



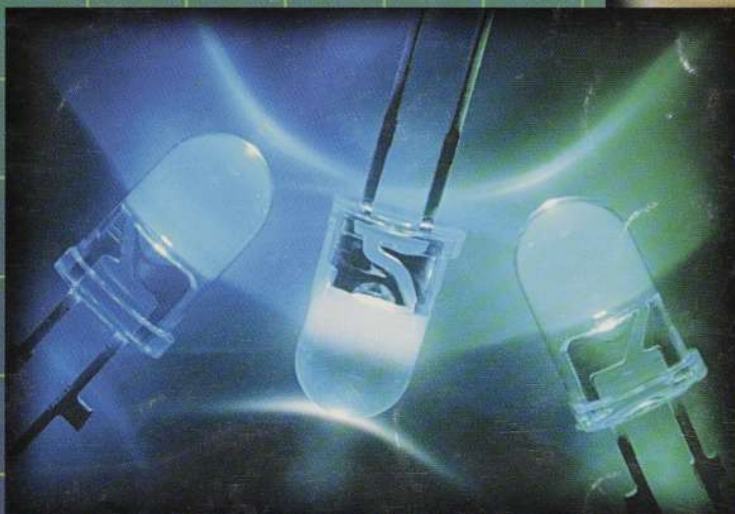
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June 1999

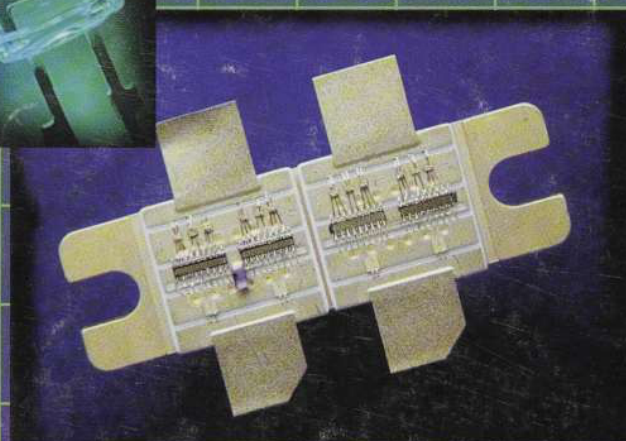
Volume 5 Number 5

WIDE BANDGAP SEMICONDUCTORS

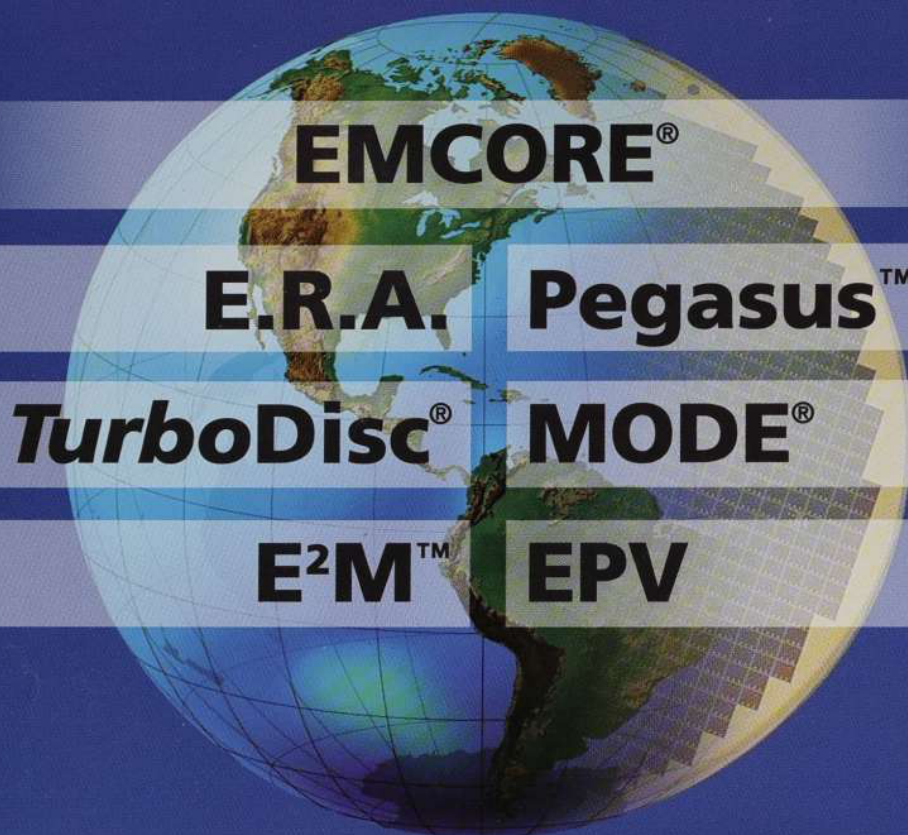


New In This Issue

GaAs ICs Section



Resources to Fuel the Evolution

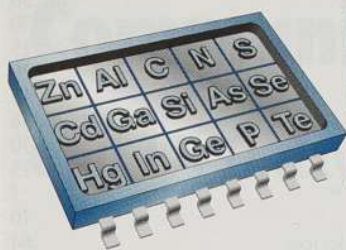


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COVER STORIES - WIDE BANDGAP MATERIALS

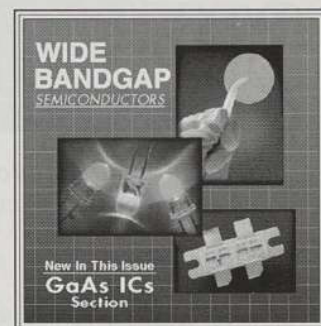
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Wide bandgap materials are the theme of this issue. Coverage begins on page 15 with an overview of new and established companies that supply the growing market for nitride-based blue and green LEDs. It resumes on page 26 with an article on the status of wide bandgap semiconductors for high temperature applications, followed by developments in AlGaIn transistors, and a description of nitride programs in Europe. Finally, the use of CdZnTe as a radiation detector is reported. This issue also introduces a new section on GaAs ICs. [The cover art is based on photographs kindly supplied by Cree Research.]

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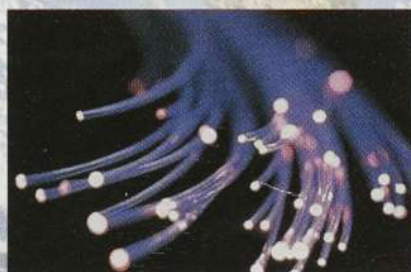
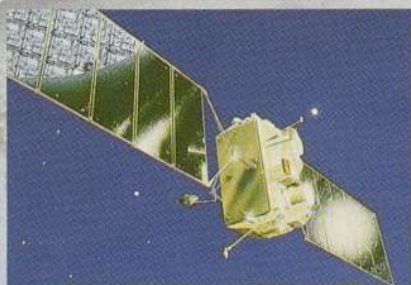
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New in This Issue....

As part of our on-going efforts to improve our publication, we are introducing in this issue a new section dedicated to the GaAs IC industry. It begins on page 41. Coverage of GaAs-related topics has long been a mainstay of our magazine. But in the past this information was scattered throughout each issue. By establishing this new section, modeled after our popular "Nitride News" section, we hope to provide you with a more organized and reader-friendly presentation of the news from this vital sector of our industry.

Participate in our 1999 Directory...

We are in the process of planning the 1999 edition of our Suppliers Directory. In 1998 we had participation from more than 200 companies supplying equipment, materials and services to the compound semiconductor industry (see CS 4(9), p. 36). If you missed out on that edition, but would like to be included in 1999, please contact Marie Meyer at TEL [1] 978 927 9994; FAX [1] 978 927 9893, or Email mmeyer@compsem.com

MBE and MOCVD Growers Merge, Form IQE plc

Two of the world's largest epitaxial wafer foundries - Epitaxial Products International, Ltd. (EPI) and Quantum Epitaxial Designs, Inc. (QED) - have merged to form a new, publicly traded company, IQE (International Quantum Epitaxy) plc. EPI, which is headquartered in Cardiff, Wales, is one of the world's largest producers of MOCVD-grown epiwafers; QED, headquartered in Bethlehem, PA, is the largest manufacturer of MBE-grown epiwafers. The two companies had combined annual sales of \$26.7 million in 1998, and are growing at approximately 35% per year. The merger was announced on May 4 and the new company began trading as IQE plc on the Easdaq exchange in Belgium on May 28.

IQE bills itself as "the world's leading 'pure play' merchant epiwafer supplier". Drew Nelson, the former CEO of EPI, will serve as IQE's Executive Chairman, and Tom Hierl of QED will serve as the CEO.

"Both EPI and QED are the recognized leaders in their respective markets," says Nelson. "IQE will maintain its focus on providing custom epitaxy products and services, and continue the philosophy of having no commercial device fabrication capability." This strategy is aimed at preventing potential conflicts-of-interest with IQE's customers.

According to Hierl, "The resources of QED and EPI leverage our combined expertise of MBE and MOCVD technologies and creates the world leading merchant supplier for epitaxial products and services. As the market continues to grow, IQE will continue to invest in state-of-the-art production and characterization equipment, expanded facilities and personnel resources to address growing customer demand."

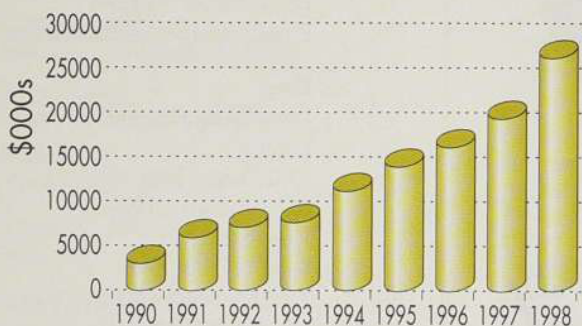
In addition to the combination of MOCVD and MBE, the merger can be seen as a combination of strengths in other areas. EPI specializes in optoelectronic materials, while QED has historically concentrated on electronic structures. And while EPI has established an international presence, deriving 65% of its sales from Europe and Asia, QED has been a dominant force in the US market, which accounts for over 90% of its revenues. At the same time the companies are relatively evenly matched in terms of profits and revenue, as well as facility sizes and numbers of employees.

And both companies are in an expansion mode. EPI recently increased their total manufacturing area in Cardiff to approximately 37,000 square feet, sufficient to house a total of 16 MOVPE production reactors. EPI is scheduled to accept two new Aixtron 2600 multi-wafer 6" MOVPE reactors by June 1999. QED has also been expanding, and

is scheduled to accept a next generation VG Semicon V150 MBE reactor by mid-year 1999. This will position QED as the world's first merchant MBE supplier with multiple 6" diameter epiwafer production capability. The companies plan to establish internal second source capability between the two sites.

IQE raised approximately \$40 million for 22% of the company's shares in the IPO. The proceeds will be used to fund further expansion.

EPI & QED: Combined Sales



IQE Wafer Production Capacity



EPI and QED, which merged on May 4 to form IQE plc, report a combined CAGR of around 35%.

IQE

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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.

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AXT Acquires Lyte Optonics

American Xtal Technology, Inc. (AXT) has announced that it has acquired Lyte Optonics Inc. of Torrance, CA, a privately held manufacturer of LEDs and laser diodes. Lyte Optonics, which had 1998 revenues of approximately \$30 million, also distributes laser pointers and alignment products for consumer and commercial markets. The total transaction is valued at approximately \$75 million, including around \$11 million of assumed debt. AXT expects that the acquisition will make a "modest" contribution to the company's 1999 financial results.

Lyte Optonics currently has around 420 employees, and will become a new division within AXT. It will be headed by Keith Halsey and Robert Shih, formerly Lyte Optonics' CEO and President, respectively. AXT will continue to run Lyte Optonics' manufacturing operations, which are located in southern California and China.

"American Xtal Technology has always considered the emerging LED and laser markets, two of the fastest growing components of optoelectronics, as key components of our growth strategy," says Morris Young, CEO of AXT. By acquiring Lyte Optonics, he said, AXT will extend its participation in these markets to offer a vertically integrated optoelectronic product line.

"We are very pleased to join forces with American Xtal Technology and to tighten the working relationship that we've enjoyed for many years," says Halsey. "We believe that together we can offer a premium end-to-end device solution for optoelectronic applications," he added.

About Lyte Optonics

Lyte Optonics, known as a distributor of laser pointers and other laser diode-based products, merged with another California-based company, Alpha Photonics, in September 1998. Alpha Photonics was a vertically integrated manufacturer of visible laser diodes, and was described in mid-1998 by Strategies Unlimited as "arguably the largest supplier of visible laser diodes in the world". Lyte Optonics retained this laser diode capability, including several in-house MOCVD growth reactors, and continues to ship large quantities of 635-670 nm laser die for laser pointers and industrial applications. The company also began to ship LED epiwafers in the current quarter. These are described as conventional red, yellow and amber devices of low to medium brightness. According to Guy Atwood, CFO of American Xtal Technology, the LED market is attractive because it is an emerging and fast-growing business. "Also, the LED substrates will play an increasing role in the success of the final LED devices," he added.

Sumitomo Electric and Emcore Sign InGaP HBT Agreement

Emcore recently announced the signing of a long term agreement with Sumitomo Electric Industries, Ltd. (SEI) of Japan to jointly develop and produce InGaP HBT epitaxial wafers for devices used in digital wireless and cellular applications. These wafers will be produced at Emcore's Epitaxial Materials (E²M) wafer foundry in Somerset, New Jersey. Shipment is expected to begin in the June quarter. SEI will market the wafers in Japan. Emcore estimates that Japanese fabs produce approximately 40% of the world's output of GaAs-based wireless devices, a market which is currently valued at \$1.7 billion/year. According to Strategies Unlimited, in 1998 HBT epitaxial wafer shipments were the fastest growing segment of the GaAs epitaxial wafer market. HBT wafer shipments grew 72% over 1997 levels, reaching nearly 400,000 square inches.

"The partnering of Sumitomo Electric and Emcore to co-develop and produce these next generation devices enables InGaP HBTs to move more rapidly into the commercial sector," said Reuben Richards, President and CEO of Emcore. "Sumitomo Electric brings to the co-operative effort unique material characterization capability and Emcore's E²M foundry has the necessary capacity needed for commercial volume production," said Masamichi Yokogawa, General Manager Engineering and Development Department, Semiconductor Division of SEI.



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Tecstar's Multi-Junction Solar Cells Fly on Deep Space 1

NASA's first New Millennium spacecraft, Deep Space 1, which has a mission to accelerate the introduction of advanced technologies into the space programs of the 21st century, is being powered by multi-junction cells supplied by Tecstar. The cells have three active junctions, marking the first time that "triple junction" cells have provided the majority of power on a spacecraft. Previously, the cells were successfully demonstrated on several flights, including NASA's TRACE satellite (see photo) and the recently launched USAF Mightysat 1 satellite.

The solar arrays for Deep Space 1 were manufactured by AEC-Able Engineering Co., and employ hemispherical linear concentrators to focus sunlight onto the linear solar cell strips. The total solar cell area is reduced by a factor of 7-8 using these concentrators.

The vast majority of dual junction III-V solar cells in production are grown by MOCVD on Ge substrates, and contain two separate p-n homojunctions fabricated from $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ and GaAs respectively. These are usually separated by heavily doped GaAs tunnel junctions. In the Tecstar triple junction cells, the third active region is an n-n heterojunction, which is formed between the n-type Ge substrate and an epitaxial $\text{n}^+\text{-GaAs}$ or $\text{n}^+\text{-AlGaAs}$ layer. These devices show a strong spectral response to photons which have energies ranging from below the bandgap of GaAs (~ 1.42 eV) to the bandgap of Ge (~ 0.66 eV), showing that the n-n heterojunction is active.

All of Tecstar's current production output of Cascade™ multi-junction cells use this triple junction design, which provides an average beginning-of-life efficiency of 24%. The record efficiency of



NASA's TRACE satellite, one of the spacecraft on which Tecstar's triple junction solar cells were successfully demonstrated.

this cell design is 26.1%, compared to about 23.5% for dual junction $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$ cells. The company reports that it has produced over 100,000 triple junction cells to date.

Leadership

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There are other triple junction variants in production; Spectrolab, a unit of Hughes Electronics, manufactures triple junction cells in which the third active region is a Ge p-n homojunction. This is formed by n-type implantation of As into the p-type Ge substrate. The GaAs and $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ cells and the tunnel junctions are then grown by MOCVD. Spectrolab states that this design is optimized for radiation hardness under electron and proton bombardment, providing very high end-of-life performance.

Both Spectrolab and Tecstar report that they are researching next generation

multi-junction cells to provide conversion efficiencies in the 30-40% range. Spectrolab is presently developing 37% efficiency solar cells under a US Air Force contract for deployment in 2002.

Contract Awards for Tecstar

Tecstar recently announced that it had received a long term contract to supply triple junction solar cell assemblies to Lockheed Martin Missiles and Space (LMMS), for use on Lockheed's A2100 and other satellite programs. Tecstar will provide 161 kW of

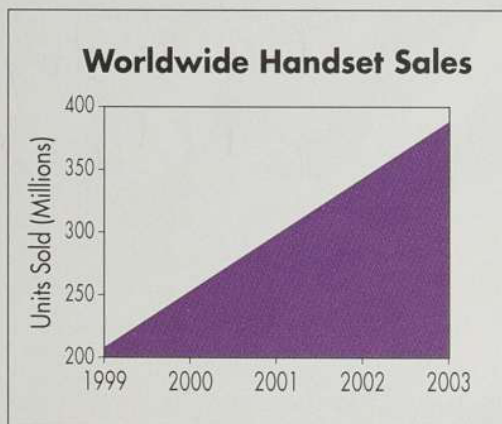
power to LMMS through December of 2000.

Tecstar was also recently awarded a follow-on contract by NASA's Jet Propulsion Laboratory (JPL) to design, fabricate, and deliver a test flight Rover solar panel for the Marie Curie Mars 2001 Program. The Marie Curie Rover will use a camera and alpha proton X-ray spectrometer to explore the possibility of past life on the planet and pave the way for future human flight to Mars. Tecstar supplied the solar panels, containing GaAs/Ge single junction cells, for the 1997 Mars Pathfinder Mission.

Healthy Forecast for Mobile Phones, 3G Cellular

The rapid growth in wireless handset sales is set to continue for the next several years according to a recent report from Cahners In-Stat Group [1], which predicts that sales will grow from 207 million units in 1999 to 392 million units in 2003. Market growth will be confined to digital cellular/PCS phones, and over 95% of the handset market will be using digital technology by the end of the forecast period. Although CDMA will have the fastest worldwide growth rate (24.7%), followed by GSM (22.7%) and TDMA (22.5%), GSM will continue to enjoy an insurmountable lead accounting for nearly 203 million of the 392 million units forecasted for 2003.

Several recent reports put the projected number of PCS/cellular subscribers between 650 and 700 million by 2003. Electronic Trend Publications [2] predicts 652 million subscribers by 2003, of which 36% will be in the Asia-Pacific region. Japan and China will have 71 million and 59 million subscribers respectively, compared to 165 million in Western Europe and 125 million in the USA.



According to Cahners In-Stat group, PCS/cellular handset sales will exceed 200 million in 1999, and will reach almost double that figure by 2003.

"The remainder of 1999 will be a pivotal time for wireless handset manufacturer," says Ray Jodoin, senior analyst for Cahners In-Stat Group's Wireless service. "As digital users begin to implement 2.5-generation (2.5G) data and Internet-ready

handsets, we will finally learn if data is the killer application that most believe it is."

2.5G and 3G Cellular - The Wireless Data Market Takes Off

The term 2.5G represents a group of intermediate wireless communication technologies that fall somewhere between the current, second generation (2G) wireless standards, and future 3G standards. 2G is largely voice-only, and is characterized by dual-mode (analog and digital) access at cellular frequencies, with numerous competing digital standards (GSM, CDMA, TDMA) at PCS frequencies. In addition to traditional voice, 3G cellular will also provide wireless data services at a speed of up to 2 Mbps - fast enough to support several channels of full-motion video and lightning-fast Internet access.

While 3G standards are being discussed (see below), some companies are already offering integrated voice and data services. US West, a major US-based carrier, recently announced the launch of the "Thin Phone", a PCS handset manufactured by Qualcomm. This digital CDMA phone is the first to fully integrate wireless Internet access with local wireless voice service. Qualcomm also offers the pdQ smartphone, the industry's first integrated CDMA digital wireless phone and 3Com Palm Computing-based organizer.

A report from Forward Concepts predicts that the worldwide market for 3G cellular terminals will total \$1.5 billion in the year 2001, and grow to \$9.2 billion in 2005 [4]. Furthermore the investment in infrastructure to support 3G cellular services will total \$1.3 billion in 2001 and will reach \$5.3 billion by 2003. A separate report from the same company predicted that the number of 3G cellular subscribers will rise from about 140,000 in 2000 to 40 million by 2005.

Allied Business Intelligence (ABI) also predicts a boom in subscribers for technologies that allow mobile Internet access



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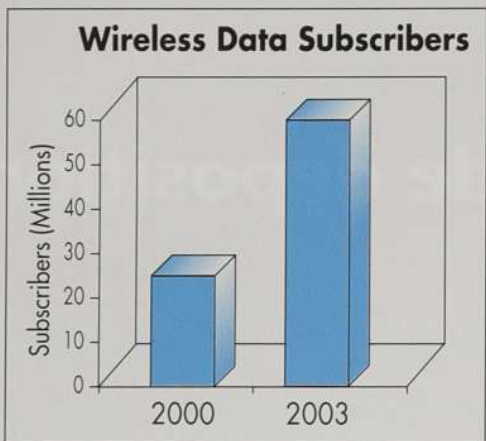
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Allied Business Intelligence

The number of wireless data subscribers could reach 60 million by 2003, according to ABI. In comparison, there are expected to be as many as 700 million PCS/cellular subscribers by that time.

through laptops, personal digital assistants (PDAs), in-vehicle phones and a new generation of handsets [3]. According to ABI, the number of wireless data subscribers will increase from around 25 million in 2000 to 60 million in 2003 [see graph].

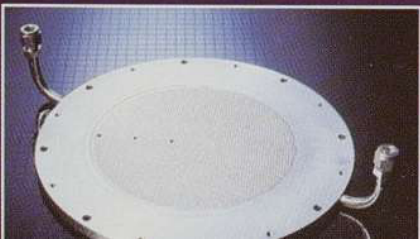
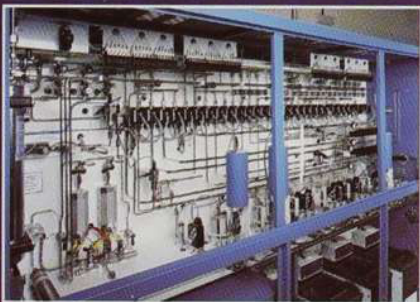
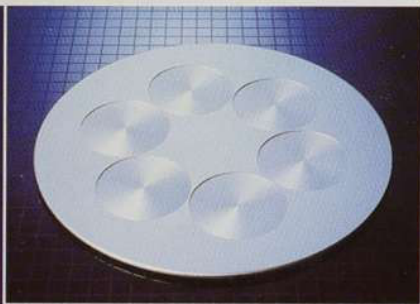
3G Dispute Resolved

One of the problems facing the implementation of 3G cellular has been the development of competing 3G standards, particularly the wideband CDMA standard (W-CDMA) developed by Ericsson, which faces direct competition from Qualcomm's cdma2000 technology. In a recent landmark decision, the two companies agreed to jointly support a single world CDMA standard with three optional modes for 3G wireless communications. Ericsson and Qualcomm will cross-license their patents, and also provide licenses to the rest of the industry on a discrimination-free basis. This is clearly good news for the future of 3G cellular, and should also be good news for GaAs. CDMA places very high linearity requirements on the power amplifiers in the handset and in general, GaAs FETs and HBTs provide higher efficiency compared to Si-based solutions when these linearity requirements are met.

NTT DoCoMo, Japan's largest

mobile communications service provider, plans to be the first operator in the world to commercially deploy a 3G mobile communications system. The W-CDMA network is scheduled for launch in 2001 and will be supplied with base station equipment by Ericsson and Matsushita. Around 10 companies will manufacture mobile handsets for the network.

- [1] "1999 Handset Unit Forecast" by Cahners In-Stat Group. Contact: Ray Jodoin. TEL [1] 480 483-4461; EMAIL rjodoin@cahnersinstat.com; WEB <http://www.cahnersinstat.com>.
- [2] "Wireless Voice Communications Markets and Trends" is available from Electronic Trend Publications. TEL [1] 408 369-7000, FAX [1] 408 369-8021.
- [3] "The Evolution of 3G: Multiple Paths to the Killer Application" is available from Allied Business Intelligence. TEL [1] 516 624-3113, FAX [1] 516 624-3115; WEB <http://www.alliedworld.com>.
- [4] "3G Cellular Market Opportunities" and "Wireless 99" are authored by Micrologic Research and are available from Forward Concepts. Contact: Will Strauss. TEL [1] 602 968 3759, FAX [1] 602 968 7145. WEB <http://www.fwdconcepts.com>.



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Cree Introduces Blue and Green InGaN-on-SiC LEDs

Cree Research has significantly expanded its product portfolio with the addition of high performance blue and green InGaN-based LEDs. As with Cree's previous products, the new devices are grown on SiC and employ Cree's proprietary conductive buffer layer. However, for the first time Cree has used an InGaN p-n junction active region, resulting in higher brightness than the GaN devices. While Cree's GaN-on-SiC blue (430 nm) LED chip has a radiant flux of 1.15 mW, the new 450 nm InGaN-based device offers 3.5 mW. These figures are for unpackaged devices; Cree does not sell packaged chips.

The new LEDs, which measure only $260 \times 260 \mu\text{m}^2$, are sufficiently bright to make them suitable for outdoor display applications. They are offered in two versions of both blue and green [see table on page 15 for further details]. Cree will continue to manufacture the older GaN-on-SiC devices alongside the new product line. Strategies Unlimited recently identified Cree as the world's highest volume producer of blue and green LED chips, based on shipments of GaN-based devices grown on SiC substrates totaling in excess of 20 million chips per month.

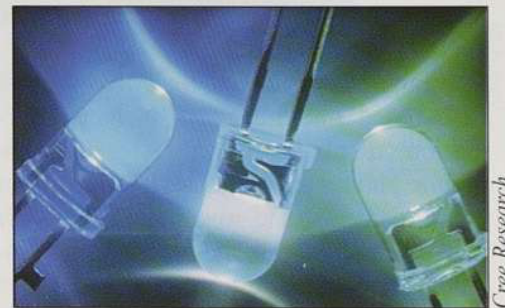
Advantages of SiC

The use of a SiC substrate and a conductive buffer layer allows the fabrication of LEDs with front and back contacts, the same device configuration used for the vast majority of red, yellow and amber LED chips. In contrast, all other manufacturers of blue and green LEDs use insulating sapphire substrates which require two front-side contacts. This makes device fabrication more difficult since a mesa-etch and two wire bonds are required, and also increases the device size (typical InGaN-on-sapphire LED chips measure $350 \times 350 \mu\text{m}^2$). According to Cree, the smaller chip size is one of several "compelling benefits" of the SiC

substrate LEDs, making them compatible with the industry's trend toward package miniaturization, particularly in surface mount LED applications such as wireless handset backlighting. The vertical chip structure requiring a single wire bond results in quicker LED assembly, reduced manufacturing costs and improved reliability. Also, Cree claims that their LEDs offer the industry's highest specification for electrostatic discharge (ESD) resistance, which they say reduces the cost, engineering effort and time to qualify nitride LEDs at customer production sites.

"The attributes of SiC have enabled Cree to develop a low cost device structure and establish a worldwide volume leadership position in the nitride LED segment," says Mike Dunn, General Manager of Cree's optoelectronic business unit. Although Cree's older GaN-on-SiC LEDs are considerably less bright than products offered by other companies, there are many high volume applications, such as cellular handset backlighting and automotive instrumentation, for which high brightness is not required. In these cases, attributes such as low cost, small chip size and improved reliability have allowed Cree to capture a large market share.

The new InGaN-on-SiC product offering competes with high brightness InGaN-on-sapphire LEDs, and is intended to access a new range of applications where higher brightness is required. "Our business objective is to grow our volume market share, and these enhanced brightness products have opened new opportunities for Cree," says Dunn. "We have already won production design wins and have been shipping high volume to customers who use our LEDs in outdoor applications." Target applications for the new products include white light LED illumination, cellular handset backlighting, full color video display signs, automotive instrumentation, and green LED traffic signals.



Cree's new product range includes two blue and two green high brightness InGaN-on-SiC LEDs.

Cree Develops Display Components for Microvision

Cree Research also recently announced the formation of a strategic partnership with Microvision, Inc. (Seattle, WA) for the development of blue and green laser diodes and edge-emitting LEDs suitable for scanned beam display systems.

Under the agreement, Microvision will fund a one-to-two year development program valued at ~\$2.6 million per year. Microvision is currently developing "virtual retinal display" technology, and will gain exclusive access to component technology developed in the program for scanned-beam display applications for three years following completion of the initial development contract. Cree has made a \$4.5 million equity investment in Microvision, acquiring just under 4% of the company's outstanding common stock.

Neal Hunter, Cree's Chairman and CEO stated, "This new endeavor should enhance our leadership position in LEDs and assist us in expediting our development of a commercially viable SiC blue laser."

Microvision's virtual retinal display technology uses a rapidly scanned beam of light to project images onto the eye's retina, allowing the viewer to see large, full-motion images without the need for a conventional display screen. Instead, the

viewer can be linked with a headset or handheld device. The light output power is low enough not to be harmful, and to the viewer, the image appears to be about an arm's length away and about the size of 17-inch monitor. The device is potentially lightweight, low power, offers a wide range of color and offers high definition at a wide angle of view.

Target applications for Microvision's LED-based micro-displays include information displays for next-generation mobile phones and pagers, viewfinders for digital cameras, and wearable displays for personal computers and interactive computer games. In addition, blue and green laser diodes could be used in a variety of military and commercial display applications that require higher luminance.

