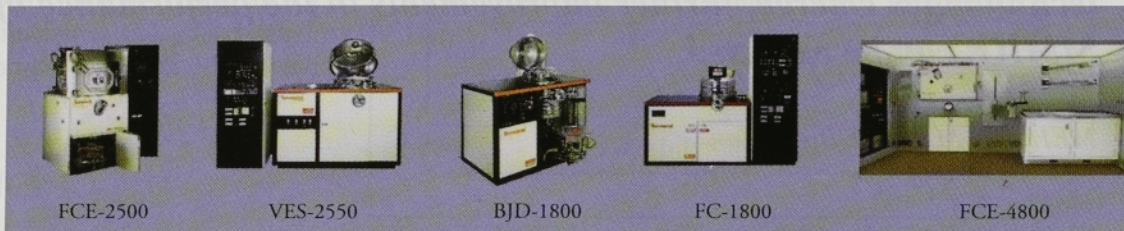
Whether you're evaporating metals onto ICs, sputtering compound films onto optical lenses or coating flat panels for a commercial product...

Whether it's for R&D prototyping or full-scale, fully automated production. Needing loadlock or not. Coating objects in the micron range or up to 4 feet square. Whatever your coating need, Temescal has a thin-film deposition system to cover it.

## Get superior components, too. Faster than ever.

Making ultra-reliable coating systems requires ultra-reliable components. So Temescal makes their own...

The performance of Temescal e-beam guns has



*Temescal offers a spectrum of state-of-the-art thin-film coating systems, from research to automated production.*

become a legend in the industry – over 12 thousand in operation around the world! The same is true in ultra-precise power supplies. So Temescal definitely is the place to go for components.

And now Temescal is maintaining *shelf stock* on all the most-asked-for components – so you can get them faster than ever. Usually shipped *within 24 hours!*

## See for yourself. Call Temescal.

For coating systems or components, call

Temescal – at (707) 423-2100. Or fax: (707) 425-1706.  
Temescal, a part of BOC Coating Technology,  
2700 Maxwell  
Way, Fairfield,  
CA 94585.



**BOC**  
COATING  
TECHNOLOGY

...NOTHING TOPS A

# Temescal



# Advances in Millimeter-Wave HEMTs

*As GaAs PHEMTs and InP-based HEMTs continue to set records and as new device technologies emerge, further improvements in the performance of millimeter-wave MMICs can be expected.*

MEHRAN MATLOUBIAN  
HRL Laboratories  
Malibu, CA

The development of millimeter-wave HEMT MMICs has proceeded at a remarkable rate over the last decade, and significant improvements in noise figure, gain, output power and efficiency have all been realized. Amplifiers with gain at 200 GHz and fundamental oscillators at 213 GHz are just two of the impressive results that have been achieved using HEMT technology. This article reviews some of the recent developments in the area of millimeter-wave HEMTs, and identifies further challenges and prospects for the next generation of HEMT devices.

Until recently, the development of millimeter-wave MMICs was driven by military applications such as radar and satellite-based communication systems. However, a number of important commercial applications have emerged in recent years, taking advantage of the allocation for commercial use of large bandwidths of the electromagnetic spectrum. Applications include local multipoint distribution service (LMDS) and related systems, wireless local area networks, and automotive radar. Together with the broadband satellite systems now being planned or built, these markets are creating a strong demand for low cost millimeter-wave MMICs.

Three types of FET are commonly used for millimeter-wave applications. These are the GaAs MESFET, the AlGaAs/InGaAs/GaAs PHEMT, and the AlInAs/InGaAs/InP

HEMT (see page 22). Devices grown on InP allow the use of channel layers with a higher In content than GaAs PHEMTs, providing improved channel properties and increased gain. Metamorphic HEMTs offer the opportunity to combine a high In content with the processing and cost advantages of working with GaAs substrates (see page 40). However, the reliability of these HEMTs is still under investigation.

## Millimeter-Wave Low Noise MMICs

InP HEMTs have emerged as the device of choice for millimeter-wave low noise applications. However, GaAs-based PHEMTs and MESFETs are still used in many commercial applications where cost rather than ultimate noise performance is the driving factor. InP HEMTs have demonstrated the highest  $f_T$  of 350 GHz and the highest  $f_{max}$  of more than 600 GHz of any transistor technology. The 350 GHz  $f_T$  result was recorded by NTT, using a 30 nm gate length HEMT lattice-matched to InP [1]. The 600 GHz  $f_{max}$  result was reported by HRL Labs using a composite channel HEMT structure to achieve very low output conductance [2].

In addition, InP HEMTs offer more than a factor of four reduction in power for comparable gain, relative to GaAs-based MMIC LNAs [3]. Modern spaceborne arrays for communication satellites typically require a large number of LNAs, and this makes low DC power consumption, high gain and compact size as important as low noise. HRL has demonstrated a five stage InP HEMT LNA exhibiting over 40 dB gain and a 1.4 dB average noise figure from 27-30 GHz. The MMIC consumed less than 40 mW DC power and occupied 3 mm<sup>2</sup>. Such a high gain amplifier permits system designers to minimize chip count and interconnects, which in turn reduces system cost and weight while improving frequency response and reliability. The device structure used was a lattice-matched InP HEMT grown by MBE on a 3-inch substrate. The electron sheet density in the channel was approximately  $2.7 \times 10^{12}$  /cm<sup>2</sup> with a mobility of 10,000-11,000 cm<sup>2</sup>/Vs at 25°C.

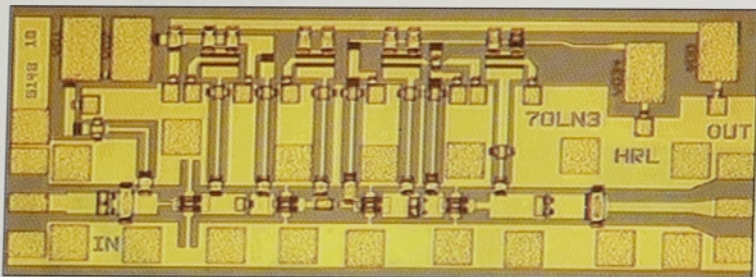


Figure 1. A state-of-the-art four-stage W-band InP HEMT fabricated at HRL. The amplifier has a noise figure of 2.5 dB with 20 dB gain at 95 GHz, and an average noise figure of ~2.5 dB from 78-118 GHz [4].



InP HEMTs have also established state-of-the-art performance at higher frequencies. Figure 1 shows a W-band LNA fabricated by HRL. The four stage MMIC amplifier had a noise figure of ~2.5 dB over the 78-118 GHz frequency range, and demonstrated 20 dB gain at 95 GHz [4]. This represents more than 2 dB reduction in noise figure compared to LNAs in this frequency range fabricated 10 years ago.

TRW has reported a number of high frequency, low noise InP HEMT MMICs including a two-stage LNA with a record 9.6 dB gain at 188 GHz. The MMICs were fabricated using an 80-nm gate length HEMT with a 20 nm thick  $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$  channel. Recently a six-stage MMIC was reported with over 15 dB gain up to 215 GHz [5].

## Millimeter-Wave Power MMICs

For power applications up to W-band (i.e. below 75 GHz), GaAs PHEMTs have become the dominant technology, and have demonstrated higher power densities and power-added efficiencies than other competing FET technologies. For example, HRL recently reported a double-doped  $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}/\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{GaAs}$  PHEMT with an output power of 26.7 dBm at 20 GHz, and a PAE of 52% and an associated power gain of 9.7 dB. This corresponds to a power density of 727 mW/mm. The results are thought to represent the best combination of power, PAE and gain at this frequency [6].

At higher frequencies, Sanders has fabricated single GaAs PHEMT MMICs with an output power of more than 4 W at 29-31 GHz [7] and 560 mW at 60 GHz [8]. The Ka-band result was realized using a 0.15  $\mu\text{m}$  single recess, fully selective PHEMT process that demonstrated in excess of 4 W output power at 25-31% PAE with 14 dB of power gain. InP-based HEMTs may have already closed the gap at 60 GHz; TRW recently reported a device with an output power of 186 mW with 36% PAE and 5.7 dB power gain at 60 GHz [9].

At W-band frequencies and above, InP HEMTs have achieved higher gain and efficiency than GaAs-based PHEMTs. TRW has reported an output power of 427 mW at 95 GHz from a single MMIC [10].

## High Gain D-Band Amplifiers

HRL achieved the highest gain per stage for an amplifier at 140 GHz, using a 3-stage InP HEMT MMIC with more than 30 dB gain [11]. The gain exceeded 10 dB in the 129-157 GHz range, and was over 5 dB up to 184 GHz. Frequencies in the D-band are attractive due to an atmospheric propagation window around 140 GHz, which could be utilized for radar systems with very small antenna apertures, or for radiometric imaging. Adjacent absorption lines at 118 GHz ( $\text{O}_2$ ) and 183 GHz (water vapor) are also important for environmental monitoring and potential ultra-broadband secure communication links. High-gain, solid-state amplifiers allow the use of direct detection schemes in millimeter-wave radiometric arrays, resulting in lower noise and lower cost systems.

MMICs were fabricated using a 0.1- $\mu\text{m}$  gate pseudomorphic

|                                             |          |          |
|---------------------------------------------|----------|----------|
| $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ | Cap      | Doped    |
| $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ | Schottky | Undoped  |
| $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ | Donor    | Si-doped |
| $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ | Spacer   | Undoped  |
| $\text{Ga}_{0.2}\text{In}_{0.8}\text{As}$   | Channel  | Undoped  |
| InP                                         | Channel  | Undoped  |
| InP                                         | Channel  | Si-doped |
| $\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ | Buffer   | Undoped  |
| InP Substrate                               |          |          |

**Figure 2. Device layer profile of a 0.1  $\mu\text{m}$  InAlAs/GaInAs/InP HEMT used to fabricate a 3-stage amplifier with a small-signal gain of 30 dB at 140 GHz [11]. The composite InGaAs/InP channel provides improved breakdown voltage and a lower output conductance.**

InP HEMT process. The device structure (see Figure 2) contains a composite InP/ $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}$  channel which acts to improve the breakdown voltage of the transistor and lower the output conductance for improved gain at high frequencies.

## Multifunction MMICs

A wide array of high performance MMICs have been developed in addition to the millimeter-wave low noise and power HEMT MMICs described above. These include InP HEMT oscillators with a record operating frequency of 213 GHz, and a travelling wave amplifier with a bandwidth of 1-180 GHz and 5 dB gain (see Figure 3) [12].

High performance HEMTs have also been used to develop digital circuits such as a 75 GHz dynamic divider and an 80 Gbit/s multiplexer (see page 30). One motivation for the development of HEMT digital circuits is the ability to integrate analog and digital functions. For example, NTT has demonstrated a 37 GHz HEMT static divider and a 62 GHz MMIC HEMT LNA in the same process [13].

## Reliability and Process Enhancement

A major problem concerning the reliability of GaAs- and InP-HEMT MMICs is the issue of hydrogen sensitivity. Many microwave packaging materials outgas hydrogen, which attacks devices with Pd or Pt in the gate structure. Hydrogen getters have been developed for use inside hermetically sealed modules, while progress has been made towards reliable, lower cost MMICs that do not require a hermetic environment [14]. At this year's GaAs ManTech meeting, the Fraunhofer Institute reported a 94 GHz InP HEMT MMIC process demonstrating sufficient reliability for satellite requirements [15]. Despite the Ti-Pt-Au gate metalization, these MMICs were insensitive to hydrogen and were hermetically sealed without degradation.



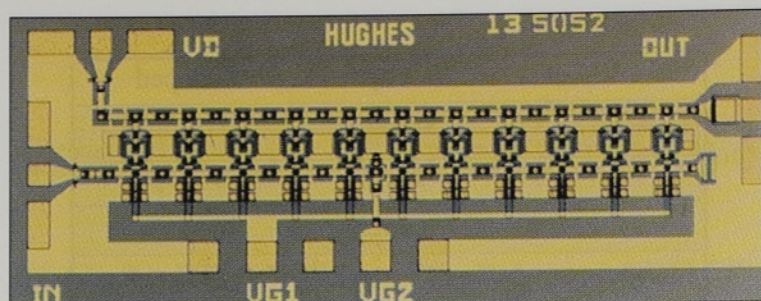


Figure 3. An InP HEMT traveling amplifier with a gain of 5 dB over the bandwidth of 1-180 GHz [12].

In order to reduce the cost of millimeter-wave MMICs, advances are being made in improving device uniformity as well as MMIC yield. The most critical processing step controlling both yield and uniformity is the fabrication of sub-micron gates. Both the definition of the gate by electron beam lithography as well as the gate recess etch can be improved. Use of etch-stop layers and selective etching has resulted in significant improvements in threshold voltage uniformity of transistors. For example, InGaP layers are now widely used as etch stop layers since these layers provide etch selectivity in excess of 100:1, allowing repeatable process control, and do not compromise the source resistance.

## Testing and Packaging

Advances in millimeter-wave testing capabilities and the availability of high performance test systems and RF probes has been critical for the rapid development of millimeter-wave MMICs. Network analyzers are now able to test devices and MMICs on-wafer in the 1-110 GHz range for a single system. With frequency extenders, this range can be increased up to 220 GHz, and systems with over 300 GHz testing capability are now under development.

Packaging is another important consideration affecting the design of millimeter-wave MMICs. Co-planar waveguide (CPW) designs can reduce packaging costs by eliminating backside processing. This approach also allows flip-chip mounting for low inductance and low parasitic interconnects, and automated assembly. Fujitsu has used this approach to develop 76 GHz MMICs for automotive radar, based on 0.15  $\mu\text{m}$  gate length InGaP/InGaAs/GaAs PHEMTs [16]. As well as providing a suitable etch stop layer, InGaP is preferred to AlGaAs as an etch-stop layer due to the possibility of higher doping, which reduces the distance between the channel and the gate.

Another novel packaging approach is to use polyimide layers for the development of 3D MMICs. NTT recently described an up- and down-converter chip set for LMDS (28-31 GHz) using the 3D "masterslice" MMIC technology, which incorporates 0.3  $\mu\text{m}$  GaAs MESFETs [17]. Embedded transmission lines have also been suggested as a technology that will significantly reduce the size of MMICs as well as simplifying packaging.

## Future Trends

Although HEMT MMICs have until now been the technology of choice in millimeter-wave arena, InP HBTs are starting to challenge this dominance. At microwave frequencies and particularly in mobile phone handsets, AlGaAs/GaAs and InGaP/GaAs HBTs have gradually replaced GaAs MESFETs in applications where high linearity power amplifiers are required. This trend will be paralleled to some degree in the millimeter-wave region, as InP HBTs replace GaAs- and InP-based HEMTs in certain applications such as linear amplifiers and low phase noise oscillators. HBTs offer several advantages, not least because they do not require sub-0.2  $\mu\text{m}$  gates for millimeter-wave operation. Much higher yield and uniformity can be obtained with HBTs compared to HEMTs. However, the much lower noise figure of HEMTs will ensure that this technology will continue to dominate for high performance, low noise applications in the foreseeable future.

## References

- [1] T. Suemitsu et al, *IEDM Tech. Digest 1998*, p. 223; *Compound Semi.* 1998, 4(8), p. 11
- [2] M. Matloubian et al, *Ultrafast Electronics and Optoelectronics Conf.*, April 1999
- [3] C. Pobanz et al, *RFIC Symp. Digest 1999*, p. 149
- [4] S. Weinreb, unpublished results
- [5] R. Lai et al, *IEEE Microwave & Guided Wave Lett.*, 1998, 8(11), p. 393; R. Lai et al, *Proc. GaAs MANTECH 1999*, p. 249; S. Weinreb et al, *IEEE Microwave & Guided Wave Lett.*, 1999, 9(7), p. 282
- [6] K. Kiziloglu et al, *IEEE MTT-S Int'l Microwave Symp. Digest*, 1999, p. 681
- [7] J. Komiak et al, *IEEE MTT-S Int'l Microwave Symp. Digest*, 1999, p. 947
- [8] O. Tang et al, *GaAs IC Symp. Digest 1996*, p. 115
- [9] R. Grundbacher et al, *Proc. Int'l Conf. InP & Related Mats.* 1999, p. 307
- [10] Y. Chen et al, *IEEE Microwave & Guided Wave Lett.*, 1998, 8(11), p. 399
- [11] C. Pobanz et al, *GaAs IC Symp. Digest 1998*, p. 41
- [12] B. Agarwal et al, *IEEE Trans. Microwave Theory & Tech.*, 1999, 46(12), p. 2553
- [13] Y. Umeda et al, *IEEE Microwave & Mm-Wave Monolithic Circuits Symp. Digest 1996*, p. 115
- [14] D. Leung et al, *RFIC Symp. Digest 1999*, p. 153; *Compound Semi.* 1999, 5(8), p. 71
- [15] M. Chertouk et al, *Proc. GaAs MANTECH 1999*, p. 25
- [16] Y. Watanabe and N. Okubo, *Compound Semi.* 1999, 5(2), p. 46
- [17] I. Toyoda et al, *RFIC Symp. Digest 1999*, p. 145
- [18] D. Docter et al, *Proc. Dev. Res. Conf.* 1999, p. 146



# BEST IS BEST

Two out of every three large-scale production MBE machines sold over the last couple of years have been RIBER systems.

Our MBE 49™ and MBE 6000™ provide the:

highest **Throughput**,

highest **Uptime**,

best **Cost Effectiveness**,

and... **Peace of Mind.**



To find out more about the industry standard for production MBE, call your RIBER representative or e-mail us at [info@riber.com](mailto:info@riber.com).

**R I B E R**

*Products and Services for the Compound Semiconductor Industry*



## Next Generation HEMTs - Mixed PSb and AsSb Materials

A great deal of recent work on GaAs PHEMTs and InP-based HEMTs has focused on device integration, circuit and system development, device manufacturability, and reliability issues. At HRL, work has also continued to improve device performance by investigating new combinations of materials. The focus of the research is to study mixed antimonide phosphide (SbP) and mixed antimonide arsenide (SbAs) compounds [18].

The materials AlGaPSb, which can be grown lattice matched to both GaAs and InP, and InAlAsSb, which can be lattice matched with InP, offer advantages compared to the traditional Schottky barrier materials. (These are InAlAs for InP HEMTs, and AlGaAs for GaAs PHEMTs.) For example, when lattice matched to InP, both AlGaPSb and InAlAsSb have a significantly larger energy bandgap ( $E_g$ ) than InAlAs. Similarly, AlGaPSb lattice matched to GaAs has a much larger  $E_g$  than  $Al_{0.25}Ga_{0.75}As$ . Another advantage is the increase in conduction band offset ( $\Delta E_c$ ) due to the smaller electron affinities associated with Sb-containing compounds, which should further improve the Schottky barrier height for gate contacts. These properties should lead to devices that have higher sheet carrier concentration ( $n_s$ ), higher breakdown voltage ( $BV_{gd}$ ), higher turn-on voltage ( $V_{on}$ ), higher gain ( $g_m$ ), higher current ( $I_{max}$ ), higher output power ( $P_{out}$ ), improved power added efficiency (PAE) and lower noise figure (NF).

### Material Growth

HRL is studying the growth of mixed group V-antimonide compounds using both MBE and MOVPE. In the past, both the lack of suitable Sb and P sources, and the difficulty of mixed group V element growth, hindered progress with these materials. However, improvements in MOVPE precursors and solid-source cracker cell designs, along with the

development of in-situ monitoring and control, has allowed considerable progress to be made. HRL's MBE reactor uses valved cracker cells for As, P and Sb, while arsine, phosphine and TESb or TMSb are used for MOVPE growth.

To evaluate material properties, I-V characteristics were measured as a function of temperature for a variety of barrier diode structures, in order to extract the thermionic emission barrier height and hence determine  $\Delta E_c$ . As shown in Table 1, much larger  $\Delta E_c$  values can be obtained in typical HEMT structures using AlGaPSb or InAlAsSb. These values translate into higher maximum sheet charge for single side doped HEMTs.

### Device Results

A number of InP-based HEMT structures were fabricated using the PSb and AsSb compounds to replace the commonly used InAlAs for the spacer, donor and barrier layers. HEMT devices with GaPSb,  $Al_{0.5}Ga_{0.5}PSb$  and  $In_{0.34}Al_{0.66}As_{0.84}Sb_{0.16}$  Schottky layers were fabricated using a standard gate recess etch process. While the InAlAsSb structure was amenable to standard InP-based HEMT processing, the PSb were sufficiently different to require alternative processing. The GaPSb and AlGaPSb devices were fabricated with 1.5  $\mu m$  gate lengths while the InAlAsSb device had an E-beam written 0.15  $\mu m$  gate.

Excellent material properties were achieved for each structure, with a channel mobility in excess of 10,000  $cm^2/Vs$  for a wide range of sheet carrier concentrations (1-5  $\times 10^{12}/cm^2$ ). All devices exhibited well-behaved characteristics with firm pinch-off and relatively high  $g_m$ , even for the device with the GaPSb Schottky layer. With a bandgap  $E_g$  of less than 1.0 eV, the  $g_m$  for this device was 380 mS/mm. Increases in  $V_{on}$  and  $BV_{gd}$  were observed for these structures compared to standard InGaAs/InAlAs/InP HEMTs (see Table 1).

| HEMT Material System                                 | Conduction band offset $\Delta E_c$ (eV) | Maximum channel sheet charge $n_s$ ( $cm^{-2}$ ) | Breakdown voltage $BV_{gd}$ (V) |
|------------------------------------------------------|------------------------------------------|--------------------------------------------------|---------------------------------|
| $In_{0.25}Ga_{0.75}As/Al_{0.25}Ga_{0.75}As$ on GaAs  | 0.35                                     |                                                  |                                 |
| $In_{0.25}Ga_{0.75}As/(Al)GaPSb$ on GaAs             | >0.37                                    |                                                  |                                 |
| $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ on InP   | 0.45                                     | $< 3.5 \times 10^{12}$                           | 4.0                             |
| $In_{0.53}Ga_{0.47}As/(Al)GaPSb$ on InP              | >0.50                                    | $< 4.5 \times 10^{12}$                           | 7.0                             |
| $In_{0.53}Ga_{0.47}As/In_{0.34}Al_{0.66}AsSb$ on InP | 0.8                                      | $< 7.0 \times 10^{12}$                           | 9.3                             |

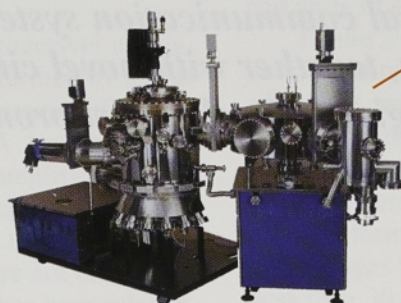
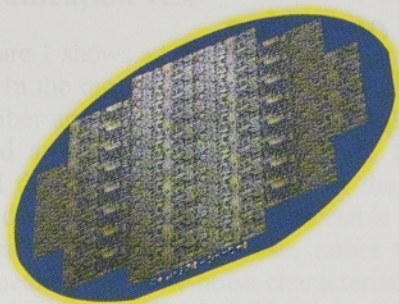
*The mixed PSb and AsSb compounds are capable of providing much larger conduction band offsets compared to more traditional materials (AlGaAs for GaAs PHEMTs, InAlAs for InP HEMTs). Estimates for the maximum achievable channel sheet carrier concentration for a single side doped InP HEMT with different Schottky layers (and a mobility of  $\sim 10,000 cm^2/Vs$ ) show the advantage of the larger  $\Delta E_c$  value. Also shown are measured breakdown voltages for different InP-based HEMTs.*





**TLC's EPI Processes are on 6", 4", 3", and 2" substrates**

**Featuring: TLC's Special *Insitu* Resistivity and Doping Monitor**  
(Patent Pending)



**NEW  
ADVANCED  
6" MBE  
SYSTEM!**



| Process          | Description                                                                                                                                                                                                                                                                                            | Performance Application                                                                                                                                                                                                                | Frequency                                                                                 |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| <b>PHEMT</b>     | Standard (Single pulse-doped)<br>Double pulse-doping (super-lattice buffer)<br>Lattice Engineered (High In-mole fraction)<br>Special PHEMTs<br>- LT GaAs with anti-SEU enhancement<br>- High P-Mobility (Transconductance)<br>- Dielectric-Insulated Gate<br><br>- Anti-Hydrogen Gate (In development) | Low-Noise<br>High-Power<br>High-Power, High-Speed OEIC<br>High-Speed, N&P Channels<br>Rad-Hard<br>High-P Gain<br>Ultra Low-P <sub>0</sub> High-Speed or<br>High P <sub>0</sub> High-Frequency<br>High-Reliability (Space applications) | mW/MMW<br>mW/MMW<br>Digital /MMW<br><br>Digital<br>Digital<br>Digital /MMW<br><br>Digital |
| <b>HEMT</b>      | AlGaAs/GaAs HEMTs<br>InP-Based Lattice-Matched<br>InP Lattice-Engineered                                                                                                                                                                                                                               | High Gain<br>Ultra-Low Noise, Ultra-High PowerMMW                                                                                                                                                                                      | mW/MMW<br>mW/MMW                                                                          |
| <b>PMESFET</b>   | Highly-Resistive Buffer, Higher PAE                                                                                                                                                                                                                                                                    | Standard                                                                                                                                                                                                                               | mW/MMW                                                                                    |
| <b>HBTs</b>      | AlGaAs/GaAs<br>AlGaAs/InGaAs<br>InP-Based                                                                                                                                                                                                                                                              | High-Power<br>High-Power, High-PAE (> 50%)<br>High-Gain, Higher Frequencies                                                                                                                                                            | mW/MMW<br>mW/MMW<br>mW/MMW                                                                |
| <b>Photonics</b> | AlGaAs/GaAs<br>AlGaAs/InGaAs<br>InP-Based<br>InGaP<br>InGaAsP                                                                                                                                                                                                                                          | High-Power<br>Multi-Process<br>High-Wavelength<br>Laser/Detector<br>Laser/Detector                                                                                                                                                     | IR<br>LW<br>LW<br>Various<br>Various                                                      |

**TLC PRECISION WAFER TECHNOLOGY, INC.**  
**1411 WEST RIVER ROAD N.**  
**MINNEAPOLIS, MN 55411**

**TEL: (612) 341-2795**  
**FAX: (612) 341-2799**  
**EMAIL: [sales@tlcprecision.com](mailto:sales@tlcprecision.com)**

**FOR DATASHEET AND PERFORMANCE INFORMATION, VISIT US ON THE WEB AT:**

**<http://www.tlcprecision.com>**



# InP HEMT ICs for Lightwave Communication at 40 Gbit/s and Beyond

*Ultrahigh-speed integrated circuit technology is one of the keys to achieving ultrahigh-capacity optical communication systems operating at or above 40 Gbit/s. InP HEMTs, together with novel circuit design and advanced packaging technologies, offer the most promising solution.*

EIICHI SANO

NTT Network Innovation Laboratories  
Kanagawa, Japan

Although the number of Internet hosts has multiplied by a factor of one thousand over the last decade, the rate of installation of commercial trunk transmission systems has been some 20 times lower over the same period. A vast increase in transmission capacity is therefore needed to bridge the gap. Much effort is being devoted to achieve trunk transmission systems beyond one terabit per second by combining time-division multiplexing (TDM) with wavelength-division multiplexing (WDM).

In WDM systems, multiple wavelengths, each carrying a separate data signal, are combined using passive multiplexer elements and simultaneously transmitted down the same optical fiber. A 40 Gbit/s system can be constructed, for example, by combining 4 channels each operating at 10 Gbit/s. In TDM systems, several low data-rate signals are interwoven by sampling at regular intervals to create a single, high data-rate stream. To achieve transmission at 40 Gbit/s, a TDM system requires ICs operating at this speed.

High-speed TDM systems have several merits [1]. Many functions, including multiplexing, demultiplexing, retiming, reshaping and regeneration, can be integrated in a simple and compact manner using high speed ICs. Also, the number of network elements is reduced,

leading to more simple network operation, administration, and maintenance. The higher bit rate of TDM channels achieves higher spectral density when using commercially available WDM filters. TDM systems beyond 40 Gbit/s, combined with WDM, offer a promising way of achieving one Tbit/s systems.

One of the major issues in implementing an ultra-high speed TDM system is the development of ultra-high speed electronic ICs. Recently, several 40 Gbit/s-class ICs have been reported, using Si bipolar technologies, GaAs-based MESFETs, HBTs and HEMTs, and InP-based HEMTs and HBTs. Among these different approaches, InP-based devices are very attractive because of the excellent electron transport properties of the material system and the capability of monolithic integration with photonic devices. Technological breakthroughs in circuit and packaging design as well as improved transistor

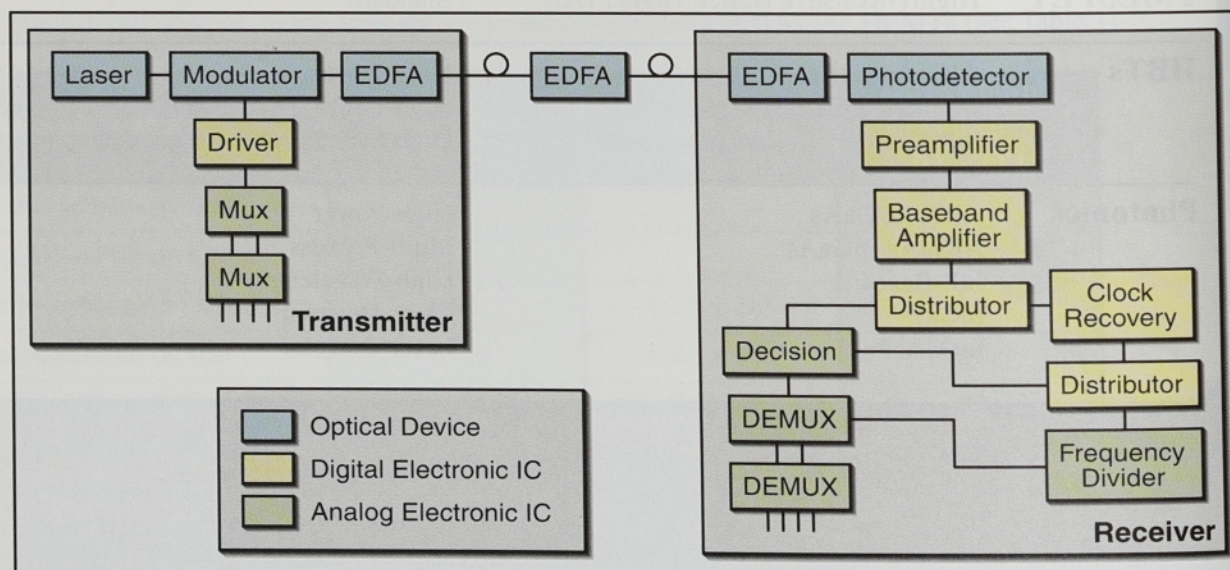


Figure 1. A typical optical transmitter/receiver configuration for use in a high-speed TDM system.



performance are needed to reach the operating region exceeding 40 Gbit/s.

Here, we describe technologies including a 0.1  $\mu\text{m}$  gate InP HEMT, novel circuit design, and broadband packaging techniques that have been developed to boost circuit speed. After describing how these technologies have been used to make 40 Gbit/s lightwave communication ICs, we review the problems in moving towards 100 Gbit/s operation.

## Requirements for Lightwave Communication ICs

Figure 1 shows a typical optical transmitter/receiver configuration. In the receiver, signal reshaping is performed by an Erbium-doped fiber amplifier (EDFA), photodetector, preamplifier, and baseband amplifier. The advent of the EDFA has drastically changed the design methodologies of the preamplifier and the baseband amplifier. Minimum detectable optical power is now determined by the EDFA noise, rather than the preamplifier noise, meaning that low-noise characteristics are not critical. Of course, the gain requirement of the amplifiers has been relaxed.