According to Microvision, the brightness of currently available "off-the-shelf" LEDs is inadequate for scanned display applications, while recent developments at Cree have set the stage for the development of low-cost, high performance micro-displays. "We have worked closely with Cree during the last year and achieved some important advances in high intensity blue and green LEDs, which gave us the confidence needed to pursue this development more aggressively," says Rick Rutkowski, president and CEO of Microvision. "The partnership with Cree gives Microvision a proprietary position in a key enabling component technology...we believe we've made a powerful technology and business combination."

Manufacturers Show Blue Laser DVD Players

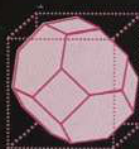
Optical disk recording systems featuring blue violet lasers attracted a great deal of attention at this year's Diskcon Japan '99 exhibition, a showcase for emerging data storage technologies. Several Japanese companies displayed DVD systems using both nitride-based lasers and second harmonic generation sources. The storage capacity of optical systems such as CD and DVD is directly related to the spot size of the laser beam when it is focused on the disk, since this determines the minimum separation of data marks on the disk. The spot size scales with wavelength, which is driving the move from red lasers at around 650 nm, to blue-violet lasers for the next generation of DVD systems.

At Diskcon '99, Pulstec Industry Co. showed a prototype device demonstrating the recording and playback capabilities of a DVD system incorporating a violet laser diode from Nichia. The laser wavelength was 410 ± 5 nm, and the objective lens had a relatively high NA of 0.65. The laser power incident on the disk was 4.7 mW while recording data marks onto the phase-change disk medium, and 0.5 mW during playback. The

optical disk had a track pitch of 0.74 μm , and the recording density was equal to that of any DVD currently in the market.

A second DVD system, also using Nichia's violet lasers, was demonstrated by Shibasaki Co. During the demos, the company reproduced data using dedicated playback disks which were 12 cm in diameter, and had a recording capacity of approximately 15 Gbytes. The laser wavelength in this case was 400 nm and the system had a 0.65 NA objective lens. The jitter was below 8%, and the readout speed along the track was 3.4 m/s.

In the Yokokawa Electric booth, a different approach was on display. The prototype system in this case used a second harmonic generation (SHG) laser developed by Matsushita. The SHG device combines an infrared AlGaAs-based DBR laser with an optical waveguide to achieve frequency doubling. The output power was 2 mW at a wavelength of 426 nm. The laser and SHG device are currently assembled by hand, while automated positioning technology is under development, with plans for mass production by the fall of 1999.



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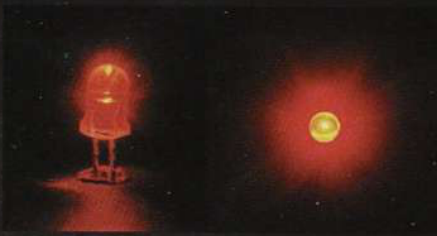
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RFMD Orders V150 MBE System...

VG Semicon has secured an order from RF Micro Devices (RFMD) for a V150 MBE system. The V150 is designed for multiple 6-inch GaAs growth, and can also be used for high throughput 4-inch production. This reactor adds to a number of VG's V100 systems acquired by North Carolina-based RFMD since 1998 for production at its GaAs HBT fab in Greensboro.

... and Plasma Etcher from Tegal

Tegal Corporation has announced a follow-on order from RFMD for a Tegal 901e diode plasma etcher. Scheduled to ship in June 1999, the system will be installed in RFMD's Greensboro manufacturing facility. This 901e system is specially configured for the wafer handling requirements of GaAs substrates and for maximized product yields. The transport system can accommodate 3- and 4-inch (75 and 100 mm) circular substrates.

Steag Installs RTA at Siemens 6-inch GaAs Fab

A rapid thermal annealing (RTA) system from Steag (Dornstadt, Germany) has been installed at Siemens

AG's 6-inch GaAs facility in Perlach near Munich. The AST 2800cs, introduced in 1998 to meet demand for 2-, 4- and 6-inch compound semiconductor wafer processing, is based on the AST 2800 platform and is designed to run metallization processes and implant anneals.

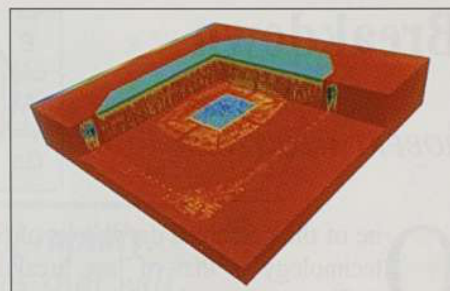
Epistar Orders Aixtron Nitride Growth Reactor

Epistar Corporation (Hsinchu, Taiwan) has placed an order with Aixtron for an 6 x 2-inch capacity Nitride Planetary Reactor for the growth of AlGaInN blue and green LEDs.

Acoustic Imaging Software for IC Analysis

Sonoscan has released software designed to produce three-dimensional images of an IC. The Zip Slice software module instructs a scanning acoustic microscope (SAM) to collect a sequence of acoustic images (produced using ultrasound), which are then assembled into a three-dimensional image of the IC. Each slice corresponds to a specified layer in the IC package and any level can be chosen for inspection.

The SAM technique relies on detecting differences in the reflected ultrasound wave as it comes into contact with discontinuities, revealing defects such as



Sonoscan

cracks, voids, delamination, inclusions and porosity. The technique has obtained images of these defects with resolutions as low as 0.1 μm . It is also non-destructive, making it well suited to process and defect analysis. While the number of slices ultimately depends on the IC thickness, 15-30 slices are typically used to form a reconstruction.

The picture shows a Zip Slice image of a plastic ball grid array (seen as red contrast), with a section chosen to show a die attachment (shown as blue contrast).

Correction: Oxford Plasma

The last issue [CS 5(4) p.22] contained an error in the news article: **Oxford Plasma Ships Tools for 6" GaAs Fab**, which reported Oxford Plasma Technology's sale of two Plasmalab System 100 modular cluster tools to Siemens in Germany. These systems are equipped with 25 wafer cassette stations, a six-way robotic handler and two large-area ICP sources designed to provide excellent uniformity for up to 8-inch wafers, not 4-inch wafers, as reported.

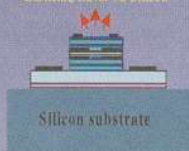
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Breakdown

ROBERT A. METZGER



One of the perceived drawbacks of Si BJT and SiGe HBT technology is that of low breakdown values of V_{CEO} (collector-emitter breakdown with open base). A case in point is IBM's SiGe BiCMOS 5HP process. This is an extremely fast RF device, with f_t and f_{max} values of 46 and 65 GHz respectively, and a value for the BV_{CEO} of 3.3 V. There is no doubt that for many power applications, as well as those cases in which higher burn-in voltages are used to test devices prior to shipment, such a low value of BV_{CEO} is simply inadequate. Many of those in the GaAs MESFET camp will point to these low values of BV_{CEO} as a primary reason as to why bipolar technologies are suitable only for low voltage niche applications, and the superior breakdown characteristics of MESFETs make them the obvious device for RF power applications.

The thing to realize, of course, is that there is no fundamental reason why the BV_{CEO} value of a bipolar device should be low. There is a direct tradeoff between RF performance and

breakdown characteristics, in which collector doping levels can be decreased and thicknesses increased to improve breakdown characteristics at the cost of RF performance. In ancient times (i.e. greater than three years in the past), many Si bipolar processes were struggling to compete with the RF performance of GaAs devices, and could not afford to tradeoff breakdown characteristics for their recently hard won RF improvements. But this is no longer the case. With primary commercial RF markets still in the 1-2 GHz regime, a 50 GHz silicon RF device can afford to exchange some of its RF capabilities for breakdown enhancements, while still having adequate RF performance to meet the needs of the 1-2 GHz marketplace.

IBM is well aware of this, and for those who need higher breakdown characteristics, it offers a SiGe process the company deems suitable for power amplifier applications. By trading RF performance for breakdown enhancements, IBM has a process which exhibits a BV_{CEO} of 5.5 V and in which the f_t has been reduced to 28 GHz. But even while f_t has been reduced, the device exhibits little penalty in the value of f_{max} , which has been kept high by the reduction in the collector-base capacitance (a consequence of the lower collector doping used to enhance the breakdown voltage).

While 5.5 V is certainly an improvement, it is still not in league with the 10V breakdown and beyond which MESFETs can offer. For silicon bipolar with 10 V BV_{CEO} values, one need only look to Toshiba. In the mid-1990s, Toshiba had established a silicon BiCMOS process, using LP-CVD epitaxially grown bases, which resulted in BV_{CEO} values of 4.7 V and f_t and f_{max} values of 23 and 63 GHz, respectively - characteristics similar to those produced by IBM's current SiGe power amplifier process. In recent work (1), Toshiba has pushed this process even harder to increase BV_{CEO} to 10 V.

The key to further enhancement in breakdown characteristics, while still maintaining adequate RF performance, continues to come through the manipulation of the base-collector junction. In the latest Toshiba process, a 1.0 μm thick collector doped at a low value of $1.5 \times 10^{16} \text{ cm}^{-3}$ is used. By employing a non-selective epitaxial silicon process coupled with shallow trench isolation instead of LOCOS, the base parasitic capacitance can be greatly reduced (which in turn helps maintain f_{max}). This is illustrated by the fact that the base-collector capacitance has been lowered from 6.2 fF in the old process to the extremely low value of 1.6 fF in the new process. As a result, even through the RF performance has been offset by the 10 V BV_{CEO} value, f_{max} is still a respectable 37 GHz, more than adequate to be used for applications in the 1-2 GHz range.

As illustrated by these results, there is no intrinsic limitation to the breakdown characteristics of silicon bipolar devices. By trading RF performance for breakdown enhancements, silicon bipolar can now compete with GaAs MESFET in a multitude of power applications.

[1] Hideaki Nii et al, "An 0.3 μm Si Epitaxial Base BiCMOS Technology with 37 GHz f_{max} and 10 V BV_{CEO} for RF Telecommunication," IEEE Trans. Electron Dev., 1999, 46(4), p. 172.

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Who's Who in Blue and Green LEDs

The market for nitride-based blue and green LEDs is growing rapidly. We take a look at established manufacturers and at companies that will soon be entering the market with their own LED products.

RICHARD DIXON

Demand for nitride-based LEDs, particularly blue and green varieties used in displays, traffic signals and interior and exterior lighting in automobiles, is growing very strongly. According to market research by Business Communication Company (BCC*), the number of units sold in 1998 was around 500 million, more than double the figure for the 1997 period. The demand for these devices (see Figure 1) shows no sign of slowing down in 1999.

So who are the major suppliers of this huge new industry? While there are many companies that package wide bandgap blue, green, and now white LEDs (usually a nitride-based blue chip in a special package), there are currently only a handful that manufacture epi-wafers and chips. We look at current sup-

pliers and at companies who plan to offer products in the near future.

Commercial Manufacturers

Nichia first began supplying nitride-based LEDs in 1993. These were grown with a p-n junction double heterostructure active region and were the first to provide luminous intensities of more than 1 cd, making them viable for outdoor applications. Nichia now reportedly produces around 30 million LEDs per month. Marc Favreau, an analyst and editor from BCC, estimates that the Japanese company was responsible for around 40% of the 500 million units produced in 1998. Current estimates (Figure 2) put Nichia in the lead for the period up to mid-1999 with 43% of market share.

In terms of products, Nichia's LED portfolio includes a range of colors and packages, including standard 3- and 5 mm, flat, oval and super oval, which are available in red, blue, and green with viewing angles of up to 120°. White LEDs are also available in standard 3 mm, 5 mm and flat packages. The highest luminous intensities originate from blue and green LEDs (2 and 6 cd, respectively) in a 5mm package, measured at a viewing angle of 15° (see Table).

Cree Research has recently established itself as one of the world's leading suppliers of blue and green LEDs, which it produces as unpackaged chips. Recently it shipped more than 20 million blue and green LEDs in one month, nearly three times that of the same time the

previous year. The North Carolina-based company says that up in the period up until June it will make shipments to at least ten customers worldwide, five of which will be multi-million unit consumers. Companies who buy and package Cree's die include China Semiconductor, Kingbright, Lite-On, QT Optoelectronics, Sharp, Siemens (now

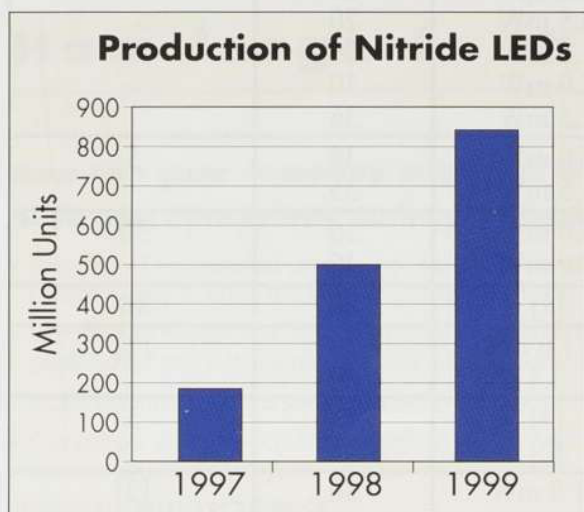


Figure 1. In 1998 production of nitride LEDs more than doubled from 190 million in 1997 to 500 million units. Further sharp increases in output are forecast in 1999.

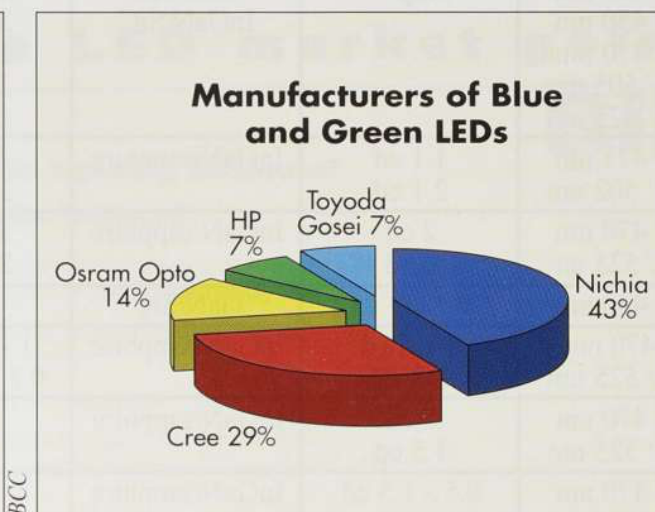


Figure 2. Current market shares of leading manufacturers of nitride-based LEDs. Nichia leads with 43% of the market, which is projected to reach around 840 million units by the end of the year.

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Marcfav@aol.com

Osram Opto Semiconductors) and Stanley Electric.

Cree's nitride LED devices use a SiC conducting substrate; all the other makers employ an insulating sapphire substrate. The advantage of the conducting substrate is that the cathode contact can be placed directly on the back of the LED; insulating substrates, on the other hand, require both contacts to be placed on top of the device. Cree's vertical chip structure results in quicker LED assembly and smaller chip size. Cree says this leads to improved yield, and also simplifies integration with other vertical chip type LEDs for display applications.

According to marketing manager Fran Barsky, Cree has no plans at present to provide packaged LEDs. "This ensures no downstream conflicts of interest with our customers and provides them the confidence to work with Cree." In contrast, many other suppliers provide both lamps and chips.

Cree has also recently updated the design of its blue and green LEDs. It now supplies a blue 'super bright' LED that exhibits a radiant flux of 3.5 mW, more than three times that of its earlier blue LED chip (1.15 mW). Cree doesn't specify the luminous intensity of its chips, as this depends on the packaging manufac-

turer's device optics. The super bright chips have the same 260 x 260 (m device dimensions as the earlier blue-emitting chip, but replace the GaN active layer with InGaN.

A total of four new nitride chips has been added. The original blue chip (which emits at 430 nm) is now supplemented by a deep blue chip at 450 nm and signal blue at 470 nm. The new green high brightness LEDs include a 505 nm signal green and 525 nm true green (see Table). The green LEDs have become a substantial portion of Cree's product mix, says Barsky.

The spectral width of the new chips is also improved, and now measures 30 nm and below (see Table). The earlier 430 nm blue GaN LED will be retained for applications where a lower light output suffices.

Who's in Front?

Exactly who is currently the leading manufacturer of these nitride devices is open to speculation. Cree and Nichia are now much closer in the race to be the top supplier of these devices. According to BCC's Favreau, comparing the situation at the end of 1998, Cree had improved its market share to 27%, from 21% in the

previous year. Given the much larger output of LEDs in 1998, Cree has a larger share of a considerably bigger pie.

In the same period, Nichia dropped from 59% market share in 1997 to 40% in 1998. But it is still shipping more devices. Current monthly production volumes quoted by both manufacturers would seem to suggest that Nichia still has the lead in overall production of nitride-based LEDs, which in Nichia's case is not limited just to blue and green devices, but includes white and red. Favreau estimates Nichia's production of the white and red nitride-based devices to be around 20% of its annual total - about 72 million devices.

Meanwhile, in Europe, **Osram Opto Semiconductors** (a joint venture from Osram and former Siemens Optoelectronics group) has made great strides in the production of blue and green LEDs in the past year. According to Dr. Ernst Nierschl, who is head of chip development for visible, infrared and magnetic sensors, Osram currently ships more than 10 million units per month, which would give it a 14% market share, ahead of both Toyoda Gosei and Hewlett Packard.

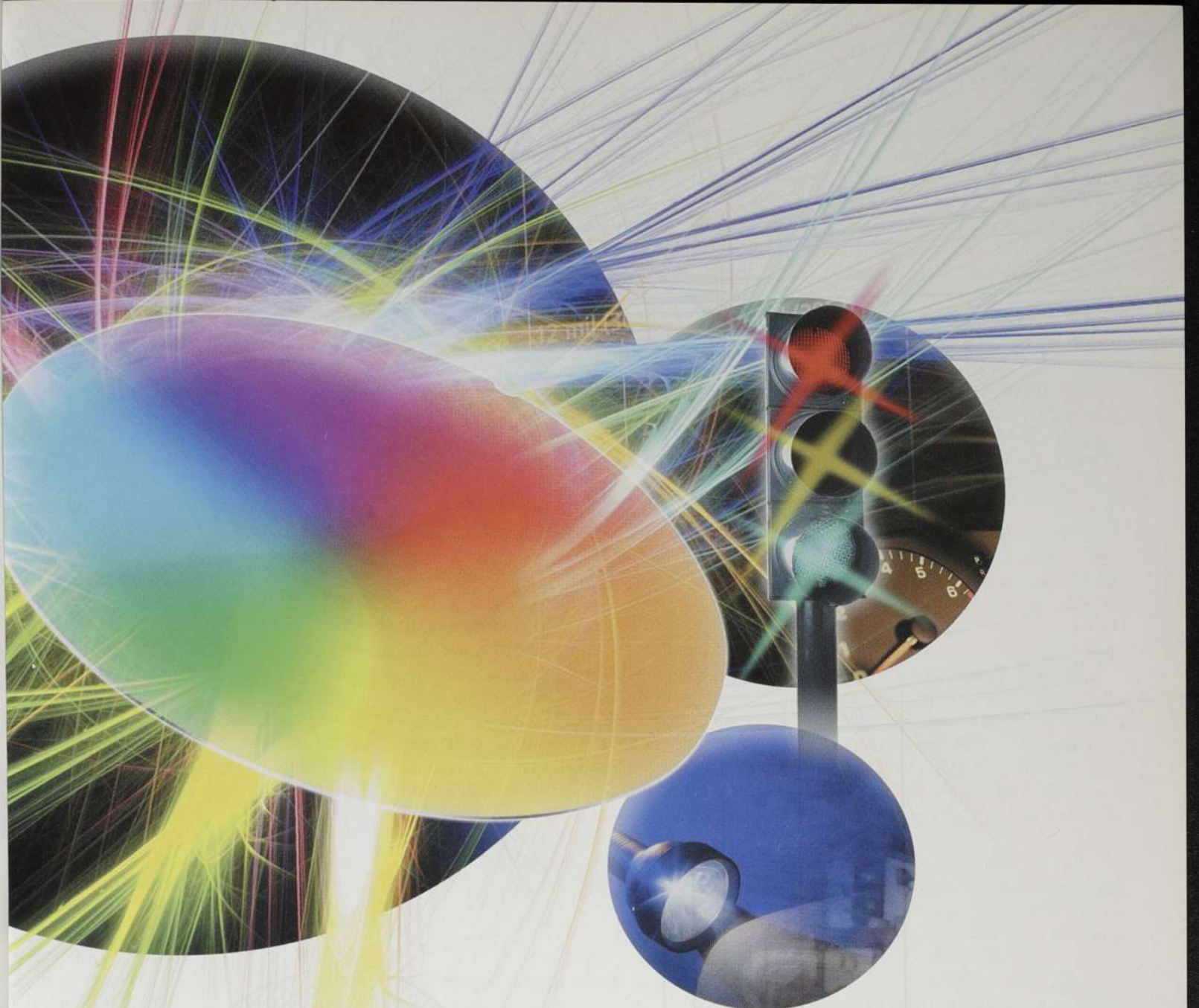
Osram manufactures its devices, both in chip and packaged forms, at its plants in Regensburg (Germany) and Malacca

Company	Color / Wavelength	Luminous Intensity [1]	Material	Radiant flux	FWHM	Current stated output (million units/month)
Cree	Blue / 430 nm	Chip**	GaN/SiC InGaN/SiC	1.15 mW	65	20
	Blue / 450 nm			3.5 mW	20	
	Blue / 470 nm			2.5 mW	26	
	Green / 505 nm			2.0 mW	30	
	Green / 525 nm			1.5 mW	36	
HP	Blue / 473 nm	1.1 cd	InGaN/sapphire	4.0 mW	35	5
	Green / 502 nm	2.1 cd		3.5 mW	35	
Nichia	Blue / 470 nm	2 cd	InGaN/sapphire	3.0 mW	30	30
	Green / 525 nm	6 cd		2.0 mW	40	
Osram Opto	Blue / 430 nm	0.125* cd	GaN/SiC	[2]	60	10
Samsung	Blue 470 nm	1-1.5 cd	InGaN/sapphire	1 - 1.6 mW	30	[2]
	Green / 525 nm	2-3 cd		0.8 - 1.1 mW	40	
Toyoda Gosei	Blue / 470 nm	5 cd	InGaN/sapphire	[2]	45	5
	Green / 525 nm	1.5 cd		[2]	35	
Uniroyal	Blue / 470 nm	0.5 - 1.5 cd	InGaN/sapphire	>1.0 mW	30	[2]
	Green / 525 nm	1.5 - 3.0 cd		>1.0 mW	34	

* (@ 10 mA)

** LEDs are supplied as die. Luminous intensity depends on individual manufacturers packaging optics.

[1] All outputs measured @ 20 mA unless stated. [2] Data not available.



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(Malaysia), respectively. It licenses Cree's proprietary blue and green nitride LED conducting buffer design, and also buys the majority of its substrates from Cree (and is one of its biggest customers). The company also obtains substrates from Freitronics GmbH as a second source. The latter is a subsidiary of Siemens based in Erlangen, Germany, set up to supply its SiC device activities.

Osram supplies blue and green LED devices in a range of packages. The most popular package is the surface mount, says Nierschl. It also uses Cree's new high brightness InGaN devices, and approximately 70% of its production is for the blue device, with the remainder for the green LEDs.

Toyoda Gosei began shipping p-n junction double heterostructure blue LEDs in 1995, and devices containing a multiquantum well structure as the active area in early 1997. It has been involved in a lawsuit with Nichia concerning these devices since July of last year (CS 5(4), p.6).

By the end of 1998, the company shipped around 5 million devices per month, and this is still assumed to be the case, says Favreau. This gives it a current market share of 7%, compared to its share of 14% in 1998. It supplies both epiwafers (to Hewlett Packard among others) and chips.

Panasonic is one of Toyoda Gosei's big customers for blue chips. It packages

the company's GaN-on-sapphire die into devices, with a 1.4 cd luminous intensity, at a rate of 1 million devices per month.

Hewlett Packard's production of blue, blue-green and green InGaN-on-sapphire LED devices is currently 5 million per month, with some of the production being used for white LEDs. This fig-

"the current market share estimates could change dramatically in a year or two, depending on when the patent issue is resolved, and on how quickly Uniroyal Technology can ramp up their production."

ure falls short of the company's own predictions [CS (3)5, p.16] of 9 million units per month for the first quarter of 1999. But HP remains the top LED manufacturer in the world, and is one of the few companies that offers a full palette of colors.

The company supplies packaged LEDs in a range of formats that include the standard 5mm type LED and surface mount type. Some of its epi materials for blue chips come from Toyoda Gosei, and the blue-green and green epitaxial materials are grown in-house.

New Players

Uniroyal Technology Corporation (UTC) is one of the recent entrants into the market [CS 5(4) p.10]. UTC has begun shipping limited quantities of nitride-based blue and green LEDs in collaboration with its joint venture supplier, Emcore, from whom it licenses the manufacturing process on a non-exclusive basis. UTC's LEDs will be manufactured at its 77,000 ft² facility in Tampa, Florida. The company says it expects to be ramping up towards full production - estimated to be around 200 million devices annually - by the latter part of the year.

According to CFO George Zulanis, the company will provide the full spectrum of colors. Of this, around 30% of production will be for blue and green LEDs, which are based on InGaN-on-sapphire. He says that UTC intends to ship epiwafers, chips and devices for high

brightness applications. Devices are expected to exhibit luminous intensities in excess of 1 cd.

Waiting in the Wings

Marketing manager Hideki Matsubara says **Sumitomo Electric Industries** has taken a different approach to the production of LEDs. "We employ ZnSe homoepitaxial structures for blue, green and white LEDs," he says. Sumitomo's structures are grown on conductive n-type ZnSe substrates by MBE and contain ZnCdSe single- or multiquantum well active layers.

Sumitomo's approach to a white LED is also unusual. "For the white LED we use only ZnSe homoepitaxial LED chips with no phosphors," says Matsubara. A common method of making white LEDs is to use a blue chip to excite a phosphor to produce a broad spectrum that appears white. In the Sumitomo white device, the epitaxial ZnCdSe active layer emits blue or bluish-green light at 480-490 nm, and part of the blue emission is absorbed, exciting a broad yellow emission at 585 nm in the ZnSe substrate. The mixing of the blue light from the epitaxial layer with the yellow light from the substrate results in white light luminescence. At 20 mA injection, the white LED device typically has an operating voltage of 2.7 V, optical output equal to 2.0 mW, and an efficiency of 8 lm/W.

Sumitomo's production of LEDs will begin later this year, although it is not yet decided whether chips or packaged devices will be shipped, says Matsubara. "I think our LEDs have a big advantage over GaN LEDs," he adds. "The operating voltage is approximately 1 V lower and the device processing cost much lower due to the use of conducting substrates." The Sumitomo LED is also not restricted by Nichia's patents, especially the one concerning the method of manufacturing the p-GaN layer.

According to BCC's Favreau, another major Japanese LED manufacturer, **Rohm Co. Ltd.**, has a blue LED device,



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Kingbright packages Cree's blue GaN-on-SiC chip into conventional round 3 mm, 5 mm and rectangular blue and white LEDs.

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However, the current dispute between Nichia and Toyoda Gosei, which relates to alleged patent infringements of Nichia's p-n junction GaN blue LEDs, is holding back the introduction of Rohm's device. "Rohm is waiting for the patent dispute to finish, that way they'll know what to do to avoid a lawsuit," he says.

Similarly, **Stanley Electric Company** is also waiting for the situation to resolve itself. Stanley is the second largest LED supplier in the world by sales revenue, behind HP, and has total revenues of \$1.5 billion from a diverse range of electronics components. Currently, the company buys and packages Cree's GaN-on-SiC blue LED chips, but it also obtains chips from other suppliers, according to marketing manager Midori Miller.

The Japanese company supplies a surface-mount, dome lens LED designed for use in relatively low brightness applications such as backlighting and light pipes. These devices measure 3.2 mm wide, 1.6 mm long and 1.85 mm high, and are available in a range of colors, including blue at a wavelength of 430 nm, which has a luminous intensity of 0.03 cd (measured at a 20 mA drive current) at viewing angles of 40° and 50°.

According to Stanley, they can be used in a standard surface mount or installed in a reverse-angle configuration, i.e. mounted on one side of the printed circuit board with the light shining through a hole in the opposite direction. A thin version of the device for applications in backlighting, cellular phones and pagers is available with a luminous intensity of 0.06 cd and 140° viewing angle.

Recently founded **Technologies & Devices, Inc** (TDI) also plans to offer new nitride LED devices. TDI started in 1997 with the aim of commercializing

crystal growth and device fabrication of SiC wafers and GaN-on-SiC epiwafers. This was in collaboration with the Crystal Growth Research Center and PhysTech WGB Research Group St. Petersburg, Russia.

According to TDI's president Vladimir Dmitriev, the company has a research and development project for GaN-based blue LEDs on 6-H-SiC substrates. The aim is to produce devices that have GaN and p-GaN p-n junction active regions, although there are no plans to sell packaged LEDs. As well as belonging to the minority of GaN devices makers that use SiC as the substrates, TDI is further unusual in that its devices are based on hydride vapor phase epitaxial (HVPE) growth. "This method is much cheaper than the MOCVD technique which is commonly used for GaN LED production," says Dmitriev. Devices are expected to be ready for market by the beginning of 2000, and will be initially targeted at the low brightness end of the market.

Although products will not be available until the fall, the **Samsung Advanced Institute of Technology** (SAIT) has also reported the successful development of high brightness blue and green LEDs, and the pulsed operation of a blue laser at room temperature. Its blue and green LEDs contain an InGaN/GaN multiquantum well structure for the active area. The brightness, measured at a 20° viewing angle, is 1.0-1.5 cd for a blue LED at a wavelength of 470 nm, and in the range 2.0-3.0 cd for a green device at 525 nm. Typically the forward voltage of both LEDs was 3.8 V.

In Taiwan, the most likely candidates for the manufacture of nitride LEDs in the near future are **United Epitaxy Company**, **Epistar** and **Visual Photonics Epitaxy Company** (VPEC). These companies are already major suppliers of high brightness AlInGaP LED devices. Both Epistar and VPEC claim that they have GaN-base blue LEDs that are close to market. Vice president of Epistar, Dr. Jacob Tarn, says that Taiwan's industry is working hard towards an infrastructure for blue and green nitride-based LEDs. The number of recent sales of MOVPE reactors to the area would seem to support this assertion.

Epistar started working on InGaN in the middle of 1998 with the aid of funding from the Taiwanese government. "The performance of our device is comparable to devices already commercial available," says Tarn. "The 470 nm blue chips exhibit a radiant flux value of greater than 1 mW, and similar results have also been obtained for both bluish-green and green devices." The decision on when to introduce these LEDs to the market is still under evaluation, but Tarn believes these products will reach the market before the end of the year.

Widgap Technology, or WiTech, was founded in 1997 to develop and commercialize microelectronic devices such as GaN/AlGaIn HEMTs (for which it has a partnership with Hughes Electronics) and InGaN LEDs in the 470-570 nm range. It is also working on AlGaIn detectors for the UV region. Situated in Goleta, California, the company aims to introduce blue, green and white LEDs in late 1999. It also has a partnership, worth \$2.9 million, with GE Lighting (funded by the US Commerce Department's NIST organization) to develop white LED lighting technology. WiTech says it will use color mixing with fluorescent phosphors in the packaging to convert the short wavelength blue emission to white output.

Other potential players, such as Japan's **Shin-Etsu** and **Sharp**, may also join the fray sometime in the future. Shin-Etsu licensed blue LED technology from Cree 2 years ago, says Favreau, but has no products as yet. Sharp says it is currently at the research and development stage.

With established companies ramping up their manufacturing capacity, further large increases in unit sales of these devices look likely in the coming year, particularly if the Nichia patent dispute with Toyoda Gosei is finally resolved. As Marc Favreau puts it: "It's worth noting that the current market share estimates could change dramatically in a year or two, depending on when the patent issue is resolved, and on how quickly Uniroyal Technology can ramp up their production." Either way, strong market growth for high-brightness wide bandgap LEDs will be good news for the compound semiconductor industry.



WiTech aims to commercialize blue, green and white LEDs by the end of the year.

Industry Shows Support for Wide Bandgap Semiconductors at the Spring MRS Meeting

BRIAN FOUTZ
CORNELL UNIVERSITY

Commercialization of, and industrial support for, emerging wide bandgap semiconductors was a central focus of the Y Symposium at this year's Materials Research Society Spring meeting, held the week of April 5th in San Francisco, California. This was one of the rare occasions when microelectronic devices, not optoelectronic devices, were the center of attention. Invited talks were given by many of the key companies in this rapidly developing field. Cree, Northrup Grumman, Siemens, Honeywell, Rockwell, HRL, Epitronics, and others presented results and outlined the role that wide bandgap semiconductors could play in their products in the next few years. The wide bandgap semiconductors of interest, SiC and the III-V nitrides, promise new levels of performance in high power and high frequency applications. These new devices include high power switches and high power amplifiers; applications range from power systems to cellular telephony.

Nitride Based HEMTs

A presentation from Cree Research reviewed the latest record results for AlGaIn/GaN HEMTs on SiC substrates. The device layout, shown in Figure 1, uses a 12 nm doped layer in the AlGaIn barrier with a 5 nm undoped spacer. Record power densities of 6.9 W/mm and 53% PAE have been achieved at 10 GHz (see Figure 2). These were small devices with only a 0.125 mm

periphery and had 680 mA/mm peak DC source to drain current. It is also interesting that these devices only use 14% aluminum in their AlGaIn barrier layer, which is somewhat lower than other group's HEMTs, which typically use between 20 and 35% aluminum. Their larger 3 mm periphery devices achieved a total power 9.1 W at 7.4 GHz, another record for nitride-based HEMTs.

Gerry Sullivan of Rockwell International presented results of their AlGaIn/GaN HEMTs. Their peak power density for small 0.320 mm periphery devices is 2.8 W/mm at 10 GHz. Large periphery multi-finger (16 x 80 μ m) devices demonstrated a total output power of 2.3 W or 1.8 W/mm. Under pulsed testing the output power increased to 3.9 W. Rockwell plans to use these devices in a 9 GHz power amplifier employing two 1.28 mm HEMTs in a hybrid configuration. According to Sullivan the advantages of these amplifiers will be fewer transistors and higher bias voltages making output impedance higher, thereby lowering losses on a system level.

Joan Redwing of Epitronics Corp. also demonstrated AlGaIn/GaN HEMTs on SiC substrates. These devices have excellent DC characteristics with a peak DC source to drain cur-

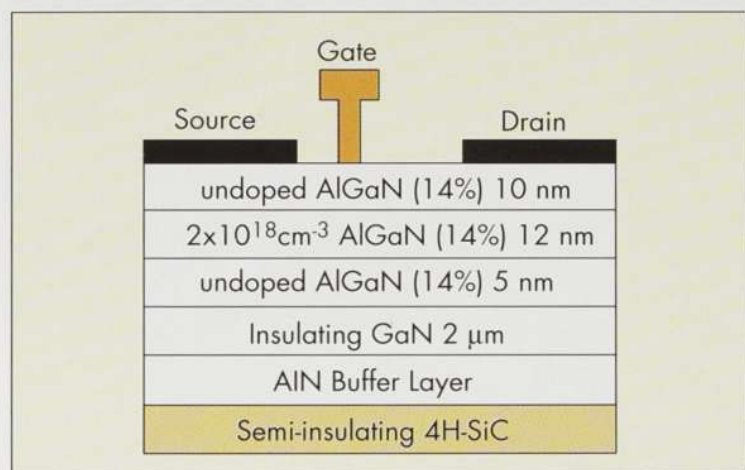


Figure 1: Cross-sectional view of Cree's GaN/AlGaIn HEMT structure grown on a semi-insulating 4H-SiC substrate.

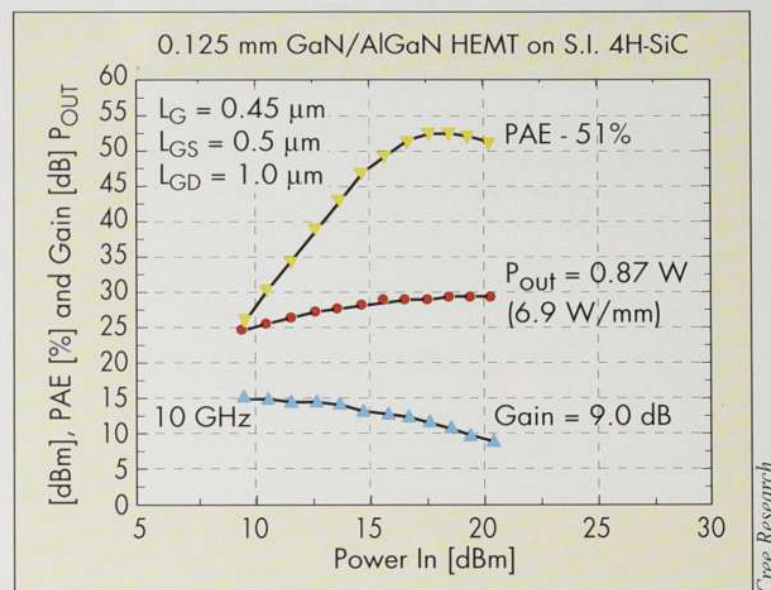


Figure 2: A 10 GHz CW power sweep of Cree's 0.125-mm GaN/AlGaIn HEMT on semi-insulating (SI) 4H-SiC. This device shows a record power density of 6.9 W/mm.

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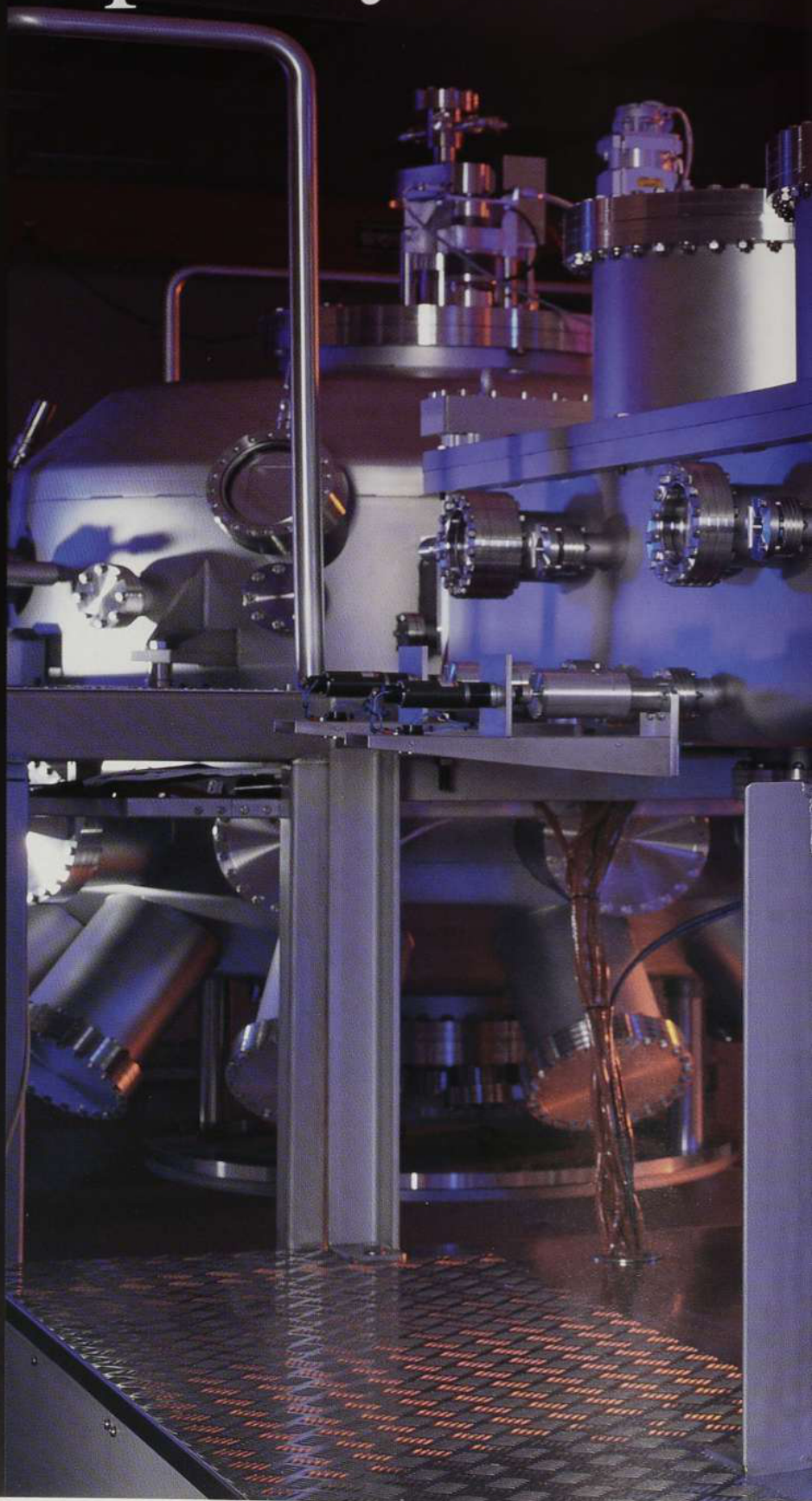
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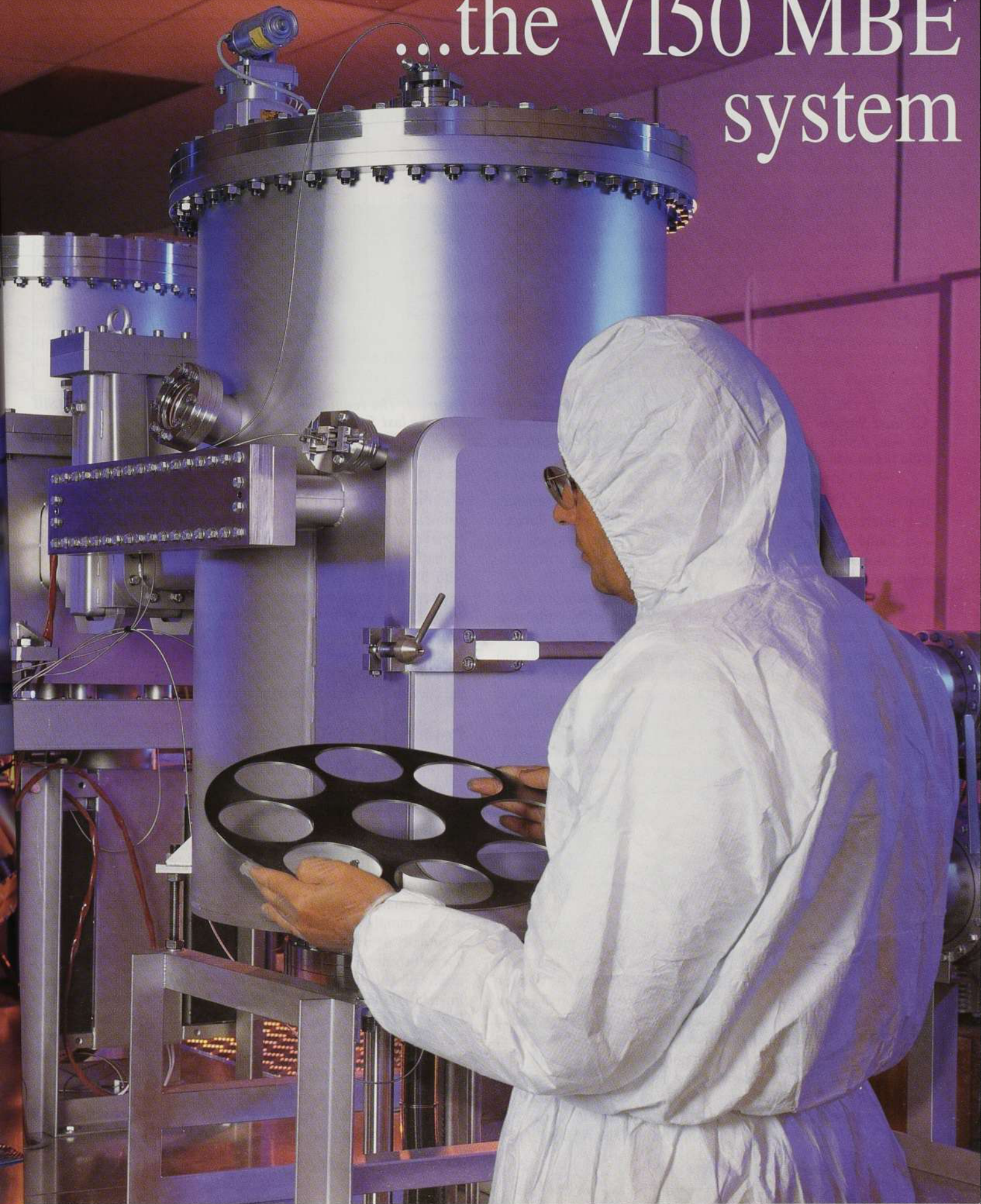
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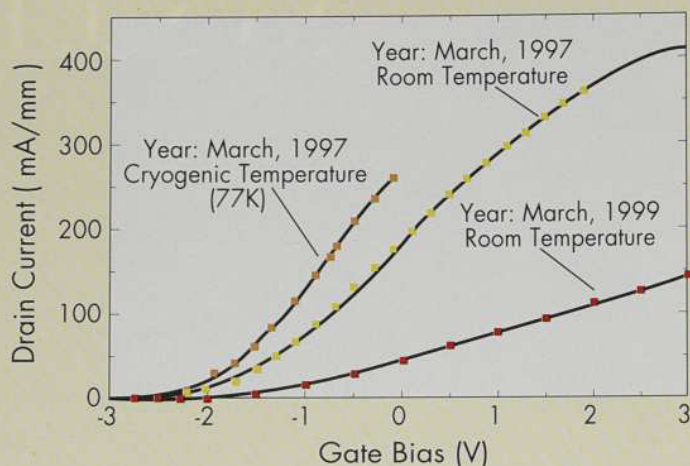
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Aging Effect in AlGaIn/GaN HFETs



Rensselaer Polytechnic Institute

Figure 3: The aging effect of AlGaIn/GaN HFETs presented by Michael Shur of Rensselaer Polytechnic Institute. These two-year-old devices show a 60% drop in drain current compared to data taken when they were new.

rents of 1.2 A/mm. However, RF power data is not yet available. It is interesting to note that Epitronics examined many devices and found that, in general, the mobility of the induced two dimensional electron gas drops with increased sheet carrier concentration.

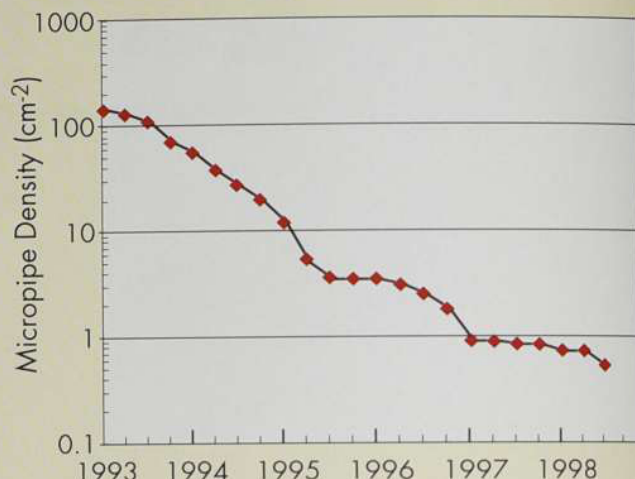
It seems that in general, however, there is still much work to be done on nitride-based power devices. Prompted by collaborations with Lester Eastman of Cornell University, Michael Shur from Rensselaer Polytechnic Institute reexamined several old AlGaIn/GaN HEMTs and compared the measurements with data taken when the devices were new, two years ago. Results showed a significant degradation of the DC current characteristics, as shown in Figure 3. His analysis showed that the primary cause of the drop in current was a drop in the 2-D electron gas mobility. This problem has yet to be reported by others and it is unclear whether new (much improved) quality material will suffer the same degradation over time.

SiC Power Devices

SiC power devices are expected to find their niche in the less than 5 GHz high power market. Power switches and MESFETs may be among the first SiC devices to be commercialized. Susesh Seshadri outlined Northrup Grumman's progress in power switching and specifically in Gate-Turn-Off Thyristors (GTOs). By connecting a SiC JFET between the anode and the gate of a GTO, the switching time of the device was reduced to less than 100ns. These high power devices typically operate at 1000 V with more than 10 A capability. These SiC devices were then used in a prototype 3-phase pulse width modulated controller which was able to directly drive a 45 V 1/4 hp motor. Peak currents were 13 A and the switching frequency was 4 kHz.

Cree Research's progress in the SiC power device area was outlined during Scott Allen's presentation. Specifically, Cree is

R&D Best SiC Substrates



Cree Research

Figure 4: The reduction of micropipe density in n-type 4H-SiC over the last 5 years in Cree's R&D process.

working on SiC MESFETs for applications in high power communications. Using an offset gate design, Cree's MESFETs have achieved peak power densities of 4.6 W/mm at 3.5 GHz. Large 48 mm gate width devices have achieved a total power of 80 W with 38% power added efficiency (PAE). The power in these devices has increased rapidly in the last year enabling this technology to be used in cellular base stations. These stations typically use voltage supplies of about 50 V that match the operating voltage of SiC based modules. Allen stated that this could result in better efficiency since voltage dividers can be eliminated from the current base station designs that use Si and GaAs technology.

Production of SiC Substrates

Production of high quality SiC substrates is a necessary step for producing high quality SiC devices and for nitride-based high power devices, which typically use SiC as a substrate. Cree Research has been the leader in SiC wafer production, and was the only commercial source of high quality wafers for many years. Scott Allen outlined the improvements of Cree's production along with their future plans. Cree has recently moved from 1 3/8" wafer size to 2" wafers as the standard product in the last several months. Throughout 1999 they plan to introduce 3" and eventually 4" wafers sizes. One factor determining the quality of the substrate is micropipe density. Cree has made steady improvements in decreasing the micropipe density from approximately 200 cm⁻² in 1993 to less than 1 cm⁻² today for the best R&D material (see Figure 4). Commercial n-type material still has micropipe densities of 10 cm⁻² and for semi-insulating substrates, necessary for good microwave performance in many devices, the micropipe density is currently 50 cm⁻².

Northrup Grumman Corporation is also working on the production of large diameter 4H-SiC substrates using physical vapor deposition, as outlined in a talk given by Vijay Balakrishna. They

are looking at production of 2" and 3" substrates, both n-type and semi-insulating. Through improvements in their bulk growth they have been able to increase the percentage of highly resistive material grown from 25% to over 70% per boule. By decreasing the impurities of the seed crystal, micropipe densities have also been reduced dramatically over time. Currently, the lowest achievable densities are around 2 cm^{-2} with 100 cm^{-2} being the average. This technology will transfer to Litton Airtron for commercialization. Sterling Semiconductor, also present at the meeting, is the second company, after Cree, to announce the availability of 2" SiC substrates commercially. Currently, n-type 4H and 6H-SiC substrates are available.

Panel Discussion

A panel discussion, with representatives from six companies interested in wide bandgap semiconductor products, was held on the evening of April 7th. Short presentations were given by representatives from Cree, Northrup Grumman, Siemens, Honeywell, Rockwell, and HRL Laboratories. Each company briefly outlined their plans for wide bandgap semiconductors and product goals for the next few years. A discussion of whether wide bandgap semiconductors would become a commercial success followed.

Calvin Carter of Cree Research discussed their blue LED products as well as their plans for larger diameter (3") SiC substrates. He also discussed a partnership with C3 Inc. to produce the SiC gemstone Moissanite. This gemstone is an ideal diamond simulate. This partnership is important for Cree because it will help drive down the costs for SiC bulk growth.

Suresh Seshadri outlined Northrup Grumman's future in wide bandgap semiconductors. Since Northrup Grumman is primarily a contractor for the military their interests are to satisfy the military's interest in stealth power and pulsed weapons. For this purpose, Northrup Grumman is focusing its efforts in Microwave SITs and MESFETs.

Roland Rupp of Siemens (now Infineon Technologies) stated that this company's interest in wide bandgap materials includes SiC Schottky diodes. An example is a prototype device they have developed which operates between 600 V -1700 V and 4 -10 A.

Earl Benser of Honeywell Inc. stated that nitride-based UV flame sensors, to be used in burners and boilers, are a focus of their efforts. These detectors will also be used for the detection of pilot lights in large systems and in turbines in aircraft. It is hoped these detectors will replace the vacuum tubes currently used for these applications. Products are currently in testing and are expected to be available in about 12 months.

Gerry Sullivan outlined Rockwell International's interest in AlGaN power HEMTs. They are aiming at the greater 10 GHz market and he believes that hybrid circuits (and not MMICs) are the way to go. David Grider from HRL Laboratories says that

they are examining SiC devices for lower frequency higher power devices and nitride-based HEMTs for higher frequency applications. These applications include cell phone base stations, satellite communications and airborne radar.

Much of the discussion after the presentations focused on the ability of the wide bandgap based devices to stay ahead of silicon based devices. Arguments were given that silicon is constantly improving and has a way of surpassing itself over time. With this being the case, can the wide bandgap semiconductors stay ahead? One of the attendees to address this question was Scott Allen of Cree Research. He argued that base station designers are sorely in need of devices that will be better impedance matched and operate around the standard 50 V. He announced that Cree SiC MESFET packages will be a superior solution available by the end of 1999. Of course, the question as to whether wide bandgap semiconductors will be able to remain competitive in the future remained unanswered.

Much of the discussion after the presentations focused on the ability of the wide bandgap based devices to stay ahead of silicon based devices. Arguments were given that silicon is constantly improving and has a way of surpassing itself over time. With this being the case, can the wide bandgap semiconductors stay ahead?

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The Current Status of Wide Bandgap Semiconductors for High Temperature Applications

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Wide bandgap semiconductors (WBS) have long been promoted for use in high temperature applications. This paper outlines the reasons why these materials offer benefits for such environments, the types of device that are already seeing service and likely future developments that will increase the potential for WBS to meet requirements that silicon alone cannot.

Introduction

Silicon-based technology currently accounts for more than 95% of the total semiconductor market¹. Silicon technology is advanced, well understood and enables the fabrication of sophisticated components and mechanisms. The value of this market is such that very large investment goes into the improvement of silicon device design and manufacture every year, driving further enhancements and increased performance, while constantly reducing unit costs. The benefits of this investment, however, are not enjoyed by all component users.

The high temperature capability of most silicon devices is limited to 70°C. Military specification components are qualified to 125°C but only certain types of device are available with this certification and there are usually price and lead time penalties. Whilst operation of the silicon die itself is often possible to temperatures as high as 250°C, packaging issues limit the use of many devices to much lower levels.

When appropriately packaged, using materials and techniques that operate successfully at high temperatures, silicon devices can address applications up to 250°C. Silicon-on-insulator technology can extend this range to 350°C and is now used routinely for oil and gas exploration applications with a rating of 225°C. For applications above this and for power applications above 200°C, new materials are required. This is where WBS come into their own, the three main candidates being silicon carbide, gallium nitride and diamond. The status of technological development of these three materials is different and their varying properties offer diverse benefits, depending on the end application.

Basic Properties

The primary challenge facing devices intended for use at high temperatures is limiting the leakage current to levels that do not compromise normal operation. The density of thermally generated (intrinsic) carriers, and hence leakage current, increases with temperature. Once this exceeds the doping density then the junction properties are destroyed and the device fails. While increasing the doping density during fabrication helps to extend the temperature range of a device, there are limits to this and beyond that point, a material with a wider bandgap is required. Figure 1 illustrates the benefits of WBG materials over silicon².

Figure 1 shows clearly the advantage gained by even a small increase in bandgap. For example, gallium arsenide has a bandgap only 0.3 eV greater than silicon but this translates to an extension in its usable temperature range of some 200°C. There are further benefits offered by WBS materials when compared with silicon and some disadvantages. For example, silicon carbide has a much better thermal conductivity than silicon but no liquid phase at atmospheric pressure, complicating its processing. Values for some of the more important properties are given in Table 1.

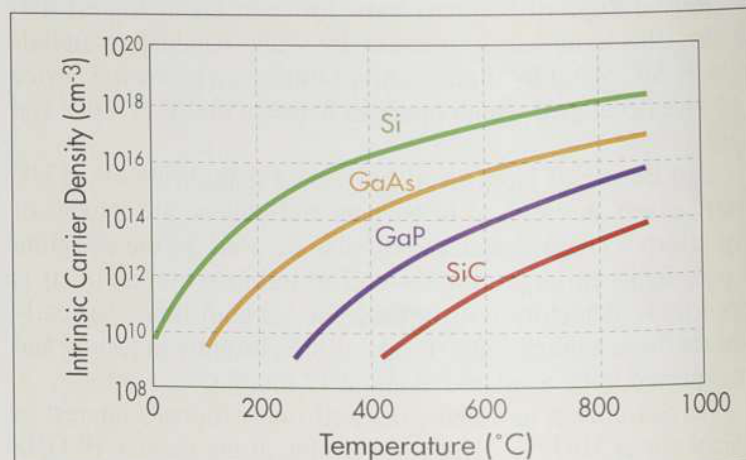


Figure 1: Change in intrinsic carrier density with temperature for three compound semiconductors compared with silicon.

Current Status of Development

A. Gallium Arsenide

The greater bandgap of gallium arsenide confers better high temperature performance on this material, although the lower thermal conductivity offsets this benefit to some extent. Gallium arsenide

Designers of power systems are constantly seeking to reduce power losses, volume and weight of their equipment. High power applications are likely to be the first to use SiC transistors because of the significantly reduced on-state and switching losses relative to silicon.

technology is relatively mature, with a wide range of devices and VLSI components being readily available. The majority of these components are unsuitable for high temperature use and there remain some difficult challenges for using GaAs devices at temperatures above 250°C.

The most mature GaAs device structure is the MESFET, although high temperature use of these devices is limited. Substrate resistivity decreases rapidly with temperature, creating a leakage path between source and drain. A second degradation mechanism is thermal emission of electrons over the Schottky barrier at the gate. These two factors combine to cause GaAs MESFETs to fail at below 200°C, even lower than silicon MOSFETs.

Introducing a buffer layer between the source and drain can raise the upper temperature limit to around 350°C. Aluminium arsenide has been shown to reduce drain leakage by thirty times in this manner⁴. Heterostructures have

proved even more successful, with HBTs, HEMTs and complementary heterostructure FETs (CHFETs) using AlGaAs with GaAs to achieve structures capable of operation up to 600°C³.

GaAs devices have been used in high temperature applications, as engine speed and ABS sensors, for example. However, current developments in GaAs are concentrating on RF and other high frequency applications. Little research is being undertaken for high temperature use and there are no current suppliers of high temperature GaAs devices. Any short or medium term benefits to the high temperature industry will be incidental to the main research effort and so cannot be relied upon to yield useful components or technology.

B. Silicon Carbide

Silicon carbide is in by far the most advanced state of development of the three main WBS materials. Development of processing and fabrication techniques has been under way for over 30 years, driven by its high temperature, high power and, to a lesser extent, high frequency capabilities.

Designers of power systems are constantly seeking to reduce power losses, volume and weight of their equipment. High power applications are likely to be the first to use SiC transmitters because of the significantly reduced on-state and switching losses relative to silicon. An inherently better performance in terms of power loss presents a double advantage by reducing the requirements for external cooling. Unipolar operation of SiC devices, in the form of Schottky diodes and FETs, can be extended to more than 2000V, giving SiC the potential to displace silicon for IGBTs, GTOs and power diodes⁵.

Remaining challenges lie in the areas of mate-

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Property	Si	GaAs	6H-SiC	GaN	Diamond
Bandgap (eV)	1.1	1.43	3.02	3.45	5.45
Melting point (°C)	1420	1238	-	2500	4000
Electron mobility (cm ² /Vs)	1500	8500	370	1250	2200
Thermal cond (W/cmK)	1.5	0.46	4.9	1.3	20
Intrinsic temp (°C)	~400	~650	>1000	>1000	>1000

Table 1: Physical properties of WBS and silicon.