Nevertheless, regeneration, performed by a decision circuit and a clock recovery circuit (composed of a differentiator, a rectifier, a microwave resonator and a limiting amplifier), is still needed to reduce the timing jitter produced by the cascaded EDFAs. The transmitter and receiver ICs, except for the clock recovery circuit, require broadband operation from near DC to the maximum bit rate with good eye openings.

## InP HEMT Technology

Source-coupled FET logic (SCFL) is widely used in high-speed digital ICs because of its advantageous series-gate configuration. Studying the factors that influence the propagation delay of an SCFL inverter ( $\tau_{pd}$ ), it is clearly important to improve both the transconductance ( $g_m$ ) and current-gain cutoff frequency ( $f_T$ ), in order to achieve higher-speed circuits.

For 50 GHz operation of a T-type flip-flop,  $\tau_{pd}$  should be 4 ps/gate if an additional transmission delay of about 1 ps for the inverter is taken into account. This means that a  $g_m$  of 1.2 S/mm and an  $f_T$  of 180 GHz are required.

Figure 2 depicts a schematic cross section of our HEMT and Schottky diode structures [2]. The layer structure and gate length of 0.1  $\mu\text{m}$  were determined to meet the  $g_m$  and  $f_T$  requirements. The most important feature of the MOCVD-grown heterostructure is the InP recess etch-stop layer introduced in the InAlAs barrier layers. This drastically improves the threshold voltage ( $V_{th}$ ) uniformity of HEMTs. The standard deviation of the threshold voltages for 0.1  $\mu\text{m}$  gate length HEMTs on 3-inch wafers was less than 30 mV. Typical  $V_{th}$ ,  $g_m$ , and  $f_T$  values for 0.1  $\mu\text{m}$  gate HEMTs were -0.6 V, 1 S/mm, and 200 GHz, respectively.

## Circuit Technology

Although on-wafer measurements of our 0.1  $\mu\text{m}$  gate InP HEMTs indicate 40 Gbit/s operation, faster operation is generally necessary due to speed losses arising from IC packaging, and

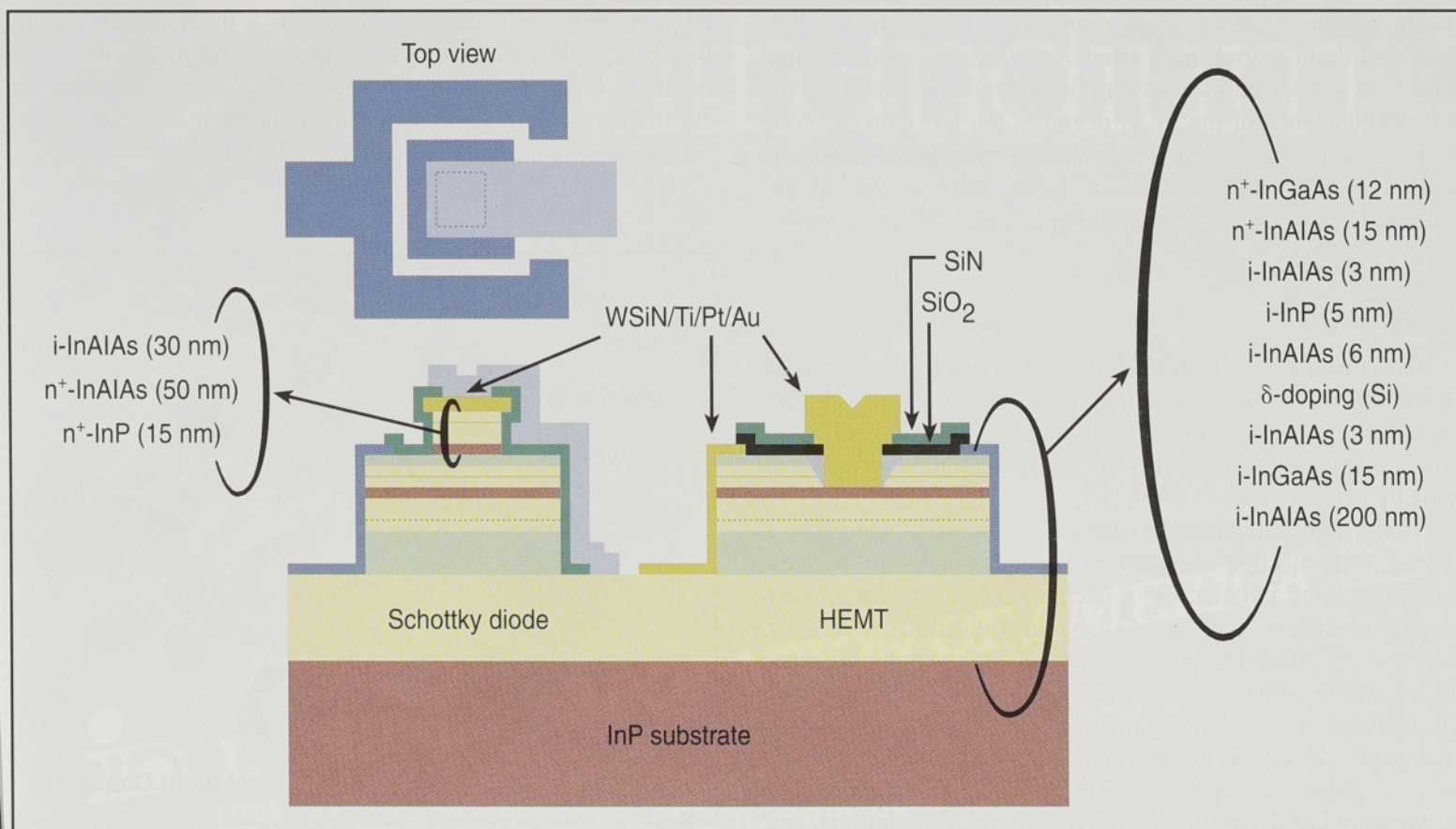


Figure 2. Schematic cross-section of NTT's HEMT and Schottky diode device structures.



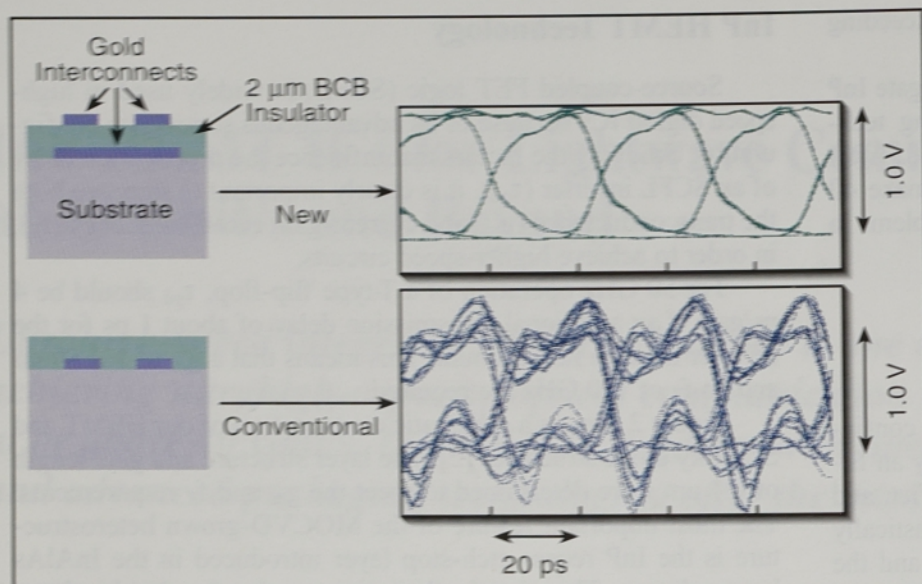


Figure 3. Effect of impedance-matched design in a multiplexer IC, for a 400  $\mu\text{m}$  interconnection. Eye diagrams were simulated by HSPICE [3].

from temperature and supply voltage deviations. Consequently, circuit design technologies are very important for achieving 40 Gbit/s class ICs.

### A. Analog ICs

Distributed amplifiers are commonly used in millimeter wave applications. Their great merit is that they can significantly widen the bandwidth. This is due to the fact that the parasitic capacitance of FETs is effectively utilized as a circuit element to enable velocity-matched signal transmission between the gate input and drain output lines. However, conventional distributed amplifiers cannot be used as baseband amplifiers, because the drain conductance of the FETs degrades the DC gain. To cope with this, a novel frequency-dependent termination scheme was devised to compensate for the DC gain, while another of our wideband designs is the drain peaking line and the loss compensation circuit.

### B. Digital ICs

The flip-flop (F/F) circuit is the most important component for constructing high-speed digital ICs. An F/F with double source followers and a high-speed latching operation F/F were found to offer higher speed, while further improvements were made by using a super-dynamic F/F.

Features of the super-dynamic F/F circuit include: (1) a series-gate connection to separate the current paths of the reading and latching circuits; (2) a latching current that is smaller than the reading current; and (3) source-coupled negative feedback pairs (SCNFPs) inserted in the first-level latching differential pair in a cascode manner. The SCNFPs drastically reduce the effective logic swing without any degradation in the signal transition slew rate. This is the key to increasing F/F speed. A super-dynamic D-F/F can operate 100% faster than a conventional master-slave D-F/F. To compensate for loss in the high frequency region, capacitive peaking is used in the source followers.

### C. Interconnection

At frequencies over 50 GHz, interconnection is a severe problem, even in an IC chip. The maximum interconnection length in our MUX IC is 400  $\mu\text{m}$ , which corresponds to around two-tenths of the wavelength at 50 GHz. This means that the distributed element characteristics should be taken into account even in IC design. To reduce the interconnection propagation delay and to obtain an impedance-matched microstrip line, we introduced a high-speed interconnection process using two metal layers consisting of Au and a 2- $\mu\text{m}$ -thick BCB film as an insulator. Figure 3 shows simulated eye diagrams at 40 Gbit/s for new and conventional interconnections. Clear eye opening is obtained with new interconnection arrangement, which is due to the fact that the characteristic impedance of the interconnection matches the output impedance of the source follower so signal reflections are sufficiently suppressed.

### Packaging Technology

Packaging is another key technology for attaining ultra-broadband signal transmission without undesirable losses due to cavity and/or parasitic resonance and coupling. The basic structure we adopted is the so-called "chip-size cavity" package in which the inner cavity is minimized in order to shift the cavity resonance outside the transmission bandwidth. Figure 4 shows a photograph of our package. A HEMT IC is interconnected to the thin-film multilayer (TFM) inner substrate by means of ribbon bonding. Placing a patterned metal lid onto the surface of the substrate makes the cavity size almost the same as the chip size. This package supports operation up to 50 GHz.

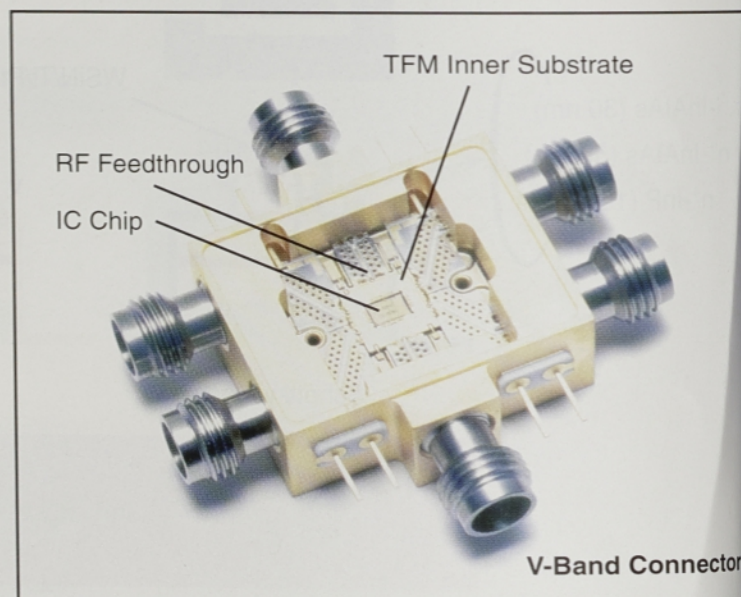


Figure 4. Photograph of chip-size cavity package.



- # IIIVS
- High Purity Indium
  - Precision Epi Sources
  - Indium Trichloride



## Get In Touch With Indium

**MEETING THE CHALLENGE**  
**INDIUM CORPORATION OF AMERICA®**  
USA 315-853-4900 or 800-4 INDIUM SINGAPORE +65 268-8678  
ITALY +39-011-655331 UK +44 (0)1908 580400  
[www.indium.com](http://www.indium.com)

65  
YEARS

ISO-9001  
CERTIFIED



## IC Performance

High-speed lightwave communication ICs were designed and fabricated using the technologies described above. Table 1 summarizes the maximum operating speed of lightwave communication ICs based on GaAs and InP. All of the packaged InP HEMT ICs achieved 40 Gbit/s operation, and higher operational speeds have been measured on-wafer. For example, a distributed baseband amplifier had a gain of 10 dB with a 90 GHz bandwidth. The MUX IC, which uses impedance-matched microstrip lines, demonstrated clear eye-opening at 80 Gbit/s, despite the insufficient bandwidth (~40 GHz) of the measurement instruments [3]. This is the highest bit rate ever reported for any electronic device.

## System Applications

A 40 Gbit/s optical transmitter/receiver prototype was fabricated using InP HEMT ICs. A high-speed, high output power unidirectional carrier photodiode was used to simplify the optical receiver configuration. The prototype was successfully used to demonstrate 40 Gbit/s, 4-channel WDM transmission over a distance of 100 km [5].

Also, InP HEMT ICs were employed in a 1.04 Tbit/s, dense WDM transmission experiment over a distance of 89 km [6]. A unique zero-dispersion-flattened transmission line, consisting of standard single-mode fiber and reverse dispersion fiber, was used. These transmission experiments clearly indicate that InP HEMT ICs are very promising for enlarging the optical transmission capacity to over one Tbit/s.

## Future Prospects

Based on the results discussed above, one might predict that operation in excess of 100 Gbit/s could be achieved by using InP-based HEMTs with the highest figure-of-merit. To satisfy this expectation, however, several technological problems have to be solved;

(a) Impedance matching design methodology, adopted in our 80 Gbit/s MUX IC, can be applied to the over-100 Gbit/s region. However, interconnection delays will occupy a larger part of the total delay when the intrinsic device speed is increased. Transistor sizes and interconnection line widths/spacings should

| Circuits           | FET              |                                   | HBT                         |                  |
|--------------------|------------------|-----------------------------------|-----------------------------|------------------|
|                    | GaAs             | InP                               | GaAs                        | InP              |
| Baseband Amplifier | 56 GHz           | 56 GHz (packaged)<br>90 GHz       | 50 GHz (packaged)<br>55 GHz | 50 GHz           |
| Distributor        |                  | 100 GHz                           |                             | 40 GHz           |
| EXOR*              |                  | 40 GHz (packaged)                 |                             |                  |
| Limiting Amplifier | 30 GHz           | 40 GHz                            | 32 GHz                      |                  |
| Decision Circuit   | 40 Gbit/s        | 46 Gbit/s (packaged)              | 40 Gbit/s                   |                  |
| Frequency Divider  |                  | 45 GHz (packaged)<br>60 GHz       | 40 GHz                      | 53 GHz           |
| DEMUX              | 40 Gbit/s        | 40 Gbit/s (packaged)              | 30 Gbit/s                   |                  |
| MUX                | 45 Gbit/s        | 52 Gbit/s (packaged)<br>80 Gbit/s | 40 Gbit/s                   | 40 Gbit/s        |
| Modulator Driver   | 40 Gbit/s, 2.9 V |                                   | 20 Gbit/s, 4 V              | 30 Gbit/s, 2.2 V |

**Table 1. Maximum operating speed of lightwave communication ICs based on GaAs and InP. Unless stated, measurements were made on wafer. Attribution of these results is given in reference [4]. \*EXOR = exclusive OR (used as a multiplier in a clock extraction circuit).**

be reduced without increasing the parasitic resistance of the transistors and the line resistance.

(b) Our package can be applied to the frequency region up to 50 GHz, which corresponds to a cutoff frequency of the higher-order mode of the coplanar waveguide (CPW) on the RF feedthrough shown in Figure 4. A finer pattern formation technology for CPWs is required to raise the cutoff frequency. Cavity resonance becomes more serious with increasing operating speed. If the concept of "chip-size cavity" package continues to be adopted, the chip size must be reduced to below 1 mm at 100 GHz. The reduction in transistor and interconnection dimensions is very important in this respect, too.

(c) 100 Gbit/s module-to-module interconnection will be a severe hurdle. Monolithic integration of the photodetector, decision IC, clock recovery circuit, and DEMUX is very attractive for eliminating 100 Gbit/s interconnection.

The combination of a 0.1- $\mu$ m gate InP HEMT technology with novel circuit design and broadband packaging technologies has increased circuit speed sufficiently to permit the realization of 40 Gbit/s lightwave communication ICs. Once the problems outlined above have been addressed, InP HEMT technology should be a promising candidate for systems capable of operating at 100 Gbit/s.

## References

- [1] Y. Miyamoto et al., *GaAs IC Symp. Tech. Dig.* 1998, p. 51
- [2] T. Enoki et al., *Jpn. J. Appl. Phys.*, 1998, Vol. 37, Part 1, p. 1359
- [3] T. Otsuji et al., *GaAs IC Symp. Tech. Dig.* 1997, p. 183
- [4] E. Sano, *Proc. InP & Rel. Mats. Conf.* 1999, p. 299
- [5] M. Yoneyama et al., *Optical Fiber Conf.* 1999, paper Th16
- [6] Y. Miyamoto et al., *ECOC'98, post-deadline paper*, p. 55



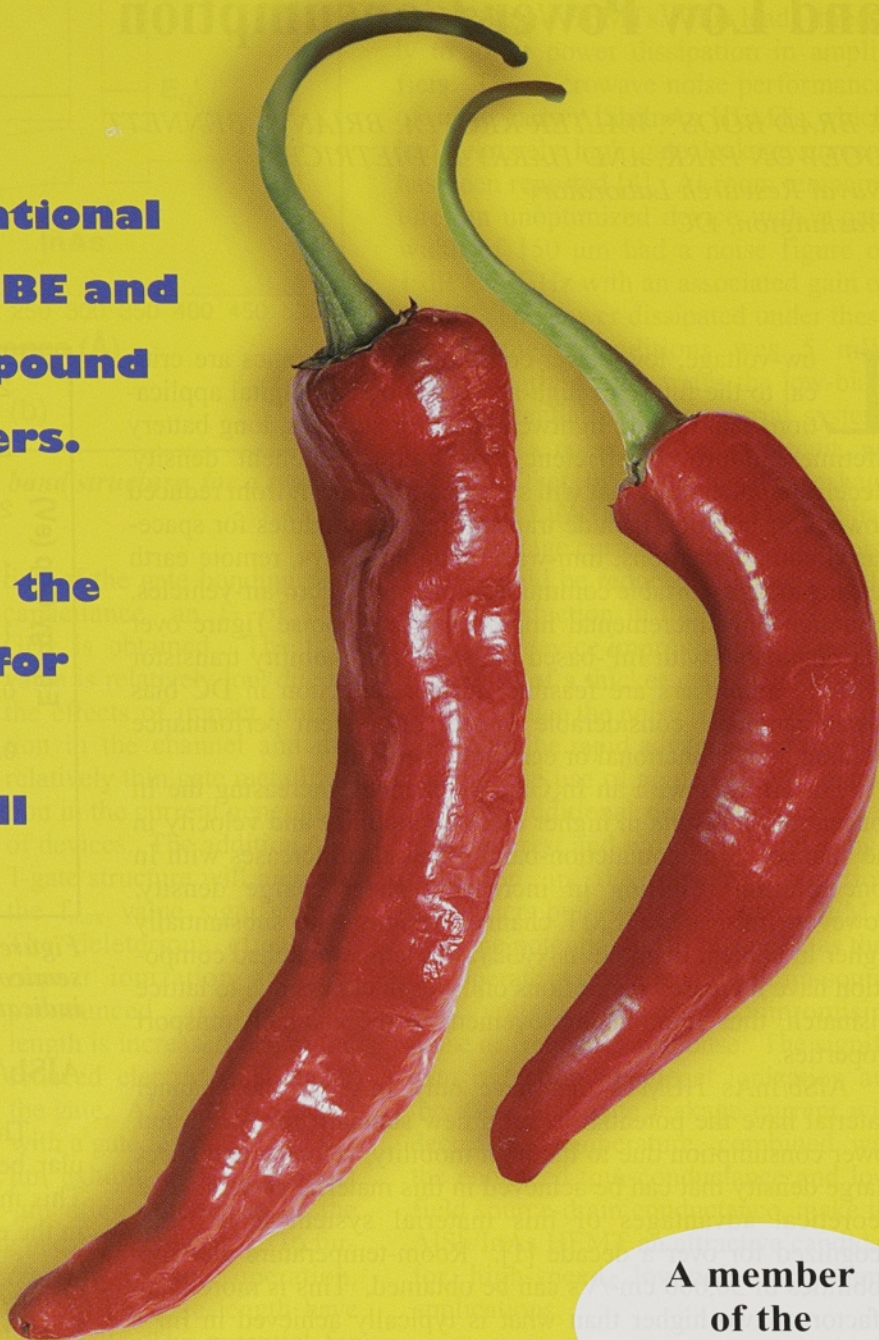
# **Need Spicier Chips?**

**We have the perfect recipe.**

**QED is a proven international leader in the field of MBE and the production of compound semiconductor epiwafers.**

**Whether you're still at the design stage or ready for mass production, talk to us and together we'll astonish the world.**

**QED... The perfect recipe for quantum performance.**



A member  
of the  
IQE plc Group



**Quantum Epitaxial Designs, Inc.**

119 Technology Drive, Bethlehem, PA 18015  
Tel: 610-861-6930 Fax: 610-861-5273  
e-mail: [info@qedmbe.com](mailto:info@qedmbe.com) web: [www.qedmbe.com](http://www.qedmbe.com)



# AlSb/InAs HEMTs with High Speed and Low Power Consumption

J. BRAD BOOS\*, WALTER KRUPPA, BRIAN R. BENNETT, DOEWON PARK, AND HARRY B. DIETRICH

Naval Research Laboratory  
Washington, DC

Low-voltage, low-power-consumption electronics are critical to the future of high-speed analog and digital applications that require lightweight power supplies, long battery lifetimes, improved efficiency, or high component density. Receiver applications that will significantly benefit from reduced power consumption include transmit/receive modules for space-based communications, mm-wave imaging arrays, remote earth sensing arrays, portable communications, and micro-air-vehicles. Although only incremental improvements of noise figure over that obtainable with InP-based high electron mobility transistor (HEMT) amplifiers are feasible, further reduction in DC bias power can have considerable impact on system performance yielding either functional or economic benefits.

For HEMTs with an  $\text{In}_x\text{Ga}_{1-x}\text{As}$  channel, increasing the In concentration results in higher electron mobility and velocity in the channel. The conduction-band offset also increases with In concentration resulting in increasing sheet charge density. However, InP-based HEMT channel designs with substantially higher In content than the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  lattice-matched composition have increased restrictions on layer thickness due to lattice mismatch, thus limiting improvement in the channel transport properties.

AlSb/InAs HEMTs that have only InAs as the channel material have the potential to set a new standard for speed and power consumption due to the high mobility, velocity, and sheet charge density that can be achieved in this material system. The theoretical advantages of this material system have been recognized for over a decade [1]. Room-temperature electron mobilities of  $30,000 \text{ cm}^2/\text{Vs}$  can be obtained. This is more than a factor of two higher than what is typically achieved in InP-based HEMTs. The larger conduction band discontinuity of the AlSb/InAs heterojunction enables the formation of a deeper quantum well with the associated benefits of a larger 2-DEG sheet charge density, superior carrier confinement, and improved modulation efficiency. The combination of high peak electron velocity at low electric field and high channel conductivity enables high-speed operation at very low drain voltage. It should be noted, however, that due to the narrow bandgap, the ionization rate for electrons in InAs is much higher than in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ . Thus the reduction and management of impact ionization is a key design requirement.

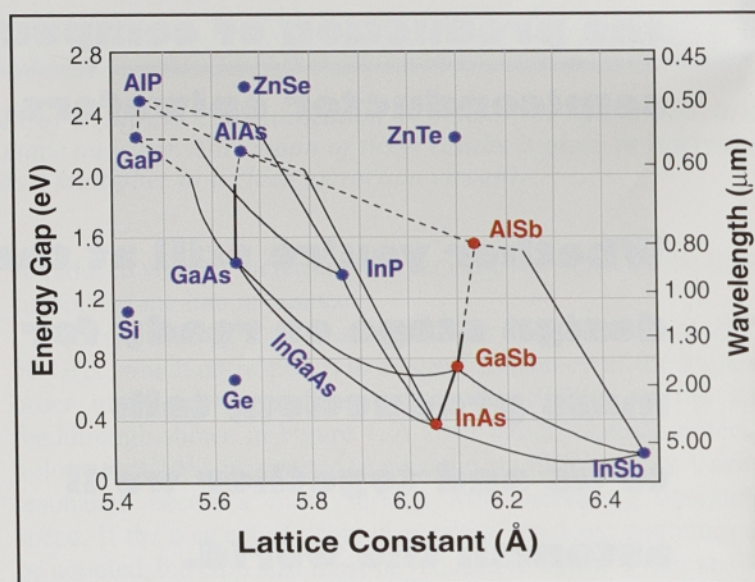


Figure 1. Energy gap ( $E_g$ ) versus lattice constant for different semiconductors. Solid lines indicate a direct  $E_g$ , dotted lines indicate an indirect  $E_g$ .

## AlSb/InAs HEMT Design

The AlSb/InAs HEMT material is typically grown by molecular beam epitaxy on a semi-insulating (100) GaAs substrate. This material system has a lattice constant near  $6.1 \text{ Å}$  as shown in the energy gap versus lattice constant diagram in Figure 1.

A cross-section of a typical layer design along with its corresponding energy band diagram for  $V_{GS} = 0$  is shown in Figure 2. Increasing the electron density in the channel is achieved through the use of Si planar-doping in an ultra-thin InAs layer located within the upper barrier material. The  $\text{In}_{0.4}\text{Al}_{0.6}\text{As}$ /AlSb composite layer enhances the insulating property of the barrier and enables the use of a gate recess etch into the upper barrier material prior to gate metal definition, which otherwise would be prohibited by the high reactivity of the AlSb in air. The thin InAs subchannel layer located below the channel is used to reduce the effects of impact ionization [2]. This subchannel has a larger effective bandgap due to size quantization. With this design,

\* e-mail: boos@nrl.navy.mil



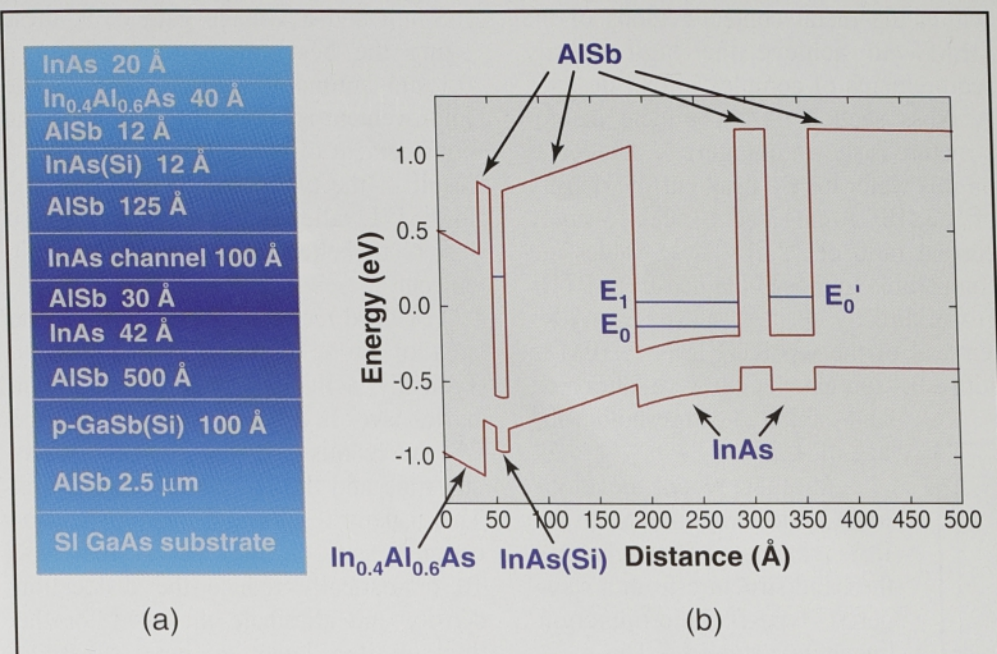


Figure 2. (a) HEMT starting material and (b) calculated band structure, for a typical AlSb/InAs HEMT.

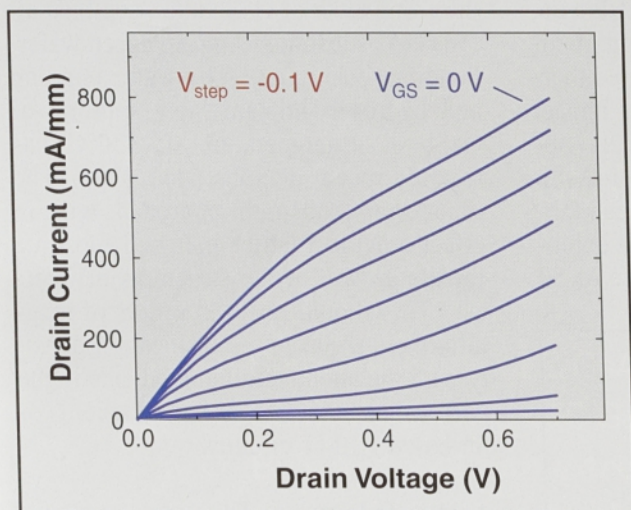


Figure 3. Drain characteristics of a 0.1 μm gate length HEMT. Drain-source distance = 1.0 μm, Gate width = 26 μm.

electrons with high energy are transferred to the subchannel before gaining enough kinetic energy for impact ionization.

### AlSb/InAs HEMT Characteristics

A typical set of drain characteristics for HEMTs with a 0.1 μm gate length is shown in Figure 3. At V<sub>DS</sub> = 0.5 V, a transconductance above 1 S/mm is obtained. The S-parameters of the HEMTs, measured on-wafer from 1 to 40 GHz, yield f<sub>T</sub> and f<sub>max</sub> values of 180 GHz and 80 GHz, respectively. After subtraction

of the gate bonding pad capacitance, an f<sub>T</sub> of 250 GHz is obtained. The f<sub>max</sub> value is relatively low due to the effects of impact ionization in the channel and the relatively thin gate metallization in the current generation of devices. The addition of a T-gate structure will increase the f<sub>max</sub> value significantly. The deleterious effects of impact ionization are less pronounced as the gate length is increased due to the reduced electric field under the gate. AlSb/InAs HEMTs with a gate length (L<sub>g</sub>) of 0.5 μm exhibit an f<sub>T</sub>L<sub>g</sub> product of 50 GHz-μm after subtraction of the gate bonding pad capacitance [3]. To further optimize low-voltage operation, HEMTs with a 60 nm gate length have also been fabricated. The potential for low-voltage operation in these HEMTs is demonstrated in Figure 4, which shows the measured f<sub>T</sub> as a function of drain voltage. At a drain voltage of only 100 mV, an f<sub>T</sub> of 90 GHz is obtained, which is the highest reported for any FET at this drain bias.