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The High Temperature Electronics Network (HITEN) is one of the networks of excellence supported by the European Commission under the Esprit programme. The bulk of the funding to run the service comes from membership subscriptions, either for individuals or in corporate form. A range of databases, reports and market analyses is provided, covering semiconductors, packaging, components, literature references and suppliers of products for high temperature applications. Access to the network is via the world wide web (<http://www.hitene.com>), members being provided with userids and passwords for full access and guests being permitted to see only an overview. Other membership benefits include a monthly newsfeed of relevant articles and periodic printed newsletters.

HITEN also organises training courses and one day awareness seminars throughout Europe on various aspects of high temperature electronics (HTE), as well as the biennial European conference, due to take place this July in Berlin.

rial quality and metallisation. Two inch wafers with micropipe defect densities below 0.8 cm^{-2} are commercially available and three inch wafers are likely to be on the market by the end of 1999. Further improvements in quality are essential for market acceptability and the necessary developments look likely to take place within a year or two.

Reliability is the second main technical challenge and is related to the high temperature stability of metal contacts. Whilst low resistance contacts to n-SiC can be formed with nickel and tungsten, p-SiC presents greater challenges as metals with a sufficiently large bandgap are not available. Aluminium based contacts have proved the most successful to date but are not sufficiently stable at high tem-

perature to provide long term operation. Electromigration is an issue that is particularly awkward at high current densities.

On the positive side, the formation of high grade silicon dioxide on the surface of silicon carbide is possible by a thermal oxidation process. Although the quality of this oxide does not match that achievable with silicon, high temperature operation of MOS devices in silicon carbide is achievable and lifetimes of many hundreds of years at 2 MV/cm and 350°C have been reported⁵.

SiC devices have been used in high power radar systems (MOSFETs), as flame indication sensors in aerospace engines and are essential for logging in geothermal wells in the petroleum industry.

C. Gallium Nitride

Gallium nitride development is some years behind that for silicon carbide. Currently driven by the market for blue LEDs and lasers, other device types are proving more difficult to manufacture. While optoelectronic devices have been available since 1993 and a heterojunction bipolar transistor was reported in 1996⁶, the first MOSFET using gallium nitride has only just been demonstrated⁷.

The main difficulties facing the use of gallium nitride at high temperatures are similar to those that existed a few years ago for silicon carbide, i.e. material quality, etching and contacts.

No suitable lattice matched substrate for gallium nitride exists. Those that have been used for bulk growth exhibit a very high dislocation density at the boundary (silicon carbide and sapphire) or have poor thermal conductivity (sapphire, zinc oxide, etc).

Gallium nitride is chemically inert in nearly all the main wet etch processes. Dry processing by reactive ion etching is used for all reported device fabrication.

Good ohmic contact quality is a critical issue for efficient device operation, especially for power devices. A combination of titanium and gold has been used for n-GaN, resulting in a resistance that is around 100 times greater than that achievable with silicon and gallium arsenide but low enough for initial device demonstrations.

D. Diamond

Diamond offers electronic characteristics that are superior to all the other materials discussed here. However, the technical challenges facing the manufacture of diamond devices are the most severe. The formation of diamond substrates has been achieved with good success³. On the other hand, doping has proved very difficult and contact metals present a range of problems related to the reactivity of carbon. Very simple diode and FET devices have been demonstrated but it likely to be many years before useful diamond devices are available for high temperature applications.

Conclusion

WBS offer significant performance benefits over silicon for high temperature applications. Challenges remain in terms of substrate quality and reliable contact materials, as well as packaging technology. However, usable devices are now starting to emerge, especially in silicon carbide, and the next few years promise some exciting advances and significant leaps forward for reliable high temperature electronics.

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Nitride Semiconductor Transistors Poised to Revolutionize DOD Systems

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The US Department of Defense (DOD) has historically pioneered development of advanced solid state transistor and circuit technology. This dates back to the early days of silicon integrated circuit technology, continued with the development of GaAs microwave monolithic integrated circuits (MMICs), and continues with the wide bandgap semiconductors, SiC and AlGaN. Revolutionary developments have been driven by the DOD need for improved computation, communication, radar, and electronic warfare systems. The systems require high power, bandwidth, linearity, efficiency, and sensitivity in compact configurations. While many of today's systems are well served

by GaAs or InP microwave components together with vacuum electronic transmitters, new solutions are required to meet the system needs of the future.

AlGaN power transistors have outperformed the best AlGaAs HEMTs and PHEMTs in power density. SiC static induction transistors (SITs) and MESFET are also making inroads for transmitters below X-band (8-12 GHz).

Table I lists present state-of-the-art performance for AlGaN HEMTs and SiC MESFETs at 3 GHz and 10 GHz. SiC devices presently show an absolute power advantage at 3 GHz (80 W cw demonstrated at 3 GHz from a single transistor¹) that is largely due to supe-

Property	AlGaAs/GaAs	4H SiC	AlGaN/GaN
Power density (W/mm)			
3 GHz	1.7 ^a	5.8 ^d	2.8 ^f
10 GHz	1.4	4.5 ^d	6.9 ^g
PAE (%)			
3 GHz	85 ^b	60 (0.8 GHz) ^e	78 ^f
10 GHz	75 ^c	41 (8 GHz) ^e	62 ^h

Table I: Demonstrated microwave power density and power-added-efficiency (PAE) for AlGaAs/GaAs, 4H SiC, and AlGaN/GaN FETs.

- ^a K. Asano, Y. Miyoshi, K. Ishikura, Y. Nashimoto, M. Kuzuhara, and M. Mizuta, 1998 IEDM, p. 59 (1998).
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- ^f simultaneous with 78% PAE, private communication Prof. Lester Eastman, Cornell University.
- ^g S. T. Sheppard, K. Doverspike, W. L. Pribble, S. T. Allen, J. W. Palmour, L. T. Kehias, and T. J. Jenkins, IEEE Elec. Dev. Letts. 20, 161 (1999).
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rior thermal conductivity and a more mature substrate technology. SiC devices, however, will be hard-pressed to match the power-added-efficiency (PAE) of AlGaIn HEMTs. Frequencies below 10 GHz are of interest for commercial wireless base-stations while both 3 and 10 GHz bands are critical for DOD radar, EW, and communications.

AlGaIn transistors are poised to supplant conventional III-V devices for many defense and commercial applications.

The material properties in Table II help to explain the advantages of AlGaIn over SiC and GaAs. AlGaIn has a dielectric strength (breakdown field) comparable or higher than SiC, and seven times that of GaAs. The thermal conductivity of GaN is also three times that of GaAs (although three times lower than SiC). The larger bandgap also reduces carrier generation-recombination for operation at elevated temperatures. Spontaneous and piezoelectric polarization effects in AlGaIn/GaN plus the traditional heterostructure advantages (e. g. modulation doping and reduced gate leakage), allow the realization of a two dimensional electron gas (2DEG) with a carrier density two to four times that of AlGaAs/GaAs. This high carrier density plus the high breakdown field enables power densities 10 times that of GaAs with comparable or higher efficiency, greater bandwidth, and higher output impedance. The lack of the 2DEG for SiC technology limits its frequency and efficiency performance.

The efficiency advantage is critical for many DOD systems and results from the higher operating voltages.² The factor of three higher thermal conductivity and the eight-fold higher breakdown strength for AlGaIn/GaN compared to AlGaAs/GaAs further enhances efficiency by enabling class-B push/pull amplifier circuits. Class B operation is not practical with AlGaAs/GaAs transistors, where thermal and dielectric strength simultaneously limit operation power. The thermal limit is reached first in GaN, leaving the extra dielectric strength to implement a push-pull configuration. Going from a class A to class B a push/pull design increases the theoretical linear region efficiency limit from 50% to 78.5%. The balanced nature of the class B design also cancels even-order harmonics that is beneficial for anticipated wide band-width multi-function EM systems.

Future DOD electromagnetic systems (communications, radar, and electronic warfare) require extremely high bandwidth (up to 5:1) and low noise floors. The bandwidth requirement demands minimal parasitic elements such as gate capacitance (C_{GS}). The higher power-density capability of AlGaIn/GaN allows narrower transistor fingers (smaller W_g) for equivalent power levels, thereby reducing gate capacitance C_{GS} , (C_{GS} is proportional to W_g). Reduced C_{GS} allows larger bandwidth since the upper frequency for circuit operation (f_{high}) is defined as:

$$f_{high} = \frac{1}{2\pi Z_0 C_{GS}}$$

where Z_0 is the characteristic load impedance.

To reduce system noise floors, a low phase-noise transmitter is required. This requirement will be best served by a wide bandgap heterostructure bipolar transistor (HBT) power amplifier that is predicted to have low phase noise due to its vertical transport. Development of AlGaIn HBTs is just starting with functional DC devices reported, however, microwave operation has not yet been achieved.

In summary, AlGaIn transistors are poised to supplant conventional III-V devices for many defense and commercial applications. The DOD support has focused initially on FET structures with record power densities demonstrated (over five times that of GaAs). High power densities were also achieved with high (over 60 %) PAE and gain over 10 dB at 10 GHz. The next challenge is to develop nitride semiconductor heterojunction bipolar transistors with the low phase noise of conventional III-V HBTs, but with five to ten times higher power densities than AlGaAs HBTs. While AlGaIn/GaN and AlGaIn/SiC HBTs have been reported with modest DC performance, increased p-type conductivities are needed to achieve competitive microwave performance. The system payoff is attractive, so once again the DOD will lead the way in developing the next generation of solid state microwave technology.

Property	(Al)GaAs/GaAs	4H-SiC	(Al)GaN/GaN
Maximum sheet electron density (cm^{-2})	$2\text{-}4 \times 10^{12}$	NA	$1\text{-}5 \times 10^{13}$
Breakdown field (V/cm) ($\times 10^5$)	4	20	33
2 dimensional electron mobility ($\text{cm}^2/\text{V s}$)	8500	NA	2000
Saturated electron velocity ($\times 10^7 \text{ cm/s}$)	1.0	2.0	1.5
Thermal conductivity (W/cm K)	0.53	4.9	$\geq 1.7^a$

Table II: Summary of key material parameters for AlGaAs/GaAs, 4H SiC, and AlGaIn/GaN (after Refs 3, 4, 5).

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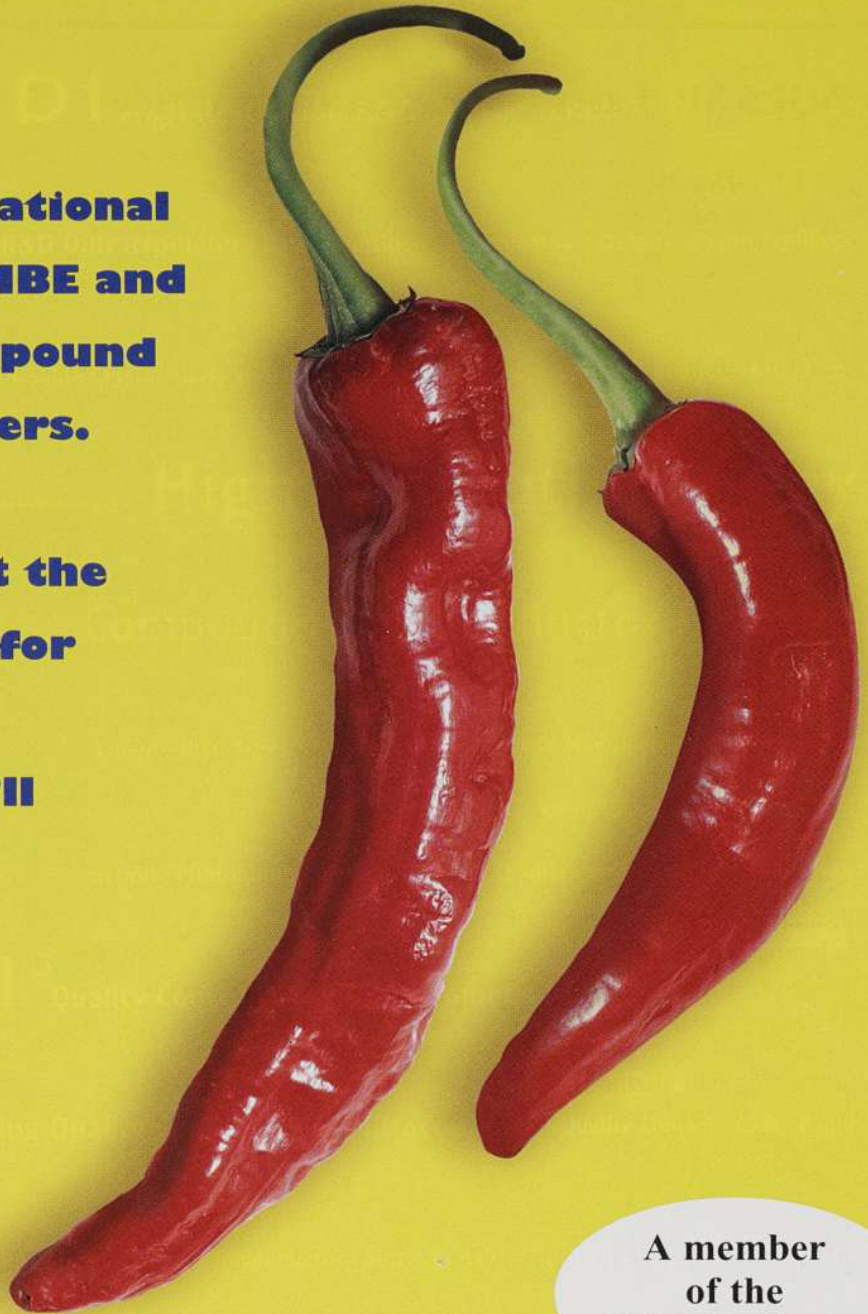
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Nitrides in Europe

The European Union is currently funding several major projects with nitride-related themes. We summarize five of the programs.

LAQUANI: Laser Quality Gallium Nitride

PIERRE GIBART

Project Coordinator, CRHEA-CNRS, France

LAQUANI is a long-term research project within the Esprit 4 program, which began on February 1, 1996 and will finish at the end of June 1999. The EU provided a contribution of 1.250 million Euros (~\$1.32M) towards the total cost of 2.5 million Euros (~\$2.65M). Participants include five research laboratories - the Centre de Recherche sur l'Hétéroépitaxie et ses Applications (CRHEA-CNRS), France; the University of Nottingham, UK; the Institut de Micro- et d'Optoélectronique, France; Ecole Polytechnique Fédérale de Lausanne (IMO-EPFL), Switzerland; the Universidad Politécnica de Madrid, Spain; and the Universität-GH-Paderborn, Germany - with Aixtron as the industrial partner.

The central aim of LAQUANI is to produce high quality GaN substrates for nitride-based heterostructure laser diodes. Nichia's recent report of long lifetime CW laser diodes was largely due to a significant reduction in defects attained by using epitaxial lateral overgrowth (ELO). In the next generation of high power, high temperature lasers, crystal quality will again be a key issue. It was also planned in the LAQUANI project to answer open questions about the nature of residual donors and the origin of yellow luminescence using advanced characterization methods.

Laser structures were grown on ELO GaN, using both GSMBE and MOVPE. Full control of n- and p-type doping of (Al)GaN was achieved, using Si and Mg respectively, for both epitaxial growth methods. Be was also investigated and was found to give the shallowest acceptor level. In addition, techniques for the growth of GaN on Si (111) by MBE have been developed [1].

Epitaxial Lateral Overgrowth

Because of the extremely high nitrogen pressures needed, the direct growth of GaN substrates of adequate size by classical techniques does not appear feasible. We have therefore developed epitaxial lateral overgrowth of GaN on patterned GaN/sapphire substrates to produce GaN epilayers with reduced dislocation densities. This technique has in the past proven to be effective in reducing the dislocation density of GaAs or InP on Si substrates and is presently implemented in several laboratories. The samples for ELO consisted of 2.4 μm thick GaN films grown on (0001) sapphire and patterned with parallel 5 μm wide stripes on 2-3 nm thick silicon nitride.

Compared to other ELO processes, we have introduced several innovations [2]. Firstly, the density of dislocations in the first GaN layer is reduced down to $10^8/\text{cm}^2$ by proper control of the growth mode of the bulk GaN layer [3]. After this step, the dielectric SiN mask was made and deposited in situ by the reaction of silane (SiH_4) and ammonia. Then, after the definition of

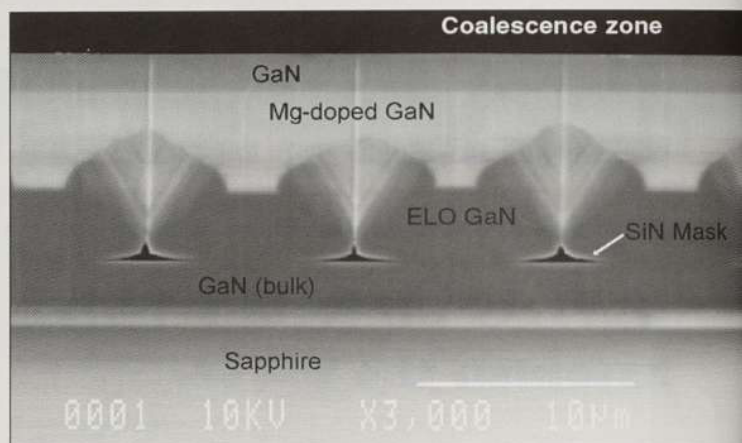


Figure 1. SEM cross section on GaN ELO on patterned substrates

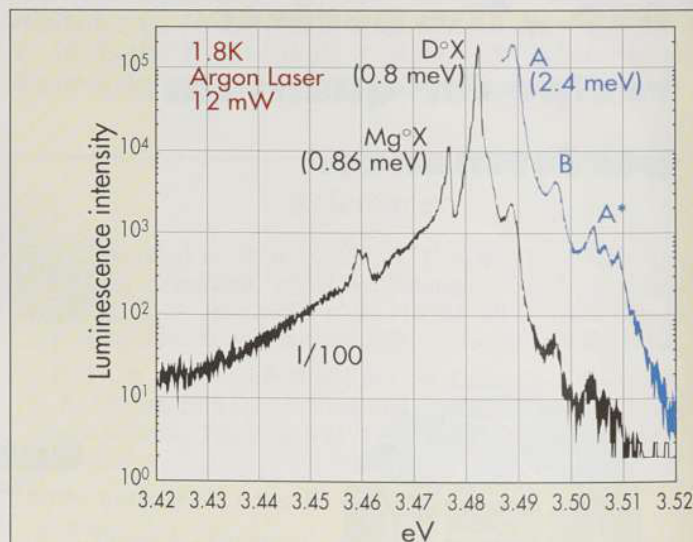


Figure 2. Low temperature photoluminescence spectrum of non-intentionally doped GaN grown on top of ELO GaN obtained by the two step method. (The free exciton part of the spectrum, in blue, has been shifted for clarity)

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stripes by standard photolithography, the growth of the LEO GaN was allowed to proceed.

A two-step approach was followed: in the first step, localized growth resulted in triangular stripes with $\{11\text{-}01\}$ facets. At this stage, threading dislocations arising from the bulk GaN are bent at 90° . However the surface is not yet flat, and Mg was introduced to achieve this. It has been demonstrated that Mg impurities enhance the ratio of lateral to vertical growth rates [4]. Thereafter a flat surface is obtained. Finally, a non-intentionally doped GaN layer was grown on top. An SEM photograph of the cross section of such a structure is shown in Figure 1. Voids are in evidence above the dielectric masks and also a light line corresponding to the coalescence of two ELO layers (along these coalescence boundaries, spatially resolved PL reveals the occurrence of significant yellow luminescence [5]).

HRTEM reveals that threading dislocations from the bulk GaN do not emerge in the overgrown GaN. In the low temperature PL spectra in Figure 2, the FWHM of the bound exciton peaks are narrower than 1 meV. Furthermore, five components of the free excitons are clearly resolved.

In parallel with the effort on ELO growth by MOVPE, the group at IMO-EPFL is developing the hydride VPE growth of thick ($>20\text{ }\mu\text{m}$) GaN layers, either directly on sapphire, or on GaN seed layers, or by the ELO approach on patterned GaN/sapphire substrates. Using a specially designed horizontal reactor equipped with a rotating substrate holder, perfectly transparent crack-free layers with a mirror-like surface appearance were obtained on 2" wafers. These have excellent thickness uniformity and crystal quality as measured by X-ray diffraction (350 arc-sec halfwidth), and good electronic and optical properties as expressed in terms of photoluminescence linewidths. Presently, 2" ELO substrates grown by HVPE are also under development at the EPFL [6].

Henceforth, the ELO GaN will pave the way towards a new generation of components grown either by GSMBE or MOVPE. GaN grown by GSMBE on GaN/sapphire templates exhibit much better quality in terms of higher PL intensity and lower C contamination than state-of-the-art MBE GaN. Furthermore, yellow luminescence is not observed from these samples. High

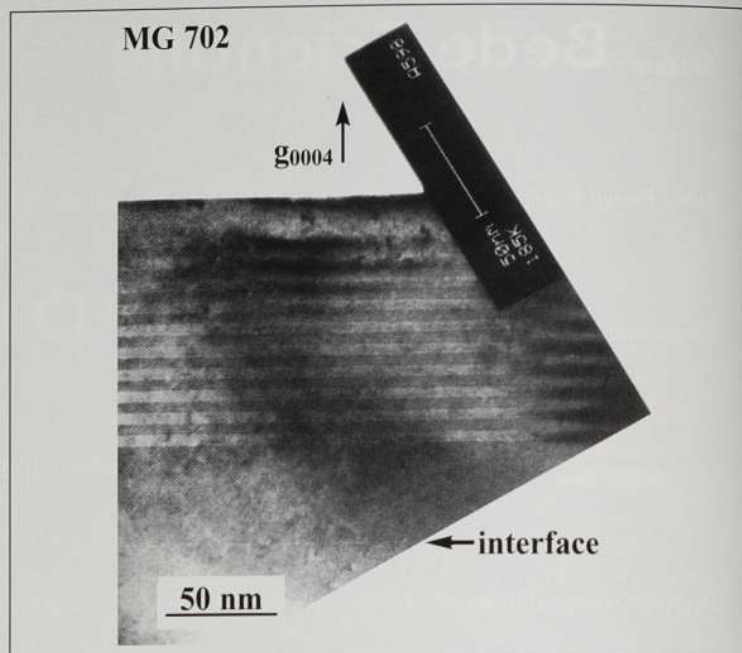


Figure 3. HRTEM of (Al,Ga)N/GaN MQWs deposited by MBE on GaN substrates (fabricated at Unipress, Poland).

structural quality (Al,Ga)N/GaN MQWs deposited by MBE on GaN substrates (fabricated at Unipress, Poland - see figure 3) have also been demonstrated [7].

Yellow Luminescence and Residual Donors

It is currently assumed that the deep defect responsible for the yellow luminescence does indeed limit the minority carrier lifetime and, consequently, the lifetime of devices. In spite of intensive investigation, the nature of the extended defect responsible for the yellow luminescence is not fully understood. Within the LAQUANI project [8], photo-capacitance measurements have shown that this deep level lies 1 eV above the valence band (Figure 4). It has also been shown that the yellow luminescence is spatially non-uniform and appears in ELO GaN in the boundary regions.

RAINBOW: Gallium Indium Aluminum Nitride for Multicolor Sources

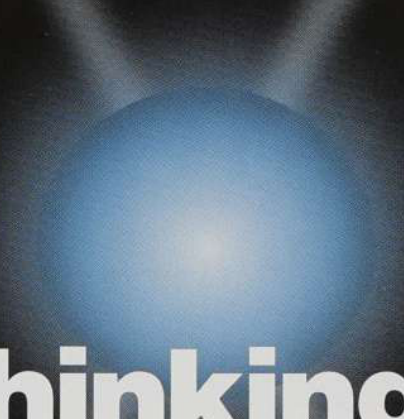
Rainbow's participants are Thomson-CSF (Fra), Epichem (UK), Philips (Netherlands), Universidade de Aveiro (Por), University of Surrey (UK), Aixtron (Ger), CRHEA-CNRS (Fra) and Universitat Erlangen Nurnberg (Ger). This is a 3-year project, which began in February 1997, and is funded by the BRITE/EURAM 3 program.

The project aims to develop the first complete European AlGaInN materials base, culminating in the mass production technology of ultra-high brightness LEDs in various colors and in the fabrication of blue nitride-based lasers.

The following objectives will be achieved in the framework of this project, with the final scope being the mass production of LEDs and lasers:

- Fabrication of UHB LEDs in the 400-590 nm range with luminous intensity of 4 cd, and laser diodes at $\sim 400\text{ nm}$ with CW output power of 5 mW at room temperature.
- Development of MOVPE growth and device processing technologies for AlGaInN-based alloys, applicable to both LEDs and lasers.
- Development of optimum group III and N precursors to allow epitaxial growth with reduced pre-reaction and reduced V/III ratios (from the present 1000:1 to below 100:1).

After completion of the 3-year project, it is expected that an additional six months will be required to optimize LED and laser prototypes. After that, six more months will be needed to introduce the multicolored LED prototype to the market place.



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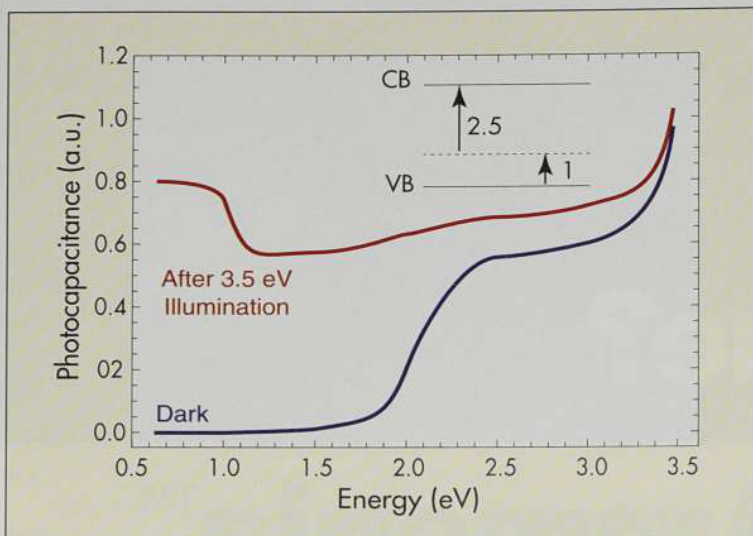


Figure 4. Photocapacitance spectra of an undoped sample, under dark conditions and after 3.5 eV illumination. Optical thresholds at 1 eV and 2.5 eV are related to a level located at 1 eV above the VB. The abrupt step detected at 1 eV in the upper curve is related to the electron capture from the valence band by a level located 1 eV higher in energy, and is related to the yellow emission.

Oxygen is believed to be the main residual donor in GaN. Theoretical evaluation of the behavior of O and Si in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloys led to the conclusion that the donor state linked to O (in the N site) is expected to merge into the gap for $x \sim 0.3$ whereas the state linked to Si (in the Ga site) is not. Optical characterization using a diamond cell has proven to be a pertinent tool to investigate the behavior of this residual donor (and the yellow luminescence).

Also, optically detected magnetic resonance (ODMR) was widely used to assess the microscopic structure of the residual donors and of the defects responsible for yellow luminescence. A specially designed high-pressure cell was built for ODMR measurements up to 35 GPa, and ODMR data on GaN at 1 GPa were obtained. Applying hydrostatic pressure to GaN produces a band structure modification equivalent to aluminum alloying, and it is therefore expected that the transition from extended to localized states of the residual donor should be observed.

Although the ELO process requires further progress to fulfil device technology requirements, such substrates open new possibilities for the growth of quantum structures by MBE and MOVPE.

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MIGHT: Microwave Gallium Nitride High-Power Transistors

MIGHT is a 3 year project within the BRITE/EURAM-3 program, which began in October 1998. Participants are GEC-Marconi Materials Technology (UK), Thomson-CSF (France), University of Nottingham (UK), IMEC (Belgium), Siemens AG (Germany) and Thomas Swan (UK).

After more than twenty-five years of development, current solid state devices for generating microwave power, based on GaAs, are approaching their theoretical power limits (typically about 10 W at 10 GHz). The generation of higher levels of microwave power is one of the few areas which is still the preserve of vacuum tubes. Applications requiring such levels of microwave power include air traffic control systems, satellite systems for communications and remote environmental sensing, and high definition television systems. Vacuum tubes are bulky, heavy, expensive, require high voltage levels for operation and, most importantly, are significantly less reliable than solid state devices.

Predictions of the power capability of GaN-based devices show that they can exceed the performance of GaAs devices by as much as a factor of 100, slightly greater than for SiC. Recent developments in light-emitting nitride-based devices have made high power GaN-based devices a realistic possibility.

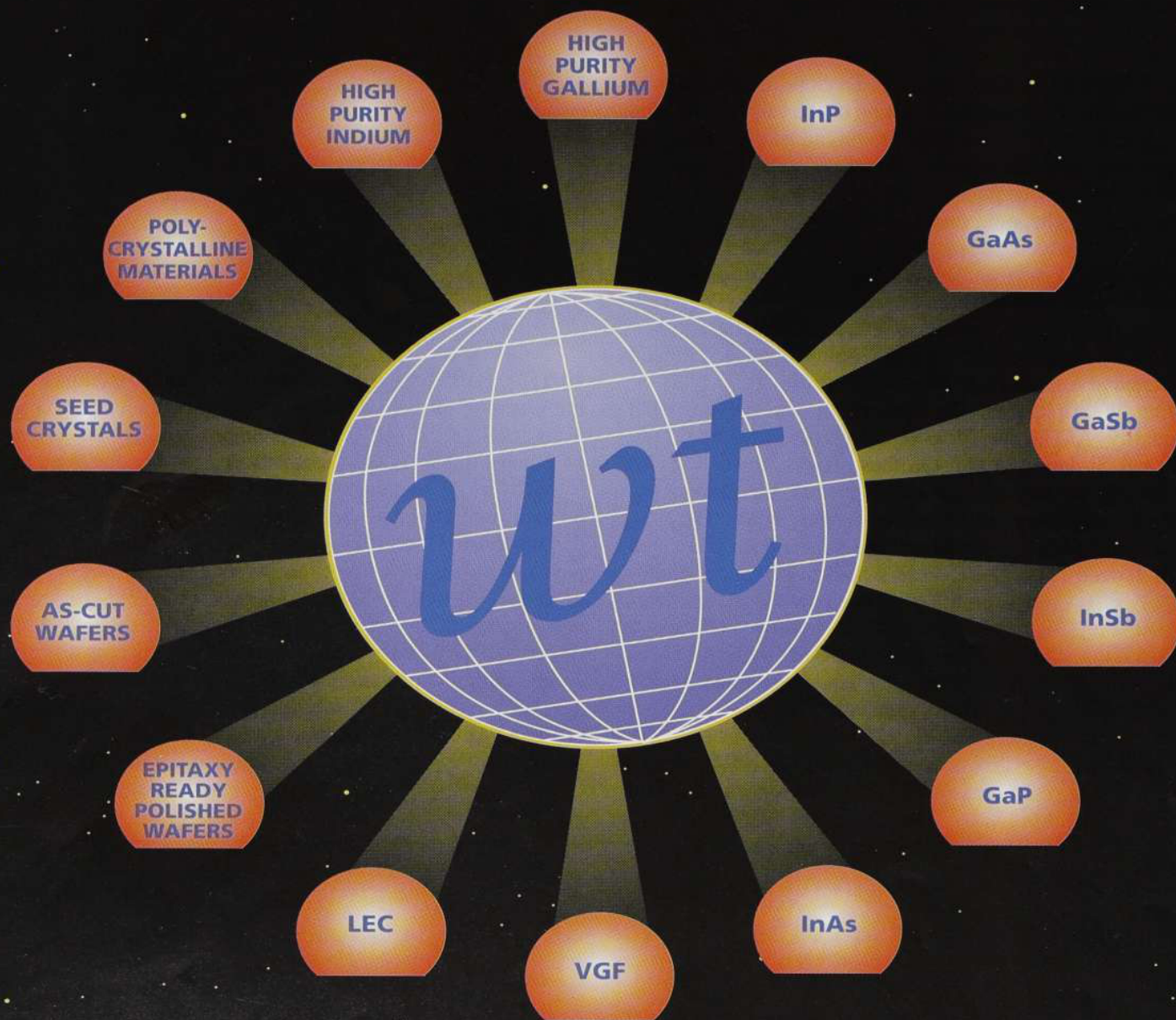
The primary aims of MIGHT are to establish the technology for the growth and fabrication of GaN-based microwave power devices capable of delivering 5 W at 10 GHz. This will form the basis for the subsequent development of very high power devices (up to and above 50 W at 10 GHz) as well as microwave power circuits capable of more complex functions. The industrial partners expect to see the first commercial exploitation within three years of the end of this project.

The highest priority research task is to establish the growth of device-quality materials, which will entail evaluating the different epitaxial growth techniques and substrates, with the development of process technology for these materials as a second priority.

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ALDUV: AlGa_N Detectors for Low Cost Solar UV-B Band Monitoring Systems

ELIAS MUÑOZ

Project Coordinator

Universidad Politécnica de Madrid (Spain)

The "ALDUV" project aims to develop AlGa_N devices specifically tuned for the detection of the solar UV-B band (320-280 nm). The new detectors should take advantage of the nitride thermal stability and radiation hardness, the intrinsic visible-blindness, and the possibility of selecting the detector cut-off wavelength by changing the Al mole fraction. ALDUV is a two-year project which began in March 1998, and which is financed by the EU Environment and Climate Program. It combines the efforts of three European research groups: Universidad Politécnica de Madrid (Spain), Centre de Recherche sur l'Heteroepitaxy et ses Applications-CNRS (Valbonne, France), and Universidad Autónoma de Madrid (Spain).

During the first year, the consortium has demonstrated device-quality Al_xGa_{1-x}N (0 < x < 0.35) epitaxial layers, both undoped and Si-doped [9,10]. On these layers, three types of devices have been fabricated: photoconductors, metal-semiconductor-metal photodiodes and Schottky barrier photodiodes.

High-gain Al_xGa_{1-x}N photoconductors have been fabricated and characterized [11]. These devices present persistent photoconductivity effects and a poor UV/visible contrast. Both linearity and visible rejection can be considerably improved by using a lock-in detection system, although the internal gain decreases markedly. A detailed model to explain the anomalous performance of these devices has been presented.

Planar Schottky barrier photodetectors with cutoff wavelengths from 365 nm to 295 nm have been reported [12], showing a linear and fast (ns) response, with a UV/visible contrast of

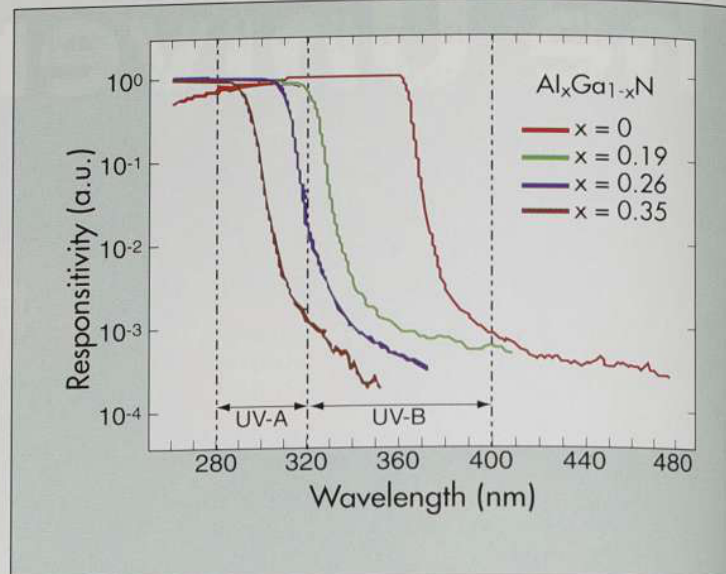


Figure 6. Spectral response of Al_xGa_{1-x}N Schottky barrier detectors.

10³ (Fig. 1). By proper selection of the Al mole fraction, the spectral response of these devices can simulate the erythema action. Thus, both radiometric and biologically-weighted UV-meters based on AlGa_N Schottky photodiodes can be fabricated.

Al_xGa_{1-x}N metal-semiconductor-metal photodiodes, based on two interdigitated Schottky contacts, have recently been demonstrated [13]. They show a linear behavior with optical power, with a visible rejection higher than 10⁴ and a fast time response (< 1 ns), in absence of internal gain. With these characteristics, together with an extremely low noise equivalent power (NEP* < 17 pW/Hz^{1/2}), these devices have become a promising choice for high-speed high-contrast UV detection.

For the second year of work, ALDUV will focus on the use of ELOG substrates to increase the UV/visible contrast ratio, and on the development of high Al-content p-n junction detectors.

[References on page x.]

OPTIVAN: Optical Interconnects Using VCSELs Based on As/N Compounds

The Optivan project began in July 1998 and is scheduled to run for 3 years. Participants are Siemens AG (Germany), Epichem (UK), IMEC (Belgium), University of Strathclyde (UK), Epitaxial Products International (UK) and the Commissariat à l'Energie Atomique (France).

Although a relatively mature technology exists for VCSELs operating in the 0.6-1.0 μm wavelength range, there is also a demand for devices in the 1.3-1.55 μm wavelength range for compatibility with optical fiber-based telecommunications. Furthermore VCSELs in the 1.2-1.3 μm wavelength range will be required for the next generation of high performance optical data links where they offer significant advantages over conventional 850 nm devices. The production of long wavelength VCSELs using InP-based technology has

many problems, particularly the growth of monolithic, high reflectivity mirrors. An alternative approach is to use an active region based on N-containing quaternary, GaInNAs, which can be grown lattice-matched to GaAs. The objectives of this project are to:

- Grow high quality GaInNAs/GaAs layers and SQWs by MOCVD and GSMBE
- Improve the N incorporation to achieve a 1.3 μm absorption edge combined with the excellent layer stability and reproducibility
- Achieve photoluminescence and electroluminescence from the DH and SQW structures at 1.2 μm and 1.3 μm
- Achieve edge-emitting lasers and CW LW-VCSELs emitting at 1.2 μm and 1.3 μm based on GaInNAs/AlGaAs QWs in the active region.

CdZnTe Radiation Detectors

TIM WHITAKER

Although the compound semiconductor industry is currently dominated by III-V materials, particularly those which are GaAs-based, InP-based or nitride-based, there are still a number of applications addressed by II-VI materials. The highest resolution infrared imaging cameras contain detector arrays fabricated from narrow bandgap mercury cadmium telluride (HgCdTe) alloys. Wide bandgap II-VI materials have been used to fabricate blue and green lasers containing ZnCdSe active layers, and BeMgZnSe photodetectors with a cut-off wavelength of ~430 nm have also been realized. At still higher photon energies, cadmium zinc telluride (CdZnTe) has become established as perhaps the most suitable material for the detection of X-rays and gamma-rays. Discrete detectors and arrays fabricated from $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ (where $x = 0.08 - 0.3$) are becoming more widely used to detect nuclear radiation in medicine, industry and scientific research. It should also be noted that $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ ($x = 0.04$) is the most common choice of substrate for MBE or LPE growth of HgCdTe for IR imaging applications.

Why CdZnTe?

CdZnTe has some unique and exciting properties, as far as X-ray and gamma-ray detection is concerned, one of the most important being room temperature detector operation. Devices fabricated from the most common detector material, germanium, offer high resolution but require liquid nitrogen cooling. Although NaI scintillators do not require cooling, they suffer from low resolution compared to CdZnTe, and are bulky. NaI relies on secondary detection; photons hit the scintillator, producing light, which is in turn detected by a photomultiplier tube. In contrast, photons reaching the CdZnTe detector are directly converted into an electronic signal, which is then amplified

or manipulated by standard electronic circuitry.

Although the nominal bandgap of $\text{Cd}_{0.90}\text{Zn}_{0.10}\text{Te}$ is 1.56 eV, it takes around 4.4 eV to create a single electron-hole pair. This additional energy is due to the binding energy of the electron in the valence band. The so-called Fano factor is typically used to correct for this effect when measuring the absolute energy resolution. The detector shows a signal proportional to the number of electron-hole pairs that are created when an X-ray or gamma-ray photon interacts with the material. The relatively high density (5.78 g/cm³) of CdZnTe provides good absorption efficiency, and this is very important considering that the typical range of detected photon energies is 10 keV to 1 MeV.

In addition, CdZnTe can be manufactured in a variety of different configurations up to a size of 8 x 12 cm², and can also be fabricated into monolithic arrays. Such arrays function in the same basic way as IR imagers. The only real difference is that different photon energies are detected. CdZnTe detectors are stable over a wide range of temperatures, allowing reliable operation from -30°C to +80°C with little peak shift over that temperature range. They are suitable for use in most industrial environments where temperature swing, shock, vibration and magnetic fields may all be present.

A High Volume Source

Although CdZnTe has been around for 3 decades, and has been widely touted to replace Ge for most (if not all) radiation detector applications, progress has been slow. "Until now, no-one has invested heavily in CdZnTe technology to establish a facility geared towards volume manufacturing," says Bruce Glick, General Manager of eV Products, a division of II-VI Inc. The company has established a 35,000 ft² manufacturing facility



eV Products

eV Products' new SPEAR detector contains a discrete 5x5x5 mm³ CdZnTe detector crystal, and is used for high resolution measurements and isotope identification.



Lunar Corp

The Prodigy system manufactured by Lunar Corp. uses a CdZnTe detector to perform bone densitometry measurements.

in Saxonburg, PA, which houses crystal growth furnaces, detector and hybrid electronics fabrication lines, and product assembly capabilities. "We have the capacity to grow more than 200 kg of material per month, and are currently producing around 1200 kg annually," says Glick, who goes on to claim that eV Products' monthly output of CdZnTe

exceeds the annual production volume of its nearest competitor.

At eV Products, CdZnTe is grown inside either modified standard or vertical furnaces by the high pressure Bridgman technique. The high vapor pressure of inert gas inside the crucible (typically 100 atm of argon) limits evaporation of the most volatile component, Cd. Typical CdZnTe ingots have a characteristic columnar structure, with large monocrystalline grains parallel to the growth axis which are 2-12 cm in size. Radiation detectors cut from this material are typically polycrystalline or are single crystals containing twin boundaries.

These crystal imperfections can have a detrimental effect on detector performance for some applications. Once the CdZnTe boule or ingot is grown by the HPB technique, the material is then cut, polished and metalized to fabricate metal-semiconductor-metal (MSM) devices. The high bulk resistivity of CdZnTe (around $3 \times 10^{10} \Omega\text{cm}$) results in low leakage currents in MSM devices, and allows the use of a higher bias voltage. In turn, this improves the charge-collection efficiency and allows the fabrication of large volume detectors. While it is possible to fabricate p-n junction devices, these structures do not offer significant improvement over the MSM structure.

To complement the detector line, eV Products includes the fabrication of thin-film and thick-film hybrid surface mount electronics to interface with the detectors, and has complete product assembly capabilities. "We sell CdZnTe material, metalized devices, electronics, and packaged detectors," says Glick. "We are a vertically integrated company, but we also sell product from any point in the manufacturing chain - whatever the customer wants."

Another product is $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ ($x = 0.04$) substrates for epitaxial growth of HgCdTe IR focal plane array detectors. The company has been supplying such substrates for use on military and other projects for almost 20 years. Single crystal CdZnTe wafers of up to $8 \times 12 \text{ cm}^2$ surface area and 15 mm thick are grown by both vertical and horizontal conventional Bridgman techniques. These wafers are optimized for high IR transmission (the arrays are hybridized to silicon readout circuits and backside illuminated), with a low density of dislocations and twins. This technology has also been developed by eV Products for radiation detector applications.

Applications for CdZnTe Detectors

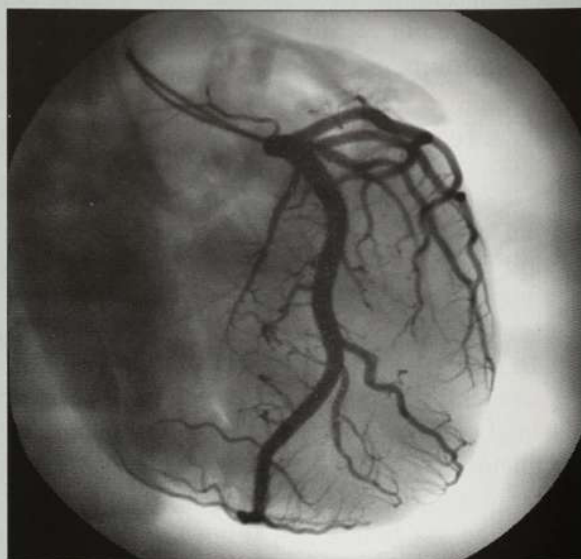
Radiation detectors are being widely used in medicine, industrial manufacturing, astronomy, the nuclear industry and scientific research. Industrial applications include gauging the levels of liquids on a bottling line, measuring paint thicknesses on a car, or non-destructive evaluation of structural failures.

There are many examples of the use of CdZnTe detectors in medical imaging and diagnostics, ranging from simple X-rays carried out in a dentist's office to cardiac angiography (imaging "slices" through the heart - see below) and bone densitometry measurements. A previous article described the use of nuclear medicine to pinpoint areas of activity within the brain, to help characterize conditions such as epilepsy [see CS 3(5), p. 22]. This same article also described how astronomers are using CdZnTe arrays to study the origin of high energy gamma-ray bursts.

CdZnTe is also suited for high resolution measurements and isotope identification in the nuclear industry and for X-ray radiography applications. Because no two isotopes emit exactly the same energy spectrum, the radiation can be used as a "fingerprint" for the isotope. The SPEAR (single point extended area radiation) detector, recently launched by eV Products, is a complete probe measuring only 0.5" in diameter by 3" in length (see photo, previous page). The probe contains a $5 \times 5 \times 5 \text{ mm}^3$ CdZnTe detector crystal together with a low noise hybrid preamplifier and operates at room temperature with a much higher resolution than NaI scintillators.

Cardiac Angiography

A scanning beam X-ray system for cardiac angiography, developed by Cardiac Mariners (Los Gatos, CA) is capable of producing tomographic images of the heart [see photo]. The system employs a large area scanning X-ray source, in combination with a CdZnTe detector from eV Products which measures $5.4 \times 5.4 \text{ cm}^2$. The detector is composed of a 4×4 array of detector hybrids. Each hybrid consists of a 12×12 element CdZnTe array, which is bump-bonded to a custom silicon IC containing the photon detection and counting circuitry. The pixel pitch in these 12×12 arrays is 1.125 mm, compared to pitches in the order of $50 \mu\text{m}$ or less in large staring infrared arrays. In the cardiac angiography application, the X-ray source is scanned across the detector at up to 30 frames per second, and a custom digital processor simultaneously reconstructs sixteen $1,000^2$ pixel tomographic images in real time. The slices are spaced 1.2 cm apart and cover the entire cardiac anatomy.



Tomographic scanning-beam digital X-ray (SBDX) image through a heart, showing coronary arteries. The SBDX system, manufactured by Cardiac Mariners, contains a CdZnTe detector fabricated by eV Products.

Cardiac Mariners

We are pleased to introduce this section of our magazine devoted to GaAs ICs, which will appear as a regular feature from now on. In addition to GaAs IC-related news items below, this month's section includes a report from the 1999 GaAs Mantech conference. Also, a Forum article from NEC describes RFIC developments for cellular phones, while a second article compares HBTs, HEMTs and MESFETs.

RF Micro Devices Supplies CATV Amplifiers to Motorola

RF Micro Devices (RFMD) recently announced that it is supplying GaAs HBT-based amplifiers for Motorola's CableComm[®] cable access unit. This unit provides subscriber access to cable telephony services i.e. voice services which are provided using cable TV distribution networks. Each cable access unit contains a modem operating in the range of 5-40 GHz or 5-65 MHz for the upstream path and 300-750 MHz for the downstream path, and provides voice over cable with the lowest subscriber unit power consumption in the industry.

As the number of channels and additional subscribers for cable TV services increases, and demand for voice and data services over cable also grows, this places increasing stress on the

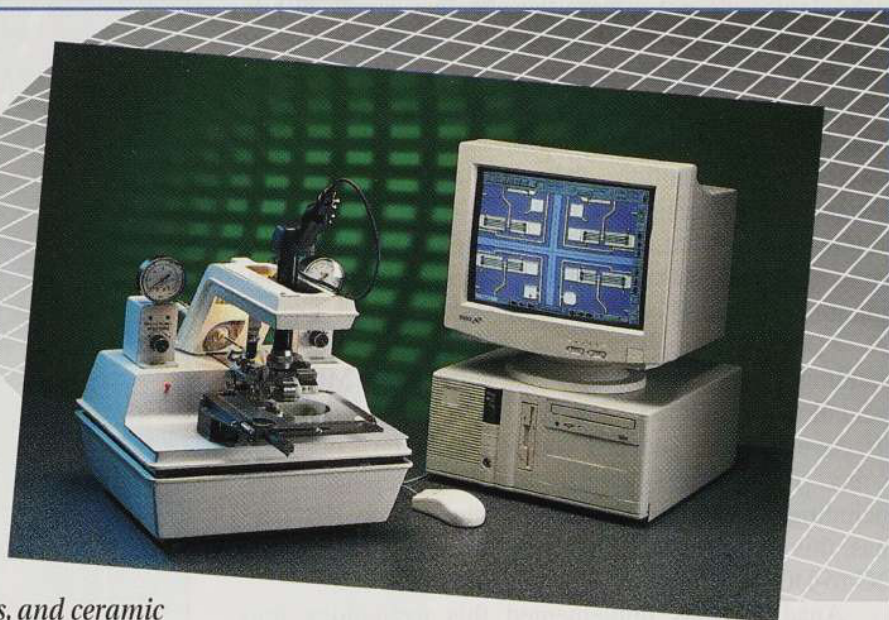
communications channels which carry the signals. In particular, more bandwidth and power capacity must be provided without degrading linearity, in order to limit the amount of interference between the multiple carrier channels. According to RFMD, the overriding concern is to maximize the linearity of the amplifier with minimum power consumption, and to do so at a reasonable price. Having evaluated GaAs MESFET and silicon bipolar and CMOS technologies, RFMD concluded that GaAs HBTs were the optimum solution for this application, offering the best frequency response and the highest linearity (for a given DC power consumption) of any commercially available IC.

"RFMD provides a high-performance, cost-effective amplifier solution for Motorola," says Jerry Neal, RFMD's VP of sales and marketing. "This new business from Motorola is indicative of the success we have been enjoying with our line of cable TV

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products. RFMD continues to focus on cable TV amplifiers as a growing application for our GaAs HBT technology; Motorola is designated as a key account for RFMD, and we anticipate continued opportunities for our products."

RFMD will supply Motorola with RF2317 amplifier ICs, which operate from DC to 3.0 GHz with an internally-matched input and output. The small signal gain is 15 dB and the noise figure is 4.9 dB. An output power of +26 dBm is achieved, and the IC requires a single 12-15 V power supply.

The RF2317 is part of a family of CATV amplifiers designed for signal amplification at the subscriber connection. RFMD's cable TV product offering also includes new line amplifiers for use at nodes linking fiber and coax sections of the distribution system, and up/down-converters for set-top converters.

Anadigics Receives Patent for PA Technology

One of the disadvantages of using depletion mode GaAs FETs as power amplifiers is that they require a negative voltage generator circuit, which adds both cost and complexity to the RF board design. Other solutions, including enhancement mode FETs, HBTs and Si MOS technologies, do not require the negative supply. While some manufacturers employ a separate negative voltage generator IC, others have developed on-chip solutions.

Anadigics recently announced that it has been awarded a US patent for its on-chip, single polarity power supply solution, that enables phone handset designers to use a single-chip GaAs MESFET-based PA solution. The patent, US5892400, is entitled "Amplifier using a single polarity power supply and including depletion mode FET and negative voltage generator."

"This technology provides designers with the outstanding performance associated with GaAs MESFET technology combined with the convenience and cost-effectiveness of a reduced component count," observes Robert Bayruns, VP of Advanced Development. "By including an on-chip negative voltage supply for gate bias, this technology eliminated the need for an external DC-to-DC converter IC."

Anadigics has implemented this technology into many of its power amplifier designs since its development in 1996. The high resistivity GaAs substrate provides a way to simplify the DC-to-DC converter function, as compared to typical Si implementations. The new PA design combines a switched-capacitor DC-to-DC converter with a level-shifting gate bias circuit that acts as a voltage regulator. A current mirror regulates the negative supply, allowing constant output under challenging conditions such as high mismatch and/or temperature. By combining high-performance on-chip capacitors with low-current MESFET switches, designers can also realize a low standby current for the circuit.

TriQuint, RF Integration Announce Product Development Alliance

TriQuint Semiconductor has announced an alliance with RF Integration of Billerica, MA to provide RFIC product development services in conjunction with TriQuint's GaAs IC foundry. RF integration provides turnkey RF product development services including both board level design and highly integrated, full custom IC designs on both GaAs and Si processes. It uses the latest design tools together with a fully automated RF test and measurement laboratory. In the new alliance, RF Integration's staff will be responsible for product development from project inception through pre-production. In production, TriQuint's GaAs IC foundry will provide wafer manufacturing, die packaging and IC testing services. TriQuint offers a wide variety of GaAs semiconductor technologies including E/D MESFET, PHEMT, HFET and VPIN, and is developing a network of independent certified design centers to support its market-leading GaAs foundry services.

TriQuint Plans Conversion to 72-Inch Wafers



While the rest of the industry slowly converts to using 6" GaAs, TriQuint has leapt ahead by announcing the start-up of the industry's first 72-inch wafer assembly line, according to a recent company press release circulated at the GaAs Mantech conference. There is no word yet on who will be supplying the substrates. Photo courtesy of Ron Smith. For more on the MANTECH conference, see page 44.

Vitesse Acquires XaQti

Vitesse Semiconductor has acquired all the equity interests of XaQti Corp., a fabless design house based in Santa Clara, CA. XaQti designs "active-flow processors" for the Internet, as well as system control ICs for Gigabit Ethernet and LAN/WAN networks. The acquisition, for \$65 million in common stock, enables Vitesse to enter some new and large networking chip markets.

"The addition of XaQti's chips to the Vitesse CrossStream chipset provides a very powerful, flexible and cost-effective solution for enterprise class Ethernet and IP routers and switches," says Lou Tomasetta, Vitesse's President and CEO. "The acquisition is a continuation of Vitesse's product expansion into higher layers of network processing, which positions us to offer extensive chipsets to new and existing customers."

Vitesse also recently acquired Vermont Scientific Technologies, a supplier of chips for ATM and Sonet, and Serano Systems Corp., which supplies chips for Fibre Channel and SCSI applications.

New Turnkey Service for High Density Modules

Micro Interconnect Inc. (MII), a new provider of design, test and assembly services for RF/mixed signal high density modules, has announced partnerships with two Taiwanese manufacturing foundries.

APack Technologies Inc. will provide a leading-edge interconnect technology, developed by Lucent Technologies, that incorporates embedded passives and utilizes flip-chip die attach onto a high density, wafer level, silicon interconnect substrate. This will include the capability to combine flip-chip bonded GaAs ICs with thin film devices (inductors, capacitors and resistors) on the silicon substrate.

The second manufacturer, Tong Hsing Electronics Industries Ltd., will offer the most advanced techniques in high volume ceramic and laminate module manufacturing.

According to Chuck Wheatley, President and CEO of MII, the new partnerships create one of the industry's first single-source, turnkey suppliers of high density modules for wireless communications and Internet access markets.



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TIM WHITAKER

The theme of the 1999 GaAs Mantech Conference, which was held in sunny (sic) Vancouver, was "GaAs manufacturing; Meeting customer demands in cost, quality and availability." Opening the conference, **Rudyard Istvan** of **Motorola** described the two telecommunications trends, both arising from widespread digitization throughout the industry, which will drive demand for high frequency III-V devices. The first trend is a series of convergences; most importantly the blending of voice and data services and the integration of wireless and wireline networks. The second major trend is the rapid increase in bandwidth; voice networks at 12 kbps are giving way to third-generation systems offering voice and data at 56 kbps. Further increases eventually enable such capabilities as video email - NTSC quality digital real time video with MPEG2 compression - at 1.5 Mbps, or DVD-quality video at 8 Mbps. More bandwidth means the growth of hybrid fiber coax systems, and the use of higher frequencies and smaller cells in wireless networks. The cost and size of base stations for these microcells is decreasing rapidly as demand grows. Istvan described how Motorola is retrofitting the entire city core in Paris with microcells because of teledensity problems.

This activity presents a number of challenges to the GaAs industry. There will be pressure to rationalize some of the many different design approaches in GaAs; this will push discrete or special purpose devices towards becoming mainstream parts, which are used with common platform specifications. Also, there is a need for much more integration, including resistor, inductor and capacitor elements. Creation of multichip modules, integration with passives in multilayer ceramic integrated circuits, and overall packaging are all seen as major challenges. Finally, GaAs itself faces technical challenges, notably from SiGe at frequencies up to a few GHz. According to Istvan, many problems remain to be solved with SiGe but the potential price/performance is attractive. Also, InP may offer potential for microcells and picocells operating at several tens of GHz.

Comparing Technologies

Comparison of different device types and technologies was a theme throughout the conference. **Dimitris Pavlidis** of the **University of Michigan** compared MESFETs, HEMTs and HBTs [see page 56], and **Otto Berger** of **Infineon** (formerly

Siemens Semiconductor) compared these devices with advanced silicon technologies, as summarized in the Table. Infineon runs all these processes, including a 45 GHz Si BiCMOS process and a SiGe HBT process with an f_T of 75 GHz, which is due to be launched by the end of the year.

The low noise performance necessary for applications below 2 GHz can be met

Performance Parameters	GaAs-Based Technologies			Si-Based Technologies	
	MESFET	HEMT	HBT	Si BJT	SiGe HBT
Low Noise @ <100 MHz	o	o	+	++	++
Low Noise @ ~2 GHz	++	++	++	+	+
Low Noise @ ~10 GHz	+	++	+		o
Gain	+	++	++	++	++
Power @ <0.5 W	++	++	++	+	+
Power @ >2 W	++	++	++		
Efficiency	+	++	+	o	o
Low Voltage	+	++	+	+	+
Integrating RF functions	++	++	++	o	o
Integrating RF & digital	o	o	o	++	++
Power Supply	+	+	++	++	++
Cost Position	++	o+	+	++(+)	+

Performance comparison of GaAs and Si technologies. Key: ++ best, + good, o moderate. Courtesy of Infineon Technologies.