The theoretical noise performance of AlSb/InAs HEMTs is better than that of the InP-based HEMTs because of the

higher carrier velocity and mobility associated with the higher In content of the channel material. Of particular technological interest is the expectation of excellent low-noise performance at drain voltages one third to one half of those used for InP-based HEMTs. This leads directly to lower power dissipation in amplifiers. The microwave noise performance of some early AlSb/InAs HEMTs which had relatively high gate leakage current has been reported [4]. At room temperature, an unoptimized device with a gate width of 150 μm had a noise figure of 1 dB at 4 GHz with an associated gain of 13 dB. The power dissipated under these measurement conditions was 5 mW, which clearly demonstrates the low-bias-power potential of this material system. Based on a noise equivalent circuit, we conclude that by reducing the leakage current to 1 μA (the measured device had a gate leakage current of 20 μA) the noise figure could be reduced to about 0.3 dB. Further reduction in the leakage current and other device improvements, especially the use of a thicker gate metallization, should reduce the noise figure even more.

With the rapid advancement of cryocoolers, the use of cooled HEMT amplifiers for additional noise reduction is of great interest and will be facilitated by a reduction in the power dissipation. Amplifiers built with AlSb/InAs HEMTs have the potential to fill this need, as they can operate at extremely low drain-source bias voltages without compromising noise or frequency response. The significant reduction in impact ionization and the associated gate leakage current with decreasing temperature, combined with the enhanced transconductance and low-field source-drain conductance, make the AlSb/InAs HEMT an attractive candidate for high-speed, low-noise, cryogenic applications.

### Latest Developments

Ultra-high-speed, ultra-low-power digital circuits are needed in future multi-function radar, electronic warfare, and communication systems. An attractive approach to achieve the required speed with reduced power dissipation is to integrate Sb-based resonant tunneling diodes (RTDs) and HEMTs. This combination



enables designs with very high functionality due to the self-latching nature of RTD circuits. The HEMT performs optimally at a very low drain voltage making it possible to exploit the high peak current at low drain voltage and large peak-to-valley ratio attainable in the RTD. Sb-based RTDs have been shown to switch in 1.7 ps. The integration of Sb-based RTDs and HEMTs has recently been demonstrated [5]. The RTDs are grown above the HEMT layer structure and are located

within the metal contact regions of the HEMT to achieve the high density requirements of complex circuit designs. A cross section of a complete heterostructure is shown in Figure 5. The RTDs on this wafer have a peak current density of  $1.3 \times 10^4$  A/cm<sup>2</sup> and a peak-to-valley current ratio of 12.5. These values are comparable to those obtained from RTDs grown directly on InAs substrates. After removal of the top RTD layers, HEMTs with a 0.1  $\mu$ m gate length were fabricated and exhibited a threshold voltage of -0.5 V.

Another recent development is the addition of Sb to the InAs channel, which changes the band structure from a staggered type-II heterojunction lineup to a type-I. The existence of hole barriers on both sides of the quantum well, not present in the type II-lineup, enables the confinement of holes which are generated thermally or as a result of impact ionization in the channel. Sb-based HEMTs with an InAsSb channel have recently been fabricated [6]. The HEMTs exhibit an output conductance of 50

mS/mm and a voltage gain of 9, these being the best values reported for a 0.1  $\mu$ m antimonide-based HEMT. The improvement is believed to be due to the confinement of holes in the channel as a result of the type-I band lineup and the lower  $\Gamma$ -L valley energy separation which results in better saturation of the drain current.

A third recent development is in the area of Sb-based materials integration. Typically, a thick (> 1  $\mu$ m) antimonide buffer layer is used to accommodate the 7% lattice mismatch between the GaAs substrate and the HEMT layer structure. This usually results in a threading dislocation density on the order of  $10^7$  cm<sup>-2</sup>. To dramatically reduce the dislocation density and eliminate the need for the thick buffer layer, a new substrate fabrication technique is being investigated. The basic approach is to transfer an ultra-thin layer of GaSb to a semi-insulating GaAs substrate using advanced wafer-bonding techniques. The wafer bonding and hydrogen implant layer splitting of GaSb at a temperature of 150°C has recently been demonstrated [7]. The transferred substrate approach will in effect provide a lattice-matched substrate for the growth of the structures of interest. This should result in orders of magnitude reduction in the dislocation density with the attendant improvements in the performance, reliability, and yield of Sb-based HEMT circuits.

**Acknowledgement:** This work was supported by the Office of Naval Research.

## References

- [1] G. Tuttle et al., *J. Appl. Phys.*, 1989, 65(12), p. 5239; C. R. Bolognesi et al., *IEEE Electron Device Lett.*, 1994, 15(1), p. 16
- [2] J. B. Boos et al, *Electron. Lett.*, 1998, 34(15), p. 1525
- [3] J. B. Boos et al, *IEEE Trans. on Electron Devices*, 1998, 45(9), p. 1869
- [4] W. Kruppa et al, *Electron. Lett.*, 1997, 33(12), p. 1092
- [5] B. R. Bennett et al, submitted to *J. Vac. Sci. Technol. B*
- [6] J. B. Boos et al, *Electron. Lett.*, 1999, 35(10), p. 847
- [7] K. D. Hobart and F. J. Kub, *Electron. Lett.*, 1999, 35(8), p. 675

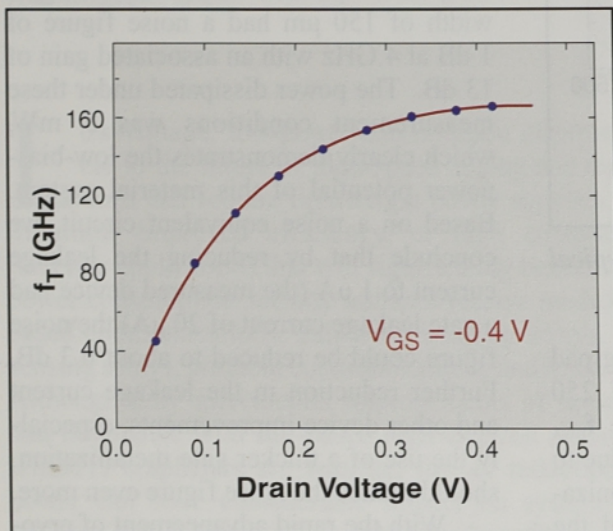


Figure 4. Measured current gain cutoff frequency ( $f_T$ ) versus drain voltage. Gate length = 60 nm.

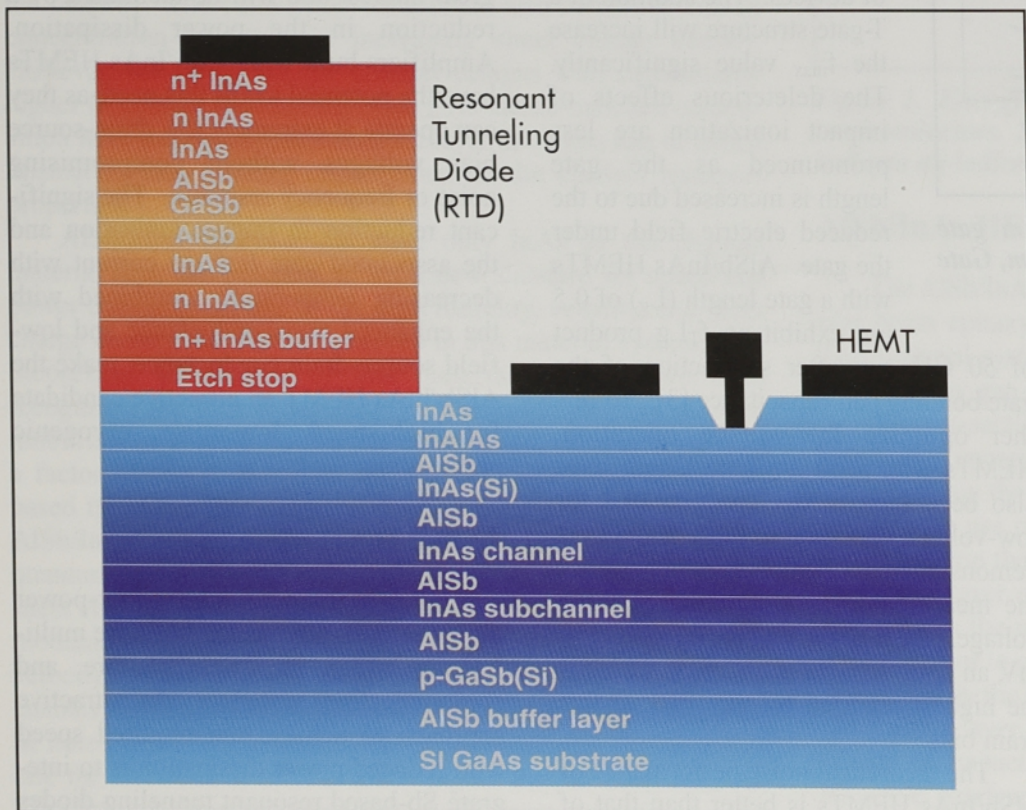


Figure 5. RTD/HEMT starting material cross-section.



# Freiberger

in alliance with the future



ISO 9001

## Gallium Arsenide

substrates for micro and optoelectronics

- Semi-insulating LEC-GaAs 2"- 6" diameter
- Semi-conducting LEC-GaAs 2" and 3" diameter
- Bulk material with extremely low residual impurity concentration controlled carbon level and high uniformity of electrical parameters
- One and double side polished wafers
- Excellent surface quality for epitaxial growth processes
- Laser marking option
- Comprehensive crystal and wafer characterization
- Quick order turn around

### FREIBERGER COMPOUND MATERIALS GmbH

Am Junger Löwe Schacht 5, D-09599 Freiberg, Germany

Phone: (49) 37 31/28 04 80, Fax: (49) 37 31/28 01 06, Email: [info@fcm-germany.com](mailto:info@fcm-germany.com)

<http://www.fcm-germany.com>

#### West-Europe except Germany, Austria

Dr. Elie Prudhommeaux  
Promecome  
68. Av. du Général Michel Bizot  
F-75012 Paris  
Phone: (33) (1) 44 73 10 70  
Fax: (33) (1) 43 46 85 92

#### USA

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

#### Japan

Kazunori Anzai  
Pechiney Japon  
29 Fl. Shinjuku Mitsui Bldg.  
2-1-1 Nishi Shinjuku  
Shinjuku-ku. Tokyo 163-04  
Phone: (81) 33349-6705  
Fax: (81) 33349-6778

#### Korea

Jin Han Jung  
Seokyo Commerce Co., Ltd.  
Baekje Bldg. #201  
980 - 29, Bangbae Dong, Seocho-ku Seoul  
137 - 060, Korea  
Phone: (82) 2597 3961  
Fax: (82) 2597 3964

#### Republic of China

Albert Hong  
V-TEK Co., Ltd.  
No. 205 Kao Tsui Road  
Hsinchu, Taiwan, R. O. C.  
Phone: (886) 3 5777 362  
Fax: (886) 3 5777 353



# Metamorphic InAlAs/InGaAs HEMTs

*Metamorphic HEMTs combine high In content channels with the processing advantages of GaAs substrates, offering several advantages for microwave and millimeter-wave applications.*

A. CAPPY, Y. CORDIER, S. BOLLAERT AND M. ZAKNOUNE  
Institut d'Electronique et de Microelectronique du Nord (IEMN)  
France

InAlAs/InGaAs HEMTs on InP substrates have demonstrated extremely low noise figures and very high output powers. However, from a processing viewpoint, GaAs substrates are preferred for production of high performance monolithic micro- and millimeter-wave ICs because GaAs is less expensive and less brittle than InP, and is also available in sizes up to 6 inches in diameter. For these reasons, InAlAs/InGaAs metamorphic HEMTs on GaAs (MM-HEMTs) are attracting a great deal of interest for high frequency and high speed applications.

## More Indium

For InGaAs channel HEMTs, increasing the In content in the channel results in a higher electron mobility and peak saturated velocity, leading to higher gain. Pseudomorphic HEMTs on GaAs (PHEMTs) contain strained InGaAs channels in which the In content is limited to about 30%. A MM-HEMT incorporates a thick buffer layer to accommodate the lattice mismatch between

the InGaAs channel and the GaAs substrate, allowing higher In content in the channel (see page 22). Using the metamorphic buffer concept, high quality unstrained InAlAs/InGaAs heterostructures with an arbitrarily chosen In content (0.3 to 0.6 in practice) can be grown. The In content value constitutes a supplementary degree of freedom in the device performance optimization.

In unstrained InAlAs/InGaAs heterostructures, two antagonist effects can be observed when the In content varies from 0.3 to 0.6 (Figure 1). On one hand, the sheet carrier density in the InGaAs channel decreases when the In content increases due to the decrease of the conduction band discontinuity. On the other

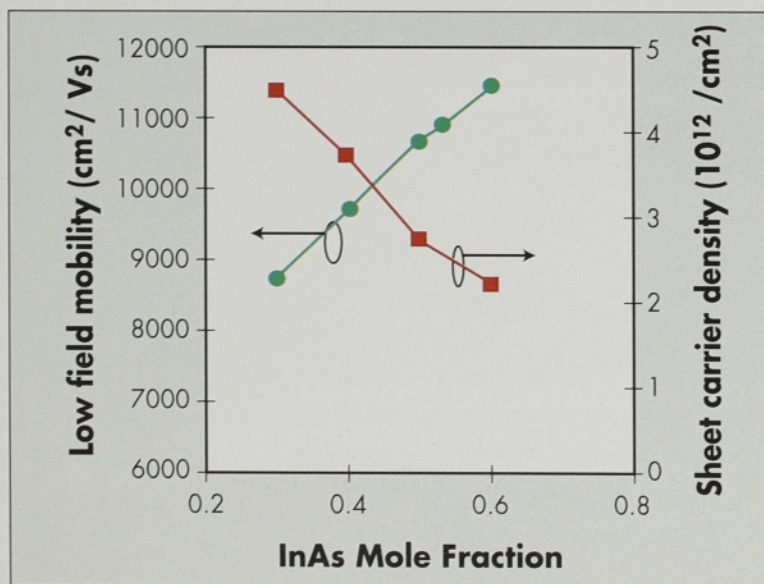


Figure 1. Calculated low field mobility and sheet carrier density for InAlAs/InGaAs heterostructures.

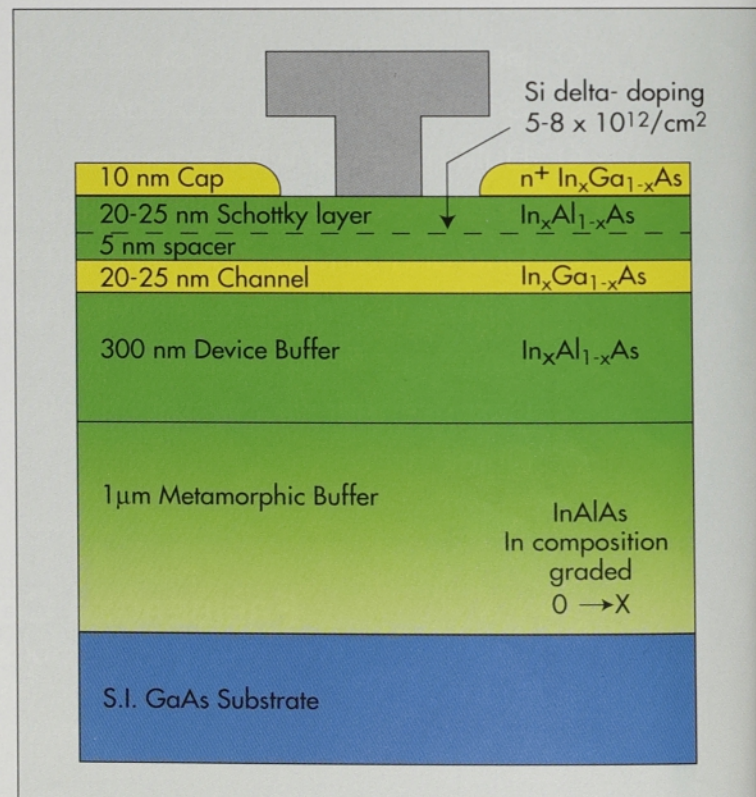
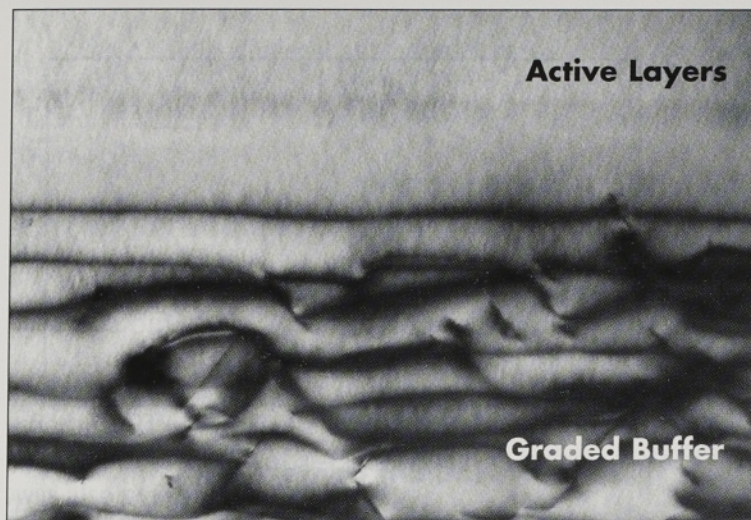


Figure 2. Structure of the metamorphic HEMT active layer. The value of the In content  $x$  is usually in the range 0.3 to 0.6.





**Figure 3:** Cross-sectional TEM of a graded buffer with an inverse step (0.33 In content structure). Dislocations are trapped within the graded buffer layer.

hand, the increase of the In content involves better transport properties in the InGaAs channel due to a decrease of the electron effective mass [1].

## Material Properties

The active layer structure of a MM-HEMT is shown in Figure 2. The main difficulty with the growth of this structure concerns the metamorphic buffer layer. The role of this buffer layer is twofold: to accommodate the large lattice mismatch between the device active layer and the GaAs substrate by formation of misfit dislocations and to trap these dislocations to prevent their propagation in the device active layer grown on this buffer (Figure 3).

For this purpose, InGaAs, InAlAs, InGaAlAs or AlGaAsSb buffer layer materials have been proposed with continuous or step grading of the lattice parameter. In MBE, which is usually used for the growth of MM-HEMTs, the buffer layers are grown at low substrate temperatures ( $T_s = 350^\circ\text{C}$  for InGaAs,  $T_s = 400^\circ\text{C}$  for InAlAs) to avoid island formation.

Compared with lattice matched (LM) layers, MM layers show three main differences: a residual strain, a

rough surface associated with a crosshatch pattern and a residual threading dislocation density. These features are strongly related to the metamorphic buffer structure. To improve these parameters, graded buffers with inverse steps have been used [2,3]. When the highest value of In content in the graded MM buffer matches the In content in the subsequently-grown device layers, the extent of relaxation in the buffer can only reach around 85%. However, if the top layers of the graded buffer have an In content exceeding that of the device layers (i.e. an inverse step), then up to 98% relaxation can be achieved in the buffer.

The relaxation of mismatch strain in the buffer layer generates a well-defined surface morphology known as a cross-hatch structure, with main ridges parallel to the [01-1] direction. Surface roughness strongly depends on the final In composition. For 50% In, rms roughness of about 2 nm is usually measured for InAlAs graded buffers, while rms roughness close to 1 nm was reported for an InGaAlAs graded buffer [4]. After optimization of the growth conditions, several authors reported that for the same indium content (i.e. 50 %) and the same active layer structure, equivalent Hall mobility and sheet carrier density are obtained for MM layers and for LM layers on InP [2,5].

Typical Hall results and sheet carrier densities for as-grown MM material are given in the top section of Table 1. Two points should be emphasized. First, the growth technique used is MBE for almost all reported results and second, very few results concerning the influence of the MM buffer type on the material thermal stability have been reported, although this is a key issue for device reliability.

## Device Processing and Performance

The different processing steps necessary for HEMT realization are directly derived from those of the LM-HEMT on InP. Either mesa formation or ion implantation is used for device iso-

|                                                                    | MM GaAs HEMT |       |       | LM InP HEMT |
|--------------------------------------------------------------------|--------------|-------|-------|-------------|
| In content                                                         | 0.33         | 0.4   | 0.5   | 0.53        |
| Hall mobility @ 300 K ( $\text{cm}^2/\text{Vs}$ )                  | 8250         | 8250  | 9180  | 9570        |
| Sheet carrier density @ 300 K ( $\times 10^{12} \text{ cm}^{-2}$ ) | 3.39         | 4.16  | 4.18  | 3.48        |
| Pinch-off voltage (V)                                              | -0.9         | -0.9  | -0.65 | -0.5        |
| Schottky breakdown voltage (V)                                     | -14.2        | -10.5 | -7.0  | -8.0        |
| Maximum drain-to-source current $I_{ds}$ (mA/mm)                   | 650          | 640   | 550   | 510         |
| Maximum extrinsic transconductance (mS/mm)                         | 750          | 780   | 860   | 940         |
| Cutoff frequency $f_T$ (GHz)                                       | 150          | 195   | 200   | 210         |

**Table 1.** Properties of IEMN's metamorphic HEMTs with 33%, 40% and 50% In, compared to lattice matched InP HEMTs. (top) Hall mobility and sheet carrier density for HEMT layers. (middle) DC characteristics for devices with a nominal gate geometry of  $2 \times 50 \mu\text{m} \times 0.1 \mu\text{m}$ . (bottom) Cutoff frequency of extrinsic current gain for devices with the same gate geometry.



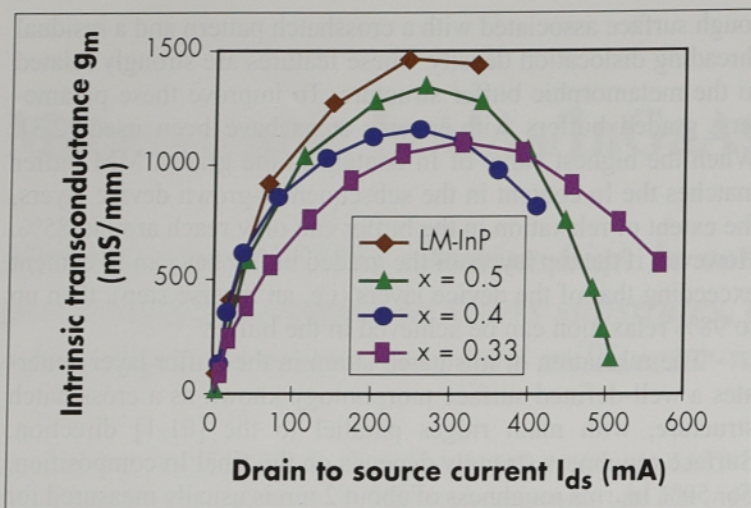


Figure 4: Intrinsic transconductance  $g_m$  versus drain current  $I_{ds}$  for MM-HEMTs ( $x = 0.33, 0.4$  and  $0.5$ ) and for a LM-HEMT on InP. The device widths are  $2 \times 50 \mu\text{m}$  with a T-gate length of  $0.1 \mu\text{m}$ .

lation. Using metallization schemes employing AuGeNi or TiMoAu, ohmic contact resistances better than  $0.1 \Omega/\text{mm}$  have been reported. Either TiPtAu or PtTiPtAu is used as the gate metal. No problems related to surface roughness were reported for the photolithography steps.

The In content has a large influence on the performance of MM-HEMTs. The central part of Table 1 gives the DC characteristics of MM-HEMTs realized at IEMN. The nominal gate geometry is  $2 \times 50 \mu\text{m} \times 0.1 \mu\text{m}$ , the active layer structures are similar and the same processing steps were used. From the table, the following remarks can be made:

(i) The lower In-content device shows a high drain current and a large reverse Schottky breakdown voltage. Therefore, low In content MM-HEMTs are mainly devoted to power applications. Using 30% In, a  $0.2 \mu\text{m}$  gate MM-HEMT presented a power density of  $240 \text{ mW/mm}$  at  $60 \text{ GHz}$  [6]. Recently,  $26.6 \text{ dBm}$  of output power,  $13.6 \text{ dB}$  of associated gain and  $59\%$  PAE were obtained with a  $0.15 \mu\text{m} \times 0.6 \text{ mm}$  gate geometry MM-HEMT (with  $x = 0.32$ ) at  $6 \text{ V}$  drain bias [7].

(ii) In terms of drain current, extrinsic transconductance and reverse Schottky breakdown voltage, the device performance of MM-HEMTs with 40% or 50% In is very close to the performance of LM-HEMTs on InP.

The small signal equivalent circuit of the MM-HEMTs gives useful information on the material properties. Figure 4 shows the intrinsic transconductance ( $g_m$ ) versus DC drain-to-source current ( $I_{ds}$ ). A maximum transconductance exceeding  $1 \text{ S/mm}$  is obtained for all the devices assessed. As expected, the maximum transconductance increases as the In content increases. The highest value ( $1350 \text{ mS/mm}$ ) for a MM-HEMT is obtained with the device containing 50% In; this value is close to that obtained for the LM-HEMT ( $1450 \text{ mS/mm}$ ).

Another interesting parameter is the output conductance ( $g_d$ ). Very low output conductance of  $20\text{--}30 \text{ mS/mm}$  is obtained for the lower In content MM-HEMT ( $x = 0.33$ ). This behavior can be related to the very good electron confinement at low In composition.

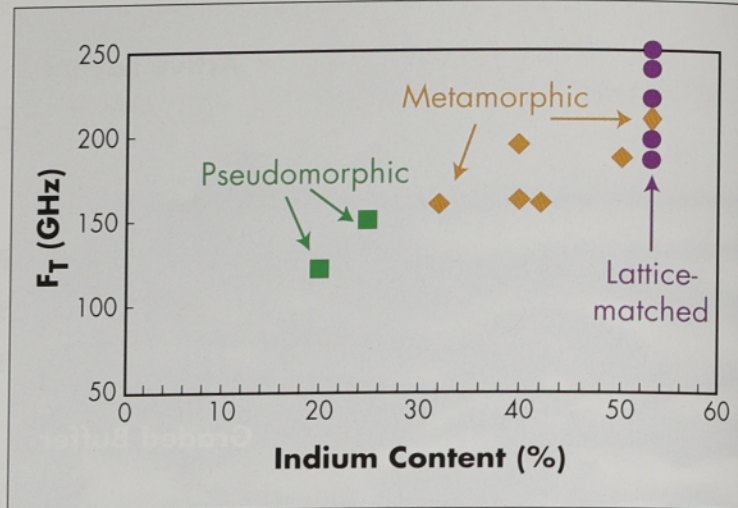


Figure 5. State of the art  $f_T$  values for metamorphic and pseudomorphic HEMTs on GaAs, and lattice-matched HEMTs on InP.

## Extrinsic Cutoff Frequency

The bottom of Table 1 gives the measured extrinsic cutoff frequency ( $f_T$ ) of MM-HEMTs. The T-gate gate geometry is  $2 \times 50 \mu\text{m} \times 0.1 \mu\text{m}$ . It should be noted that for  $x = 0.4$  and  $x = 0.5$ ,  $f_T$  values close to  $200 \text{ GHz}$  are obtained. These results are in agreement with the Hall and transconductance data previously given.

State-of-the-art  $f_T$  values for  $0.1 \mu\text{m}$  gate length MM-HEMTs are shown in Figure 5 as a function of In content. These data are compared with LM-HEMT on InP and pseudomorphic (PM) HEMT on GaAs data. As a general trend,  $f_T$  increases when the In content in the channel increases. As a consequence, MM-HEMTs show better performance than PHEMTs, and slightly lower performance than LM-HEMTs. This is in agreement with Hall mobility and sheet carrier density data. Concerning the noise performance of MM-HEMTs, only a few results are available but since the noise figure is strongly related to  $f_T$ , an improvement of the noise performance is expected when the In content increases. At  $18 \text{ GHz}$  for instance, a noise figure as low as  $0.41 \text{ dB}$  with  $11.4 \text{ dB}$  gain has been obtained for a  $0.15 \mu\text{m}$  gate MM-HEMT with  $x = 0.53$  [4].

## Device Reliability

Reliability results have been reported for 50% In content MM-HEMTs using InAlAs linearly-graded buffer layers [4, 5]. The devices were biased under low noise conditions and stressed at channel temperatures in the  $200\text{--}240^\circ\text{C}$  range. An activation energy of  $1.7 \text{ eV}$  and an extrapolated mean time to failure (MTTF) of  $7.6 \times 10^6$  hours at a channel temperature of  $125^\circ\text{C}$  were determined. These values are comparable to published results for devices on InP. Experiments at higher temperatures ( $600^\circ\text{C}$  for 1 hour) were also performed and it was shown that the annealing lead to slightly improved electrical and optical properties. No propagation of dislocations was observed [8].



These results demonstrate that metamorphic InAlAs linearly graded buffer layers are not the dominant factor in the degradation mechanisms. No results for other metamorphic buffer types are available.

### Circuit Performance

Several types of circuits using MM-HEMTs with 50% In have been fabricated. A 25 dB gain at 50 GHz was obtained with a three stage broadband MMIC amplifier using coplanar wave guides [5] while a single chip downconverter has shown 32 dB gain and 6 dB noise figure at 60GHz [9]. A static divide-by-4 circuit with a total of 97 MM-HEMTs with an average yield of 45% was also reported [5].

More recently, a single stage MM-HEMT-based distributed amplifier was reported to exhibit 10 dB gain from 7 to 22 GHz, with a good linearity [10].

### Conclusions

InAlAs/InGaAs MM-HEMTs with 30% to 50% In content have demonstrated excellent performance for low noise and power applications. For 40 % and 50% In, MM-HEMTs show better performance than PM-HEMTs and comparable performance to InP-based HEMTs. Preliminary results concerning MM-

HEMT reliability indicate that the metamorphic nature of the material does not introduce new degradation mechanisms, at least under low-noise bias conditions. For power applications the question of reliability of MM-HEMT is still an open question. The demonstrated performance of MMICs makes this technology attractive for many microwave and millimeter-wave applications.

**Acknowledgment:** This work is supported by the French Ministry of Defense under contract no. 97055. Thanks are due to J.-M. Chauveau, J. Dipersio and D. Ferre for the study of strain relaxation.

### References

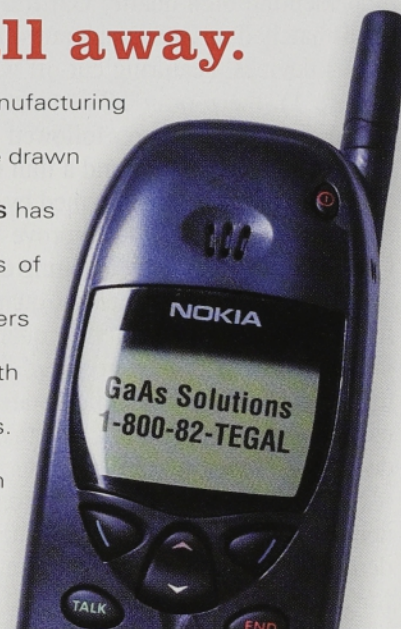
- [1] P. Win et al., *Jpn. J. Appl. Phys.*, 1994, 33, p. 177
- [2] Y. Cordier et al., *Jpn. J. Appl. Phys.*, 1999, 38, p. 1164
- [3] Y. Cordier et al., *Applied Surface Science*, 1998, 123/124, p. 734
- [4] A. Wakita et al., *Proc. Intl. Conf. InP & Rel. Mats.*, 1998, p. 223
- [5] H. Rohdin et al., *Hewlett-Packard Journal*, Article 4, Feb 1998
- [6] M. Zaknoute et al., *IEEE Electron Dev. Lett.*, 1998, 19(6), p. 345
- [7] C. Whelan et al., *Proc. MTT-S Intl. Microwave Symp.* 1999, p. 1187
- [8] T. Mishima et al., *J. Crystal Growth*, 1999, 200/201, p. 271
- [9] R. Van Tuyl., *APMC 98, workshop WS5*, 1998
- [10] P. Marsh et al., *Proc. MTT-S Intl. Microwave Symp.* 1999, p. 105

**You Can Get There From Here**

## GaAs solutions are just a phone call away.

It's a fact. The rapid growth of wireless and high-bandwidth communications brings new manufacturing and scalability challenges to plasma etch in high-volume GaAs device fabrication. At Tegal, we've drawn on over fifteen years of experience to produce **two specialized solutions**. The **900G Series** has been configured with special sensors and electrode designs to address the unique demands of GaAs production. Scalable from 3- to 6-inch wafers at an affordable price, the 900G Series offers the most flexible transport available for GaAs substrates. The **6500 Series** provides you with advanced gold interconnect etch capabilities—the new alternative to traditional lift-off techniques. The 6500 Series is great for GaAs mesa etch, too. Both systems are production-proven with guaranteed uptime greater than 90%. So give us a call!

Call 1-707-763-5600 or visit [www.tegal.com](http://www.tegal.com)



Si<sub>3</sub>N<sub>4</sub>

InP

SiO<sub>2</sub>

**tegal**

Polyimide

Au

GaAs

TEGAL CORPORATION

2201 S. McDowell Boulevard PO Box 6020 Petaluma, California 94955-6020 tel 707.763.5600 fax 707.773.3015 [www.tegal.com](http://www.tegal.com)



# Third International Conference on Mid-Infrared Optoelectronics - Materials and Devices

AACHEN, GERMANY  
SEPTEMBER 5- 7

K. HEIME<sup>1</sup>

**M**IO MD III, the Third International Conference on Mid-infrared Optoelectronics - Materials and Devices, was held recently in the historic German city of Aachen. The 90 attendees and 50 presentations are an indication of the level of interest in devices that operate in the mid-infrared spectral range.

In general, most of the presentations focused on Sb-containing III-V compound semiconductors. For devices employing aluminum-containing material (e.g.  $\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$  and  $\text{Al}_x\text{In}_{1-x}\text{As}_y\text{Sb}_{1-y}$ ), MBE was the dominant growth method. However, in spite of problems with the nature of the MO precursors, and the strong tendency for phase separation in these materials, several contributions also underlined the potential of the MOVPE technique for growth of these materials.

## Thermophotovoltaic Devices (TPVs)

Christine Wang from MIT Lincoln Labs began the program by presenting high-quality  $\text{Ga}_{1-x}\text{In}_x\text{As}_y\text{Sb}_{1-y}$  epitaxial layers, lattice-matched to GaSb substrates, for use in thermophotovoltaic (TPV) devices. Featuring cut-off wavelengths as long as 2.5  $\mu\text{m}$  (Figure 1), the *p-on-n* TPV structures consisted of 1  $\mu\text{m}$  of *n*-doped GaInAsSb base, followed by a 4  $\mu\text{m}$  thick *p*-doped GaInAsSb emitter layer and a thin GaSb window.

The growth was performed by MOVPE at the relatively low temperature of 525°C to improve the quality of the metastable GaInAsSb alloy, and the resulting devices, which have a bandgap of 0.5 eV, featured an external quantum efficiency of up to 60% (corresponding to an internal quantum efficiency of 90%). No reflective coatings were required in the device. Wang notes that these results are comparable to devices reported by other groups using AlGaAsSb windows, and that the simpler GaSb alloy window layer is also effective in reducing surface recombination.

L. Zheng and S. Haywood from the University of Hull (UK) demonstrated a *p*-GaSb/*n*-GaAs-heterojunction for TPV and tandem solar cell applications. The authors discussed the potential for these materials as replacements for GaSb homojunctions, in which the higher cost associated with MOVPE growth could be offset by the use of cheaper GaAs substrates. In an interesting demonstration of the potential of TPVs for conversion of heat into electricity, Andreas Bett of the Fraunhofer Institute for Solar

Energy Systems (Fraunhofer ISE) in Freiburg (Germany) showed how the mid-infrared radiation from a small gas flame could be converted using 16 GaSb-based TPV cells to power a pocket radio (Figure 2).

Two contributions from Aixtron and the Fraunhofer ISE described the MOVPE growth of Sb-containing compounds using Aixtron's multi-wafer planetary MOVPE-reactors, providing a perspective of the potential for mass production of mid-infrared devices. M. Heuken from Aixtron in Aachen introduced epitaxial uniformity and electrical data from the growth of a range of compounds based on InSb and GaSb. Carsten Agert of Fraunhofer ISE alluded to a concept for a monolithic 4-junction tandem solar cell device using AlGaAsSb for the top cell and GaSb for the bottom cell. In this work, a 5 x 2-inch production environment reactor was used to investigate the growth conditions for GaSb-based materials.

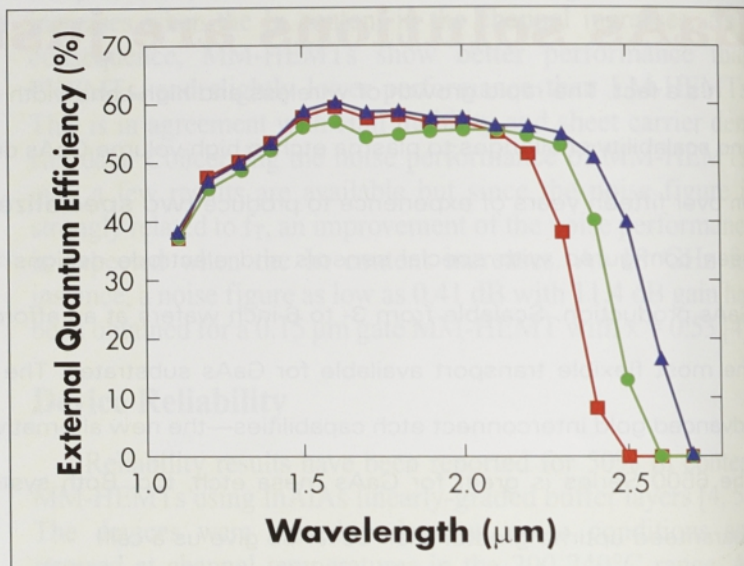


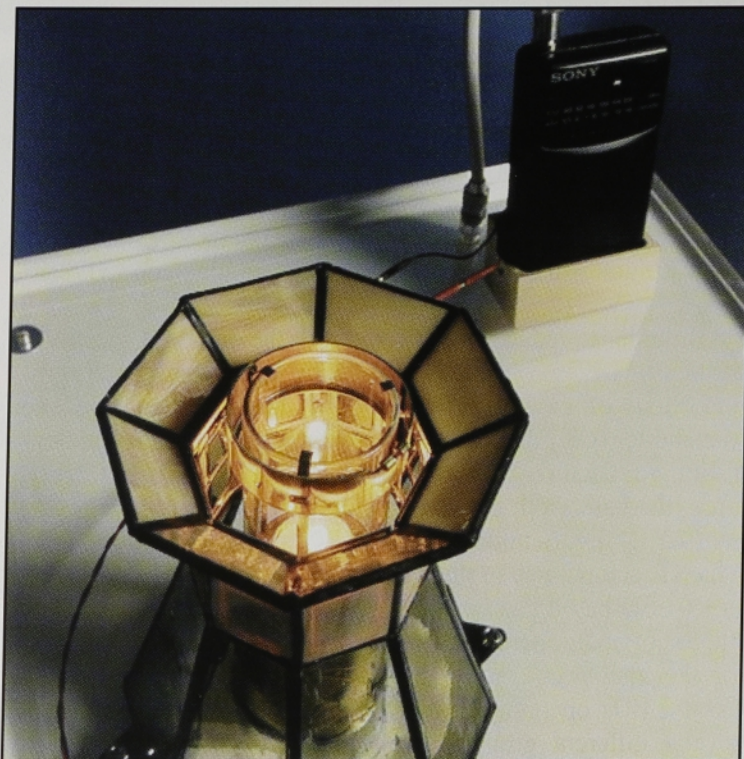
Figure 1. The external quantum efficiency (QE) of three GaInAsSb/GaSb TPV devices as a function of wavelength. The wavelength response extends out to 2.7  $\mu\text{m}$  (0.495 eV device response shown by blue data points), one of the longest wavelengths reported for TPV's in this materials system. For all three devices, the spectral response is almost flat between 1.6 and 2.2  $\mu\text{m}$ , with a maximum QE of 60% at 1.6  $\mu\text{m}$  (0.549 eV device represented by red squares). The green data is for a TPV with a bandgap of 0.523 eV.

<sup>1</sup> Prof. K. Heime, Institut für Halbleitertechnik, RWTH Aachen, Germany. Fax: +49-241-8888199; email: mailbox@iht.rwth-aachen.de



Work presented by Lancaster University (UK) showed that it is also possible to realize complex device structures using the LPE technique. A. Krier presented two papers concerning the growth of InAs/InAsSb quantum wells with excellent thickness uniformity and abrupt interfaces. In a paper with X. Huang he discussed the growth of Sb-based quantum dots; in a second with Z. Lambadi, he described the optical properties of type II InAs/InAsSbP quantum wells. Vasilov and coworkers at the Ioffe Physico-Technical Institute of the Russian Academy of Sciences were the first to demonstrate the LPE growth of the pentanary GaInAsPSb from Sb-rich melts, which could be useful for optoelectronic devices in the 2-5  $\mu\text{m}$  wavelength range.

Thomas Schwarzl from the Johannes Kepler University Linz (Austria) outlined the advantages of lead salt (PbTe, PbEuTe) microcavities for the 4-7  $\mu\text{m}$  spectral region compared to those based on the AlAs/GaAs system. The authors used MBE to achieve a Bragg reflectivity of 99.7% using only three pairs per mirror. The PbTe resonator layer between the reflectors has an optical length of  $\lambda/2$ , yielding a first-order cavity. The transmission spectra of the microcavities show a narrow Fabry-Perot resonance at a wavelength of 5.32  $\mu\text{m}$ , and a very high cavity finesse of 1700 (Figure 3). This offers potential for the fabrication of highly efficient vertical cavity surface emitting lasers (VCSELs) operating at these long wavelengths.



Fraunhofer ISE

*Figure 2. The Fraunhofer Institute for Solar Energy Systems used candle light to demonstrate the principle of TPV devices. 16 GaSb TPV cells with a bandgap of 0.7 eV are connected in series to deliver the energy to a pocket radio.*

## CUSTOM EPIWAFERS FOR

### MICROWAVE APPLICATIONS:

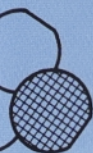
- InP HBT • InP HEMT
- PHEMT • InGaP HBT

### OPTOELECTRONICS APPLICATIONS:

- LD • APD
- PIN • RCLED

### MATERIALS FOR R&D

- InGaAsP • AlGaInAs
- AlGaInP



**Nordic Epitaxy**

[www.nordicepitaxy.com](http://www.nordicepitaxy.com)

Korkeakoulunkatu 1  
FIN-33720 Tampere  
Finland  
Tel. +358 3 365 2994  
Fax. +358 3 365 2995  
Email. [epiwafer@nordicepitaxy.com](mailto:epiwafer@nordicepitaxy.com)



# Mid-Infrared LEDs

New results in the field of mid-infrared LEDs were presented mainly for the 2  $\mu\text{m}$  spectral range, and for the range between 3.5 and 5  $\mu\text{m}$ . An InP-based Al-free LED employing compressively strained GaInAs MQWs was demonstrated by the Fraunhofer Institut für Angewandte Festkörperphysik (IAF) in Freiburg. These LEDs exhibited room temperature emission at about 1.9  $\mu\text{m}$ , which is suitable for use in humidity and CO<sub>2</sub> sensors.

In order to reduce the half-width of the emission spectra of gas sensor LEDs, which is significantly larger than the absorption bands of gaseous species, B. M. Poole from UMIST in Manchester (UK) demonstrated similar structures with additional Bragg reflectors. With an emission at 1.7  $\mu\text{m}$  at room temperature, the half-width of the emission spectrum from these resonant cavity light-emitting diodes (RCLEDs) was only 20 nm, which is comparable to the width of the absorption bands. Thus, in RCLED-based gas sensing systems, the noise is reduced and the use of additional filters is unnecessary.

For the spectral range between 3.5  $\mu\text{m}$  and 5  $\mu\text{m}$ , InAsSb-based LEDs operating at room temperature were presented by several different groups. A. Krier from Lancaster University (UK) presented a LPE-grown double heterostructure LED which exhibited about 1 mW radiative power at a wavelength of 4.6  $\mu\text{m}$ . This was possible through the addition of Gd and Yb, which get Si and S contamination, thus avoiding the high background doping in LPE-grown InAs and InAsSb.

L. Song and coworkers from IMEC (Belgium) and the Fraunhofer IAF presented a monolithically integrated, highly-efficient near-infrared LED coupled to an InAs/InAsSb superlattice structure. According to Song, optical pumping with an LED without crossing the air-semiconductor interface is beneficial, as

nearly all the electrical power is transferred into optical pumping power. In this instance, the LED device pumps the superlattice to produce an emission at a wavelength of 4.16  $\mu\text{m}$  (measured at 77 K).

# Photodetectors

The contributions concerning photodetectors for infrared detection and imaging comprised a two-color 640 x 480 pixel infrared focal plane array (FPA) camera from S. Gunapala et al from the Jet Propulsion Laboratory (Pasadena, CA), and a multi-spectral HgCdTe photodiode (Jensen).

Gunapala's two-color integrated chip is based on the AlGaAs/GaAs material system and allows the simultaneous detection of the 8-9  $\mu\text{m}$  and 14-15  $\mu\text{m}$  spectral bands using dedicated quantum well infrared photodiodes (QWIPs). The use of this chip may eliminate beam splitters, filters and complex optical systems which are necessary for two-color imaging with a conventional single-color FPA. A camera based on this FPA was demonstrated.

The multi-spectral HgCdTe photodiode presented by Hughes Research Laboratories' John Jensen featured the performance of an  $np^+n$  triple-layer heterojunction multilayer. This was deposited on a (211) CdZnTe substrate in a continuous MBE growth process that included the dopants. Devices absorbing layers with compositional profiles and layer thicknesses that resulted in sharp spectral response cut-off values for the detection of two closely-spaced bands at 4.2 and 4.9  $\mu\text{m}$ . Quantum efficiencies were measured at greater than 70% with less than 0.5% cross-talk.

A different approach to mid-infrared monitoring was presented in the form of a wavelength conversion device consisting of a stacked mid-infrared QW photodetector and near-infrared LED. H. C. Liu of the National Research Council in Ottawa (Canada) discussed a device that allows a direct wavelength con-

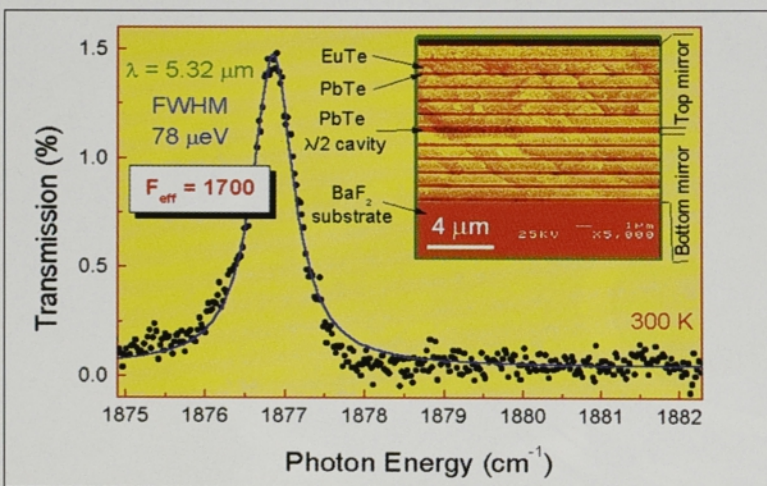


Figure 3. FTIR transmission spectrum at 300 K for a ( $\lambda/2$ ) PbTe/EuTe microcavity with five pair top and bottom Bragg mirrors showing the cavity resonance peak. The dots represent the measured data and the solid line a Lorentz fit, which yields a peak width of 0.63  $\text{cm}^{-1}$  78 eV. This corresponds to an effective finesse (the free spectral range/FWHM of peak) of 1700. The inset shows an SEM image of the selectively etched cleavage edge of the microcavity structure with an additional ( $\lambda/4$ ) EuTe cap layer.

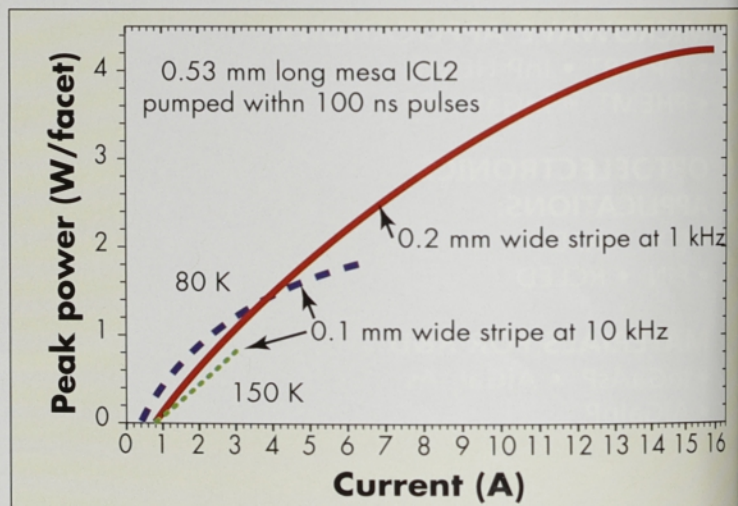
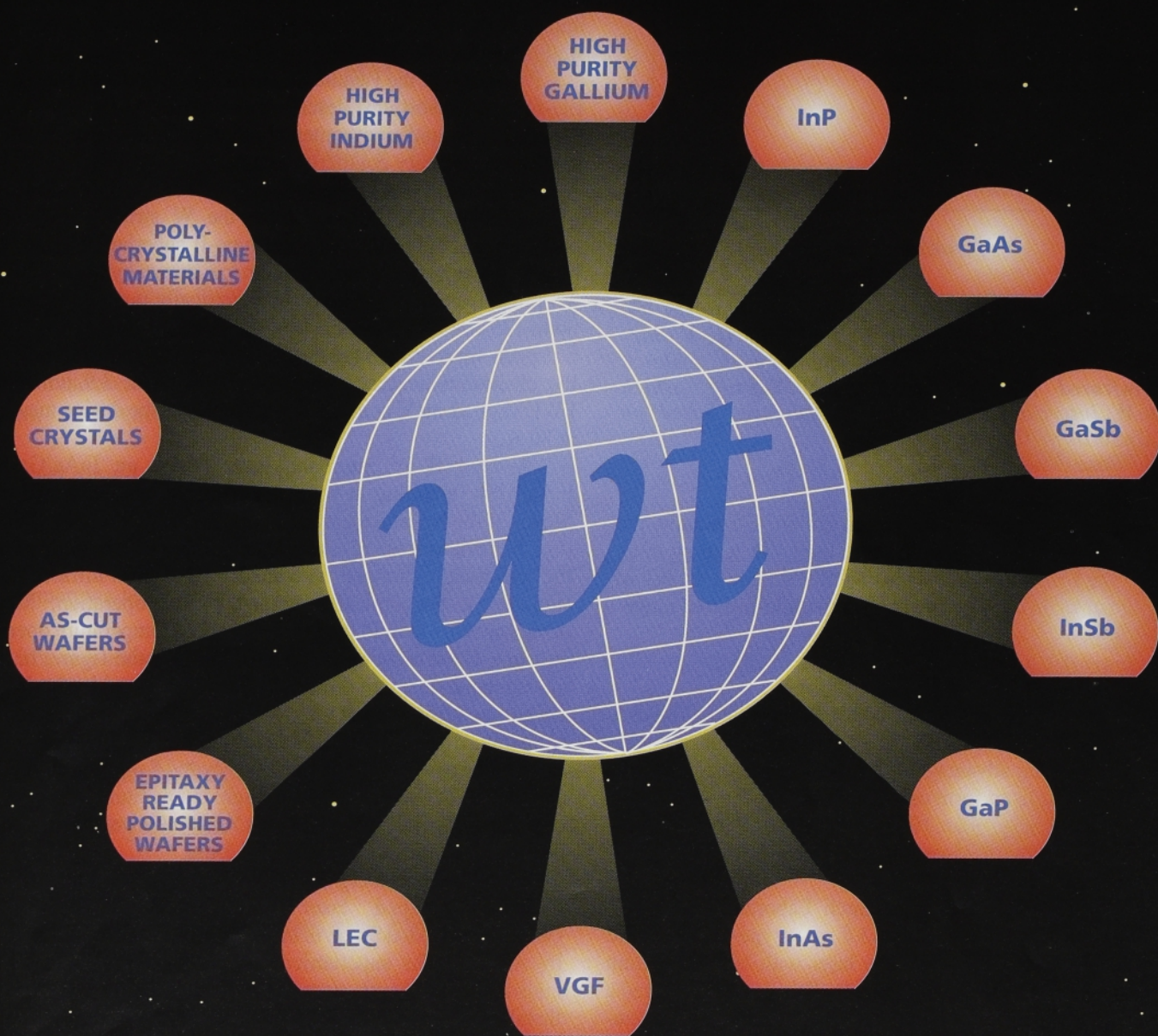


Figure 4. The peak power observed from the two mesa laser (0.2 mm wide x 0.1 mm stripes) from a type II interband cascade laser (ICL2) pumped by large pulsed currents at frequencies of 1 and 10 kHz. Rui Yang has observed external differential quantum efficiencies exceed 450% and peak power exceeding 4 W/facet (at 80 K).



# The Universal Choice



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

Whatever your substrate demands we're equipped to respond.  
**Wafer Technology - for all your III-V needs**

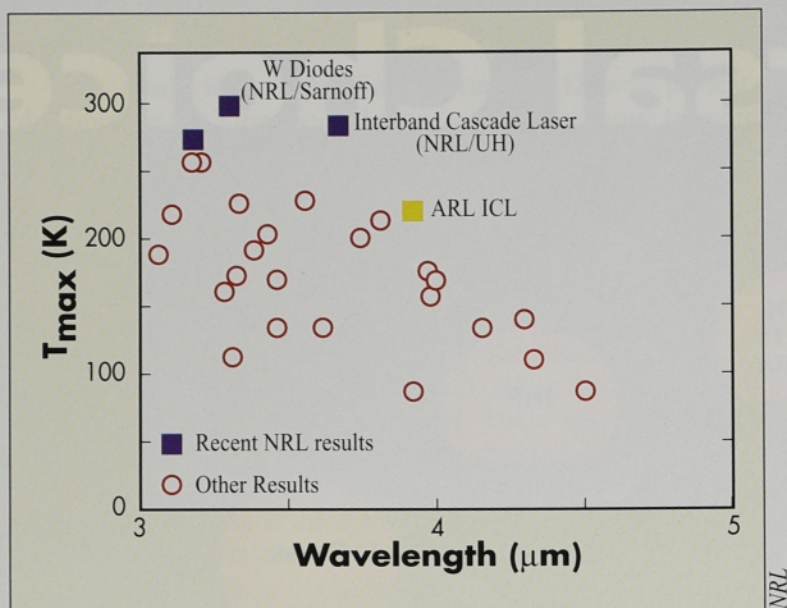
Visit us on the WWW at <http://www.wafertech.co.uk>

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



Quality system  
approved to  
BS EN ISO  
9002:1994





**Figure 5.** Maximum pulsed operating temperatures vs. wavelength for electrically-pumped interband III-V mid-infrared lasers. Room temperature operation is achieved in mid-infrared diode lasers by NRL/Sarnoff, which employs W interband type II laser structures based on InAs/GaInSb/InAs/AlSb.

version to be performed without amplification. Essentially, the photocurrent from the QWIP is fed into the LED, leading to an increase in the LED emission. This effectively allows the use of a conventional CCD chip for imaging in the mid-infrared range.

## Mid-Infrared Lasers

Type II quantum cascade lasers have received attention as a new source of mid-infrared light. These lasers re-use each injected electron by taking advantage of the broken gap alignment in type II quantum wells to form cascade stages, leading to a quantum efficiencies greater than 100%. Furthermore, they circumvent fast phonon scattering losses in intersubband lasers and suppress Auger recombination.

Rui Yang from US Army Research Laboratory (Adelphi, MD) introduced a MBE-grown 3.8  $\mu\text{m}$  type-II interband InAs/InGaSb/AlSb quantum cascade laser with 500% quantum efficiency measured at 110 K (Figure 4). This device exhibited a threshold current density of 300 A/cm<sup>2</sup> and a characteristic temperature for the threshold,  $T_0$ , of 135 K. A  $T_{\text{max}}$  value of 180 K was also reported. In addition, Yang has observed peak powers exceeding 4 W/facet at 80 K.

Mid-infrared lasers emitting in the 2  $\mu\text{m}$  range were presented by C. Mermelstein et al (Freiburg's Fraunhofer Institut für Angewandte Festkörperphysik). The authors proffered the characteristics of a GaInAsSb/AlGaAsSb separate confinement heterostructure quantum well laser with CW operation up to 260 K. The operation wavelength is centered at 2.35  $\mu\text{m}$ , and the characteristic temperature for the threshold  $T_0$  value is 110 K.

## Type II 'W' Interband Lasers

Several presentations described improvements in the performance of lasers using a type-II 'W' design for the active regions. The type II structure offers the advantages of greater electrical confinement and reduced Auger recombination, loss mechanisms that have seriously hampered the development of room temperature cw devices. The W configuration considerably improves the optical gain compared to a single type II quantum well per period.

P. Christol of the Faculté Sciences d'Avignon, (and part of an EU-funded consortium) described the use of Al-free 'W' lasers for use as gas- and environmental monitors, and in medical diagnostics and military countermeasures.

The active region, consisting of ten periods of InAsSb/InAsP/InAsSb, constitutes the W structure, which is based on several periods of short type-II superlattices separated by a type-I barrier. The resulting device, grown by MOVPE, is an 3.3  $\mu\text{m}$  wavelength Al-free laser, electrically pumped to operate up to 135 K with a  $T_0$  value of 30 K. The authors also discuss the prospects for room temperature operation, and note that at 300 K, the electroluminescence peak is positioned at 3.9  $\mu\text{m}$  with a FWHM of 52 meV, compared to 18 meV for the device measured at 80 K.

A type II W interband laser based on InAs/GaInSb/InAs/AlSb operating at room temperature was presented by J. Meyer of the Naval Research Laboratory in Washington. In addition, he reviewed the results from a number of laboratories making electrically-pumped interband III-V mid-infrared lasers (Figure 5). For optically-pumped pulsed operation, Meyer's device appears to hold the record for room temperature operation at 3  $\mu\text{m}$ . By specifying interband III-V's in the figure, he says, intersubband quantum cascade lasers (QCLs) and lead salt lasers are not included, both of which have recently demonstrated room temperature performance. "Intersubband QCLs are more complicated and work best at wavelengths beyond 5  $\mu\text{m}$ ," he says. "They are much less likely to yield high temperature cw operation because of their high thresholds." Meyer also discussed long wavelength lasers emitting up to 7.3  $\mu\text{m}$ .

Thomas Hasenberg of the University of Iowa introduced an optically pumped laser employing InAs/AlAsSb/InAs/GaInSb/InAs/AlAsSb/InAs broken-gap quantum wells separated by AlGaSb/InAs superlattice barriers. The device featured an emission wavelength near 3.5  $\mu\text{m}$ , and a room temperature threshold current density of 750 A/cm<sup>2</sup>. The Auger lifetime was found to be 940 ps. Hasenberg says this is a significant improvement compared to results from previous broken gap superlattices, which were measured at 350 ps.

In the mid-infrared regime, group III-V semiconductors are penetrating deeper and deeper into territory so far dominated by II-VI and IV-VI materials. A major issue remains the room-temperature dc-operation of the devices, particularly the lasers. The story will continue at MIOMD IV, to be held in Montpellier in the spring of 2001.



# STRATEGIES IN LIGHT

## Business Opportunities in Advanced Light-Emitting Diodes

**February 10-11, 2000**  
**Hyatt Regency San Francisco Airport**  
**Burlingame, California**

In the past few years, there has been tremendous growth in the use of advanced light-emitting diodes (LEDs) in a multitude of signalling, display and illumination applications. To address this expanding market, Strategies Unlimited, the world's leading market research firm in the area of compound semiconductors, is sponsoring the first-ever business opportunities conference on advanced LEDs.

Directed toward users as well as suppliers, *STRATEGIES IN LIGHT* will focus on the market outlook, applications prospects, and business opportunities available to all participants in the LED supply chain during the coming decade. A special presentation on organic LEDs will address the technology status and business prospects for this exciting new emerging technology.

The one-and-a-half day conference will have sessions on the following key topics:

**High-Brightness LED Market Overview and Forecast**

**High-Brightness LED Applications and Trends**

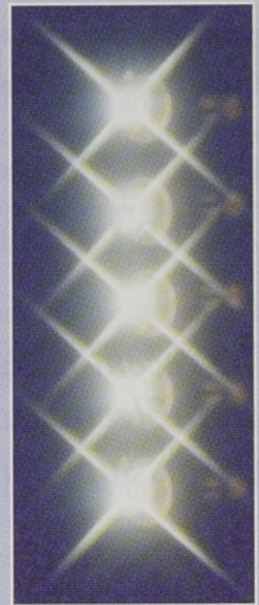
**Industry Perspective on LEDs in Illumination Applications**

**The Future of Advanced LED Technology**

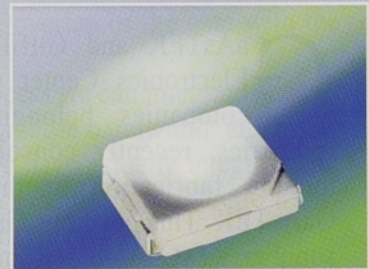
**Business and Financial Issues**

With presentations by major supplier and end-user industry participants, as well as interactive panel discussions, the conference will address all the important issues that affect the current and future market for high-brightness LEDs. Senior management, marketing managers and strategic planners in LED manufacturing and end-use companies and their supporting industries, as well as potential users of advanced LEDs, should plan to attend this unique industry event.

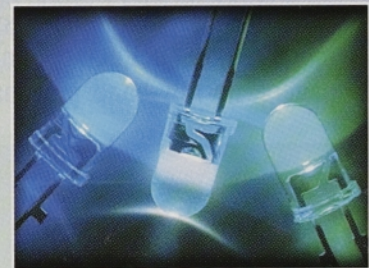
To be placed on the mailing list for further information on the *STRATEGIES IN LIGHT* conference, please contact Strategies Unlimited at +1 (650) 941-3438 (voice) or +1 (650) 941-5120 (fax), or e-mail [info@strategies-u.com](mailto:info@strategies-u.com). Also, check the company's web site at <http://www.strategies-u.com> for ongoing conference updates and information.



*Sumitomo Electric*



*Osram Opto Semiconductor*



*Hewlett-Packard*



*Hewlett-Packard*



*Hewlett-Packard*



## GaAsTEK Offers MMIC Modules

*The recent merger of ITT's GaAsTEK and ITT Gilfillan's MicroElectronics Center positions GaAsTEK as a module-level systems supplier for RF, microwave and millimeter wave ICs.*

RICHARD DIXON

**G**aAsTEK and Gilfillan's MicroElectronics Center (MEC), two companies belonging to ITT Industries, recently consolidated their module fabrication operations under GaAsTEK. This positions GaAsTEK as a supplier of GaAs-based modules. The company's MMICs are employed in a range of millimeter, microwave and RF applications, including switches and modules for cellular phones, two-way pagers, narrow-band personal communi-

cations systems, and other wireless voice and data products. They are also employed in a wide range of military applications, such as active array radar and electronic warfare systems.

The MicroElectronics Center (MEC), now known as the MicroElectronics Operations (MEO), manufactures modular packages using GaAsTEK's discrete and integrated 'multi-function' devices.

According to Paul Gralnick, president of ITT GaAsTEK, its customer base has in the past year increasingly requested module-level solutions. "By making MEC a part of GaAsTEK, we are now positioned to supply our customers with high-volume, customer-specific module solutions," he says.