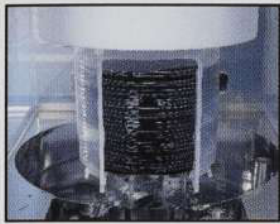
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Combined Immersion and Single-Wafer Processing

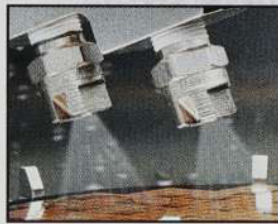
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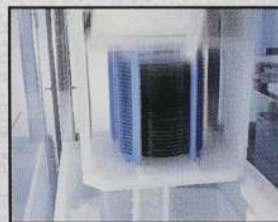
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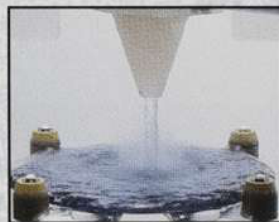
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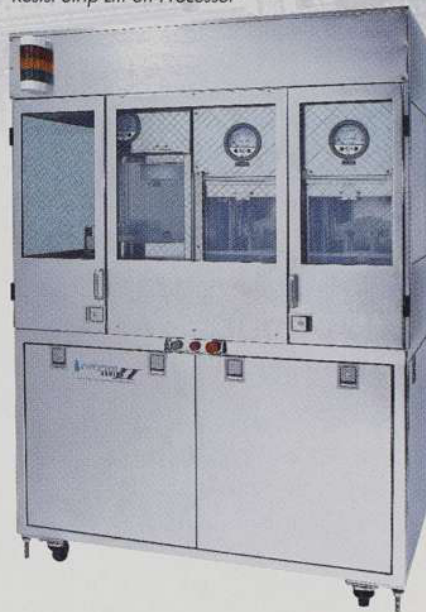
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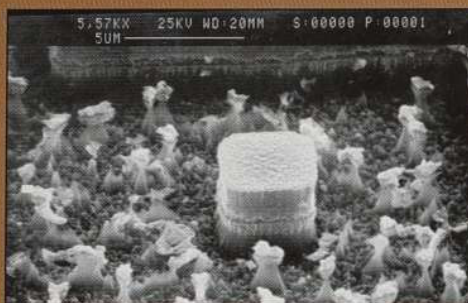
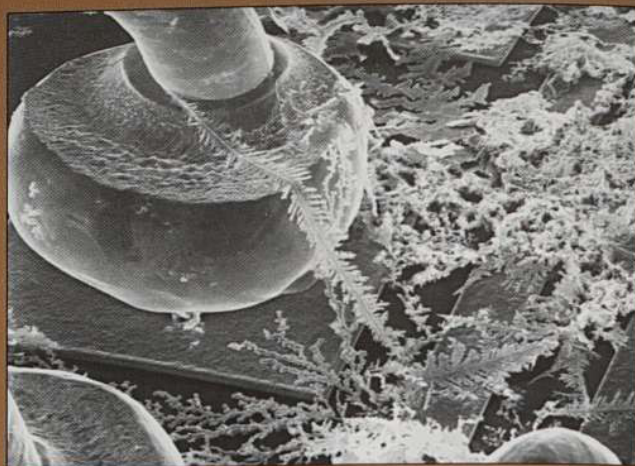
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The Ugly Picture Contest

One of the most interesting and entertaining features of this year's Mantech conference was the "Ugly Picture Contest." Rather than being an opportunity for engineers to send in pictures of their bosses in compromising situations, this was promoted as a forum for attendees to share some of their processing problems. "We thought it would be fun and instructive to give people a chance to show their colleagues in the industry problems and improvements that didn't warrant a full paper, but which might be quite important, or at least interesting," says Bob Surridge of Nortel, who organized the contest. "We hoped it would be another useful way to exchange and gather valuable manufacturing information." The winners, whose entries are shown here, were presented with digital cameras for their pains.

The Winner. This 1990 scanning electron microscope image shows silver dendrite growth on the die surface. The dendrites originated from the die attach epoxy, and migrated across the edge of the die and onto the top of the circuit. The conditions leading to the dendritic growth were 15 PSI, 121°C, 4 Volts

static bias, and 100% humidity (saturated steam). The samples were mounted in open cavity packages and inverted above boiling water in the test chamber. The growth occurred in less than one hour. When the dendrites were removed with a water spray, the die functioned normally. Recent formulations of die attach material have eliminated the dendrites. Nowadays, unsaturated tests are more common and devices are encapsulated in molded packages.



The Runner-Up. At left is the rough surface obtained after an initial plasma etch experiment of InGaAs/InAlAs with a chlorine based plasma chemistry. The rough surface is possibly due to the low volatility of the indium chloride etch products. The figure at right shows the smooth surface morphology of an etched surface after proper plasma parameter adjustment.

by both GaAs- and Si-based technologies, said Berger. Si will be used for many low noise receiver applications, and will allow high levels of integration. Power applications of 1 W or 2 W compressed power will continue to be the domain of GaAs, with competition between MESFET, HEMT and HBT. The low voltage trend for handsets may favor HEMTs, because of their higher gain and PAE. HEMTs will also clearly dominate millimeter-wave broadband applications. The semi-insulating nature of GaAs substrates allows the integration of RF functions into MMICs, while Si technologies have the advantage of integrating analog bipolar functions with digital CMOS functions, such as D/A converters.

Berger predicted that today's situation, in which about 15-20% of all RF applications are covered by GaAs, will not change significantly in the future. Si dominates the receiver market up to 2 GHz, while GaAs is the preferred material for PAs above 0.5 W output due to a higher PAE at lower supply voltages. Comparing costs, Berger stated that a 4" GaAs MESFET wafer is comparable in cost to a 6" Si Bipolar wafer, although normally

the die only contributes about 1/3 to the total device cost. The main potential of SiGe HBT technology is in receivers in the 2-20 GHz range; SiGe will not replace Si Bipolar technologies in mobile phone handset applications, since SiGe offers only minor improvements at a cost premium.

Robert Hadaway of Nortel Networks described some of the challenges facing GaAs. For example, SiC FETs and GaN HEMTs have shown a significant power delivery advantage when large supply voltages are required. SiC has missed an opportunity to access 2 GHz cellular base station applications; GaAs is now facing a very strong challenge in this area from Si LDMOS. GaAs HBT technology is incumbent in 10 Gbps optical communications, and will continue to dominate extended voltage/power applications. However, SiGe HBT is the only technology which appears ready for large volume, cost-competitive deployment and will soon make inroads at frequencies of 10 GHz and higher, particularly where high levels of integration are advantageous. Finally, InP HBTs are seen as an emerging technology for very high speed (20 Gbps and above) applications.

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6" Upgrades and Process Transfer

Several delegates spoke about their company's experiences in converting to 6" GaAs. **Jim Mikkelsen** of **Vitesse** stated that, "the overwhelming reason to convert to 150 mm wafers for a new GaAs fabrication line was that state-of-the-art processing equipment was not available for wafers smaller than 150 mm." He also described how the selection of an equipment set was the most difficult and high risk part of the entire project. Since no 150 mm GaAs processing capability actually existed at that stage, it was not possible to evaluate the actual performance of the equipment, and many vendors refused to run GaAs wafers in their Si-oriented demonstration labs. The dielectric and metallization processes were not developed and tested until the new fab was operational. The Vitesse facility, the first to run 6" GaAs wafers, was brought into operation in less than two years. This consisted of nine months to build the facility, three months to install the equipment, one month to produce the first working circuits, and six months for process control, characterization, and yield improvement. There are now around 400 wafer starts per week at the Colorado Springs facility.

Infineon's decision to build a 6" fab at their Munich Perlach site was driven by the ever-increasing demand for RF products. According to **Otto Berger**, Siemens (now **Infineon**) had a production volume of around 40,000 4" wafer starts in 1998, corresponding to about 70 million components, of which about 50% were MMICs. Infineon's schedule for 6" conversion is even tighter than Vitesse's, thanks largely to the availability of a building previously used for DRAM fabrication. From a starting point in May 1998, almost all the process equipment is now installed, and the first GaAs wafers will be run by mid-May 1999, with production expected to commence in October 1999. As soon as possible, all three existing technologies - MESFET, HEMT and HBT - will be transferred to the new facility.

Mike Fresina of **RFMD** described the transfer of TRW's HBT process from TRW's 3" line in Redondo Beach, CA to RFMD's new 4" fabrication line in

Greensboro, NC.

This was carried out to ensure a qualified second source for the HBT product. The aim of the transfer was to produce an identical on-wafer product, not to reproduce the exact processes used at TRW. In fact, tools could not be replicated in some cases due to the move to 4" wafers, and several photo processes were also changed. However, passive device and interconnect layouts and general circuit design were the same. A 3 V GSM-standard mobile phone PA was chosen as the qualification vehicle for the new fab, and the performance difference from the two fabs was less than typical lot-to-lot variations. A major customer qualified both parts interchangeably and large volumes have been delivered from both fabs concurrently.

High Frequency MMICs

Compared to GaAs MESFETs, the PHEMT offers higher electron velocity, current density and transconductance, resulting in significantly higher power gain and efficiency at millimeter-wave frequencies. **Pane Chao** of **Sanders** reported a high performance and highly reliable PHEMT MMIC technology for V-band (50-75 GHz) space applications, which provides a superior alternative to travelling-wave tube amplifiers and IMPATT diodes for crosslinks between satellites. MMICs were fabricated from 0.1 μm T-gate, single recess, AlGaAs/InGaAs/AlGaAs/GaAs double heterojunction PHEMTs grown by MBE. Slot via holes were used to provide direct source grounding for reduced source inductance and improved thermal resistance, which is critical for V-band power applications. The balanced 2-stage power MMIC was based on a 300 μm gate width transistor cell containing four 75 μm gate fingers. An output power of 550 mW (0.46 W/mm) with 23.5% power-added efficiency was demonstrated, and a mean-time-to-failure of 1×10^7 hours at a chan-

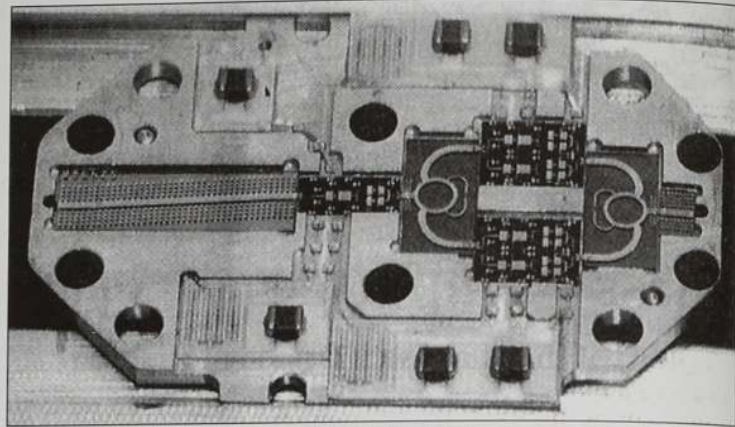


Figure 1. 60 GHz power module fabricated using a 0.1 μm GaAs PHEMT MMIC technology. Photo courtesy of Sanders.

nel temperature of 120°C was projected for the MMIC at 60 GHz. Power modules (see figure 1) were assembled, and did not show current or power degradation after burn-in at 175°C. The devices are sensitive to hydrogen, so Sanders' hydrogen getter was applied to the sealed flight modules.

Tony Immorlica of **Sanders** described other methods to remediate against hydrogen poisoning, which is observed mainly in GaAs FETs with Pd or Pt in the gate structure. Many common microwave packaging materials can out-gas hydrogen, posing a reliability risk in hermetically sealed modules such as the 60 GHz power MMIC module described above (the gate is Ti/Pt/Au). Aside from including a getter, it is possible to introduce a controlled leak into the package, using a material which allows permeation of hydrogen, or to investigate package bakeout. In some cases where poisoning does not result in catastrophic failure, it is possible to shift the bias to compensate for changes in device characteristics. It is also possible to use metallization technologies which are hydrogen-insensitive, and these are likely to be employed by emerging technologies such as InP HEMTs.

The 2000 GaAs Mantech Conference

will be held in Washington, DC
on May 1-4.

<http://www.gaasmantech.org>

InP for High Speed, High Frequency Applications

Based on speed, power and producibility advantages, InP HBT technology appears to be the ideal technology for high data rate IC applications, including 100 Gbps light wave communications, according to **Marko Sokolich** of **HRL Labs**. Other technologies have critical defects; SiGe consumes too much power, E/D HEMT technology is limited by non-uniformity in threshold voltage, and GaAs-based HBTs require high power (because of the higher turn-on voltage) and do not have the necessary inherent speed. There is likely to be a low volume demand for 100 Gbps chipsets, in the order of 1,000-10,000 per year, within a 5 year timeframe. The primary need is for small and medium scale integrated circuits such as multiplexers, demultiplexers and drivers, with most of the signal processing carried out at much lower data rates. HRL Labs has an InP HBT process,

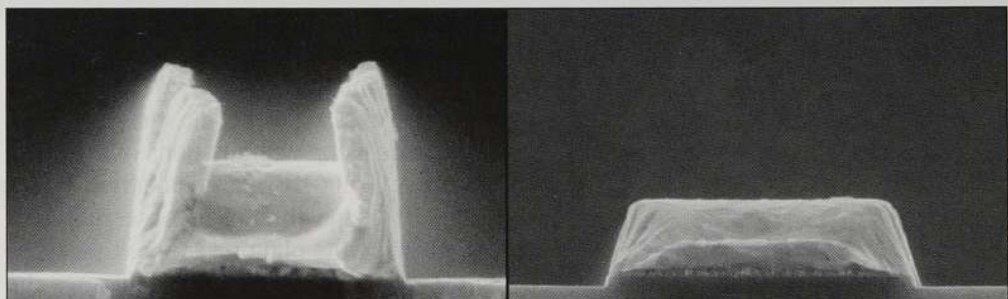


Figure 2. (Left) Result of etching with HBr/Ar mixture, after removal of the photoresist. Post-etch veils are formed by redeposition of the etch product on the photoresist sidewalls. (Right) Etching with Cl₂/Ar and a hard etch mask results in a uniform etch profile without veils. Photos courtesy of Tegal Corp.

based on AlInAs/InGaAs/InP device layers grown by MBE, which is capable of producing circuits with clock rates well in excess of 40 GHz. The process is already sufficiently mature to yield ICs with 500-1000 transistors.

Elsewhere in the program, **Richard Lai** of **TRW** described the development of a production-worthy 0.1 μm InP HEMT MMIC process on 75 mm InP substrates. The InGaAs/InAlAs/InP

HEMT process shares 75% commonality with the TRW's high volume 0.15 μm InGaAs/AlGaAs/GaAs HEMT production process, the only major differences being in the chemical etchants, annealing conditions and backside processing. Dry etch vias were found to be essential for achieving high performance with high yield and repeatability. TRW has demonstrated a family of state-of-the-art mm-wave LNAs, ranging in frequency from

HITEN'99 Conference

Announcement

**The Westin Grand Hotel
Berlin, Germany
July 4 - 7, 1999**

The third European conference on High Temperature Electronics will take place in the Westin Grand Hotel in Berlin, Germany between 4th and 7th July 1999. The conference will consider the issues associated with designing and manufacturing electronic components, materials and systems for use at high temperatures as well as dealing with the practical aspects of using these items in real applications. High temperature electronics has been a research topic for many years but has now emerged as an industrial sector in its own right with significant usage starting to be observed in the oil and gas, aerospace and automotive industries.

The conference programme and up to date information, together with on-line registration forms, can be found at <http://www.hitent.com>. Exhibition stands are available for companies and organisations wishing to promote their products and services. Please ask for more details.

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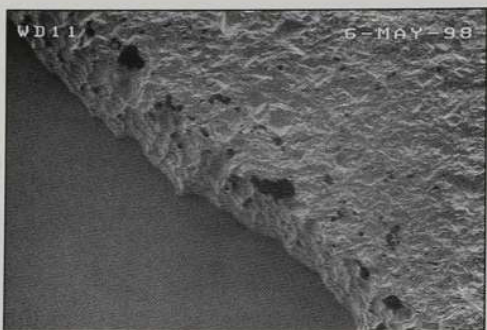


Figure 3. Results of reactive ion etching of GaAs, showing a typical smooth etched surface at left, alongside the pre-etch (chemical-mechanical polished) rough surface (right) that was masked during the selective etch. Photo courtesy of Sanders.

2-200 GHz. For example, data was presented from over 2,000 manufactured 44 GHz LNAs with greater than 80% yield and typical performance of 25 dB gain and 2.2 dB noise figure. Other examples include a 3-stage single-ended LNA with 4.0 dB noise figure and 17 dB gain at 112-120 GHz, and a 3-stage single-ended LNA with 3.3 dB noise figure and 18 dB gain at 94 GHz.

Etching

Gold is used extensively in the GaAs industry for interconnect metallization, principally due to its high electrical conductivity and relative chemical inertness. Vitesse is unique in the use of aluminum, and while copper is all the rage in the silicon industry, the entry cost to use Cu (equipment costs and huge process development activity) is too high for GaAs fabs to give this much consideration at present. There are two broad techniques for thin film patterning; subtractive processes (e.g. wet chemical etching, plasma etching and ion milling) in which the thin film is removed in areas where it is not protected by a photoresist or other mask; and additive processes (e.g. electroplating, selective film deposition and photoresist lift-off processes). The lift-off technique is most widely used by GaAs device manufacturers for patterning gold films, but is disadvantaged by complex process flows. Gold is relatively resistant to wet etching, and ion milling is often hampered by film redeposition and poor selectivity. Plasma

etching potentially offers high packing densities and a simpler process flow.

A paper from **Paul Werbaneth** of **Tegal Corp.** reported the etching of Au on GaAs using combinations of HBr, Cl₂ and Ar. Using HBr/Ar chemistries, heavy sidewall deposition was observed after removal of the photoresist mask (see figure 2a). These "veils" form because the etch product is not completely volatilized and sticks to the photoresist sidewalls. When Cl₂ was used instead of HBr, the etch rate increased and veils were much smaller. The best results (see figure 2b) were obtained by replacing the photoresist with a thin hard mask, resulting in etch profiles exceeding 75° with no sidewall deposition.

Gunn diodes convert DC power into an RF output and are typically used as local oscillators and voltage-controlled oscillators for radar and communication transmitters. Low cost, high performance Gunn diodes are in demand for today's expanding millimeter-wave markets, but achieving high throughput and process consistency has proved difficult for InP-based Gunn devices, partly due to the anisotropic mesa etch. A paper from **J. Lui** of **Filtron Solid State** reported that, unlike conventional FeCl₃-based photochemical etches, dry etching with an inductively coupled plasma (ICP) offers excellent sidewall anisotropy and uniformity, without undercutting (see figure 3). A gas mixture of HBr/BCl₃/Ar/H₂ was used for the ICP process, and an etch rate of 10x higher than a standard CH₄/H₂/Ar RIE etch was achieved.

Quantum well infrared photodetectors (QWIPs) operating at wavelengths from about 3 - 18 μm are most commonly fabricated from MBE-grown epitaxial structures grown on GaAs. After the QWIP array has been processed and bonded to a silicon readout IC, the GaAs substrate is removed. This improves the photoresponse, eliminates optical crosstalk between pixels and reduces the thermal mismatch between the GaAs detector and the silicon readout IC. At Mantech, **Ron Olson** of **Sanders** described the use of a dry-etching process to completely remove GaAs substrates from QWIP detectors, resulting in improved focal plane arrays which can

resolve target temperature differences smaller than 20 mK. The reactive ion etching process used a SF₆/SiCl₄ mixture that has a high GaAs to AlGaAs selectivity. This enables the use of much thinner etch stop layers (<50 nm) compared to the 1000 nm AlGaAs layers required for chemical-mechanical polishing. The etch process was extremely uniform (see figure 3) with an etch rate of 3 μm/min and minimal device damage.

InGaP Etch-Stop Layers for PHEMTs

According to **David Danzilio** of **AMP M/A-COM**, the performance advantage of GaAs PHEMTs over MESFETs comes at the price of a more challenging process, particularly in the critical gate recess operation. The high effective doping level under the gate results in a strong dependence of drain current on etch depth. The critical gate-recess operation is greatly simplified by the incorporation of an etch-stop layer within the PHEMT structure, making the value and uniformity of various critical FET parameters (I_{dss} , g_m , I_{max} , V_p etc) dependent solely on the epitaxial growth process. The most common approach is to use an Al_xGa_{1-x}As etch-stop layer in combination with a buffered citric acid or succinic acid solution. Typically, x should be greater than 0.35 to provide adequate selectivity, but the incorporation of a high Al mole fraction layer disrupts the current flow through the material and increases the ohmic resistance. Very tight control of the Al content is required for x~0.35 to ensure long term process reproducibility.

Danzilio described the use of a 35 Å In_{0.5}Ga_{0.5}P etch-stop layer, which is positioned between the AlGaAs schottky layer and the n⁺ GaAs contact layer. A simple H₂SO₄:H₂O₂:H₂O etch chemistry is used to achieve greater than 150:1 GaAs:In_{0.5}Ga_{0.5}P etch selectivity. The GaAs etch rate was about 10-15 Å/sec, lower than with citric and succinic acid etches, and this limits the extent of lateral etching once the etch-stop layer is reached. The InGaP etch stop process has been incorporated into M/A-COM baseline 0.5 μm and 0.2 μm PHEMT processes.

Development of RF Devices for Cellular Telephones

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Cellular telephones have become widespread in Japan since 1988, with the total number of subscribers exceeding 45 million and sales growing at an average annual growth rate of 156% over the last 3 years. The main reasons for this remarkable growth rate are firstly that the cost to the consumer has dropped because many telephone companies sell their telephone sets at a very low price, and secondly that the market environment has changed due to the increased number of operators entering the market, which has caused a drop in telephone service rates. Looking from the viewpoint of the RF devices for the front-end block, this growth is backed up by the advent of compact and lightweight telephone sets and long calling time made possible by the dramatic improvement in the performance and integration scale of GaAs and silicon RF devices.

PDC (Personal Digital Cellular) remains the most popular cell phone standard in Japan. But a survey of the cellular telephone market shows that, to handle the rising number of cellular

telephone subscribers and the growing need for high-speed data communications, services using new CDMA-based technology in addition to the current PDC system are being started. As international standardization progresses, needs for RF devices will become increasingly diversified and RF technology will become increasingly sophisticated.

This article discusses the role that GaAs plays in NEC's RF devices for cellular telephones.

Current Status of RF Devices

Handset RF blocks require the following in terms of basic performance: 3-V operation, low current, large scale integration, and a small package. To realize these basic performance requirements, NEC has developed various RF devices by using a mixed technology solution consisting of GaAs devices that can realize high performance, and silicon high-frequency devices that are suitable for large-scale integration. This solution is also in keeping with NEC's commitment to cost performance.

The RF block mainly consists of a transmitter block, a receiver block, and a common block containing, among other things, an antenna switch and a VCO control block. Because the performance required from each of these sub-blocks is completely different from that of the others, a single-chip GaAs IC or a single-chip silicon MMIC is not a practical solution. NEC therefore configures RF blocks by using devices optimized for each sub-block, as shown in Figure 1.

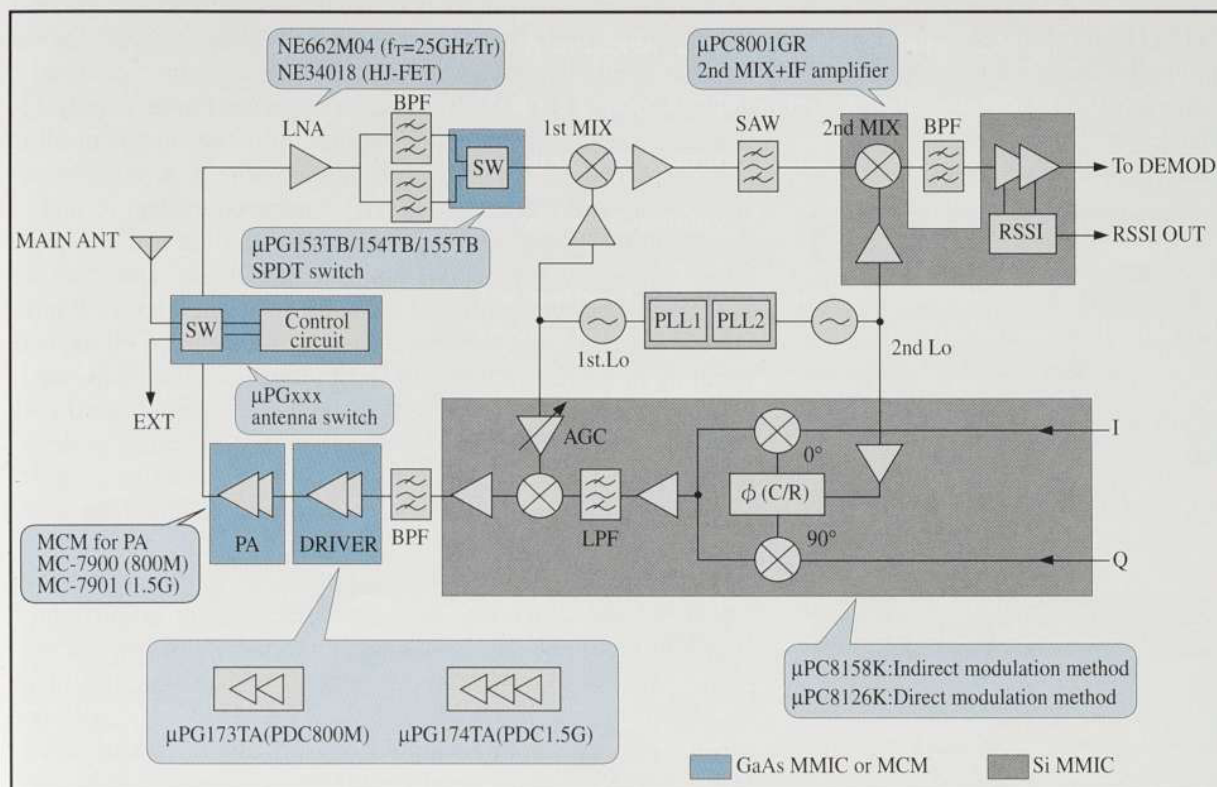


Figure 1. Example of configurations in the handset RF block

Configuration of Transmission Block

For the transmission block, NEC has developed the μ PC8126K and μ PC8158K, two silicon MMICs used as quadrature modulators that perform phase modulation of RF carriers by using digital signals from the baseband. Two GaAs MMICs, the μ PG173TA (for 800 MHz) and μ PG174TA (for 1.5 GHz), are also available as driver amplifiers for modulated signals. In addition, two power amplifier modules, the MC-7900 (for 800 MHz) and MC-7901 (for 1.5 GHz), are available for 1-W power amplification at the final stage. Table 1 shows the major specifications of the GaAs driver amplifiers. The features of these GaAs ICs are as follows:

- Driver amplifiers (μ PG173TA/ μ PG174TA)
 - High power gain and low current
 - 6-pin mini-mold small package
- Power amplifiers (MC-7900/MC-7901)
 - Can operate with one lithium-ion battery (3.6 V).
 - 0.1 cc (7 x 7 x 2 mm) package, half the size of existing amplifiers
 - High power-added-efficiency of 55% (TYP.)

Devices like these quadrature modulators, driver amplifiers, and power amplifiers optimize the size and cost performance of the transmission block.

Configuration of Reception Block

For the reception block, NEC has developed GaAs SPDT switch ICs which select a reception band by switching the band-pass filters, and high-performance transistors with $f_T = 25$ GHz, which are ideal for low-noise amplifiers. Tables 2 and 3 show the specifications of these devices. The features of these devices are as follows:

- Switches (μ PG153TB/ μ PG154TB/ μ PG155TB)
 - Lineup of three different models designed to minimize insertion loss and maximize isolation
 - Small 6-pin mini-mold package
- Transistors (NE661M04/NE662M04/NE663M04)

Parameter	Symbol	μ PG173TA	μ PG174TA
Operating frequency	f (MHz)	925 to 960	1429 to 1453
Supply voltage	V_{DD} (V)	2.8	2.8
Circuit current	I_{DD} (mA)	25	35
Power gain	G_p (dB)	28.5	34.0
Leakage power between adjacent channels 1 ($\Delta = \pm 50$ kHz)	P_{adj1} (dBc)	-60	-60
Output power	P_{out} (dBm)	+9	+10
Package		6-pin mini-mold	6-pin mini-mold

Table 1. GaAs PA driver ICs

Part Number	Output power	Insertion Loss	Isolation	Package
	P_{1dB} (dBm)	L_{ins} (dB)	I_{So} (dB)	
μ PG153TB	33	0.7	13	6-pin super mini-mold
μ PG154TB	30	0.65	20	6-pin super mini-mold
μ PG155TB	34	0.8	16	6-pin super mini-mold

@f=2GHz, $V_{cont}=+3V/0V$

Table 2. GaAs SPDT Switch IC Series

Parameter/Symbol	Part Number	NE661M04	NE662M04	NE663M04
Gain bandwidth product	f_T (GHz)	25	25	17
Power gain at minimum NF	Ga (dB)	17	16	10
Noise figure	NF (dB)	1.1	1.1	1.3
Forward insertion gain	$ S_{21} ^2$ (dB)	17	17	11
Maximum stable power gain	G (dB)	22	20	15
Maximum collector current	I_{cmax} (mA)	12	35	100
Package	MSG (dB)	Flat-lead 4-pin thin small mini-mold (2.0 x 1.25 x 0.59)		

Table 3. GaAs transistor series for $f_T=25$ GHz

- High power gain and low noise realized by $f_T = 25$ GHz
- Lineup of three products with different maximum collector currents
- Newly developed flat-lead, 4-pin small mini-mold package to contribute to the miniaturization and high performance of the system

By combining a GaAs SPDT switch IC and a high-performance transistor, a reception block that saves space and consumes less power can be created.

Future Product Development

Cellular telephones using the PDC standard are expected to improve in performance as their size and weight go down and calling time and standby time are extended. A compact and highly efficient power amplifier is essential to achieve the above. As shown in Figure 2, however, existing power amplifiers have already reached a very small package size and a very high efficiency and no significant improvements can be expected in these areas. The next issue to be addressed, therefore, is how to minimize the number of peripheral components to maximize total space efficiency. The most effective means is to use a single positive power supply, instead of the positive and negative power supplies currently used. The existing power amplifiers have a depletion-type FET that requires a negative power supply for characteristics optimization, so in the future, development of an enhancement-type FET that can operate with a positive power supply only and still realize a performance equivalent to that of the depletion-type FET is necessary. If operation using a single positive power supply can be realized, the DC-DC converter for the negative power supply and the drain switch elements for turning off the current in the power-saving mode can be eliminated, resulting in space efficiency and cost reduction. The challenge is how to create such an enhancement-type FET without sacrificing high efficiency. In rising to this challenge, NEC plans to develop just such an enhancement-type FET as the next step toward creating and supplying the device ideal for the cellular telephones of the future.

A roadmap of the development of GaAs and silicon MMICs which are the other key devices besides power amplifiers is shown in Figure 3. The ultimate solution for optimizing the cost performance is considered to be a three-chip configuration made up of a power amplifier module, a GaAs MMIC, and a silicon MMIC. To realize this solution, NEC plans to develop GaAs MMICs with low-noise amplifiers (LNAs) and mixer blocks, and improve the performance and hybridization of each core block.