### GaAsTEK

GaAsTEK was originally set up in 1981 as the GaAs technology center of ITT Industries to supply components to other ITT companies such as Gilfillan. Part of the Defense and Electronics division of ITT, Gilfillan is a California-based supplier of radar systems that uses GaAs MMICs in its active array antennas for both military defense and commercial air traffic control (Figure 1).

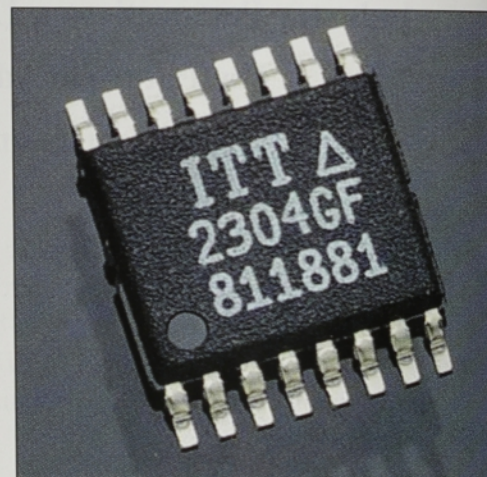
GaAsTEK employs about 200 staff, primarily in the manufacture of microwave and millimeter wave ICs for use as power amplifiers, attenuators and switches. These are available in die, IC or module form, and can be found in VSAT terminals, point-to-point radios, phased-

array antennas, electronic warfare systems and pulsed high-power transmitters.

According to Mike Russin, GaAsTEK's marketing communications manager, the company shifted emphasis from military to commercial markets around five years ago, and now does the majority of its business in this sector. "We sell mostly to customers such as Motorola, Ericsson, Philips and Siemens, as well as smaller companies like Bang and Olufson," says Russin. "A small portion of our wafer production goes into ITT Gilfillan's active array radar applications; the revenues remain high because the complexity of these types of devices keeps the costs relatively high. But we're moving strongly into the module market



**Figure 1.** Ground Control Approach (PAR-2000) radar system produced by ITT's Gilfillan division. These systems are in use at several commercial airports and feature much increased safety as a result of the sheer number of modules contributing to radar detection.



**Figure 2.** GaAsTEK's GaAs MESFET-based device uses a planar self-aligned gate process called MSAG to allow the integration of enhancement- and depletion-mode FET logic, low-noise FETs and power FETs on a single chip.



now that we have merged with MEO, and also into making microwave frequency ICs - these are currently major thrusts for GaAsTEK."

The company's range of power amplifiers cover the C to Ku (4.5-14.5 GHz) bands. In performance terms, devices at these frequencies offer saturated output powers of up to 39.5 dBm and power-added efficiencies as high as 47%, with 16 dB of gain. For the millimeter wave market, GaAsTEK's power amplifiers operate in the 26-30 GHz frequency range and can deliver maximum ratings of up to 30 dBm, gains up to 13 dB, and typically 17% power added efficiency.

Many of these power amplifier chips are integrated with low noise amplifiers (LNAs) and switches into compact transmit/receive modules assembled by MEO.

According to Mike Russin, module solutions are now being sought in many applications, driven by such factors as the product footprint, design time and cost. "By integrating more functions, modules save space, which is especially important in handheld and embedded devices," he says. For the buyer, this translates into less time spent designing, eased component compatibility, less assembly and tuning, and reduced inventory. "MEO has already begun to work with us on our wireless cell-phone products," Russin adds.

### Multi-Functional Self Aligned Gate Process

Providing the MMICs for these modules is GaAsTEK's foundry, located in a 40,000 ft<sup>2</sup> facility at Roanoke, Virginia. This houses a 4-inch GaAs wafer fab line that uses a patented diffusion and anneal MESFET process called MSAG, or Multi-functional Self-Aligned Gate.

*"We have actually integrated all the microwave functions on a T/R module into a single transceiver chip. We call these devices 'radar on a chip.'"*

While planar self-aligned gate processes are not new, GaAsTEK uses the multi-function technique to incorporate power, small signal and digital devices on the same chip. According to Mike Petz, marketing manager for ITT's radar manufacturer, Gilfillan, the MSAG approach uses the metallization layer of the gate region as a mask for implant; this results in excellent uniformity and yield, he says. Multiple implants are also possible on one chip due to this inherent masking, which allows the integration of different devices.

The MSAG approach also improves device processing accuracy by removing the tight tolerances necessary with photolithographic mask registration, says Petz. This is particularly important in forming the channel regions in FETs, while at the same time reducing parasitic capacitances that arise from a large overlap of the gate with the source and drain regions.

"Using GaAsTEK's MSAG process we can integrate devices into radar with multiple functions, a large bandwidth, and a low power consumption," says Petz. "We have actually integrated all the microwave functions on a T/R module into a single transceiver chip. We call these devices 'radar on a chip.'"

The inherently high-yield process using the self-aligned gate approach cost-effectively allows enhancement- and depletion-mode FET logic, low-noise FETs and power FETs on a single IC. According to Gilfillan's Tom Brukiewa, manager of Active Array Radar Systems, the resulting transceiver chip reduces the cost of the transmit/receive module by eliminating many of the microwave discontinuities and interconnects.

For the RFIC devices, a proprietary process called MSAG-Lite has been developed. RF power amplifiers based on this process are designed to match DECT (Digital European Cordless



**Global  
Communication  
Semiconductors, Inc.**

**Providing Compound Semiconductor  
Foundry Services to the Telecommunication  
and Optoelectronic Industries**

**Our High Volume Wafer Manufacturing Expertise  
Provides Cost Effective Foundry Solutions For**

- HBT
- PHEMT
- MESFET
- Backside Vias
- Optoelectronics
- Epitaxial Materials

**Global Communication Semiconductors, Inc.**

23155 Kashiwa Court Tel: 310-530-7274  
Torrance, CA 90505 Fax: 310-530-7279

Email: [info@gcsincorp.com](mailto:info@gcsincorp.com) Web Site: [www.gcsincorp.com](http://www.gcsincorp.com)





Telecom-munications), WLL (Wireless Local Loop) and SWAP (Shared Wireless Access Protocol) specifications.

GaAsTEK also manufactures RFICs for the Bluetooth industry standard frequency of 2.4 GHz. Its front-end chip consists of an integrated single-bias RF power amplifier, transmit/receive switch and LNA in a single package (Figure 2). All three functions operate from a 2.0-5.5 V power supply. Company data sheets put the transmitter output at 25 dB with a 3.6 V supply through the T/R switch, and a power added efficiency of 55%. The LNA has a noise figure of 1.8 dB, with 14 dB of gain, while consuming only 4 mA of current.

For cellular and wireless area network (WAN), the company offers a 3 W power amplifier operating between 825 and 975 MHz that delivers an output power of 34.8 dBm from a 4.8 V supply. This device has a gain of 34.8 dB and PAE of 45%.

## MEO and Gilfillan - Radar Applications

The Microelectronics operation of GaAsTEK is located next door to GaAsTEK in Roanoke. It was established by ITT Gilfillan in 1991 to assemble transmit/receive modules for radar systems for the US Navy. It emerged along with companies such as Raytheon, TI,

Westinghouse and Hughes as a major supplier of these systems.

At the outset the business also benefited from funding from the US Department of Defense's Manufacturing Technology program (ManTech). This was part of a one billion dollar investment made by the US government for the development of GaAs MMICs and related T/R module technology in the last 10 years.

"Even before MEC was formed, GaAsTEK and Gilfillan worked closely together on solid-state radar," says Gilfillan's Mike Petz. "MEC was brought on-line with the ManTech program to reduce the cost of manufacturing."

MEO uses GaAsTEK's ICs in its Transmit/Receive Integrated Module Manufacturing line, or T/RIMMline. The heart of MEO is an automated materials handling and shop floor control system that includes chip positioning, ball bonding, vacuum solder reflow and RF test.

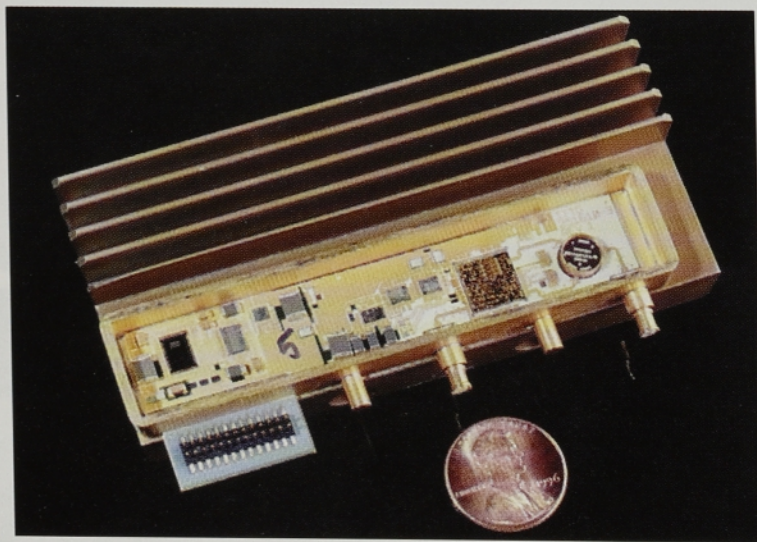
Modules for Gilfillan's radar consists of a high degree of functional integration, resulting in less than 40 parts (Figure 3). All microwave functions, which consist of LNAs, switches, attenuators, phase shifters and driver amplifiers, are contained on a single GaAsTEK transceiver chip. Discrete resistor components are printed on or embedded in the single multilayer ceramic substrate. This simplicity leads to high-volume production and

lower costs. The reduced number of parts makes them reliable and leads to a smaller footprint. The module is ideal for radar systems, and can be mounted directly on an antenna, replacing the traditional bulky central transmitter. Typically, a module operating in the X-band has a final output power of the order of 4 W.

## Active vs. Phased Array Radar

ITT Gilfillan's radar for air traffic control and defense applications is based on active array technology. Essentially each radar transmit and receive 'element' is powered and controlled by the transceiver chip and functional circuitry contained in the compact module. This differs from the traditional 'phased array' antenna, which provides power and sends information on positioning to its antenna elements from a central transmitter via waveguides and remote electronics.

This has several advantages: the power consumption is much lower due to the reduced dispersion from external feeds and waveguides (which can add as much as 8 dB), resulting in more power being available to send signals from the antenna, and both bandwidth and spectral purity are improved. Also, the agility of the transmitted radar beam and the number of functions can be increased. This allows simultaneous search and track, communication or missile guidance, all of



**Figure 3.** MEO module incorporating GaAsTEK chips designed for Gilfillan's GCA-2000 radar system. MEO has supplied several thousand modules for this application, and sales projections indicate a potential production rate of several hundred units/month in future.



**Figure 4.** Portable MPN-25 X-band transmit/receive radar system used in military applications. Depending on the exact system, the active electronic scanned antenna can contain as many as a 1000 modules.



# Build Your Future on a Solid Foundation



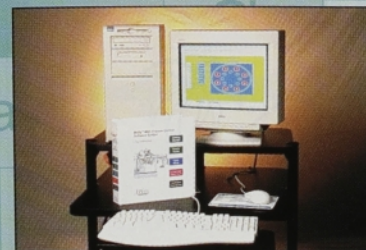
Patented valved cracking effusion cells enable wide dynamic range and precise flux control.



Material specific effusion cells are designed to accommodate unique characteristics of various materials.



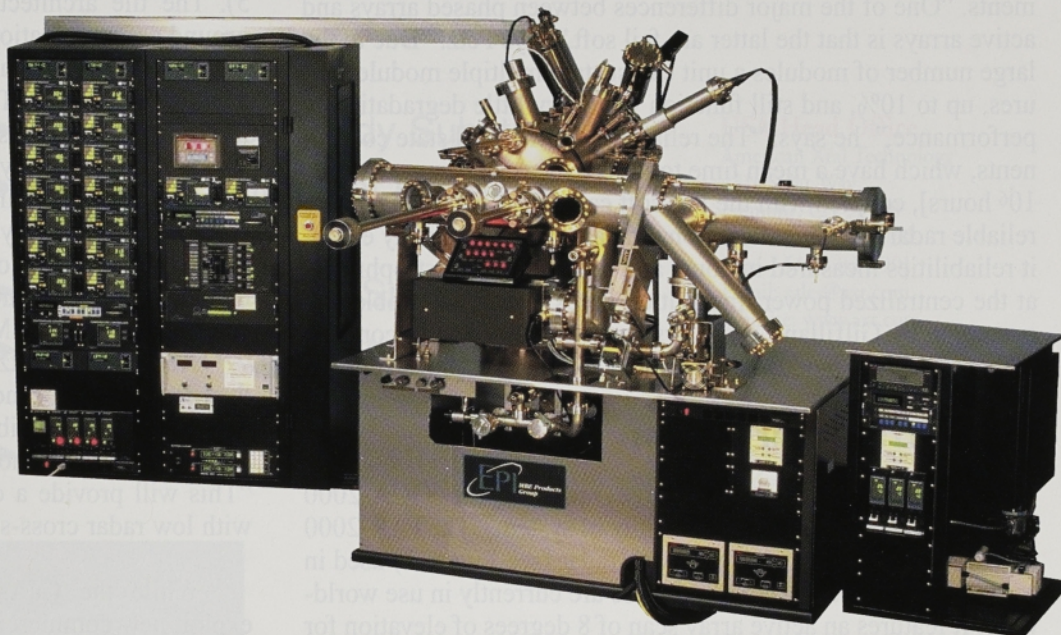
Patented, large capacity SUMO™ Cells promote maximum up-time and stable Group III flux.



Molly™ MBE Process Control Software provides consistent, reproducible, automated film growth.



Specifically designed electronics provide precise control for MBE.



## Modular **GEN II** MBE — The Solid Choice for Epitaxial Growth

### ■ Solid Source Materials

EPI Valved Crackers and SUMO™ Effusion Cells define the industry standard in solid source MBE.

### ■ Solid Reputation

With over 200 systems operational worldwide, the GEN II is the system of choice for all types of compound semiconductor research and single-wafer production. The GEN II has proven itself to be the premier MBE system for optoelectronic device manufacture.

**4-INCH CAPABILITY STANDARD.**

### ■ Solid Investment

The combination of low cost, maximum up-time, high yield and high throughput provides an excellent return on your investment.

For more information, please contact EPI System Sales or visit our web site at [www.epimbe.com](http://www.epimbe.com).



**EPI**  
4900 Constellation Drive  
St. Paul, MN 55127 USA  
TEL (651) 482-0800  
FAX (651) 482-0600  
E-mail [info@epimbe.com](mailto:info@epimbe.com)

**EPI Europe**  
147 Chorley New Road  
Horwich, Bolton BL6 5QE  
Greater Manchester, UK  
TEL (+44) 1-204-668366  
FAX (+44) 1-204-668466  
E-mail [europe@epimbe.com](mailto:europe@epimbe.com)

**Japan**  
Vieetech Japan Company Ltd.  
1316-3 Katsukura  
Hitachinaka Ibaraki 312  
Japan  
TEL (+81) 29-272-8161  
FAX (+81) 29-272-9814  
E-mail [vieetech@mito.ne.jp](mailto:vieetech@mito.ne.jp)



which are particularly useful in military applications.

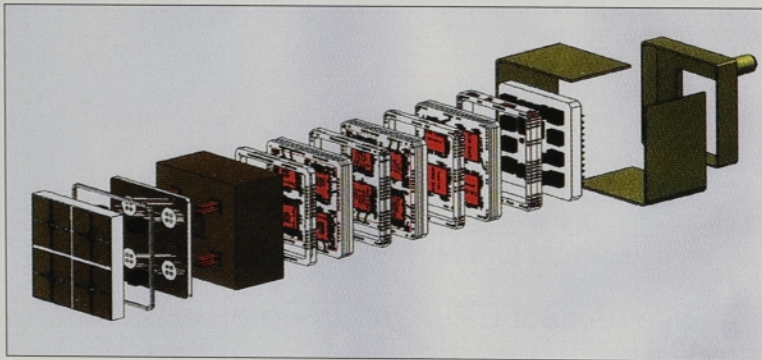
There are also reliability and cost advantages. Costs are reduced by combining compact MMIC modules with as many commercially-available off-the-shelf components as possible.

And radar reliability increases with the number of active elements. "One of the major differences between phased arrays and active arrays is that the latter are fail soft," says Petz. "Due to the large number of modules a unit can sustain multiple module failures, up to 10%, and still function with very little degradation to performance," he says. "The reliability of the solid state components, which have a mean time to failure measured in years [ $10^5$ - $10^6$  hours], coupled with the fail-soft capability, make this a very reliable radar system." Traditional radar systems typically exhibit reliabilities measured in hours and usually fail catastrophically at the centralized power transmitter, notes Petz. This problem is overcome by Gilfillan's radar systems, which typically contains 180 GaAs-based modules that are fail soft and simple to replace.

## Active Array Radar Systems

Gilfillan's most recent active radar is the GCA-2000 (Ground Controlled Approach) family of systems. The PAR-2000 variant is a fixed precision approach radar (see Figure 1) used in commercial airports. About 8 of these are currently in use worldwide. It features an active array scan of 8 degrees of elevation for tracking aircraft during landing at distances up to 20 nautical miles. In the azimuth plane, the signal coverage is 30 degrees. The MPN-25, a GCA-2000 precision approach and surveillance system, is a mobile version for the military. It uses Gilfillan's active electronic scanned antenna (AESA). The transmit power can be distributed over 100 to a 1000 modules, depending on the type of system (Figure 4).

According to Gilfillan, the GCA systems have become, and will remain, NATO's standard radar system until 2015. Which is good news for the GaAsTEK-MEO venture. MEO has supplied these radar modules for several years, says GaAsTEK's president Paul Gralnick, and has so far delivered several thousand modules. Recent sales of these systems have included the air forces of the United Kingdom and Turkey, and most recently, that of Brazil. Future GCA system sales indicate a potential production rate of several hundred modules per month, says the company.



**Figure 5.** ITT Gilfillan's multi-functional tiles are a component of active arrays which simultaneously provides synthetic aperture radar, satellite and ground communications from aircraft, necessitating a light, efficiently-packed arrangement of modules.

## Tile Modules

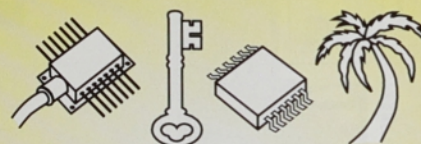
MEO has also collaborated with Gilfillan on 'tile' modules - a thin, flat radar configuration for unmanned aerial vehicle platforms, communications and wide-band data transmission (Figure 5). The tile architecture is best suited to radar, satellite and ground communications from aircraft, says Tom Brukiewa.

In general, modules can take the form of a brick or a tile, explains Brukiewa. "The GCA-2000 is a brick configuration, and has all the electronics coplanar mounted on a single substrate." The tile differs, he says, in that it has all the electronics mounted behind the radiating elements in a stacked geometry. "This stacking enables very high packing efficiencies and allows the radar to be mounted on a surface," he says. Anywhere from 4 to 16 T/R elements are contained in a single tile - each element containing several MMIC functions.

According to Petz, considerable work has been done to make the tiles thinner for mounting on surfaces, and in future it should be amenable to distribution over a curved surface. "Eventually, the aim is to 'skin-mount' tiles on an aircraft fuselage," he says. "This will provide a combination of many electronic functions with low radar cross-sections."

While the GaAsTEK-MEO venture will be seeking to exploit new commercial applications for its modular products, it will still play an important role in many of ITT's divisions in future, says Mike Petz. "If MEO can reduce its costs by designing modules for GaAsTEK's high-level commercial applications, Gilfillan and other ITT divisions, such as Avionics and Communications, could all benefit from the GaAsTEK MSAG process and MEO's high-volume module production capability."

## Plan to attend!



## Key Conference 2000

**Compound Semiconductors  
in Communications**

Key West, FL • March 13-14, 2000

For more information,  
see our ad on the inside front cover  
or  
visit our website at  
[www.keyconference.com](http://www.keyconference.com)

Presented  
by  
**Compound Semiconductor Magazine.**

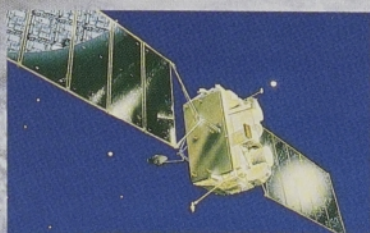


# The Core of Advanced Communication Technologies



## Call Us Today For:

- ▶ Up to 150mm GaAs Substrates
- ▶ Up to 100mm InP Substrates
- ▶ Up to 100mm Ge Substrates
- ▶ Low-EPD Epi-Ready Substrates
- ▶ Uniform Ion-Implant Ready VGF Substrates
- ▶ High-Volume LED Substrates
- ▶ High-Mechanical Strength VGF Substrates
- ▶ Ultra-Thin VGF Substrates



### USA Head Office

American Xtal Technology  
4311 Solar Way  
Fremont, CA 94538  
Tel: 510-683-5900  
Fax: 510-683-5901  
Email: sales@axt.com  
Website: www.axt.com

### Japan

AXT-Japan  
302 Urban Plaza Izumi  
2-26-4 Myojin-cho  
Hachioji, Tokyo 192-0046, Japan  
Tel: (81) 0426-56-2032  
Fax: (81) 0426-56-6885  
Email: axtpjapan@cg.netlaputa.ne.jp

### France & Germany

SO.FRA.S.I.L  
109 Rue De Javel  
75015 Paris, France  
Tel: (33) 1-4554-4000  
Fax: (33) 1-4554-4004  
E-mail:  
ralph\_hananel@CSI.com

### United Kingdom

West Associates  
46 Leigh Road, Cobham, Surrey  
United Kingdom, KT11 2LD  
Tel: (44) 1932-868-006  
Fax: (44) 1932-860-932  
E-mail:  
mwtest@westassociates.co.uk

### Taiwan

Conary Enterprises Co., Ltd.  
10 F-2, No. 33, Sec. 2  
Chien-Kuo North Road  
Taipei, Taiwan, ROC  
Tel: (886) 2-2509-1399  
(886) 2-2509-3174/5  
Fax: (886) 2-2501-6279  
E-mail: conary@top2.ficnet.net.tw

### Korea

Dong Kyung Electronic Industry  
Co., Ltd.  
#302 Daegun Bldg.  
677-1 Ryeoksam Dong  
Kangnam-Gu  
Seoul 135-080, Korea  
Tel: (82) 2-569-6723/5  
(82) 2-568-5261/2  
Fax: (82) 2-561-1185  
E-mail:  
dkekorea@nownuri.nowcom.co.kr





# GaAs IC Technology in ATE Applications

*GaAs IC technology is widely used in the timing chain of high-speed automatic equipment used to test logic, mixed-signal and memory circuits.*

ALLAN ARMSTRONG

Vitesse Semiconductor Corporation  
Camarillo, CA

Test and evaluation of high-speed logic, mixed-signal and memory circuits requires the use of high-performance automatic test equipment (ATE). For these applications, GaAs has emerged as a key enabling technology and GaAs ICs have been widely used in mainstream production and characterization testers. Because of their high speed, precise timing accuracy, and high levels of integration, GaAs ICs have displaced silicon in many applications and have been successfully used in the entire digital channel from timing generators and sequencers to pin electronics.

Following increasing speed demands in digital system development, GaAs technology is now extensively used in the digital channels of logic, mixed-signal (also called system-on-a-chip or SoC), and memory testers. Nearly every major tester manufac-

turer has used GaAs ICs in some part of the digital timing channel of their high-speed testers. Vitesse's sales of GaAs MESFET-based IC into this application exceeded \$40 million in 1998, accounting for around 26% of the company's total sales. The remaining 74% of sales were into the communications market.

## Processors Speeds Drive Tester Development

The rapid increase in microprocessor speeds in recent years has been the driving force for the development of more advanced automatic test equipment (see Figure 1). To reliably produce high-speed processors operating up to and beyond 1 GHz, semiconductor manufacturers must be able to test at speed. Typically, a technology must be tested using devices made from a more

advanced technology. Thus, ATE manufacturers have turned to high-speed technologies like GaAs to build their timing channels.

High-speed alone is not enough to qualify a technology for use in ATE equipment. Because processors and memories can be sold for different prices depending on their speed performance, accurate testing of properties including setup and hold times, propagation delays, and cycle times is essential. Figure 2 illustrates how timing errors force IC manufacturers to guard-band test specifications and reject otherwise

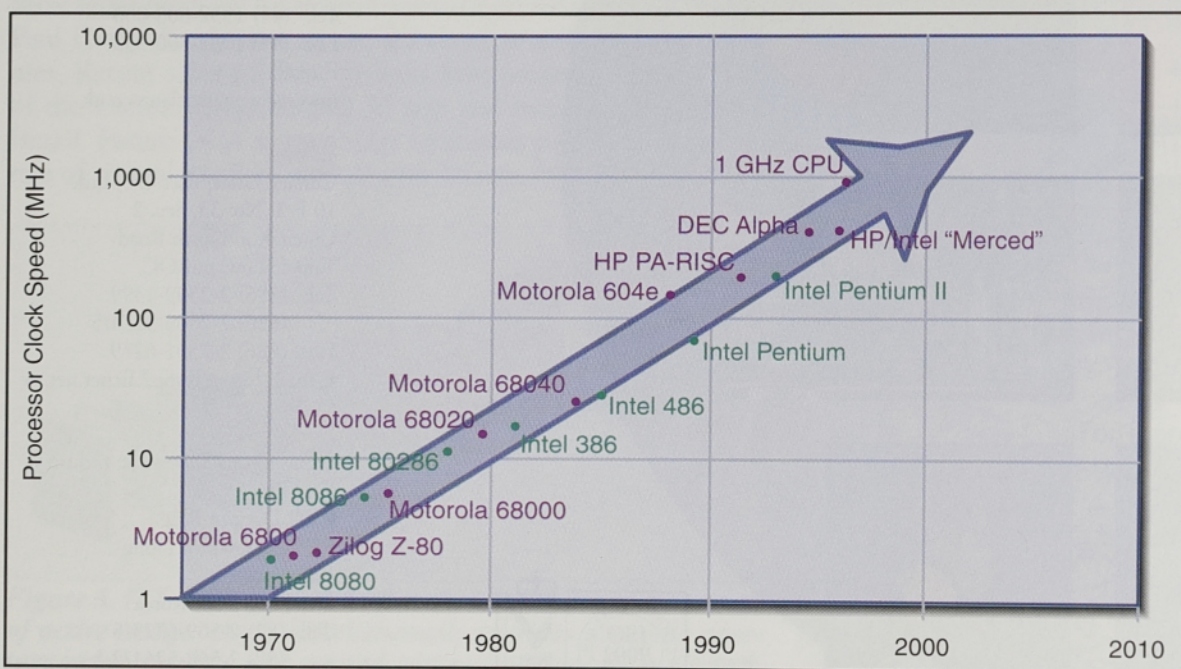
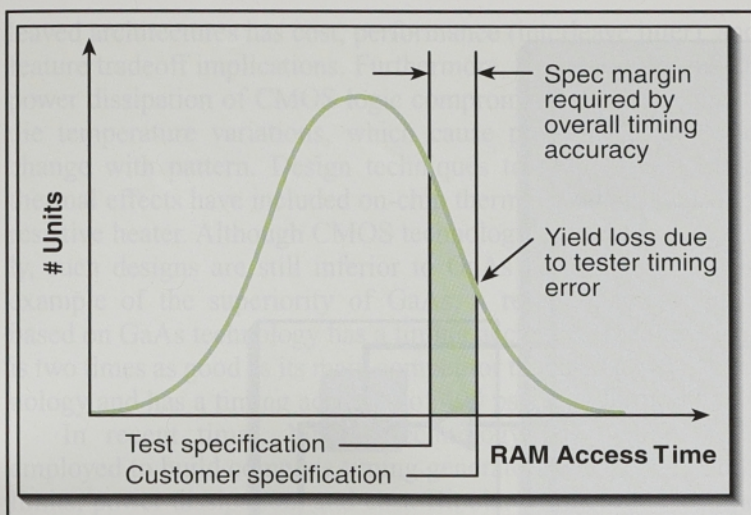


Figure 1. The rapid increase in microprocessor speeds in recent years has been the driving force for the development of more advanced automatic test equipment.





**Figure 2.** Parts with an access time below the customer's specification should be accepted. However, there is a lower "test specification" set by timing errors in the test equipment. Parts that should be usable are rejected (green shaded area) due to this timing error.

usable parts. Thus, the economic value of timing accuracy is a major decision factor in high-speed tester purchases.

Current trends in both mixed-signal and memory test also favor GaAs technology. Development of system-on-a-chip devices has increased the pin count and speed requirements of mixed-signal testers. Introduction of RAMBUS technology has caused a rapid escalation in the speed and accuracy requirements of memory testers.

## The Digital Timing Channel

Figure 3 shows a block diagram of a typical digital timing channel that drives one pin of a device under test (DUT). A typical tester will have a large number of such channels or pins. Testers currently have 64 to 1024 pins, while testers of the future will have many more than 1024.

The timing channel generally contains three main elements: a sequencer or pattern generator, a timing generator, and pin electronics. The sequencer controls the operation of the digital pin. It interprets test as the microcode of the tester and issues commands to the timing generator.

The timing generator provides variable timing edges and formats data to drive the DUT pin. It also compares DUT responses against expected values and detects errors. The timing generator generally contains high-speed RAM to store timeset and formatting information, counters and timing verniers to create timing edges with coarse and fine control, a formatter to construct the output pulse, and compare strobes and an error processor to identify DUT failures. Implementing such a device requires a combination of high-performance digital and analog technology: high-speed static RAMs and counters, verniers with precise timing control and accuracy, and an extremely stable timing path.

The pin electronics interfaces with the analog voltages at the DUT pin and allows logic levels and compare thresholds to be

controlled accurately and varied under program control. Pin electronics consists of three functions: a pin driver to drive the pin, a window comparator to observe the pin, and a programmable load.

Timing accuracy is one of the biggest challenges in ATE component design. Many physical effects cause timing errors. Non-linearity of the timing vernier causes an edge placement error. Edge placement drifts between calibrations because propagation delay depends on power supply and temperature. Propagation delay also changes due to variations in the pattern, duty cycle, or data being driven to the pin. Such pattern effects can be caused by settling as the vernier changes codes, duty cycle effects due to thermal, trapping, and bandwidth effects, and intersymbol interference due to transmission line reflections in the packaging. Finally, jitter due to 1/f and broadband noise adds random timing error.

## GaAs Timing Technology

GaAs technology has seen broad application in both the sequencer and the timing generator in many commercial testers. The majority of GaAs IC ATE revenue comes from these applications.

Building a sequencer is difficult because instructions must be fetched, decoded, and executed in a single tester period. This requires a technology that can implement high-speed memory

### For Precise Wafer Processing

## PM5 auto-lap

**Confidently achieve a high quality surface finish and flatness on your II-VI & III-V materials**

*Automation means higher sample repeatability and less operator involvement*

*Touch button control of delicate wafer processing*

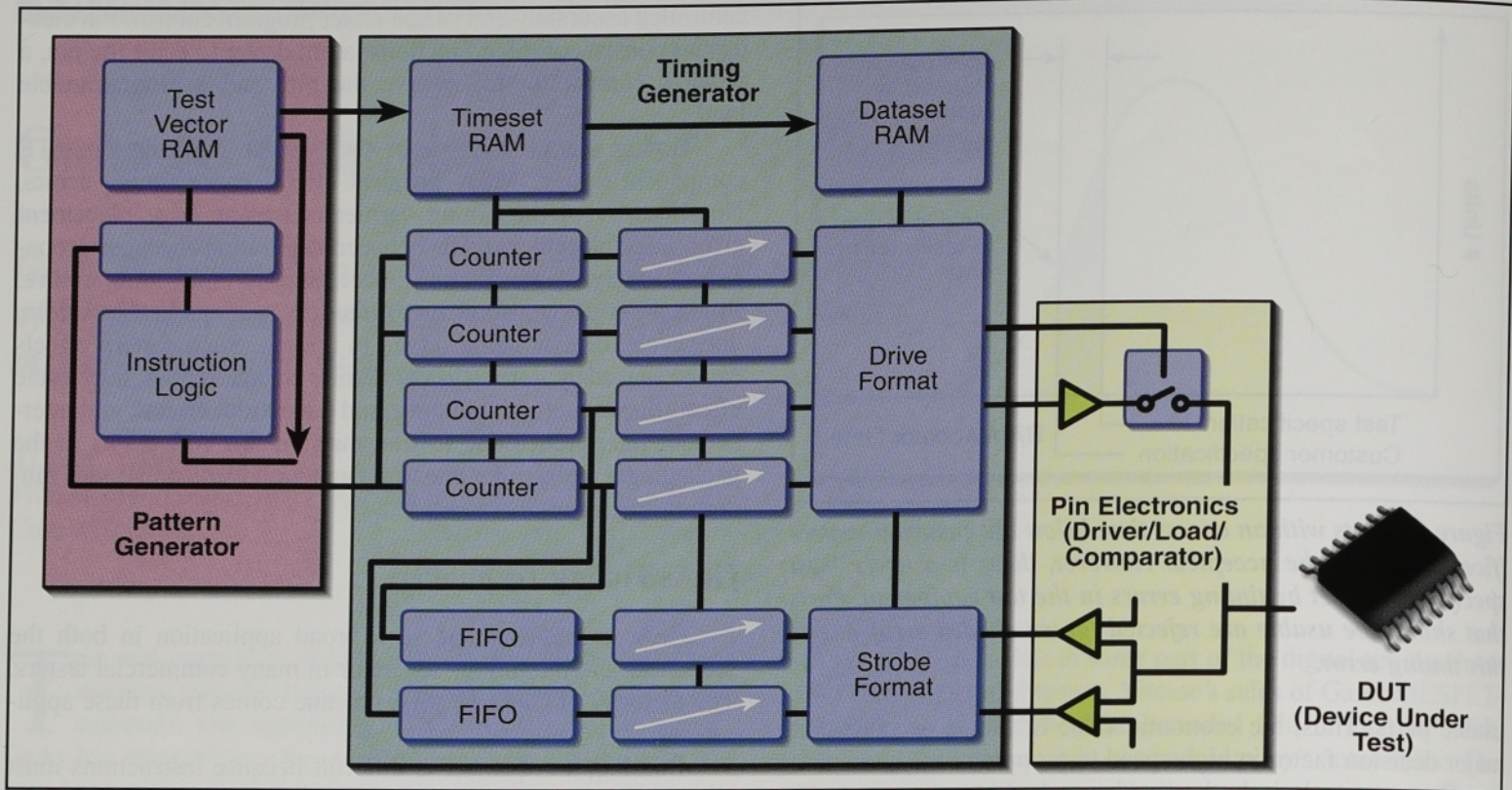
*Sub-micron sample flatness*

*Plate conditioning during processing eliminated*

**Quality Materials Processing Technology**

Logitech Product Group,  
A Division of Struers Inc.  
810 Sharon Drive, Westlake, Ohio 44145  
Tel. (440) 871 0071  
Fax. (440) 871 8188  
<http://www.logitech-us.com>





**Figure 3.** Block diagram of a digital timing channel that drives one pin of the device under test. Typical testers have between 64 and 1024 pins.

memories (such as 4 ns, 1000 3 18 SRAMs) with high-speed logic to create sequencers for many high-speed ATE machines. Such designs typically use the on-chip RAM as an instruction or execution cache, and store test vectors in a larger off-chip RAM.

As GaAs technology has advanced, GaAs ICs have been used first to build parts of a timing generator, and later to build the entire timing generator on a single chip. Successful recent timing generator ICs have combined more than 100,000 gates of high-speed logic with high-speed (2 ns) RAMs, very accurate verniers (8 ps timing resolution, 1.5 ps rms jitter), and precision formatters capable of creating very narrow pulses (500 ps minimum pulse width). Such timing generators are capable of generating test signals at up to 2 Gb/s for applications such as micro-processor and RAMBUS test. In timing applications, GaAs ICs are widely used in advanced logic, mixed-signal and memory testers.

### GaAs Pin Electronics Technology

GaAs pin electronics technology began its development in the late 1980s. The first commercial success of GaAs technology in pin-driver applications was a family of high-speed pulse generator instruments introduced by HP in 1988. GaAs pin drivers provided good waveform quality, with rise/fall times and voltage swings that were not achievable in silicon technology due to  $f_T$  and  $BV_{CEO}$  limitations of bipolar devices.

This technology was soon applied to the ATE market by a number of tester manufacturing companies. GaAs pin drivers

provided a large speed advantage over existing silicon bipolar designs, and only recently has silicon technology neared the performance of the first GaAs results. Commercial GaAs devices still retain a speed advantage over production silicon devices.

### Why GaAs is Successful

The competitive playing field in ATE semiconductors is complex, with many simultaneously difficult requirements. Key drivers for ATE technology are speed, timing accuracy, integration, and cost. GaAs has successfully competed with bipolar, CMOS, and hybrid solutions, winning with a different combination of benefits in different applications.

The key challenges for GaAs technology are timing accuracy and cost/yield. Recessed-gate processes cannot yield highly complex devices (>100,000 transistors) and have unacceptable timing errors due to trapping effects. Circuit design techniques to address these problems have been partly successful, but the most important contribution to timing accuracy in GaAs has been the combination of buried p-well technology with self-aligned gates. Combining such a process with special circuit design techniques, GaAs technology has matched the timing accuracy of the best competing bipolar devices.

Low- and mid-performance testers have employed CMOS technology for the timing generator function. Although CMOS can effectively implement the timing generator function at a reasonable cost, achieving high-speed operation in CMOS can be difficult. Solving CMOS speed problems with parallel inter-



leaved architectures has cost, performance (interleave jitter), and feature tradeoff implications. Furthermore, frequency-dependent power dissipation of CMOS logic compromises accuracy due to die temperature variations, which cause propagation delay to change with pattern. Design techniques to reduce the CMOS thermal effects have included on-chip thermal regulation using a resistive heater. Although CMOS technology is advancing rapidly, such designs are still inferior to GaAs performance. As an example of the superiority of GaAs, a recent memory tester based on GaAs technology has a timing accuracy of 200 ps. This is two times as good as its main competitor that uses CMOS technology and has a timing accuracy of 400 ps.

In recent times, bipolar technology has seldom been employed to build complete timing generators due to integration limits, power dissipation, and cost. Bipolar technology has been successful at building verniers and formatters, and these verniers and formatters have achieved good timing accuracy and speed, but complete timing generator ICs built in bipolar technology have had minimal feature sets and unacceptably high cost.

High-performance testers have employed either single-chip GaAs timing generators or hybrids implemented in multi-chip modules (MCM). In such modules, the digital portion (logic and memory) has been implemented in either CMOS or GaAs technology and the analog portion (verniers and formatter) has been implemented in either bipolar or GaAs technology. Splitting the analog and digital portions of the timing generator IC allows development projects to proceed independently and reduces con-

cerns about timing errors due to digital switching noise. Unfortunately, split architectures require a wide and fast bus between the analog and digital portions. Such a bus has so far demanded MCM technology. As tester speeds increase the bus constraints will only get more difficult.

A major disadvantage of the MCM approach is the total cost of the timing generator module due to the aggregate cost of multiple (2-7) die and the cross yield implications of MCM manufacturing. The cost advantage of GaAs technology over silicon-based MCM solutions has been a major factor in the recent success of GaAs. Additionally, future trends require that the timing generator be integrated into the test head and multi-die MCMs are physically too large.

## Summary

GaAs technology has experienced great success in ATE applications with extensive use in sequencer, timing generator, and pin electronics. The annual IC revenue in this market exceeds \$40 million. To achieve this success, GaAs solutions have had to compete creatively against a variety of silicon solutions. Technology developed for ATE applications has been radically different from "main-stream" GaAs technology used for microwave and RF applications. Development of ATE semiconductors continues in GaAs technology with an eye to providing faster and more accurate future testers for logic, system-on-a-chip, and memory applications.

# SOURCES OF EXCELLENCE

More than any other component, crackers and effusion cells have a direct impact on the quality of materials grown by MBE. With over 4000 MBE sources in the field, RIBER has the largest installed base of any company. Our experience in high quality components and years of close cooperation with major research and production groups have brought RIBER to the forefront of MBE source technology. *To find out more about our product range, call your RIBER representative.*

## RIBER

*Products and Services for the Compound Semiconductor Industry*

Tel: +33 1 47 08 92 50 - Fax: +33 1 47 08 32 39 - E-mail: [info@riber.com](mailto:info@riber.com) - Website: [www.riber.com](http://www.riber.com)



# Si-on-GaAs Wafers for Monolithic Optoelectronic Integration

J.M. LONDON, A. H. LOOMIS,\*

J.F. AHADIAN, and C.G. FONSTAD, JR.

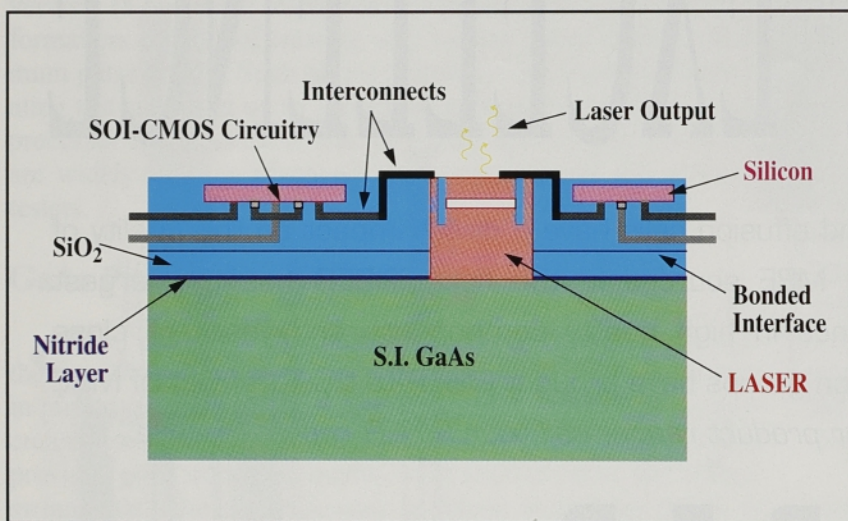
Massachusetts Institute of Technology, Cambridge, MA

\*MIT Lincoln Laboratory, Lexington, MA

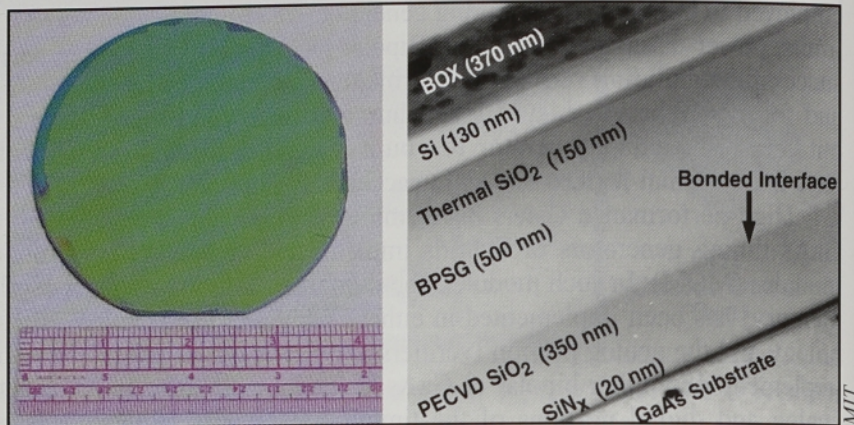
Monolithic integration of III-V optoelectronic devices such as laser diodes and *p-i-n* detectors with complex high-density, high-performance silicon CMOS circuits is desirable to economically produce robust optoelectronic integrated circuits. While GaAs-on-Si research continues to this day, the lattice constant mismatch is cited as the main difficulty with this approach. However, the more important issue is the large difference in thermal expansion coefficient and associated stresses.

We recognized that optoelectronic devices are intrinsically very thick (typically 1  $\mu\text{m}$ ) and thus very sensitive to stress. In contrast, Si MOS transistors need only be a few tens of nanometers thick and are consequently much less stress sensitive. Thus, wafer bonding and SOI techniques have been employed to attach 100 nm thick Si single crystal layers using intervening oxide layers on to 4-inch GaAs substrates, a process we call SonG (Si-on-GaAs). The goal of SonG is to integrate fully processed CMOS devices with optoelectronic devices (Figure 1).

The technique uses 670  $\mu\text{m}$  thick 4-inch GaAs wafers and 550  $\mu\text{m}$  thick SIMOX (Separation by IMplantation of OXYgen) wafers. The latter contain a nominal 370 nm thick buried oxide (BOX) layer and a 200 nm thick silicon top layer. A 20 nm thick



**Figure 1. Schematic diagram of Si-on-GaAs (SonG) IC. The goal is to bond thin SOI CMOS circuitry to GaAs substrates, and then etch back to the GaAs substrate for subsequent epitaxial growth of optoelectronic III-V devices.**



**Figure 2. (left) Photograph of a SIMOX substrate wafer bonded to a 4-inch GaAs wafer. The uniform appearance of the layer across the majority of the wafer testified to the integrity of the bonding process. (right) TEM cross-section micrograph of the SonG wafer sandwich. (courtesy Bulsara, Leitz and Garratt-Reed).**

layer of  $\text{Si}_3\text{N}_4$  followed by 350 nm of  $\text{SiO}_2$  were deposited by PECVD on the GaAs, and densified at 700°C for 30 min. A 150 nm thick thermal oxide was grown on the SIMOX wafer, followed by 500 nm of borophosphosilicate glass (BPSG) at 400°C, and subsequently densified at 925°C.

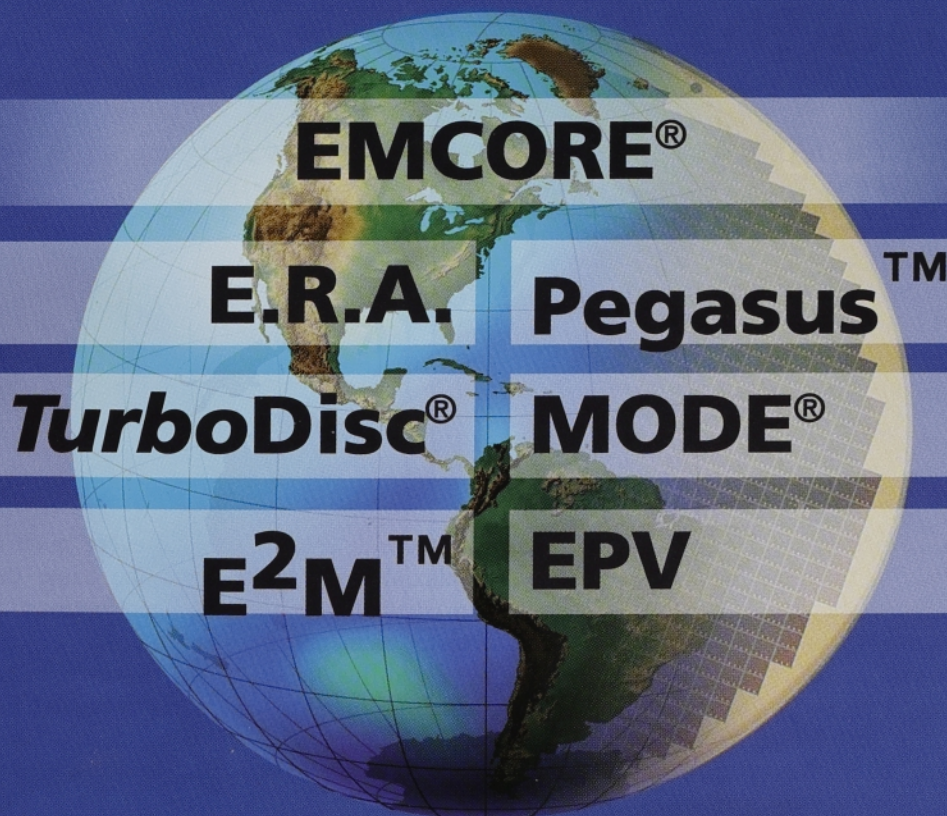
The top surfaces of the wafers were finally treated with a chemical-mechanical polish, cleaned and brought into contact under pressure at room temperature to form a hydrophilic bond. An anneal was applied to strengthen this bond.

The SonG process is completed by removing the SIMOX substrate down to a thickness of 50  $\mu\text{m}$ , and selectively wet etching the remaining silicon of the SIMOX wafer substrate with respect to the buried oxide. At this stage the oxide/silicon/oxide sandwich on the GaAs wafer surface is about 1.3  $\mu\text{m}$  thick (Figure 2).

To test the bonded wafer under 'real' thermal processing conditions, heating experiments were performed up to 700°C, with no sign of bond degradation. This process opens the door to further research leading into the monolithic integration of GaAs-based optoelectronic devices with silicon CMOS electronics using the epitaxy-on-electronics technique. SonG substrates can also be used to advantage with more common indium bump bonding hybrid integration techniques of optoelectronic integration.



# Resources to Fuel the Evolution



EMCORE Corporation is the leading provider of integrated compound semiconductor solutions. Due to superior uniformity, reliability and throughput, prominent manufacturers throughout the world turn to EMCORE. EMCORE's production systems, materials, and processes are the enabling technology behind a variety of advanced electronic and photonic applications.

- **E.R.A.**—One of the largest MOCVD-based development laboratories in the world, the EMCORE Research and Applications laboratory provides critical feedback for designing new *TurboDisc*® systems, and improving the performance of epitaxial wafers and package-ready devices.
- **TurboDisc**®—Manufactures the most reliable high volume Metallorganic Chemical Vapor Deposition (MOCVD) systems in the world, proven to produce epitaxial material with excellent uniformity and reproducibility.
- **E²M**™—Using *TurboDisc*® MOCVD production systems, E²M is the largest manufacturer of epitaxial wafers and provider of wafer foundry services. Wafers are produced on a foundry basis in partnership with specific customers according to the customer's requirements, and under strict confidentiality.
- **Pegasus**™—Designs and produces package-ready devices to meet the customer's performance and packaging requirements; and manufactures a full line of InSb sensor products for automotive and non-automotive applications. The devices are fabricated from epitaxial materials created by the E²M division; and then tested according to specifications worked out in partnership with the customer.
- **MODE**®—Designs and manufactures Vertical Cavity Surface Emitting Lasers (VCSELs), which provide enhanced performance benefits to optoelectronic applications such as Internet access, onboard photonics, gigabit Ethernets, DVDs, and fiberoptic switching.
- **EPV**—Manufactures advanced solar cells to accomplish satellite weight reduction by 50%, wing area reduction, improved radiation tolerance, and higher light to power conversion, which increases payload capacity and economic return.

EMCORE Corporation Headquarters  
394 Elizabeth Avenue, Somerset, NJ 08873 USA  
Tel: + 1 (732) 271-9090 • Fax: + 1 (732) 271-9686  
WEB: [www.emcore.com](http://www.emcore.com) • E-mail: [info@emcore.com](mailto:info@emcore.com)





# Characterization of InP Substrates for Large-Area Focal Plane Arrays

*High yield, large-area detector arrays for near-IR cameras have created a unique requirement for larger diameter semiconducting InP wafers.*

GREGORY H. OLSEN,<sup>1</sup> MICHAEL J. LANGE, ALAN. R. SUGG, MARTIN H. ETTEBERG, JOHN J. SUDOL, and STEVEN R. FORREST\*

Sensors Unlimited, Inc., Princeton, NJ

\* Princeton University, Princeton, NJ

Near-infrared cameras, which detect emissions in the 0.9-1.7  $\mu\text{m}$  range, are gaining in importance for applications such as ice detection on aircraft and bridges, night vision, laser-beam profiling, and semiconductor wafer analysis (Figure 1). Due to a very high room temperature sensitivity ( $D^* > 1 \times 10^{13} \text{ cm (Hz)}^{1/2}/\text{W}$ ), InGaAs/InP detectors are highly suited for near-IR sensing and imaging applications.

In order to fabricate these detectors, n-type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  epitaxial layers are grown on 2-inch (51 mm) diameter semiconducting wafers. Detector elements or pixels are formed by Zn diffusion to create p-n junctions, which (after nitride passivation) are subsequently hybridized by bump bonding with indium to a silicon multiplexer (Figure 2).

## Demand for Larger Wafers

The first cameras appeared in a 128 x 128 pixel format, but are now sold as 320 x 240 arrays with a long dimension of 14 mm [see CS 4(4) p. 20]. In addition, 256 x 1 and 512 x 1 linear arrays are also available for signal monitoring in wavelength division multiplexing applications. In future, focal plane arrays will feature 640 x 512 pixels on a chip size of 12 x 18 mm. Clearly, only a certain number of these large detector arrays can be obtained from a single InP substrate. At present, only four detector chips are obtained per 2-inch wafer, and this is creating a need for larger diameters. Also,

since every pixel in the array needs to have the same detectivity, this places stringent uniformity requirements on the substrates.

However, larger wafers are not seen as a priority for the telecommunications laser industry, the biggest market sector for semiconducting InP. One of the reasons is that much of the work, which includes forming the facets and measuring the devices, can only take place at the bar level. In addition, burn in is at the chip level. As most of the work takes place in these phases, it is uneconomical to throw bad die out, and increases in wafer size do not affect this situation. Currently, bottlenecks are experienced at later stages, such as test and burn-in, rather than from wafer throughput constraints [see CS 5(3), p.28].

The focal plane array application therefore creates a unique requirement for larger size InP wafers. To address this, last year Sensors Unlimited was awarded a major program from the National Institute of Standards and Technology Advanced Technology Program (NIST-ATP) Photonics Division to scale up InGaAs/InP wafer processing from 2-inch to 4-inch diameter InP. Some of the results of this program are described below.

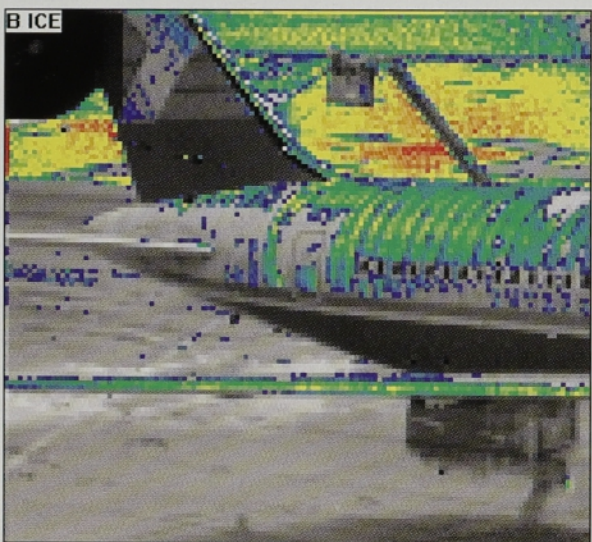
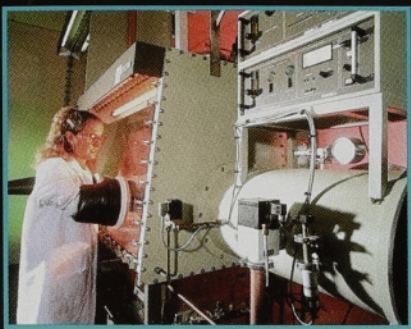


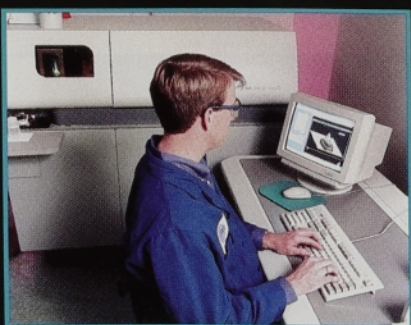
Figure 1. Near-IR cameras have evolved from expensive military systems into affordable technology for civil applications. InGaAs/InP-based room temperature cameras can improve safety at airports by detecting the presence of ice prior to take-off. In the image, the green contrast corresponds to the ice.

<sup>1</sup> Adapted from G.H. Olsen et al, a presentation given at the IPRM '99, Davos, Switzerland, May 16-20, 1999.





**Manufacture**



**Analysis**



**Precursor Screening by CVD**



# High Purity Chemicals for CVD

**Extensive range  
of precursors for:**

**Silicon Technology  
III-V and II-VI MOVPE  
Superconductors and  
metal oxides**

**Continuous innovation  
through collaborative  
research in all aspects  
of MOVPE, CBE and  
CVD processes.**

## **EPICHEM UK**

Power Road • Bromborough  
Wirral, Merseyside L62 3QF

Tel: (44) 151-334-2774

Fax: (44) 151-334-6422

## **EPICHEM USA**

4905 Tilghman Street • Suite 150  
Allentown, PA 18104

Tel: (610) 706-0606

Fax: (610) 706-0888

**[WWW.EPICHEM.COM](http://WWW.EPICHEM.COM)**



## Scaling Up

Clearly, to improve the yield of large-area chips, an increase in wafer size is an economical solution. Currently, a 2-inch wafer yields 4 devices, each chip costing \$2500. An increase to 24 devices and potential for devices costing \$400 is possible with 4-inch (100 mm) InP substrates.

However, scaling up to the larger wafer sizes is accompanied by many technological hurdles, not least the difficulty in wafer handling, but also the processing issues involved. These include the zinc diffusion process for p-type doping, which is not amenable to scaling up and would be a limiting factor in the processing stage for InP. Scaling up also places constraints on substrate and epitaxy uniformity. InP wafers will be required to achieve dark currents (the background current in the absence of light) of less than 10 pA, with a uniformity of  $\pm 5\%$  across a 2-inch span.

Near-IR detectors based on the chips used in Sensors Unlimited's cameras represent a method of characterizing larger InP wafers. These chips consist of large 2-dimensional arrays of uniform, densely-packed p-i-n diodes. The dark current values of these devices are an extremely sensitive, quantitative measure of defect density and material quality. In this article we report the use of  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  photodetectors to characterize processed epiwafers grown on 2-inch wafers using dif-

ferent growth techniques, and some initial results for MBE growth on 3-inch (76 mm) diameter InP substrates.

In addition, we have characterized commercially available 2-, 3- and 4-inch diameter InP substrates using transmission x-ray topography (XRT). Finally, advances in device processing of larger epiwafers, including a new zinc diffusion process, will also be discussed.

## Wafer Characterization: 2-, 3- and 4-Inch InP

The typical defect density of commercially available InP substrates can be seen in the transmission XRT images in Figure 3. Sulfur-doped ( $S \sim 3 \times 10^{18}\text{cm}^{-3}$ ) 2- and 3-inch diameter semiconducting substrates, and iron-doped 4-inch diameter semi-insulating (SI) substrates are shown. In general, the defects mostly comprise grown-in dislocations, with slip-dislocations evident near the wafer edges.

The 2-inch sulfur-doped InP wafer shown in Figure 3a is nearly defect free in the middle, with slip bands, probably due to thermal stresses, evident within 10 mm of the edge. The 3-inch sulfur-doped InP substrate (Figure 3b) also consists of good quality material in the middle, but contains a larger region of slip bands at the edge. The slip bands present in both sizes of wafer arise from thermal gradients during growth, and can be reduced by increasing the sulfur doping to a value

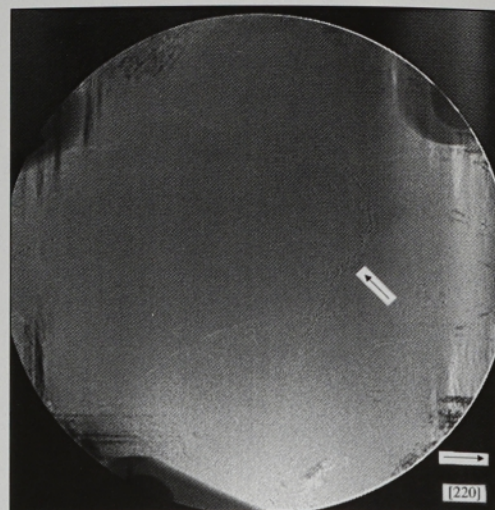


Figure 3a. 2-inch diameter S-doped; arrow indicates a polishing-induced defect.

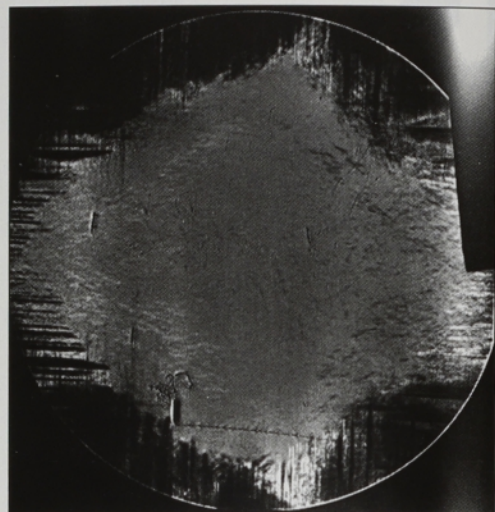


Figure 3b. 3-inch diameter S-doped.

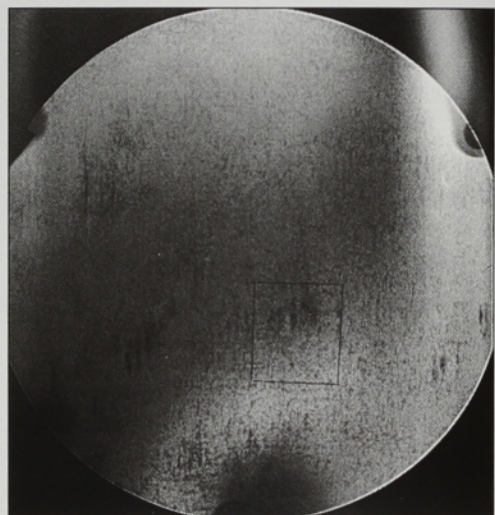


Figure 3c. 4-inch diameter Fe-doped.

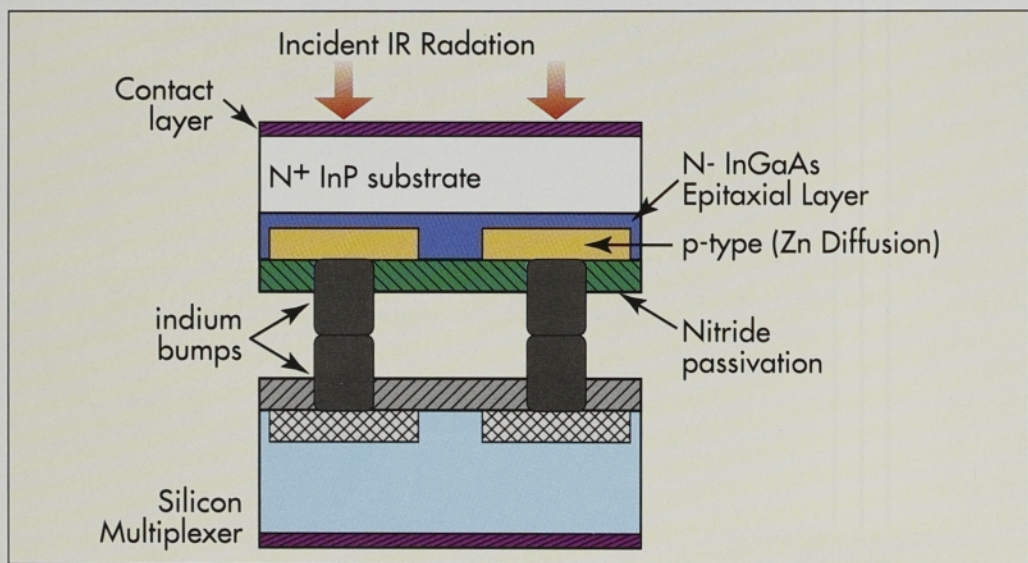


Figure 2. Schematic diagram showing two pixels of Sensors Unlimited's InGaAs/InP-based detector, bump-bonded to a Si multiplexer.