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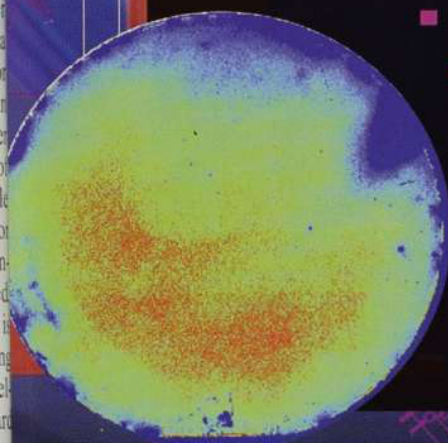


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The non-PDC cellular telephone market is expected to expand and diversify with the advent of systems such as high-speed data communication terminals and with the increase in the number of bands and modes, enabling cellular telephones of different modes and frequencies to communicate with each other. Examples of new telephone systems include the GSM+DCS1800 in Europe, the TDMA system based on the IS-136 standard, and the N-CDMA system based on the IS-95 standard in North America, a hybrid system combining the N-CDMA and TACS systems in Japan, and the W-CDMA system, which is expected to be on the market in 2001. As described above, the performance and scale of integration of mature systems such as PDC have reached a technological peak. On the other hand, several technical issues remain to be resolved for kits consisting of relatively small-scale MMICs and high-performance discrete devices. One such issue is how to deal with the increase in carrier frequencies expected in the vicinity of 2 GHz.

NEC will develop and release GaAs MMICs and silicon MMICs for these new systems as shown in Figure 3. In addition, it will continue developing chips and packages that can realize the world's top level of performance (refer to Figure 4), because improving the characteristics of transistors is essential not only for low-noise amplification and performance enhancement of VCOs, but also for improving the performance of silicon MMICs. NEC's technology roadmap calls for a ~30% reduction in transistor package size per year from 1997 to 2001. To achieve this goal, very small (less than 0.5 mm³) lead less packages were introduced in 1998. In the near future flip chip packages will be used, and chip size packaging will be introduced in the 2000 - 2001 time frame.

Conclusion

Electronic devices are now in the age of SOC (System-On-a-Chip). If SOC is viewed as a means or concept to optimize the cost performance of a total system, SOC in the RF field can be said to be an RF sub-system-on-chips. Based on the concept of RF SOC, NEC will continue contributing to the development of the cellular telephone market by using its mixed technology solutions of GaAs devices and silicon high-frequency devices.

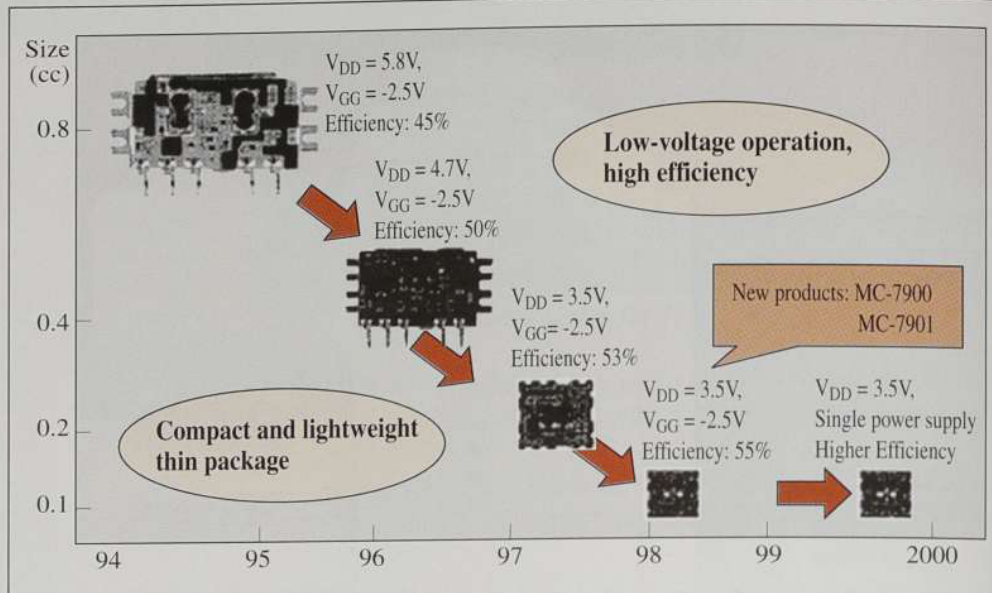


Figure 2. Trends in cellular telephone power amplifier modules

Year		'97	'98	'99	'00	'01
GaAs MMIC	Antenna switch	μPG152TA 6-pin SPDT	μPG153TB/154TB/155TB 6-pin small SPDT Switch with control function (20-pin TSSOP)	Development for GSM, IS-136, CDMA applications	Higher levels of integration	
	PA driver	μPG173TA PDC 900 MHz (6-pinMM)	μPG174TA PDC 1.5 GHz (6-pin MM) AGC + driver (6-pin MM)	6-pin small mini-mold package Development for IS-136, CDMA applications		
	LNA mixer		LNA+MIX for PDC	Development for GSM, IS-136, CDMA applications		
Si MMIC	For transmission stage	•μPC8106/09T up converter •μPC8119/20/30/31T AGC amplifier (6-pin MM)	•μPC8158K quadrature modulator + up converter •μPC8126K quadrature modulator (28-pin LLQFP)	Integration of quadrature amplifier (transmission stage)and 2nd IFprocessing block (reception stage)	Miniaturization and high performance backed up by large scale of integration and small high-pin-count package	
	For reception stage	μPC8112T down converter (6-pin MM)				

In mass production Under development In planning

□ In mass production □ Under development □ In planning

Figure 3. Roadmap for MMIC product development

Year	'97	'98	'99	'00	'01	
Process Performance		$f_{\max}=30\text{GHz}$	$f_{\max}=40\text{GHz}$		$f_{\max}=60\text{GHz}$	
For Amplifier	LNA •Low current •Low NF	IC = 5mA •NF 1.1dB •Ga 16dB @ 2GHz	→	IC = 3.5mA •NF 0.8dB •Ga 16dB @ 2GHz	→	IC = 2mA •NF 0.5dB •Ga 16dB @ 2GHz
	Medium output •High gain	IC = 20mA • $ S_{21} ^2$ 10dB @2GHz	→	IC = 20mA • $ S_{21} ^2$ 12dB @2GHz	→	IC = 20mA • $ S_{21} ^2$ 15dB @2GHz
For VCO		Reduced low frequency noise and CCB				
		$f_c=4\text{kHz}$	→	$f_c=2\text{kHz}$	→	$f_c=1\text{kHz}$

f_c : Low frequency noise corner frequency

Figure 4. Roadmap for the development of signal transistor products

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- C-Doped HBTs
- InP HBTs
- P-HEMTs
- Solar Cells



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- GaP
- GaInP
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HBT vs. PHEMT vs. MESFET: What's Best and Why*

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GaAs-based devices and circuits have a well-defined place in commercial and defense applications as evidenced by their use in a variety of products and systems. Applications extend from the low-frequency spectrum of several hundred MHz to the millimeter-wave range. The choice of a device is influenced by its maturity in terms of manufacturing but also by other criteria, which are related to fundamental operation mechanisms and determine the performance. Although MESFETs have for long been considered the most mature components, HEMT and HBT technology made significant advances due to the lessons learnt from both III-V and Si manufacturing approaches. This paper presents basic considerations regarding the properties of HBTs, HEMTs/PHEMTs and MESFETs and addresses the relative merits of each technology.

Low-Noise Applications

The PHEMT is generally recognized as the best choice for low-noise amplifier applications, followed up by the MESFET. The main noise source in FETs is of the thermal-diffusion type, which arises from random variations in carrier speed in the device channel. The latter leads to current variations and thus noise. Of particular importance is the presence of capacitive cou-

pling between the gate and the channel, which results in the overall noise being determined by subtracting part of the gate noise from the drain noise. This is a unique property of FETs, which leads to very low-noise performance.

Best noise performance is obtained by minimizing the source access resistance and maximizing the current gain cutoff frequency (f_t). The latter necessitates device design for maximum transconductance (g_m) and minimum gate capacitance (C_{gs}) conditions that can also be controlled to some extent by proper bias choice. As a general rule, minimum noise (F_{min}) is obtained under $\sim I_{dss}/10$ bias conditions. There is, however, a difference in the bias range necessary for this purpose in MESFETs and HEMTs; HEMTs appear to have a broader range of I_{ds} values than MESFETs over which F_{min} is achieved. This provides a larger margin in LNA circuit design. Since high gain is in general desired from the amplifier, and bias for F_{min} does not often coincide with bias for maximum gain, a trade-off is often made in gain vs. noise. This turns out to be less severe in HEMTs due to their broader range of bias for F_{min} . Large gain also requires device designs with a heterojunction or other type of buffer below the channel to minimize carrier injection and reduce the output conductance.

The possibility of high base doping opens new opportunities for HBTs, which could be of interest for wide bandwidth, low-noise operation. An analysis of noise characteristics also shows that PHEMTs offer smaller bias sensitivity of noise performance than MESFETs. InP-based HEMTs offer the ultimate solution to low-noise operation. They are also the best choice for optoelectronic applications, which require compatibility with InP-based optical devices and operating speeds of 40 Gbit/s and above. Figure 1 summarizes the noise performance of various device types as a function of frequency. One observes excellent performance from InP-based HEMTs up to millimeter-wave frequencies i.e., NF of 1.2 dB at 94 GHz using lattice-matched or strained designs.

Low frequency noise is in general smaller in HBTs. With proper circuit design for reduced influence of non-linearities and thus small noise upconversion, HBT oscillators can be designed with very small phase-noise performance [1].

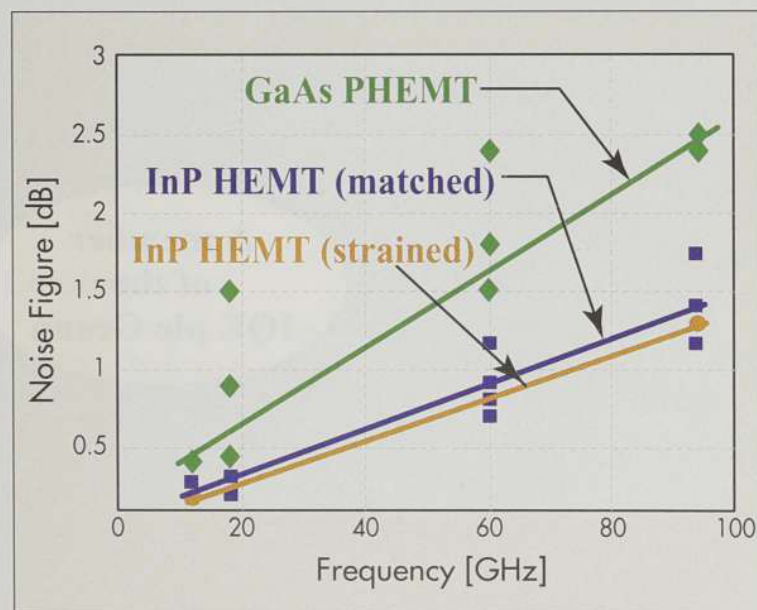


Figure 1. Noise performance of GaAs- and InP-based HEMTs as a function of frequency

* This paper was presented at the 1999 GaAs MANTECH Conference, held in Vancouver, Canada on April 19-22. Reproduced with kind permission from GaAs Mantech Inc. See www.gaasmantech.org

Power Applications

Power amplification is characterized by parameters such as power compression, third order intermodulation (IMD) and power added efficiency (PAE), which are not normally examined in low-noise amplifiers. The most mature III-V technology - the MESFET - is not necessarily the best choice for power, especially when the operating frequency is high. This is due to the requirement of small gate length imposed by the high frequency, which translates to smaller channel thickness. This imposes higher doping in order to conserve the I_{ds} performance and thus smaller breakdown and power.

Despite these limitations, reasonable power characteristics of 0.53 W/mm have been obtained at 18 GHz from a MESFET with 600 μm gate periphery [2]. More recently, a 0.3 μm long gate MESFET with GaAs channel on Al_2O_3 demonstrated record PAE of 89% at 8 GHz with 9.6 dB gain, 0.12 W/mm output power and a small V_{ds} bias of 3V [3]. The Al_2O_3 insulating buffer was obtained by wet oxidation of $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ on low-temperature AlGaAs.

Figure 2 summarizes the power performance of HEMTs, MESFETs and HBTs. The use of heterojunctions opens new possibilities in optimizing device performance. AlGaAs/GaAs HEMTs allow higher frequency of operation than MESFETs. These devices are, however, limited in terms of sheet carrier density n_s (10^{12} cm^{-2}) and thus current and power due to their small conduction band discontinuity (ΔE_c). Despite this limitation, 100 W of power have been obtained at 2.1 GHz using a 86.4 mm gate width HEMT [4]. Improved performance can be obtained by adding heterojunction channels or increasing ΔE_c . The former leads to higher overall n_s without at the same time compromising in breakdown since the doping of individual channels remains the same. The latter can be realized using the so-called pseudomorphic PHEMT approach where the GaAs channel is replaced by $\text{In}_x\text{Ga}_{1-x}\text{As}$ (x is usually about 0.2). The channel thickness is in this case of the order of 150 Å in order to ensure reasonably good material properties. PHEMTs have n_s values of at least $4 \times 10^{12} \text{ cm}^{-2}$ and therefore currents exceeding 1 A/mm can be achieved. A power exceeding 0.44 W/mm has been obtained with this approach at 44.5 GHz using a 1800 μm gate width device [5].

Further n_s and thus I_{ds} improvement can be obtained by fabricating HEMTs on InP substrates. Although InP has a higher thermal conductivity than GaAs, InP substrates and the related technology are less mature than GaAs. Most popular among all devices for power applications is the PHEMT. From the technological point of view, further improvements in PHEMT performance can be envisaged by employing double and asymmetric recess. Moreover, for InP-based HEMTs, which are in general limited in breakdown due to their low-bandgap InGaAs channel, some improvement can be envisaged by employing InGaAs/InP composite channels. The use of heterojunction barriers can help by reducing the leakage of holes (generated by impact ionization) to the gate.

Power back off is normally required for better linearity performance of PHEMTs. This appears to be a much less demanding requirement in case of HBTs, which appear to

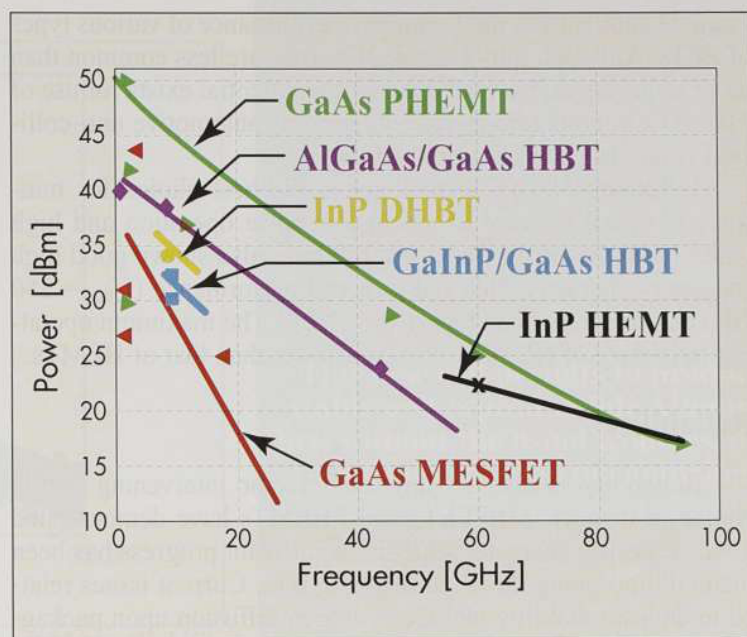


Figure 2. Power performance of HEMTs, MESFETs and HBTs as a function of frequency.

combine good linearity performance at an input power level which is appropriate for good PAE.

Power applications and development of small size, high efficiency chips have benefited from the availability of HBTs. Although less mature in technology than PHEMTs, these devices offer higher breakdown voltage, better threshold voltage uniformity and exponential rather than power-law transfer characteristics. Of major importance is the consideration of thermal issues due to self- and adjacent device heating. This can lead to significant power performance difference in CW vs. pulsed operation which is not so pronounced in FETs. Large-signal modeling of HBTs including thermal effects has led to very satisfactory results and agreement with experiment [6]. Moreover, thermally stable cascode (TSC) HBT designs have demonstrated lower temperature increases than conventional HBTs while at the same time offering higher gain [6]. Other approaches include thermal shunts for heat removal from the top of the chip, but in general these add to the cost of technology.

Good power performance has been achieved with GaAs HBTs such as 10 mW/ μm^2 at 10 GHz and 4 mW/ μm^2 at 25 GHz [7]. InP double HBTs have also been reported with 3.6 mW/ μm^2 at 9 GHz, while InP single HBTs from the University of Michigan had a record performance of 1.4 mW/ μm^2 , and a PAE of 43%. The InP-based design offers an attractive solution in terms of gain and high frequency of operation. These devices are also the best choice for high linearity operation due to the cancellation of currents at high harmonics, which takes place at the internal nodes of the HBT.

High-Frequency Operation

If high frequency operation is required, PHEMTs offer the best choice due to their high gain up to millimeter-wave (mm-wave) frequencies and their good noise and power performance.

Figure 3 summarizes the frequency performance of various types of FETs. Although mm-wave applications are less common than those requiring microwave devices, the potential exists for use of PHEMTs in commercial systems such as automotive anti-collision radar, and in space applications.

InP-based HEMT technology is the best choice for mm-wave systems, offering excellent low-noise operation and high gain. HBTs based on GaAs and InP have also shown good high frequency characteristics and a record performance ($f_{\max} = 250$ GHz) has recently been reported by NEC. The maximum operating frequency of HBTs is, however, lower than that of HEMTs.

Reliability

Reliability is also an important factor intervening in the choice of device. MESFETs and PHEMTs have demonstrated good reliability characteristics and significant progress has been made in improving the reliability of HBTs. Current issues related to device reliability include hydrogen diffusion upon packaging of FETs which results in threshold voltage (V_{th}) variation. Gate sinking due to the inter-diffusion of the Schottky gate metal (e.g. Ti/Pt/Au) in the semiconductor channel also leads to V_{th} shift and can be controlled to some degree by insertion of metals such as Mo. The reliability of PHEMTs is considered to be acceptable for many applications but InP-based HEMTs trail by about an order of magnitude in performance. Thermal stability related to donor material changes has been suggested as a possible reason but more work is needed to fully analyze these effects.

Base-emitter junction variations have been observed in HBTs due to base dopant diffusion and defect formation in this critical region. These result in gain variations with time and are the subject of current investigations. AlGaAs/GaAs HBTs show lifetimes that are almost inverse-square related to the operation current density. Activation energy (E_A) values obtained from temperature dependent tests showed relatively low values of 1.5

eV. This implies at first the need for reducing the operating current density and controlling the device temperature, either of which would handicap device use in circuits. Compensation of such effects by employing larger device size is not desirable since this reduces the device impedance and can make matching more challenging. Material and processing improvements have led to better reliability that extends up to 10^9 hours for a junction temperature of 120°C and a current density that can exceed 25 kA/cm^2 [8]. The use of In co-doping in the base and GaInP instead of AlGaAs in the emitter has also led to reliability improvement; E_A values of 1.8 eV can for example be achieved with GaInP with more than 10^8 hours operation at the same junction temperature but lower current density.

Techniques have been recently introduced to screen HBT reliability by evaluating the low frequency noise characteristics [8]. This technique also allows identification of the source and nature of the mechanisms that lead to current gain degradation. The base current noise spectral density was found to be much smaller and with a weaker dependence on bias in higher reliability devices.

Applications

There is a large variety of applications for all three device types discussed. GaAs MESFETs are widely used in a wide range of analog-digital cellular applications. Digital cordless telephones also employ power MESFETs. However, the handset size imposes a need for low voltage, single power supply and high PAE. Biasing in MESFETs used in such applications is therefore arranged by employing a source resistor, which leads to the required negative gate bias. This approach results, however, in high frequency gain degradation and PAE reduction.

The alternative approach is to use HBTs, which can be operated using a single power supply and have a low I-V curve knee voltage. The change from analog to digital cellular phone systems using for example a $\pi/4$ -shifted QPSK signal, imposes a requirement of much higher output power for even lower supply voltage. The adjacent channel leakage power should also be kept low in this application with less than -48 dBc at 50 kHz off-center frequency. Performance within these specifications and with 1 W output power at 950 MHz using 1.5 V supply has been demonstrated with PHEMTs [9]. High PAE is also important for long battery life in wireless applications and in satellite applications where the available power is limited. The PAE requirement in satellite systems increases as phased arrays are introduced to produce multiple beam spots and improve communication performance.

InP-based HEMTs and other InP-based components such as PIN diodes are particularly suitable for millimeter-wave applications such as mobile satellite communication systems and automotive radar systems.

HBTs are proving very attractive at cellular radio frequencies for power amplification. This can range from the Watt level for handsets to 150 W or more for base stations. The advantages offered are high gain per amplification stage and competitive if not better linearity and PAE. An important advantage of HBTs is that they offer good linearity properties without necessarily back-

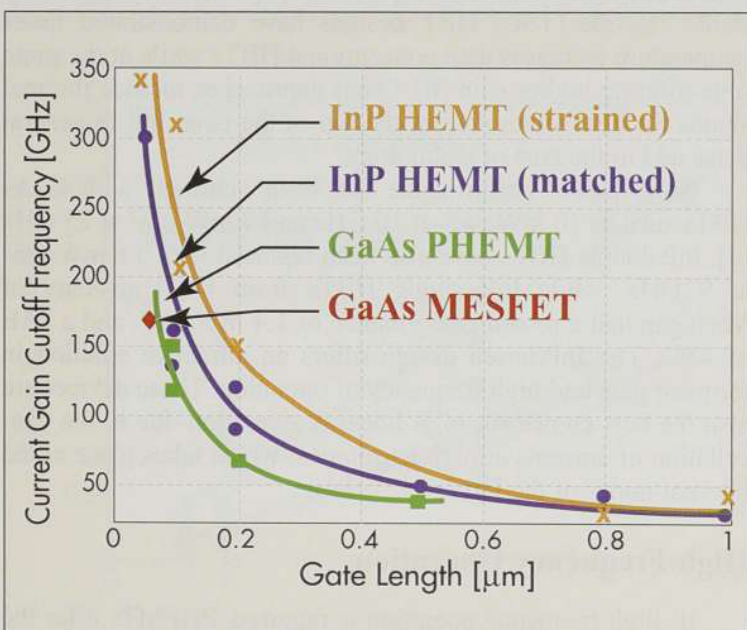


Figure 3. High frequency performance of HEMTs and MESFETs as a function of frequency

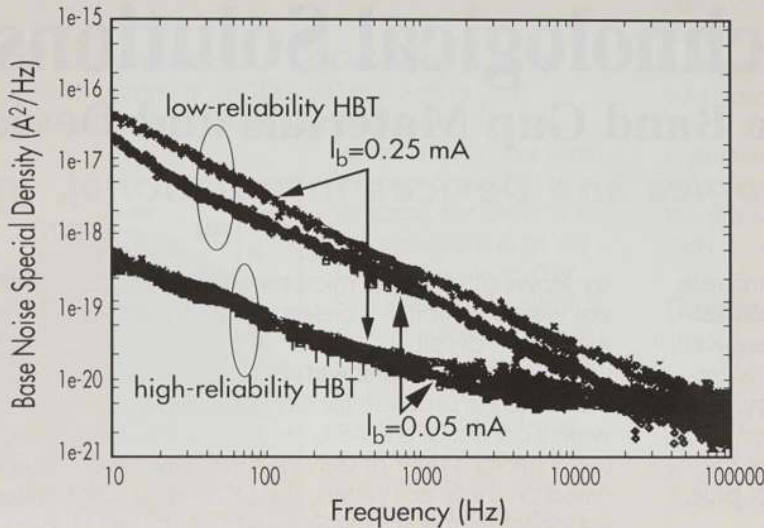


Figure 4. Comparison of low frequency base current noise of high and low reliability HBTs.

ing up the power as is often done in FETs. This leads to good linearity properties combined with high PAE. On the other hand, the smaller operating voltage imposed by handset applications leads to difficulty in achieving high PAE. The V_{ce} offset voltage of the HBT, together with the collector-emitter resistance, determines the on-state voltage, which limits the output signal. Reduction of V_{be} is also often sought despite the fact that a high value can be useful for power down of an amplifier. The use of GaAs double-HBTs and InP-based technology can be attractive for this purpose.

High-speed, low power applications using small area devices also benefit from GaInP designs due to their large valence band discontinuity, which increases injection efficiency and thus enables higher based doping and speed, while the low surface recombination velocity of InGaP leads to reduced base leakage. The use of small emitter area HBTs is the most effective way for reducing power consumption while keeping the current density high. Although the latter guarantees high-speed performance, the small emitter size compensates the speed improvement by increased emitter resistance R_E . Graded emitter designs have been proposed for this purpose [10].

HBTs have also been introduced in fiber optic transmission systems operating at 10 Gbit/s and higher speed systems

are currently envisaged. Although the actual operating speeds can be satisfied using GaAs technology, InP HBTs are the preferred solution for future generations that are envisaged up to 80 Gbit/s.

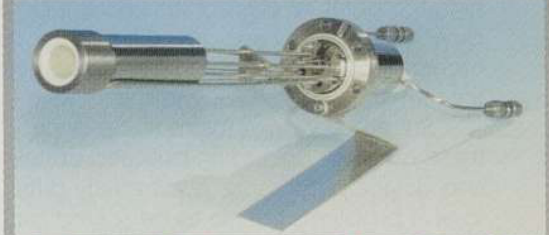
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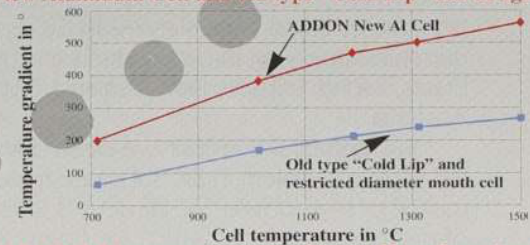
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Technological Solutions

for Wide Band Gap Materials and Devices

Technologies and Devices International, Inc.

Wide bandgap semiconductors will play an exciting role in the next generations of solid state electronics. Silicon carbide (SiC) and the Group III-Nitrides (GaN, AlN, InN) are well-recognized as the prime candidate materials for short-wavelength optoelectronics and high-power, high-frequency, and high-temperature electronics. Recent demonstrations of device capability have driven home the message about the tremendous market potential of these materials for GaN blue light emitters and SiC power microwave circuits.

But much work remains to be done. The technology of these materials, including bulk and epitaxial growth, doping, and device processing, is extremely difficult. Many technological problems remain to be solved before wide bandgap semiconductors will become a proper part of compound semiconductor market.

Technologies and Devices International, Inc. (TDI) was founded in August 1997 to commercialize basic research and new technological developments in crystal growth and device fabrication of wide band-gap semiconductors. Today, TDI develops, manufactures and markets SiC and Group III-Nitride epitaxial wafers. New products are under development in collaboration with research teams from Rensselaer Polytechnic Institute, Howard University, Murray State University, Mississippi State University, and the Crystal Growth Research Center (St. Petersburg, Russia).

Products

In 1998, TDI started a small-scale production of two products, SiC epitaxial wafers and GaN/SiC epitaxial wafers. TDI is currently supplying these products to customers in the United States, Japan, Europe, New Zealand, South Africa, and Australia.

SiC epitaxial wafers have been developed to solve the micropipe problem in SiC substrate materials. The performance of high-power SiC devices is limited by high densities of micropipe defects, which are open core defects (tubes) penetrating from the substrate in to device area and causing device failure.

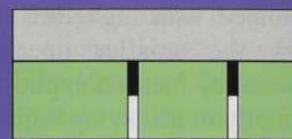
The micropipe filling technology developed at TDI resulted in the first 2 inch diameter 6H- and 4H-SiC wafers (Fig. 1) with micropipe densities less than 10 cm^{-2} [1]. The idea is simple: repair commercially available SiC wafers

by growing SiC inside micropipe channels. The resulting SiC epi wafers exhibit 1-2 orders of magnitude improvement in micropipe density.

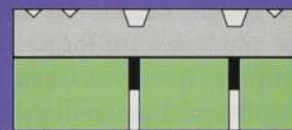
GaN/SiC epitaxial wafers have been developed to solve the substrate problem for GaN homoepitaxy. These epi wafers consist of a 6H-SiC on-axis initial substrate and thin (~ 0.5 micron) layer of GaN [2]. For GaN-based devices fabricated on these epi wafers, the SiC plays a role of heat sink, an important feature for high-power GaN-based devices. These wafers may also be used as substrates for GaN homoepitaxial growth by conventional MOCVD or MBE processes.

Step-by-step etching of 4H-SiC CVD layer grown on 4H-SiC wafer with filled micropipes

Schematic view (right) of the sample before etching: green - initial SiC wafer with micropipes, black - filled micropipes (SiC is grown inside micropipe channels), gray - CVD grown layer.



After the 1st etching step



Sample after the first chemical etching in molten KOH at 500°C ; etch pits related to dislocations (small) and former micropipes (two large) are clearly seen. Note that micropipe related etch pits have bottoms. There are no open core defects in CVD grown layer.

After 2d and 3d etching steps



Photographs of the same spot on SiC sample after 2d and 3d etching. Only after the 3d etching one of micropipe related etch pits become an open core defect. These results prove that the investigated CVD layers grown on TDI's epi wafers have no micropipes.

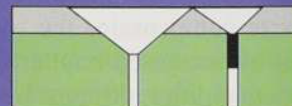


Figure 2.



Figure 1. 2 inch 6H- and 4H-SiC epi wafer with reduced micropipe density.