Transmission XRT images of InP substrates (courtesy of B. Jiang and G. A. Rozgonyi, North Carolina State University).



# New Products/ New Literature

## Information about New Products/New Literature Advertisements

An ad in New Products/New Literature is the most cost effective way to introduce your latest developments to the entire compound semiconductor industry. Quarter (~100 words) and half (~200 words) page ads are available, and they can be submitted as Quark or Pagemaker files, or as unformatted text and graphics.

For more information, contact:

Marie Meyer  
Franklin Publishing  
163 Cabot Street, Beverly  
MA 01970 USA

TEL [1] 978 927 9994 • FAX [1] 978 927 9893  
Email: mmeyer@compsem.com

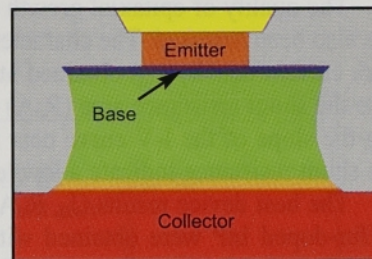
# ISE

Join the leaders:  
**HP Labs and HRL**  
in using the most advanced software for  
**Heterojunction Device  
Simulation Featuring...**

- ◆ Arbitrary Semiconductor Materials
- ◆ 1D/2D and true 3D Geometries
- ◆ State-of-the-art Transport Models

- ✓ Drift Diffusion
- ✓ Thermal (lattice temperature)
- ✓ Hydrodynamic

- ◆ Most robust numerical algorithms
- ◆ Highest quality grids
- ◆ Graphical User Interface for Device Structure Creation



**Integrated Systems Engineering, Inc.**  
111 N. Market Street, San Jose, CA 95113  
Tel (408) 918-6300 ext. 110  
Fax (408) 918-6306  
sales@ise.com or visit www.ise.com

Come visit us at GaAs IC'99, October 17 - 19, Booth #29

# Lepel®

## MODEL LCG

*Induction Heating Power Supply For Crystal Growing*

- 1% power output regulation assures uniform crystal growth
- Automatic restart with power ramp-up allows continued growth after power interruption
- Power output set point can be adjusted from a remote controller
- Extended power range allows output to be reduced to less than 2% for controlled crystal cool down



# Lepel

**Product Information:** Lepel West, 445 Capricorn Street, Brea, CA 92821 • Tel: (714) 257-1360 • Fax: (714) 257-1443  
**Corporate Headquarters:** 50 Heartland Boulevard, Edgewood, NY 11717 • Tel: (800) 548-8520 • (516) 586-3300 • Fax: (516) 586-3232  
**Web Address:** <http://www.lepel.com> • **E-mail Address:** [lepel@lepel.com](mailto:lepel@lepel.com)  
Lepel® is a registered trademark of Lepel Corporation., an Inductotherm Company. © 1999 Lepel Corporation.



greater than  $5 \times 10^{18} \text{ cm}^{-3}$ . This effect is similar to precipitation hardening, which is used to reduce the dislocation motion in metals.

The 4-inch iron-doped (SI) InP substrate (resistivity  $\sim 3.8 \times 10^8 \text{ ohm-cm}$ ) shown in Figure 3c contained a uniform defect density of around  $1 \times 10^4 \text{ cm}^{-2}$ , with no evidence of slip bands near the edge.

## Epitaxial Growth on 2- and 3-Inch InP

The quality of epitaxial growth on 2-inch diameter wafers has also been assessed. The characterization results include the dark current density ( $J_d$ ) obtained at a reverse bias of 1 V, and also the shunt resistance area ( $R_oA$ ) product, measured by taking the slope of the I-V curve near zero bias. High values of the shunt resistance indicate a low leakage current.

The best device results ( $J_d$ ,  $R_oA$ , uniformity) achieved for sulfur-doped InP were obtained with devices processed from  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layers grown by OMVPE (see Table). Good films were also obtained with chloride-based vapor phase epitaxy (C-VPE), but so far results with MBE have not been as promising.

For the MBE-grown epitaxial layers, while the shunt resistance and dark current density values are very uniform from different portions of the 2-inch wafer, the  $R_oA$  value is the lowest obtained of the three growth methods ( $10,000 \text{ ohm-cm}^2$ ), suggesting high leakage currents.

The MOVPE-grown photodetectors exhibit  $R_oA$  values that are an order of magnitude higher than those grown by MBE, and exhibit  $J_d$  values of  $1 \mu\text{A/cm}^2$ . The C-VPE grown devices exhibit the most variation (10%) across the wafer. However, a  $R_oA$  value of  $80,000 \text{ ohm-cm}^2$  indicates low leakage currents.

It is not yet known whether these differences are fundamental in nature, e.g. due to vacancy concentrations, or are a result of the parameters chosen, e.g. growth temperature. We have processed several hundred OMVPE epiwafers in the last five years and have observed an order of magnitude improvement in shunt resistance from  $10,000$  to  $100,000 \text{ ohm-cm}^2$  during that time. Less than ten of the other kinds of wafers (MBE and C-VPE) have been examined, and improvements are expected in future. One interesting difference is that the top-most InP layer of the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$  photodetectors grown by OMVPE exhibits a much higher PL intensity than that for with MBE-grown devices. While not yet understood, this effect may well represent differences in point defect concentration, due to differences in growth conditions and temperature.

| Technique | $R_oA$ (ohm-cm <sup>2</sup> ) | $J_d$ (A/cm <sup>2</sup> ) | Uniformity |
|-----------|-------------------------------|----------------------------|------------|
| OMVPE     | 100,000                       | 1                          | 5%         |
| C-VPE     | 80,000                        | 2                          | 10%        |
| MBE       | 10,000                        | 8                          | 2%         |

**Table.** Photodetector data taken from  $40 \times 250 \mu\text{m}$  linear array  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$  pixels grown on 50 mm sulfur-doped InP wafers. The best results are obtained from OMVPE-grown devices, which exhibit the lowest leakage currents and dark current densities.

## 3" InP Photodetector Results

In the case of the 3-inch diameter InP substrates, we have just begun to fabricate photodetectors from  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  epitaxial layers grown in-house. However, 3-inch epitaxial wafers are also available from commercial sources (e.g. IQE in Cardiff, UK), and some telecommunication companies have also been working with larger diameter InP wafers.

To date, we have only examined MBE material, with results similar to those shown in the Table for 2-inch S-doped material. As we would expect from the results obtained above, better results would be expected with OMVPE. The high uniformity of these devices is encouraging for the long (256- and 512-element) linear arrays, with no evidence of 'dropouts', which are pixels with very high dark current or open circuits. This is a requirement for the monitoring of wavelength uniformity in dense wavelength division multiplexing systems used in high-capacity fiber optic systems.

## Spin-On Zinc Diffusion

Current commercial fabrication of InGaAs photodetectors uses closed-tube zinc diffusion for the p-n junction formation. This step is time-consuming and becomes unwieldy and very expensive for 3- and 4-inch wafers.

A better method for larger diameter wafers is to use a 'spin-on' zinc diffusion technique, which is similar to a photoresist application. A film of zinc phosphide dopant is spun onto the InP, and the wafer surface sealed with a thin glass coating. The dopant is then diffused with a rapid thermal anneal furnace to form the p-n junction. This can lead to reduced processing times (e.g. 2 hours, a factor of up to 2-3 x faster) and can be used for any wafer size. In addition, dark current values well within commercial specifications, i.e. less than  $2 \mu\text{A/cm}^2$ , have resulted from devices processed with this technique.

## Future

The crystallographic quality of the substrate has been found to have a significant effect upon detector and camera performance. 3-inch semiconducting (S-doped) InP wafers typically have been found to have a low defect density, and are suited to optoelectronic devices, which, prior to the introduction of  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  cameras, did not require a large chip size. 4-inch semiconducting (S-doped) InP substrates have become available in the last few months, but these have not yet been characterized for use in detectors.

However, the emerging use of InGaAs cameras for night vision, machine vision and ice detection could create an even greater demand for 4-inch diameter sulfur-doped InP substrates in future. Sensors Unlimited is currently developing a 'D-cell' sized camera: this is a small,  $320 \times 240$  pixel InGaAs camera that will consume only 2 W and remotely transmit the image to a monitor up to one mile away. Cameras mounted on vehicles, personnel, and in remote locations with a price tag of a few thousand dollars could be possible in the near future.

*The authors would like to thank NIST-ATP for financial support of this work.*



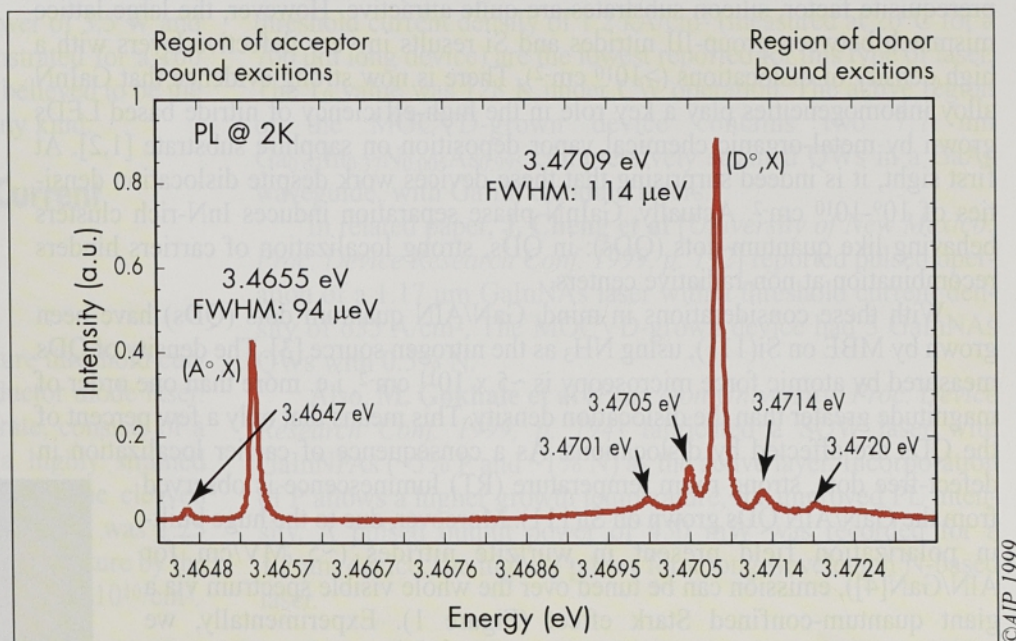
## Wide Bandgap Materials and Devices

### Homoepitaxial Growth of GaN With Extremely High Optical Quality

C. Kirchner et al, University of Ulm (Germany) and High Pressure Research Center (Poland)  
Appl. Phys. Lett., 1999, 75(8), p. 1098

GaN growth still suffers from the lack of a perfect substrate, and heteroepitaxial growth on sapphire and SiC results in high dislocation densities, limiting device performance and lifetime. Homoepitaxial growth implies matching of lattice parameters and thermal expansion coefficients, and GaN substrates also offer a high thermal conductivity for high power applications. Two-dimensional layer-by-layer growth can be obtained on GaN substrates and the generation of dislocations is inhibited, resulting in a reduction of the threading dislocation density by up to six orders of magnitude. This paper describes homoepitaxial MOVPE growth of extremely high optical quality GaN exhibiting a bound exciton photoluminescence peak linewidth of only 95  $\mu\text{eV}$ . This is almost one order of magnitude narrower than the best result reported for MOVPE-grown heteroepitaxial GaN (grown using lateral epitaxial overgrowth on sapphire).

The substrates used in this case were produced from atomic nitrogen dissolved in a gallium melt under high nitrogen pressure and high temperature, resulting in flat GaN platelets with an area of 100 mm<sup>2</sup>. A surface pretreatment with CAIBE was used to obtain excellent surface morphologies. The extremely sharp PL lines also reveal fine structures not previously observed for GaN.



PL of 1.5- $\mu\text{m}$ -thick undoped GaN at 2 K, grown homoepitaxially on a Ga-face oriented GaN bulk single crystal substrate. The linewidth was 95  $\mu\text{eV}$  for the bound exciton ( $A^0, X$ ).

### Red-light Emission from Eu-doped GaN

J. Heikenfeld et al, University of Cincinnati  
Appl. Phys. Lett., 1999, 75(9), p. 1189

Next generation full color displays are required to be compact, rugged and highly efficient, and are likely to be implemented in many cases using individual colored LEDs. However, integrating red, blue and green LEDs in the same material system proves to be a difficult challenge. One possibility is through the use of GaN doped with rare earth (RE) elements. GaN provides carrier generation to excite the RE element, which then emits at a specific wavelength. GaN is also transparent to visible RE emission and is thermally and chemically rugged. GaN:RE LEDs can produce green light through in-situ Er<sup>3+</sup> doping and red light through Pr<sup>3+</sup> doping. Here, red light is observed from Eu-doped GaN layers grown by MBE on a 2-inch p-Si(111) substrate. An ITO layer was sputtered onto the GaN:Eu layer to form optically transparent contacts. Both electroluminescence and photoluminescence were observed at room temperature with a dominant red line at 621-3 nm.



Photograph of red emission from a ring structure ITO/GaN:Eu LED of area  $7.65 \times 10^{-4} \text{ cm}^2$  and ring width 75  $\mu\text{m}$ , operating with 50 V and 0.6 mA. The dark notch in the upper part of the ring is caused by the probe tip obscuring the emission.



# Visible Emission from GaN Quantum Dots on Silicon

B. Damilano, N. Grandjean, F. Semond,  
J. Massies and M. Leroux  
CRHEA/CNRS  
Sophia Antipolis, France

A considerable research effort worldwide is presently devoted to the realization of solid-state semiconductor devices for white light production. Low cost being a prerequisite factor, silicon substrates are quite attractive. However, the large lattice mismatch between group-III nitrides and Si results in very defective layers with a high density of dislocations ( $>10^{10} \text{ cm}^{-2}$ ). There is now strong evidence that GaInN alloy inhomogeneities play a key role in the high-efficiency of nitride based LEDs grown by metal-organic chemical vapor deposition on sapphire substrate [1,2]. At first sight, it is indeed surprising that these devices work despite dislocation densities of  $10^9$ - $10^{10} \text{ cm}^{-2}$ . Actually, GaInN phase separation induces InN-rich clusters behaving like quantum dots (QDs): in QDs, strong localization of carriers hinders recombination at non-radiative centers.

With these considerations in mind, GaN/AlN quantum dots (QDs) have been grown by MBE on Si(111), using  $\text{NH}_3$  as the nitrogen source [3]. The density of QDs measured by atomic force microscopy is  $\sim 5 \times 10^{11} \text{ cm}^{-2}$ , i.e. more than one order of magnitude greater than the dislocation density. This means that only a few percent of the QDs are affected by dislocations. As a consequence of carrier localization in defect-free dots, strong room temperature (RT) luminescence is observed from the GaN/AlN QDs grown on Si(111). Moreover, due to the huge built-in polarization field present in wurtzite nitrides ( $\sim 5 \text{ MV/cm}$  for AlN/GaN[4]), emission can be tuned over the whole visible spectrum via a giant quantum-confined Stark effect (Figure 1). Experimentally, we achieved QD luminescence at RT from blue to orange (see Figure 2). Finally, the combination of four planes of QDs with properly chosen sizes results in the emission of white light emission [3]. Regarding applications, the use of such dots in actual devices, with electrical injection, is likely prohibited since AlN is insulating. Extension of this concept to the highly strained GaN/GaInN QD system will bypass the difficulties associated with AlN.

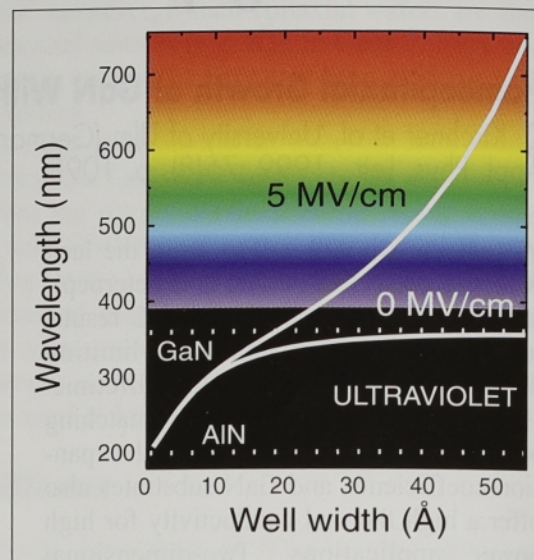


Figure 1: GaN/AlN quantum well emission wavelength versus well width with (marked as 5 MV/cm) and without (0 MV/cm) the built-in polarization field.

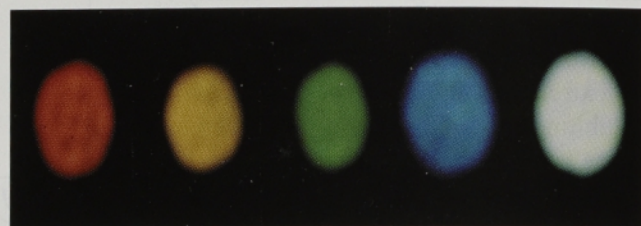


Figure 2: RT luminescence of GaN/AlN QDs of varying sizes obtained under HeCd (325 nm) laser excitation (the power density is  $300 \text{ mW/cm}^2$  and the spot size is  $1.5 \times 2 \text{ mm}^2$ ). The white spot corresponds to stacking of four planes of properly chosen size for white light emission by color addition.

- [1] Y. Narukawa et al., *Appl. Phys. Lett.* 1997, 70, p. 981  
[2] S. Nakamura and G. Fasol, 'The Blue Laser Diode', Springer - Berlin, 1997  
[3] B. Damilano et al., *Appl. Phys. Lett.* 1999, 75, p. 962  
[4] F. Widmann et al, *Phys. Rev. B*, 1998, 58, R15989

## Increased Thermal Conductivity in LEO GaN

V. Asnin et al, CUNY Brooklyn and Emcore  
*Appl. Phys. Lett.*, 1999, 75(9), p. 1240

Certain GaN devices including laser diodes and high power FETs would benefit greatly from more efficient heat extraction. Lattice thermal conductivity is a function of the mean free path of phonons and hence is determined by both phonon-phonon and phonon-defect scattering factors. Therefore, thermal conductivity is expected to increase in material with a lower defect density. A scanning thermal microscope was used to perform high spatial resolution thermal conductivity measurements on GaN samples grown by lateral epitaxial overgrowth (LEO). In a number of regions,

the thermal conductivity was found to be 1.7-1.8 W/cm.K, which is substantially higher than previous measurements (1.3 W/cm.K) made on bulk HVPE-grown GaN. Since the paper was published, the resolution of the system was improved to around  $1 \mu\text{m}$ . This was sufficient to distinguish overgrown material (i.e. material grown laterally over the mask) from material grown through the mask window. The thermal conductivity was clearly higher in the overgrown regions as a result of the lower dislocation density of this material.



# Optoelectronic Devices

## 3.5 W Quantum Dot Lasers

A. Kovsh et al, A.F. Ioffe Institute and Technische Universität Berlin  
Elec. Lett., 1999, 35(14), p. 1161

High power quantum dot lasers with an active region based on composite vertically coupled self-organized InAlAs-InAs QDs in an AlGaAs matrix were grown by MBE. Room temperature CW operation with a maximum output power of 3.5 W and peak conversion efficiency of 45% was demonstrated for a 100  $\mu\text{m}$  wide stripe with uncoated facets. These are believed to be the highest values ever reported for QD lasers of any kind.

## QD Laser with 26 A/cm<sup>2</sup> Threshold Current Density

G. Liu et al, University of New Mexico  
Elec. Lett., 1999, 35(14), p. 1163

This paper reports the lowest room temperature threshold current density, 26 A/cm<sup>2</sup>, from any semiconductor diode laser. The device, grown by MBE on a GaAs substrate, consists of a single InAs quantum dot contained within a highly strained In<sub>0.15</sub>Ga<sub>0.85</sub>As quantum well. The cavity length of the cleaved facet laser was 7.8  $\mu\text{m}$ , and the emission wavelength was 1.25  $\mu\text{m}$ . This "dot in a well" approach improves carrier capture by the dots and increases the density of the dots to around  $7 \times 10^{10}/\text{cm}^2$ .

## Mixed Group V-Nitride Lasers

The GaInN(P)As/GaAs material system has the potential to provide 1.3  $\mu\text{m}$  lasers with improved high temperature performance, due to strong electron confinement.

S. Sato and S. Satoh [Ricoh: Elec. Lett., 1999, 35(15), p. 1251] reported CW operation of a highly strained 1.3  $\mu\text{m}$  GaInNAs DQW ridge laser. The threshold current of 63 mA and threshold current density of 1.2 kA/cm<sup>2</sup> (measured at 20°C for a 700  $\mu\text{m}$  long device) are the lowest reported for this type of laser. The T<sub>0</sub> value was 128 K under CW operation. The active region of the MOCVD-grown device contains two 7.7 nm Ga<sub>0.63</sub>In<sub>0.37</sub>N<sub>0.005</sub>As<sub>0.995</sub> compressively strained QWs in a GaAs waveguide, with GaInP cladding layers.

In related paper, J. Cheng et al [University of New Mexico: Proc. Device Research Conf. 1999, p. 192] reported pulsed operation of a 1.17  $\mu\text{m}$  GaInNAs laser with a threshold current density of 635 A/cm<sup>2</sup>. The MOCVD-grown device had 3 GaInNAs QWs with 0.5% N.

Also, M. Gokhale et al [Princeton University: Proc. Device Research Conf. 1999, p. 194] fabricated a SQW laser with GaInNPAs (~5% P and ~1% N) as the active layer. Incorporation of P allows a higher growth temperature, for improved PL intensity. A pulsed output power of 450 mW was recorded for a 1.2  $\mu\text{m}$  device, the highest power for a long wavelength N-based laser.



Twelfth International Conference on  
Indium Phosphide and Related Materials  
**IPRM '00**  
**14-18 May 2000**  
*Williamsburg, Virginia USA*



**Sponsors: IEEE Lasers and Electro-Optics Society (LEOS) and IEEE Electron Devices Society (EDS)**

**Conference Program and Registration Information:** <http://www.ieee.leos/conferences>

**ABSTRACT DUE DATE: 10 December 1999**

IPRM '00 will continue the tradition of highlighting a wide variety of important developments in InP-related materials, devices, processing, and system applications. The venue for the millennial IPRM meeting is Williamsburg, in the culturally and historically rich Tidewater region of eastern Virginia.

*The following five topical areas comprise the scope of the Conference and papers are solicited in these areas:*

**Optoelectronics**  
**Electron Devices**  
**Epitaxy**  
**Processing**  
**Characterization and Bulk Materials**

**Conference Chair:** Russell D. Dupuis, The University of Texas at Austin, Austin TX, USA (e-mail: [dupuis@mail.utexas.edu](mailto:dupuis@mail.utexas.edu); 512 471-0957)

**Program Chair:** Brad Boos, Naval Research Laboratory, Washington DC, USA (e-mail: [boos@estd.nrl.navy.mil](mailto:boos@estd.nrl.navy.mil); FAX: 202 767-0455)

**Publicity Chair:** Joe Lorenzo, AF Research Laboratory, Hanscom AFB MA, USA (e-mail: [lorenzo@maxwell.rl.plh.af.mil](mailto:lorenzo@maxwell.rl.plh.af.mil); FAX: 617-377-6765)

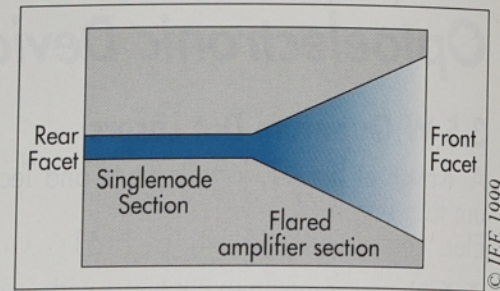


## Very High Power 1.48 $\mu\text{m}$ Lasers

A. Mathur et al, SDL  
Elec. Lett., 1999, 35(12), p. 983

High power 1.48  $\mu\text{m}$  laser diodes are desired for pumping erbium-doped fiber amplifiers, and narrow stripe diode lasers have previously reached an output power of 380 mW. This paper reports significantly higher output powers from an MOCVD-grown laser structure with a compressively strained MQW InGaAsP active region. Gain-guided broad area lasers with 100  $\mu\text{m}$  wide stripes had an output power of 3.2 W at 9.5 A. Narrow stripe singlemode lasers with 3-4  $\mu\text{m}$

wide stripes showed an output power of 410 mW, the highest reported output power for any InP-based single lateral mode laser. A flared laser structure was also fabricated, consisting of a single-mode lasing section and a laterally tapered amplifying section (see figure). The output from the ridge section is amplified in the tapered section while it is diverging in the lateral direction. The maximum output power under CW operation was 2.35 W, and 1.8 W of diffraction-



*Schematic diagram of a flared laser. The singlemode output from the 1000  $\mu\text{m}$  long ridge section is amplified in the 1500  $\mu\text{m}$  long tapered section while it is diverging in the lateral direction.*

limited power was also recorded. Both these values are records for flared lasers in the 1.48-1.55  $\mu\text{m}$  wavelength range.

## High Power 1.8-1.9 $\mu\text{m}$ Lasers

M. Maiorov et al, Sensors Unlimited and Sarnoff Corp.,  
IEEE Photonics Tech. Lett., 1999, 11(8), p. 961

X. He et al, Opto Power, Elec. Lett., 1999, 35(16),  
p. 1343

Diode lasers at 1.8-2.1  $\mu\text{m}$  have potential applications as high power pumps and for medical uses, remote sensing and eye-safe illumination. Maiorov et al. report broad waveguide, separate confinement heterostructure InGaAs/InP QW lasers, containing two InGaAsP QWs. Single element lasers with an aperture width of 100  $\mu\text{m}$  and a cavity length of 2 mm had a CW output of 2.1 W at 15°C, with emission at 1.83  $\mu\text{m}$ . A 1 cm wide, 10 element array reached a power level of 11.5 W.

He et al report a 1.9  $\mu\text{m}$  laser with a single strained InGaAs QW. CW powers of 1.12 W and 1.43 W were recorded for 100  $\mu\text{m}$  and 150  $\mu\text{m}$  aperture width devices, respectively. A 1 mm array with sixteen 100  $\mu\text{m}$ -wide aperture devices had an optical power of 13.5 W at 10°C, and 11 W at 25°C. A 500 hour lifetest indicated that these diodes operate reliably at 7 W at 20°C, and 6 W at 30°C.

## Temperature-Insensitive 1.06 $\mu\text{m}$ Lasers

H. Asano et al, Fuji Photo Film Co. (Japan)  
Appl. Phys. Lett., 1999, 75(21), p. 3090

In optical communications systems, temperature-insensitive laser characteristics are desired for high reliability, stable operation and low cost of laser modules without the need to use a thermo-electric cooler. Here, a characteristic temperature for the threshold current ( $T_0$ ) of 437 K is achieved with no variation in slope efficiency in the 20-80°C range. The 1.06  $\mu\text{m}$  buried-ridge laser features a single, compressively strained InGaAs QW, large bandgap (1.63 eV) GaAsP barriers with tensile strain, and a large bandgap AlGaInP current blocking layer.

## Wafer-Bonded Bottom-Emitting VCSELs on GaP

C-K Lin et al, University of Southern California, LA  
IEEE Photonics Tech. Lett., 1999, 11(8), p. 937

Bottom-emitting VCSEL arrays are highly suited for flip-chip bonding to Si circuitry [see CS 4(9), p. 11]. However, GaAs substrates are absorbing at the standard wavelength for short distance communications of 850 nm. In this paper, a wafer-bonding technique is used to transfer the VCSEL array from a GaAs substrate to a transparent GaP substrate. The two wafers were placed in contact, subjected to a pressure of 2.5 kg/cm<sup>2</sup> and annealed in H<sub>2</sub> ambient at 750°C for 30 minutes. The GaAs substrate was then removed and oxide-aperture VCSELs were fabricated. Devices with a 4 x 4  $\mu\text{m}^2$  current aperture exhibited a 24% external quantum efficiency and a threshold current of 400  $\mu\text{A}$ . Threshold voltages ranged from 1.71 to 1.8 V for different aperture sizes.

## Monolithic 1.55 $\mu\text{m}$ VCSEL with Sb Mirrors

E. Hall et al, University of California at Santa Barbara  
Elec. Lett., 1999, 35(16), p. 1337

A 1.55  $\mu\text{m}$  VCSEL operating at room temperature under electrical pumping in the pulsed mode has been fabricated from a single, MBE-grown epitaxial structure. The lower and upper DBR mirrors were n-type AlGaAsSb/AlAsSb layers, with 23 and 30 periods respectively, lattice-matched to the InP substrate. The use of two n-type mirrors reduces both the voltage drop and optical losses in the structure. A thin, heavily doped tunnel junction was incorporated between the top of the active layer and the upper n-type mirror. The active region contained 5 AlInGaAs QWs. Pillars were etched to fabricate the devices; a 25  $\mu\text{m}$  diameter pillar had a threshold current of 7 mA, a threshold current density of 1.4 kA/cm<sup>2</sup>, an external quantum efficiency of 18% and a maximum power of ~2 mW. Lasing was achieved up to 45°C.

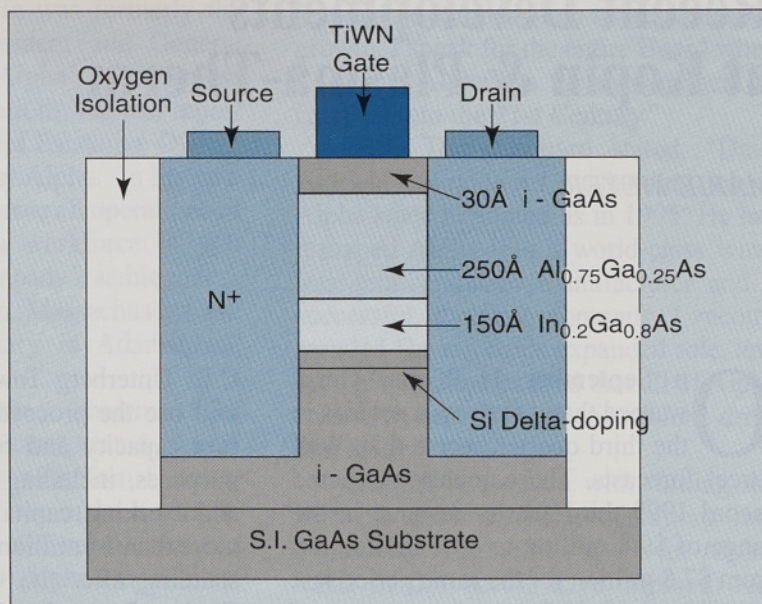


# Microelectronic Devices and Circuits

## True Enhancement-mode FETs

E. Glass et al, Motorola Semiconductor Products Sector  
Proc. RFIC Symp. 1999, p. 135

Elimination of the negative voltage generator and drain supply switch from the power amplifier in mobile phone handsets is an effective way to reduce product cost and size [see CS 5(4), p. 42]. Unlike MESFETs and PHEMTs, HBTs and enhancement-mode (E-mode) FETs require only a single supply voltage. Motorola has developed a true E-mode device suitable for dual-band, dual-mode power amplifier applications. The device (see figure) has sufficiently low leakage current to allow elimination of the drain switch, and has a turn-on voltage of 1.8 V at a leakage current of 1 mA/mm. In TDMA mode at 1800 MHz and  $V_{ds} = 3.6$  V, a PAE of 50.3% was achieved at +30.6 dBm output power, with -30 dBc adjacent channel power and -49 dBc alternate channel power.



Cross-sectional view of Motorola's enhancement mode device structure.

## High-Reliability, Non-Hermetic MMICs

D. Leung et al, TRW  
Proc. RFIC Symp. 1999, p. 135

Although GaAs PHEMT MMICs operate in a hermetic environment for space and defense applications, non-hermetic operation is desired to reduce costs for commercial applications. This paper reports reliability evaluations of Ka-band low noise MMIC amplifiers in an air environment. Devices were fabricated on TRW's standard 0.15  $\mu$ m gate PHEMT process, using a double-doped  $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}/\text{In}_{0.22}\text{Ga}_{0.78}\text{As}/\text{GaAs}$  structure. A three-temperature lifetest in an air ambient resulted in an activation energy of 1.6 eV, with a projected median-time-to-failure of  $7 \times 10^9$  hours at a junction temperature of 125°C.

## 123 W MESFET-based PA

S. Morimoto et al, Matsushita  
IEEE MTT-S Int'l Microwave Symp. Digest, 1999, p. 325

A compact power amplifier module for third generation cellular systems (2.1-2.2 GHz) was built using a simplified Wilkinson's power divider/combiner circuit. The module demonstrated 123 W (103 W) output power with a record high efficiency of 50% (54%) at a drain voltage of 12 V (10 V) with a module size of 36 x 70 mm<sup>2</sup>. An MOVPE-grown MESFET structure was used; the thickness and doping of the channel layer were designed to provide a gate-to-drain breakdown voltage of more than 30 V.

## Single chip HBT MMIC for GSM 900/1800

K. Yamamoto et al, Mitsubishi Electric Corp.  
IEEE MTT-S Int'l Microwave Symp. Digest, 1999, p. 1397

This paper reports a single-chip AlGaAs/GaAs HBT MMIC power amplifier for GSM900/1800 applications. The IC incorporates on-chip HBT bias switching circuits and operates at 3.2 V. An output power of 34.5 dBm and a PAE of 50% were delivered for GSM900 operation, and 32 dBm output power and 42% PAE were recorded for GSM1800 operation. The die size was 1.38 x 2.75 mm<sup>2</sup> and the 26-lead surface mount plastic package measured 7.0 x 6.4 x 1.0 mm<sup>3</sup>.

## Enhancement-mode HFETs

S. Yoshida et al, NEC USLI Device Development Labs  
IEEE MTT-S Int'l Microwave Symp. Digest, 1999, p. 1183

A fully enhancement-mode heterojunction FET with  $V_{th} = +0.25$  V is reported, consisting of a double-doped structure with two n-AlGaAs layers on both sides of the undoped InGaAs channel. The device exhibited 79.6% PAE at 31.5 dBm output power and 11.5 dB gain at 836 MHz. A two-stage power amplifier with a single supply voltage of +3.5 V exhibited 71.9% PAE, 31.5 dBm output power and 24.5 dB gain at 836 MHz. The total leakage current under zero gate voltage was 5  $\mu$ A.



## Recent Developments at Kopin & Plasma-Therm

MARIE MEYER

On September 16 Kopin Corp. warned that it foresaw a net loss in the third quarter, worse than Wall Street forecasts. The company predicted record 1999 third-quarter revenue in the range of \$9.4 million to \$9.7 million, up from \$7.8 million for the same period last year. However, it forecast a net loss of \$0.03 to \$0.05 a share (\$370,000 - \$650,000). Analysts had been predicting a profit of \$0.03 a share. Kopin blamed the shortfall on "increased ramp-up costs for the CyberDisplay and HBT GaAs businesses, combined with our aggressive pricing strategy for display adoption." Kopin expects to report its third-quarter results October 28. The company reported third-quarter earnings of \$0.04 a share last year.

Despite this bad news, the company is feeling sufficiently confident about its future prospects to announce plans to offer an additional 1.8 million shares to the public. The underwriters are Credit Suisse First Boston, CIBC World Markets, Pacific Growth Equities and

C.E. Unterberg Towbin. The company will use the proceeds to expand production capacity and for general corporate purposes, including capital expenditures and working capital. Kopin will have more than 14 million common shares outstanding after the offering, which was filed on September 20.

In other news, TelecomAsia Plc announced on September 17 that it has sold to unidentified buyers its 15 percent stake in Kopin for about \$35.25 million. The Thai telecoms firm had paid approximately \$27 million for its holdings.

### Business Picking Up for Plasma-Therm

On September 16 Plasma-Therm, Inc. announced its third quarter 1999 results. For the three months ended August 31, the company reported a net income of \$437,903, up 19.6% over the same period last year. Revenues for the quarter were \$10.5 million, down slightly from the same period in 1998. For the

first nine months of 1999, Plasma-Therm recorded sales of \$29 million, down 23.6% compared to the same period in 1998.

However, the worst may be behind them. The company's backlog was \$16 million at the end of the quarter, up 60% over the previous quarter. The increase was attributed to the continued growth in demand for wireless communication products and a general recovery in the semiconductor industry. This backlog is the highest since the first quarter of 1998. Plasma-Therm's book-to-bill ratio (orders received compared to orders shipped) has increased from a low of 0.5 in the first quarter to 1.55 for the third quarter.

On the downside, the company has been forced to delay the introduction of its first physical vapor deposition (PVD) system. According to Scott Deferrari, President of Plasma-Therm, R&D efforts to refine this product line will continue. However, he said, at this time the significant increase in backlog that the company is experiencing, "warrants that

**Kopin - Last 12 Months**



**Plasma-Therm - Last 12 Months**





we apply all of our energies to ensure that we deliver our current offering of products in a timely manner." The first PVD system is scheduled for shipment in the first quarter 2000. In addition, the company is further delaying construction on its proposed R&D, applications and training center.

Plasma-Therm sells systems for a variety of plasma etch and deposition processes, including reactive ion etch (RIE), inductively coupled plasma (ICP) etch, electron cyclotron resonance (ECR) deposition, plasma enhanced chemical vapor deposition (PECVD), and high density plasma (HDP) deposition. Processes are available for many materials, including GaAs and InP. In fact, compound semiconductors represent Plasma-Therm's largest market, representing 52% of the 1999 bookings to date. Their second largest niche is photomask etching, which has accounted for 23% of bookings to-date in 1999.

"Our return to profitability and the significant increase in backlog make us very optimistic about the future and have provided us with good visibility in the near term," said Deferrari. "Our fourth quarter looks excellent with bookings/backlog expected to be greater than or equal to 1.5, revenue topping the \$11 million mark and earnings rising at least 50% sequentially. In looking to the year 2000, we are expecting an accelerated recovery in our business and continued growth in revenue and earnings."

Shares in Plasma-Therm got an added boost on September 18 when Needham & Co. put out a "buy" recommendation on the company. Analyst Leonard Sanders says that Plasma-Therm has carved out a solid niche in such areas as RIE, PECVD and ICP modules for SiN etch and GaAs via hole etching and thin film deposition. He considers the company to be "the well-known and established leader" in this segment, and he predicts that they will remain the dominant force in this market.

In the compound semiconductor arena, Plasma-Therm's main competitors are Oxford Plasma Technology and Surface Technology Systems (STS), a Sumitomo subsidiary. Both of those companies are based in the UK.

## New President for Alpha

David Aldrich has been named as President and Chief Operating Officer of Alpha Industries. He was formerly the Executive Vice President and General Manager of Alpha's Wireless Semiconductor operations. He will report to Tom Leonard, Chief Executive Officer and Vice Chairman of Alpha. In his new role, Aldrich will oversee all operations of Alpha, which has a workforce of 950 employees at the company's semiconductor facility in Woburn, Massachusetts and its ceramics subsidiary in Adamstown, Maryland.

George Kariotis, Chairman of Alpha's Board of Directors, stated, "Alpha is in excellent hands with Tom Leonard and Dave Aldrich. They make a terrific team. Dave will now take on an expanded role, directing all of Alpha's operations and working with Tom on strategic initia-

tives, including acquisitions and positioning Alpha for the future. Tom has done an extraordinary job in turning Alpha around, creating shareholder value and leading the company into its next phase of growth. I speak for the entire Board when I say that Alpha has the management to carry us into the 21st Century."

CEO Tom Leonard stated, "Dave Aldrich has done an outstanding job at Alpha since he joined us in 1995. He has reshaped Alpha into a world-class wireless semiconductor manufacturer and a successful, dynamic company. I recommended Dave for this expanded role, and I am pleased and excited that all of Alpha will now benefit from his vision, drive and ability."

Aldrich is credited with turning the Wireless Semiconductor operations into the primary engine of growth for Alpha. Sales in this sector have climbed over 55% in the last two years.

| Company                                            | Symbol | Exchange  | Closing Price<br>Aug 30 | 52 Week<br>Low | 52 Week<br>High | Market<br>Cap | P/E<br>Ratio |
|----------------------------------------------------|--------|-----------|-------------------------|----------------|-----------------|---------------|--------------|
| <b>GaAs ICs</b>                                    |        |           |                         |                |                 |               |              |
| Alpha Ind.                                         | AHAA   | NASDAQ    | 55.25                   | 5.75           | 59.75           | 1.071B        | 42.18        |
| Anadigics                                          | ANAD   | NASDAQ    | 34.75                   | 4.63           | 39.88           | 516.8M        | -            |
| Celeritek                                          | CLTK   | NASDAQ    | 6.69                    | 2.50           | 7.13            | 49.4M         | -            |
| Conexant                                           | CNXT   | NASDAQ    | 81.88                   | 13.00          | 83.88           | 7.980B        | -            |
| RFMD                                               | RFMD   | NASDAQ    | 48.25                   | 3.63           | 54.88           | 3.822B        | +            |
| TriQuint                                           | TQNT   | NASDAQ    | 65.75                   | 7.31           | 72.31           | 957.9M        | 70.95        |
| Vitesse                                            | VTSS   | NASDAQ    | 89.25                   | 17.13          | 97.50           | 6.849B        | +            |
| <b>Optoelectronics</b>                             |        |           |                         |                |                 |               |              |
| APA Optics                                         | APAT   | NASDAQ    | 6.25                    | 4.00           | 10.00           | 53.2M         | -            |
| Coherent                                           | COHR   | NASDAQ    | 21.56                   | 7.50           | 21.88           | 518.8M        | 47.92        |
| Cree                                               | CREE   | NASDAQ    | 40.44                   | 6.56           | 44.75           | 1.183B        | 91.90        |
| JDS Uniphase                                       | JDSU   | NASDAQ    | 109.00                  | 15.63          | 120.88          | 18.885B       | -            |
| Ortel                                              | ORTL   | NASDAQ    | 16.00                   | 6.00           | 19.75           | 191.6M        | -            |
| SDL                                                | SDLI   | NASDAQ    | 84.00                   | 4.06           | 92.75           | 2.625B        | +            |
| Uniroyal Tech.                                     | UTCI   | NASDAQ    | 9.88                    | 7.25           | 12.63           | 119.3M        | 25.99        |
| <b>Materials and Equipment</b>                     |        |           |                         |                |                 |               |              |
| ATMI                                               | ATMI   | NASDAQ    | 34.88                   | 11.25          | 38.00           | 910.6M        | +            |
| AXT                                                | AXTI   | NASDAQ    | 17.75                   | 5.25           | 36.19           | 330.5M        | 40.34        |
| Emcore                                             | EMKR   | NASDAQ    | 17.00                   | 6.38           | 28.75           | 226.6M        | -            |
| Kopin                                              | KOPN   | NASDAQ    | 29.88                   | 11.38          | 40.75           | 375.0M        | -            |
| PlasmaTherm                                        | PTIS   | NASDAQ    | 5.00                    | 2.06           | 5.13            | 56.1M         | -            |
| Spire                                              | SPIR   | NASDAQ    | 4.13                    | 2.25           | 5.69            | 13.4M         | -            |
| <b>European Companies (Currency data in Euros)</b> |        |           |                         |                |                 |               |              |
| Aixtron                                            | AIX    | Neur Mkt. | 89.00                   | 34.10          | 98.50           | 1.335B        | +            |
| IQE plc                                            | IQEP   | Easdaq    | 14.18                   | 11.73          | 15.14           | 187.5M        | +            |
| Picogiga                                           | PICO   | N. Marche | 18.05                   | 9.91           | 22.11           | 28.5M         | 37           |

- = Loss in most recent 4 quarters    + = Over 100



## November

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

November 8-11  
San Francisco, California  
<http://www.ieee.org/society/leos/>

### 7th Int'l Workshop on Electron Devices and Optoelectronic Applications (EDMO '99)

November 22-23  
King's College, London, UK  
<http://www.ee.kcl.ac.uk/~COE/edmo99.html>

### IEE Tutorial Colloquium on Design of RFICs and MMICs

November 24, 1999  
Savoy Place, London, UK  
<http://www.iee.uk/Events/e24nov99.htm>

## December

### 1999 Fall MRS Meeting

November 29-December 3  
Boston, MA  
<http://www.mrs.org/meetings/fall99/>

### 1999 IEEE International Electron Devices Meeting (IEDM)

December 5-8  
Washington, DC  
Contact: Ms Phyllis Mahoney  
[phyllism@widerkehr.com](mailto:phyllism@widerkehr.com)

## Jan-Feb 2000

### Photonics West

January 23-28  
San Jose, CA  
<http://www.spie.org>

### Strategies in Light: Business Opportunities in LEDs

February 10-11  
San Francisco, CA  
[http://www.strategies-u.com/op/op\\_strategiesinlight.html](http://www.strategies-u.com/op/op_strategiesinlight.html)

## March-April 2000

### 3rd Int'l Symp on Blue Lasers and LEDs (ISBLLED 2000)

March 6-10  
Berlin, Germany  
*Abstract Deadline: November 15, 1999*  
<http://www.pdi-berlin.de/isblled/>

### Optical Fiber Conference

March 5-10, 1999  
Baltimore, MD  
<http://www.osa.org>

### Key Conference on Compound Semiconductors

March 13-14  
Key West, FL  
Contact: Marie Meyer  
[mmeyer@compsem.com](mailto:mmeyer@compsem.com)

### MRS Spring Meeting

April 24-28, 2000  
San Francisco, California  
*Abstract Deadline: October 18, 1999*  
<http://www.mrs.org/meetings/spring>

## May 2000

### GaAs Manufacturing Technology (GaAs MANTECH)

May 1-4  
Washington, DC  
*Abstract Deadline: November 1, 1999*  
<http://www.gaasmantech.org>

### 16th European Photovoltaic Solar Energy Conf

May 1-5  
Glasgow, Scotland, UK  
<http://www.wip.tnet.de/pv00.htm>

### Conference on Laser and Electro-Optics (CLEO) Quantum Electronics and Laser Science conference (QELS)

May 7-12  
San Francisco, CA  
*Abstract Deadline: November 16*  
[http://www.osa.org/mtg\\_conf/CLEO/](http://www.osa.org/mtg_conf/CLEO/)

### 12th Int'l Conf. on Indium Phosphide and Related Materials (IPRM)

May 14-18  
Colonial Williamsburg, VA  
*Abstract Deadline: December 10, 1999*  
<http://www.ieee.org/society/leos>

### Expert Evaluation & Control of Compound Semiconductor Materials & Technologies (EXMATEC 2000)

May 21-24, 2000  
Heraklion, Crete, Greece  
*Abstract Deadline: December 17, 1999*  
<http://www.ece.rutgers.edu/~panayot/exmatec.html>

## June-July 2000

### 10th Int'l Conf. on Metal Organic Vapor Phase Epitaxy (ICMOVPE-X)

June 5-9  
Hokkaido University, Sapporo, Japan  
*Abstract Deadline: January 14, 2000*  
<http://www2u.biglobe.ne.jp/~icmovpe/>

### IEEE/MTT-S International Microwave Symposium (IMS 2000)

June 11-16  
Boston, MA  
<http://www.ims2000.org>

### 58th Device Research Conference (DRC)

June 19-21  
Denver, CO  
<http://ece-www.colorado.edu/~drc/>

### 42nd Electronic Materials Conference

June 21-23  
Denver, CO  
<http://www.tms.org>

### 4th European GaN Workshop

July 2-5  
Nottingham, England  
*Abstract Deadline: March 1, 2000*  
[enquiries@global-meeting.co.uk](mailto:enquiries@global-meeting.co.uk)

### 11th Int'l Semiconducting and Insulating Materials Conf (SIMC-XI 2000)

July 3-7  
Canberra, Australia  
*Abstract Deadline: January 17, 2000*  
<http://rsphysse.anu.edu.au/admin/simc2000>

## Sept 2000

### 11th Int'l Conf. on Molecular Beam Epitaxy (MBE-IX)

September 10-15  
Beijing, China  
<http://159.226.99.6/~cise/MBE.html>

### Int'l Conf on Microwave and Millimeter Wave Technology

September 14-16  
Beijing, China  
<http://www.cie-china.org>

### 28th IEEE PV Specialists Conference (PVSC)

September 17-22  
Anchorage, Alaska  
<http://ieeepvsc.nrel.gov>

### Int'l Workshop on Nitride Semiconductors (IWN2000)

September 24-27  
Nagoya, Japan  
*Abstract Deadline: April 28, 2000*  
<http://www.etl.go.jp/~iwn2000/Home.html>

## Oct-Dec 2000

### European GaAs and Related III-V Compounds Application Symposium (GAAS 2000)

October 2-6  
Paris, France  
[www.eumw.com](http://www.eumw.com)

### Advanced Semiconductor Devices And Microsystems (ASDAM)

October 16-18, 2000  
Smolenice Castle, Slovakia  
*Abstract Deadline: March 31, 2000*  
<http://nic.savba.sk/~elekdam/>

### Int'l Topical Meeting on Microwave Photonics (MWP '99)

November 17-19  
Carlton, Australia  
<http://www.ee.mu.oz.au/conferences/MWP99>

### 2000 Asia-Pacific Microwave Conf (APMC 2000)

December 3-6  
Sydney, Australia  
*Abstract Deadline: April 1, 2000*  
<http://www.tip.csiro.au/Events/apmc2000>

## Conference Organizers:

Please send details of your events to:

[tim.whitaker@compsem.com](mailto:tim.whitaker@compsem.com)



## Third International Symposium on Blue Laser and Light Emitting Diodes

6-10 March 2000  
Seehotel Zeuthen  
Zeuthen/Berlin, Germany

The Third International Symposium on Blue Laser and Light Emitting Diodes (ISBLLED 2000) will be held at the Seehotel Zeuthen near Berlin, Germany, March 6 - 10, 2000. The main objective of the Symposium is to provide a joint forum for both the GaN and the ZnSe community. The Symposium will provide a unique opportunity to bring experts from industry and academia together with students and to explore issues that are common to both the GaN-based and the ZnSe-based material systems, including materials growth and characterization, defects and doping, substrate-epilayer constraints, device design and processing, device physics, novel devices and applications.

The Symposium will cover the entire spectrum of GaN-based and ZnSe-based semiconductors and their optoelectronic properties and device applications, spanning from substrate-epilayer constraints and materials growth over heterostructure formation and doping to device physics, processing and reliability. Papers will be presented in the following areas:

1. *Materials Growth and Characterization*
2. *Optoelectronic Properties*
3. *Device Design and Fabrication*
4. *Device Performance*
5. *Novel Optoelectronic Devices and Applications*

The scientific program will consist of contributed papers in both oral and poster presentations as well as invited talks, which discuss areas of major interest.

For more information, visit the conference's home page at <http://www.pdi-berlin.de/>



April 24 - April 28  
San Francisco, California

Exhibit: April 25-27

Materials Development  
Characterization Methods  
Process Technology

For additional meeting information or to request a Call for Papers booklet, a detailed 2000 MRS Spring Meeting Program, information on symposium tutorials, publications, the Exhibit, the Job Center, or Symposium Assistant positions, contact:



Member Services  
Materials Research Society  
506 Keystone Drive  
Warrendale, PA 15086-7573  
Tel 724-779-3003  
Fax 724-779-8313  
E-mail: [info@mrs.org](mailto:info@mrs.org)  
[www.mrs.org](http://www.mrs.org)

### Abstract Deadlines — In fairness to all potential authors, late abstracts will not be accepted.

October 18, 1999: for abstracts sent via e-mail, fax, or mail • November 1, 1999: for abstracts sent via the MRS Web site

#### 2000 MRS SPRING MEETING SYMPOSIA

- |                                                                                            |                                                                                                                                |
|--------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|
| A: Amorphous and Heterogeneous Silicon Thin Films—2000                                     | Q: Flat-Panel Display Materials                                                                                                |
| B: Si Front-End Processing—Physics and Technology of Dopant-Defect Interactions II         | R: Electron-Emissive Materials and Vacuum Microelectronics                                                                     |
| C: Gate Stack and Silicide Issues in Silicon Processing                                    | S: Electrically Active Polymers                                                                                                |
| D: Materials, Technology, and Reliability for Advanced Interconnects and Low-k Dielectrics | T: Wide-Bandgap Electronic Devices                                                                                             |
| E: Fundamentals and Materials Issues in Chemical-Mechanical Polishing of Materials         | U: Materials Science of Novel Oxide-Based Electronics                                                                          |
| F: Magnetic Materials, Structures, and Processing for Information Storage                  | V: Materials Development for Direct Write Technologies                                                                         |
| G: Polycrystalline Metal and Magnetic Thin Films                                           | W: Combinatorial Chemistry and Materials Science                                                                               |
| H: Corrosion of Metals and Alloys                                                          | X: Frontiers of Materials Research                                                                                             |
| I: New Methods, Mechanisms, and Models of Vapor Deposition                                 | Y: Solid Freeform and Additive Fabrication III                                                                                 |
| J: Laser-Solid Interactions for Materials Processing                                       | Z: Thermoelectric Materials 2000—The Next-Generation Materials for Small-Scale Refrigeration and Power-Generation Applications |
| K: Morphological and Compositional Evolution of Heteroepitaxial Semiconductor Thin Films   | AA: Millimeter/Submillimeter-Wave Technology—Materials, Devices, and Diagnostics                                               |
| L: Recent Developments in Oxide and Metal Epitaxy—Theory and Experiment                    | BB: The Granular State                                                                                                         |
| M: Morphology and Dynamics of Crystal Surfaces in Complex Molecular Systems                | CC: Hybrid Organic/Inorganic Materials                                                                                         |
| N: Materials for Separations in Analytical Chemistry                                       | DD: Interfacial Aspects of Soft Biomaterials                                                                                   |
| O: Materials Computation—Progress Towards Technological Impact                             | EE: Nanostructures in Polymers                                                                                                 |
| P: Multiscale Modeling of Organic Materials                                                | FF: Interfaces, Adhesion, and Processing in Polymer Systems                                                                    |
|                                                                                            | GG: When Materials Matter—Analyzing, Predicting, and Preventing Disasters                                                      |
|                                                                                            | HH: Materials Science and Engineering Education in the New Millennium                                                          |

#### 2000 MRS SPRING MEETING ACTIVITIES

##### SYMPOSIUM TUTORIAL PROGRAM

Available only to meeting registrants, the tutorials will concentrate on new, rapidly breaking areas of research.

##### EXHIBIT

Over 125 international exhibitors will display a full spectrum of equipment, instrumentation, products, software, publications, and services.

##### PUBLICATIONS DESK

A full display of over 600 books, plus videotapes and electronic databases, will be available at the MRS Publications Desk.

##### SYMPOSIUM ASSISTANT OPPORTUNITIES

Graduate students planning to attend the 2000 MRS Spring Meeting may apply for a Symposium Assistant (audio-visual aide) position.

##### JOB CENTER

A Job Center for MRS members and meeting attendees will be open Tuesday through Thursday.

The 2000 MRS Spring Meeting will serve as a key forum for discussion of interdisciplinary leading-edge materials research from around the world. Various meeting formats—oral, poster, round-table, forum and workshop sessions—are offered to maximize participation.



For rates and submission instructions for employment ads, contact the editor at  
TEL [1] 978 927 9994; FAX [1] 978 927 9893 or e-mail: editor@compsem.com



## COMPOUND SEMICONDUCTOR

### Positions Available

Compound Semiconductor is seeking to fill two newly created positions. We offer rewarding opportunities in an excellent working environment. If you have excellent communication skills and are knowledgeable about the compound semiconductor industry, we want to hear from you!

#### Business Development Manager

The Business Development Manager will be responsible for managing and growing advertising and subscription sales. Applicants should be familiar with structure of the compound semiconductor industry. Prior sales experience helpful but not mandatory. Excellent communication skills required.

#### Assistant Editor

The Assistant Editor will be responsible for writing feature articles and editing news items for print and Internet publication. Applicants should have excellent writing skills, knowledge of compound semiconductor technology, and an interest in both scientific and commercial developments.

Please send your resume to:  
Marie Meyer  
Franklin Publishing  
163 Cabot Street  
Beverly, MA 01915 USA  
FAX: [1] 978 927 9893,  
Email: mmeyer@compsem.com



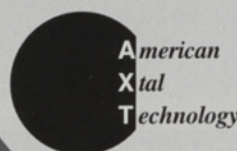
## THE FUTURE OF HIGH TECHNOLOGY BEGINS HERE.

*At American XTAL Technology, our commitment to innovation, quality and to the ability to bring our ideas to market are a way of life. We are a world leader in the compound semiconductor industry, and our products serve as the basis for high performance applications from lasers and light emitting diodes to cellular telephones and satellite communications. Come join our team and see what our future will mean to yours!*

### SENIOR R&D ENGINEER

*You are experienced in Silicon Carbide (SiC) bulk crystal growth with some knowledge of wafer processing and a results-oriented attitude. Advanced academic degrees are a plus, but 2+ years of industry experience is preferred.*

*For superlative individuals we offer competitive compensation packages, an array of attractive benefits and an unlimited upward career growth potential. Please forward your cover letter, resume and salary requirements in confidence to:*



**Director of Human Resources**  
4281 Technology Drive  
Fremont, CA 94538  
FAX: (510) 438-4798  
E-MAIL: hr@axt.com

*We are an Equal Opportunity Employer  
committed to a culturally diverse workforce.*

## MBE Field Service Engineer (USA)

VG Semicon, the world's largest supplier of production Molecular Beam Epitaxy systems, is seeking engineers to enhance its US Field Service team and to meet the challenges of the industry's rapid expansion. Applicants will need a solid background in electronics, mechanical engineering and computing. Experience working with Ultra High Vacuum systems would be an advantage. After training in the US and UK, duties will include system maintenance, customer training and installation of upgrades. A significant level of travel is required. Self motivation and the ability to work with minimal supervision is critical.

Interested parties should respond in writing to

**VG Semicon**  
Attn. FSE  
100 Cummings Center  
Suite 407J  
Beverly MA 01915



**VG Semicon**  
The MBE Company



4H and 6H Wafers  
51mm and 35mm

## silicon carbide

*We Now Have  
Silicon Carbide  
Epitaxy!*



**rising**

**Finally, a real choice in silicon carbide substrate suppliers.**



**sterling  
semiconductor**

**USA:**

Telephone: 703-834-7535,  
ext. 206

Fax: 703-736-3443

E-mail: [jlemunyon@sterling-semiconductor.com](mailto:jlemunyon@sterling-semiconductor.com)

**Europe:**

Wafer Technology, Ltd.

Telephone: +44(0) 1908 210 444

Fax: +44 (0) 1908 210 443

E-mail: [klamb@wafertech.co.uk](mailto:klamb@wafertech.co.uk)

**Japan (Tokyo):**

New Metals and Chemicals  
Corporation

Telephone: 03-3201-6585

Fax: 03-3271-5860

E-mail:

[nemechem@mail.mind.ne.jp](mailto:nemechem@mail.mind.ne.jp)

**Japan (Osaka):**

New Metals and Chemicals  
Corporation

Telephone: 06-6202-5108

Fax: 06-6223-0987

E-mail:

[matsuzak@newmetals.co.jp](mailto:matsuzak@newmetals.co.jp)



# World Beating III-V Custom Epitaxy for a World of Applications

Telecoms LDs / LEDs •

Telecoms PINs / APDs •

IR LDs / LEDs •

IR VCSELs •

Visible Lasers •

UHB Visible LEDs •

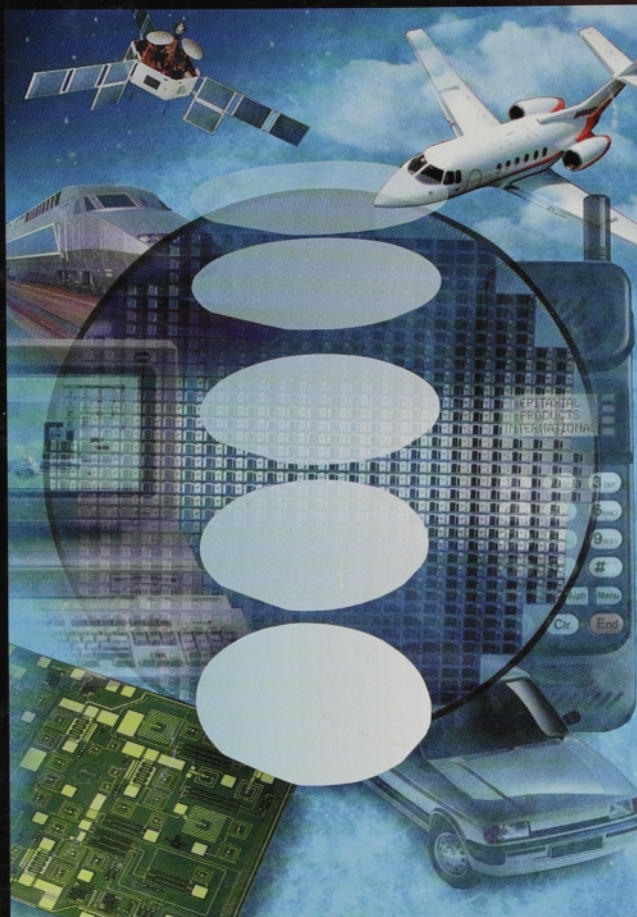
Visible VCSELs •

C-Doped HBTs •

InP HBTs •

P-HEMTs •

Solar Cells •



• GaAs

• AlGaAs

• AlGaInAs

• GaP

• GaInP

• AlGaInP

• InP

• GaInAs

• AlGaInAs

• GaInAsP

Large volume foundry, pilot production or R & D

Multiple 2", 3" and 4" capacity

Whatever your epitaxy needs, however demanding, E.P.I. can deliver. High or low volume, each wafer is fully supported by extensive characterisation data and E.P.I.'s world leading MOVPE technology, ensuring absolute quality and ultimate consistency.

For more information about the world's foremost Custom Epitaxy service, contact Epitaxial Products International today.

**Creating Profitable Business Partnerships**

**E·P·I·**

A member  
of the  
IQE plc Group

**EPITAXIAL PRODUCTS INTERNATIONAL LTD**

#### U.S.A./CANADA

Epitaxial Products Inc.  
Hilltop Center, Building B  
136 Harvey Road  
Londonberry, NH 03053  
U.S.A.  
Tel: +1 (603) 641 2002  
Fax: +1 (603) 641 2035  
email:  
73712.3265@compuserve.com

#### U.K./EUROPE

Epitaxial Products International  
Cypress Drive  
St. Mellons  
Cardiff CF3 OEG  
Wales, U. K.  
Tel: +44 1222 794422  
Fax: +44 1222 779929  
email:  
mscott@epitaxial-products.co.uk  
wjones@epitaxial-products.co.uk

#### TAIWAN

Copray Enterprises Co. Ltd.  
14F-3 No. 3  
Lane 407 Min Sheng E. Road  
Taipei  
Taiwan  
R.O.C.  
Tel: +886 2250 93174/5  
Fax: +886 2250 16279  
email:  
conray@top2.ficnet.net.tw

#### JAPAN

Electronic and Materials  
Corporation Ltd.  
11-11 Funado-cho  
Ashiya 659  
Japan  
Tel: +81 797 34 6655  
Fax: +81 797 34 5665  
email:  
candmint@osk2.threewebnet.or.jp