R&D Efforts at TDI

SiC

Recently, structural defects in SiC CVD layers grown on Mississippi State University on TDI's SiC epi wafers with reduced micropipe densities have been studied [3]. This



Figure 3. Free-standing 30 mm diameter GaN wafer fabricated by HVPE GaN growth on SiC substrate and subsequent substrate removal by reactive ion etching.

Group III-Nitrides

Substrate materials

Two technical approaches to GaN bulk materials are under investigation. The core TDI technology, hydride vapor phase epitaxy (HVPE), is being used to fabricate single crystal GaN and AlN wafers. In 1997, 30 mm diameter free-standing GaN wafers were fabricated using GaN HVPE deposition on SiC substrate and subsequent SiC substrate removal by reactive ion etching (Fig. 3) [4]. In 1998, working in a U.S. Navy SBIR program, TDI demonstrated 30x30 mm² free-standing single crystal AlN wafers grown by the HVPE technique (Fig. 4). TDI is currently engaged in a new program to develop production HVPE technology for large area free-standing GaN and AlN wafers.

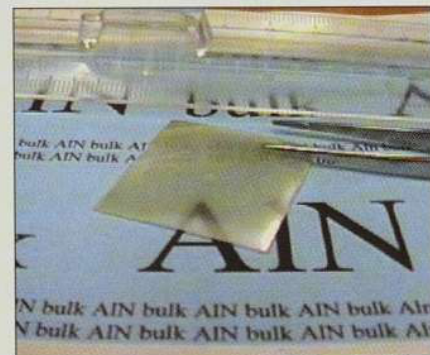


Figure 4. Free-standing 3x3 cm² AlN wafer grown by HVPE.

work showed that after the micropipe filling process, the defects do not penetrate in to the CVD grown layer (Fig. 2). This result indicates a great potential of TDI's material for the creation of large area high-power SiC devices. TDI was awarded Phase II SBIR contract to develop 2 inch and 3 inch 4H- and 6H-SiC epitaxial wafers with micropipe density less than 1 cm⁻². 3 inch SiC epi wafers with reduced micropipe densities are scheduled for production in 2000. TDI's cooperates with AXT (American Xtal Technology) on this program.

Another approach is to grow bulk GaN crystals from melt-solution. Using this growth process, GaN ingots have been grown from melt-solution at a pressure less than 2 atm and temperature less than 1100°C (Fig. 5). GaN ingots grown from melt-solution were sliced in to wafers and used for GaN homoepitaxy.

While this technique still has a long way to go before it becomes a mass production tool for GaN substrate materials, it definitely shows a high potential to be the dominate future technique for the growth of large size GaN bulk crystals.

Devices

The development and commercialization of SiC and GaN-based semiconductor devices is an integral part of TDI's business program. Figure 6 shows the spectrum of a GaN-based blue LED fabricated on a free-standing GaN substrate. The GaN-based pn structure and the GaN substrate were grown the HVPE technology. The main advantage of the HVPE method over conventional MOCVD technique is its low cost. TDI plans to demonstrate prototype blue LED product based on HVPE grown structures early next year.

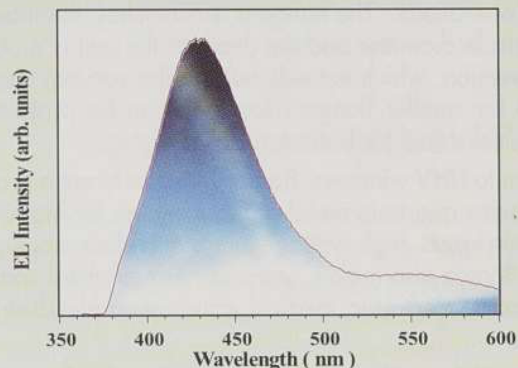


Figure 6. Electroluminescence spectrum of GaN-based LED structure grown on free-standing GaN wafer.

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- [2] V. Dmitriev et al, Mat. Res. Soc. Symp. Proc. Vol. 512 (1998) p. 451.
- [3] S. Rendakova and V. Dmitriev, reported at the MRS 1999 Spring Meeting, April 1999, San Francisco.
- [4] Yu. Melnik et al, Mat. Soc. Symp. Proc., 1998, 482, p. 269.

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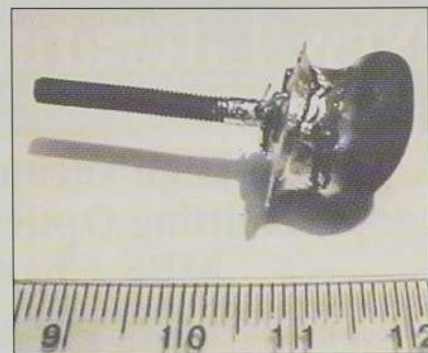


Figure 5. GaN ingot grown from a melt-solution at the Crystal Growth Research Center (joint R&D program with TDI).

New Products/ New Literature

Ultra High Vacuum Windows Permitting Optical Access to MBE Chambers

Gloucester, MA. Bomco's new UHV Windows permit the use of optical pyrometry, ellipsometry, light scattering and reflectance-difference spectroscopy (RDS) to obtain data in real time during molecular beam epitaxy (MBE) operations. The new products provide protection to UHV windows yet preserve optical access to MBE chambers. The newly-designed Re-Entrant UHV Window, unlike conventional windows, extends inside the vacuum chamber. This new design saves space and provides protection to the window during UHV operations. The flange is 4.50 inches, the tube is 2.25 inches outside diameter and the depth of the unit is 4.50 inches. Another version, which extends outside the vacuum chamber, is available for smaller flange sizes, and can be protected by a stainless steel shield for both sizes.



In addition to UHV windows, Bomco manufactures a proprietary line of tubular quartz-to-metal seal assemblies for improved performance in lasers, high-wattage lamps and electro-optical applications. Bomco also makes precision formed metal components for aerospace, electronic, medical, consumer and industrial manufacturers.

For more information, contact: Mark Standly, Bomco, Inc., 125 Gloucester Avenue, Gloucester, MA 01930-2254, Phone: 978-283-9000, Fax: 978-283-2882, E-Mail: cust-serv@bomco.co or visit our WWW site at www.bomco.com

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New Pressure Transducer

Richardson, TX. Advanced Process Technology, Inc. has developed a new line of ultra-high-purity flow through pressure transducers specifically designed to meet the demands of the semiconductor industry. This highly compact (2.25" H x 2.00" L x 1.25" W) all 316-L stainless steel flow-through pressure transducer is capable of measuring either differential or gauge pressure from inches of water to thousands of pounds.



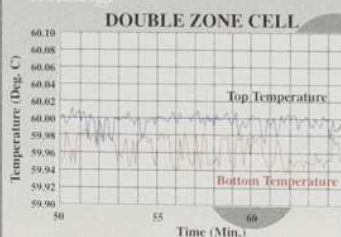
The APT pressure transducer is a magnetic transducer but because of its proprietary design it can still be constructed with nonmagnetic materials. Unlike strain gauge transducers or capacitance manometers, there is no sensing structure attached to either side of the 316-L stainless steel diaphragm. Dual outputs of 0-5 Vdc and 4-20 mA are provided with user supplied power of 12-30 Vdc. Optional pressure port styles are available. The transducers are intrinsically safe to an overpressure of 3000 psi. The unit is electro-polished, He leak checked, has zero dead volume, has a total internal volume of 0.05 in³ and is highly accurate at +/-1% of reading or better.

For more information, contact: Advance Process Technology, Inc. 911 E. Arapaho Rd., Suite 105E, Richardson, TX 75081
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Mitsubishi Family of GaAs FETs

Sunnyvale, CA. The US Electronic Device Group of Mitsubishi Electronics has announced the MGF091XA family of GaAs FETs. These products offer a low noise figure and high third-order intercept point for wide dynamic range performance from 900 MHz to more than 3 GHz. The leadless, surface-mount packages are hermetically sealed and come packaged in tape and reel form for high volume production requirements. Applications include receiver amplifiers for tower top antennas and driver and output stages in base-station transmitters. The MGF0913A device, for example, offers a typical noise factor of 2.0 dB, IP3 of +57 dBm, and an output power of +31 dBm at 1.9 GHz.

Anadigics Upconverter for CATV

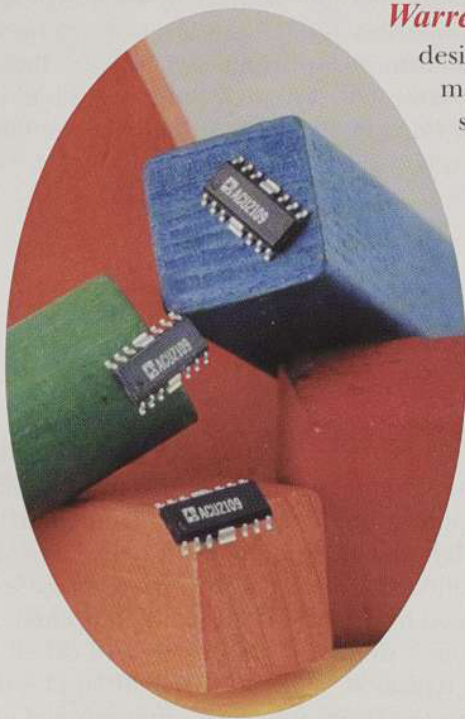
Warren, NJ. Anadigics has developed the ACU2109, a monolithic GaAs upconverter designed to support the latest 256 quadrature-amplitude modulation (QAM) digital formats. This device provides the low phase noise required for 256-QAM digital transmission, enabling increased channel capacity for expanded modem, telephony, and CATV broadcast services. The ACU2109 provides -89 dBc/Hz typical phase-noise (as compared to the Anadigics ACU50752 device, which provides -84 dBc/Hz typical phase noise for 64-QAM applications). Housed in a 16-lead SOIC package, it demonstrates a noise figure of 6.5 dB, conversion gain of 8.0 dB, and power consumption of 600 mW.

Pacific Monolithics RFIC PA

Sunnyvale, CA. A new 1 W RFIC PA has been announced by Pacific Monolithics. The PM2107 uses the same 2-stage GaAs MESFET RFIC chip from the PM2104 PA introduced in 1994. This RFIC chip is now packaged in a 10 pin injection molded plastic package measuring 0.196" long x 0.079" wide x 0.042" high (5 x 2 x 1 mm). Pacific has also released a new PM-SOP package. Plastic packages typically lack in thermal performance and are plagued with pin inductance problems above 2 GHz. Metal base or copper slug plastic packages were introduced to address the thermal issue but pin inductance problems still limit 1 W performance to operation below 2 GHz. The PM-SOP package uses fused leads to handle the thermal dissipation with no bottom side metal contact, eliminating the bottom side blind solder joint. With its small size, pin inductance is reduced, and 1 W performance is typical up to 2.5 GHz. (at 5 V).

Alcatel Fiber Amplifier

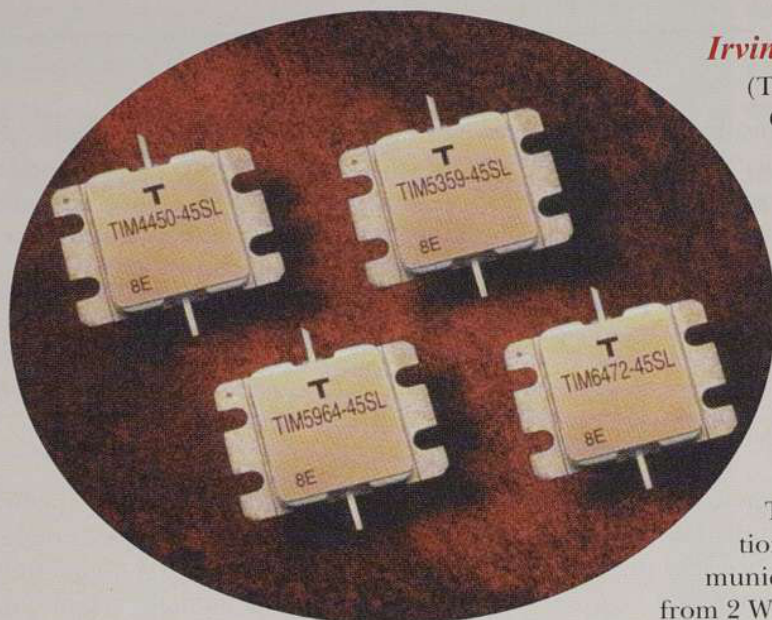
Nozay, France. Alcatel has developed the 1925 OFA '1.0 dB' fiber amplifier, which features a maximum gain differential of 1.0 dB across the wavelength range (1530-1560 nm) and temperature range (-5°C to 70°C). The new configuration, which offers a gain of 28 dB, can be positioned equally well as a booster, in-line, or preamplifier, offering mid-stage access for routing or dispersion compensation. An on-board 980 nm pump assures an output power of +14 dBm for the basic unit, with a typical noise factor of less than 5 dB across the 30 nm C-band range. As channel sets are added, the output power can be increased to +17 or +20 dBm by plugging in an additional external pump module. It also features a flat gain of less than 1.0 dB across a wide bandwidth and temperature range.



Toshiba 60 W C-Band GaAs FET

Irvine, CA. Toshiba America Electronic Components, Inc. (TAEC) has announced an internally matched 60 W C-Band GaAs FET. The TIM5964-60SL has an output power (P_{1dB}) of 48.0 dBm (typical) at a frequency range of 5.9-6.4 GHz. The PAE value is 41%. The new device is manufactured using Toshiba's new HFET process technology, and is optimized for use in PAs for satellite earth-station communication transmitters (SATCOM) and very small aperture terminals (VSAT). The TIM5964-60SL is also targeted at other wireless communications and point-to-point radio applications.

The 60W C-Band FET allows designers to achieve the power ratings necessary to boost signal strength using fewer components, thereby resulting in lower system cost. The device also helps to reduce the level of intermodulation distortion and harmonic spurious signals in satellite communications systems. Toshiba's broad C-Band products range from 2 W MMICs to 60 W GaAs FET devices. Pricing for the 60 W C-Band GaAs FET, in quantities of 100, is \$1,100 each.



UMS MMICs for Radio Communications

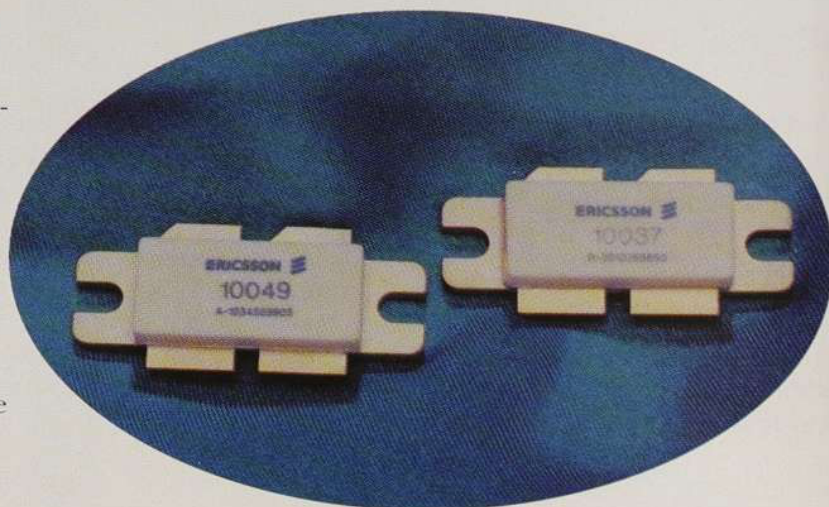
Orsay, France. United Monolithic Semiconductors (UMS) has announced its new BES Schottky diode process MMICs for radio communication systems. The CHM1190 and the CHM1191 are complementary, offer the same electrical performance and can be used in the up- or down converter configurations. Neither device requires a DC bias supply. UMS also supplies a new device for 55-60 GHz LNA for millimeter wave applications. The CHA2157 is a low noise, medium-power amplifier having a 4 dB noise figure, 15 dBm output power at 1 dB compression point, 12 dB gain for a chip size of 1.78 mm². A temperature sensor is implemented on-chip and the device is available in chip form.

Amplifier from Stanford Microdevices

Santa Clara, CA. Stanford Microdevices has announced the availability of a high-linearity PA designed for base station communication applications. The SXA 289 is manufactured using the GaAs HBT process and is ideal for use as a driver stage for PAs installed in cellular PCS infrastructure equipment, but is also used in 915 MHz ISM band equipment. The device operates from a single 5 V DC supply and offers a linearity of +42 dBm typical at 900/1900 MHz in 50 Ω systems. Packaging comes in the form of an industry standard plastic SOT-89 with backside ground.

Silicon RF Amplifiers from Ericsson

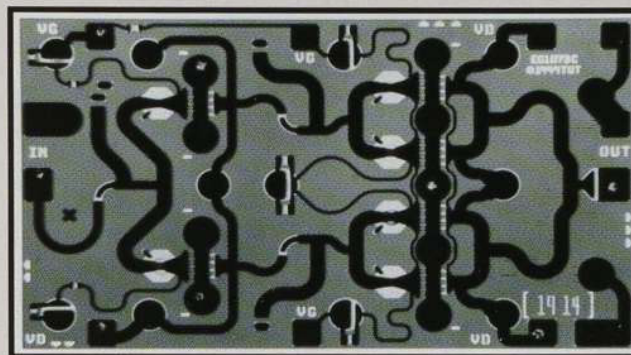
San Jose, CA. Ericsson has introduced a new range of silicon RF amplifiers. The PTF 10049 and PTF 10037 are LDMOS FET devices designed for amplification of UHF TV signals in the 470-860 MHz range. The PTF 10037 is the highest power device, delivering 120 W with 14 dB of gain. The PTF 101XX series is designed for amplification of DAB and DAR signals; the PTF 10125 device, for example, supplies 13 dB of linear gain and a saturated power capability of almost 200 W. For amplification of cellular base station signals, the PTF 10100 offers the same performance at a frequency of 900 MHz.



Four TriQuint MMIC Amplifiers

Hillsboro, OR. TriQuint Semiconductor has introduced four PA MMIC devices covering the 19-41 GHz frequency band. Designated TGA1073A, B, C, and G, these devices are based on TriQuint's 0.25 μm power pHEMT GaAs production process for the millimeter wave region. The TGA1073A is a three-stage amplifier providing 300 mW of output power and 19 dB of small signal gain. Its frequency coverage of 26-34 GHz makes it suitable for both terrestrial digital radio and Ka-Band SatCom applications. The TGA1073B, also a three-stage amplifier, covers the 27-32 GHz frequency band with an output power level of 700 mW. This device has a small signal gain level of 25 dB and is suitable for those digital radio and SATCOM applications requiring higher power than the TGA1073A.

The C version (see photo) addresses the 37-41 GHz range and is appropriate for both point-to-point and point-to-multipoint wireless data systems at 38 GHz. It exhibits 400 mW of output power with 16 dB of small signal gain. Finally, the G device (TGA1073G) can be used for several terrestrial digital radio bands (19-27 GHz), and provides 300 mW of output power and 22 dB of small signal gain. All four in the series can be operated at drain bias voltages between +5 and +7 V, and the output power will generally increase from the nominal 6 V performance at higher drain voltage operation. All devices require a separate negative gate voltage.



Honeywell Surface-Mount IR Components

HJFET from NEC

Sunnyvale, CA. NEC Electronics has launched the NE34018, an n-channel GaAs heterojunction FET. Designed for high-volume applications, the NE34018 is supplied in an industry standard MOLD package. It is targeted at LNA applications in front end communications systems such as DECT and GPS, the device offers 1 dB noise figure (0.6 dB typical) at 2 GHz, and a gain of 16 dB. Supplied on 8 mm tape and reel packaging, the 4-pin super mini MOLD package (2 x 1 x 0.9 mm) encloses a transistor of gate width of 400 μm .

Freeport, IL. The Micro Switch division of Honeywell is offering discrete surface-mount infrared components with glass lenses for applications in optical encoding for motion control, vending and point-of-sales applications, smoke detection and the medical field. The SME2470 AlGaAs infrared diode can be used with either the SMD2440 series phototransistor, tailored for applications requiring high responsiveness, or used with the SMD2420 series photodiode. The glass lenses minimize cross-talk and often eliminate the need for apertures in non-critical applications. The SME/SDM series comes in small, low-profile ceramic packages that may be mounted lens upwards or inverted on a board, allowing flexibility in layouts. The operating temperature range is -55°C to 125°C.

EiC Introduces Power Amplifiers

Freemont, CA. EIC Corporation has introduced a pair of high-output PAs for use in wireless handsets, TV tuners, and related applications. The EC-1078 and EC-2098 are low-power chips built using GaAs HBT process technology. The EC-1078 is a 3 V PA optimized for cable-TV and related applications. The device operates in the DC to 3,000 MHz range, with a low-noise specification of 3 dB at 1900 MHz. The EC-2098 PA operates in the 824-849 MHz range, and is suited for analog cellular applications. Both chips are housed in eight-pin SOIC packages.

Filtronic Introduce pHEMTs

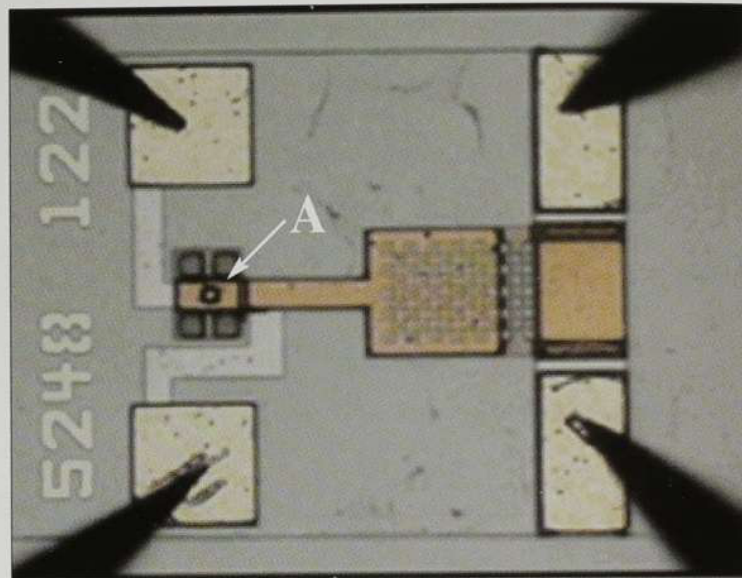
Santa Clara, CA. 0.5 and 1 W pHEMTs have been announced by Filtronic Solid State for applications in wireless and millimeter wave communication. Covering the 900 MHz - 35 GHz range, the 0.5 W LP750 device features a gain of 11 dB SSG and 55% PAE at 18 GHz. At this frequency, the P-1dB compression exceeds +28 dBm, with third order intercept levels greater than +40 dBm. The device can also be operated as a high dynamic range LNA for PCS/cellular applications, with noise figure performance of less than 1.0 dB and OTOI of +40 dBm. The LPV1500 is a 1 W pHEMT designed for millimeter wave applications from 10-32 GHz, a gain of 9.5 dB SSG and 50% PAE at 18 GHz. At 18 GHz, the P-1dB compression exceeds +31 dBm with third order intercept levels of greater than +44 dBm.

Microelectronic Devices and Circuits

GaAs-Compatible MEMS Switches

D. Hyman et al, Elec. Lett., 1999, 35(3), p. 224

A variety of switching functions are performed using III-V FET circuits and p-i-n diodes, in microwave applications such as agile filters and phased-array antennas. Insertion losses are typically high, ranging from 1 dB in the Ku band to several dB in the 40-45 GHz range, and only limited cost reductions have been achieved. This paper, from **HRL Labs and Advanced Micro Machines**, reports a microfabricated electro-mechanical systems (MEMS) technology which could lead to affordable microwave components, and open up a range of new applications. The paper describes a MEMS switch fabricated on a GaAs substrate, although the process is also compatible with other materials such as InP. The design is based on the use of a suspended cantilever which consists of a gold film sandwiched between insulating layers, in this case silicon nitride. In the closed position, the cantilever structure contacts two gold pads on the substrate. The structure is fabricated with a sacrificial silicon dioxide layer between the substrate and the cantilever; the SiO_x is removed with a highly selective HF etch to release the suspended arm. RF measurements indicated an insertion loss of <0.2 dB in the range from DC to 40 GHz, and a high isolation of >50 dB at frequencies below 2 GHz.



Microphotograph of the completed MEMS switch. The cantilever, which runs from left to right in the center of the photo, is attached to the substrate at point A. The total die size is $500\ \mu\text{m} \times 700\ \mu\text{m}$.

E-Mode InP-Based MODFET with 300 GHz f_T

D. Xu et al, Electron Dev. Lett., 1999, 20(5), p. 206

Direct-coupled FET logic (DCFL) is favored for high speed digital circuits due to its simple circuit configuration. This technology requires enhancement-mode (E-mode) MODFETs, however the performance of these devices lags behind that of D-mode devices, even in the InAlAs/InGaAs material system lattice-matched to InP. One of the most important factors is the difficulty in controlling lateral etching when deep gate grooves are etched. This paper, from **NTT**, reports the fabrication of E-mode devices by direct electrochemical etching, which allows deep and narrow gate recesses. The value of V_{th} is further increased towards zero by replacing Ti as the bottom gate metal layer with Pt, which has a higher barrier height on InAlAs than Ti.

The epitaxial structures, grown by MBE on InP, consisted of a 200 nm InAlAs buffer, an 8 nm channel, a 2 nm InAlAs spacer, a 5 nm n^+ -InAlAs supply layer, a 15 nm InAlAs barrier, and cap layers. The strained channel comprised a 4 nm InAs layer between two 2 nm $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ layers. The etching process used allowed the fabrication of $0.03\ \mu\text{m}$ gates with very little side etching. A record high current gain cutoff frequency (f_T) exceeding 300 GHz was achieved, and the a maximum extrinsic transconductance was 2 S/mm with an associated drain current of 0.5 A/mm at a drain bias of 1 V.

0.12 μm Direct Ion-Implanted GaAs MESFET

H. Hsia et al, Electron Dev. Lett., 1999, 20(5), p. 245

Implanted GaAs MESFETs are emerging to challenge PHEMTs in high bandwidth millimeter-wave applications such as LMDS, automotive radar and satellite communication systems. Self-aligned MESFETs with scaled-down gate lengths of $0.1\ \mu\text{m}$ or less have shown f_T values in excess of 100 GHz. However, this process is relatively complicated and requires a high temperature gate process, which is only used by NTT and Vitesse for digital ICs. This paper, from the **University of Illinois**, reports a simple low temperature gate process which results in $0.12\ \mu\text{m}$ gate length MESFETs with an f_T of 121 GHz and an f_{max} of 160 GHz.

The devices were fabricated on LEC-grown, 3" semiconductor-insulating GaAs wafers, using a shallow implant schedule to form a highly doped channel. The n-type channel region was formed by Si direct implantation, and a p-type Be implantation was performed to improve the device pinch-off. Wafers were then annealed at 850°C in a H_2/AsH_3 atmosphere without cap, to optimize the shallow dopant profile. The $0.12\ \mu\text{m}$ gate was fabricated by e-beam lithography and Ti/Pt/Au evaporation. A peak transconductance of 500 mS/mm was obtained at $I_{ds} = 380$ mA/mm. A noise figure of 0.9 dB with associated gain of 8.9 dB were achieved at 18 GHz. These results indicate the suitability of this device for millimeter-wave IC applications.

Optoelectronic Devices

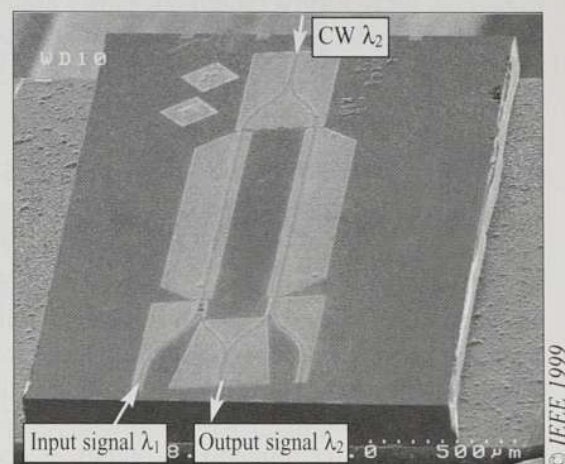
All-Active Mach-Zehnder Wavelength Converters

C. Janz et al, Elec. Lett., 1999, 35(7), p. 588;

B. Dagens et al, Photonics Tech. Lett., 1999, 11(4), p. 424

In future all-optical networks, optical signals will be routed and re-generated without conversion back to electronic signals. At present, signals are re-amplified by optical amplifiers such as EDFAs (known as 1R regeneration), but are converted into electronic form for re-shaping and re-timing (2R regeneration is re-amplification and re-shaping, 3R regeneration combines 2R with re-timing). Current DWDM systems carrying signals on a large number of different wavelengths employ passive add-drop multiplexers; these act as on or off ramps to the main DWDM trunk route, sending some wavelengths off to local hubs or other destinations, and allowing other wavelengths to rejoin the highway. Future networks will require optical cross-connects (OXC), which are capable of actively re-routing the different carrier wavelengths. After that will come wavelength-translating OXCs, which can transfer the digital modulation from one carrier wavelength to another. Semiconductor optical amplifiers (SOAs) will be key components in many of these functions, and will also provide amplification to counteract insertion losses.

These two papers, both from **OPTO+/Alcatel Corporate Research Centre**, describe an all-active wavelength converter optimized for 10 Gbps operation. Such a device is a key component of a wavelength-translating OXC, and is fabricated from five SOAs, which are integrated but operationally independent. The device (see figure) shifts the digitally modulated signal from the input wavelength λ_1 to the output wavelength λ_2 . The device layers are grown by MBE on a doped InP substrate. The active layer is tensile-strained (about -0.10%) bulk InGaAsP, which is 0.2 μm thick and has a bandgap of about 1.55 μm . This layer is within a separate confinement heterostructure consisting of undoped, 1.18 μm bandgap quaternary material, with 0.1 μm -thick layers above and below the active layer. The remaining layers are doped InP, including an MOVPE-regrowth to bury the etched stripe. The tensile strain is adjusted to achieve near-polarization independence. The device demonstrated an input sensitivity of -10 dBm, for 1 dB conversion penalty, at 10 Gbps.



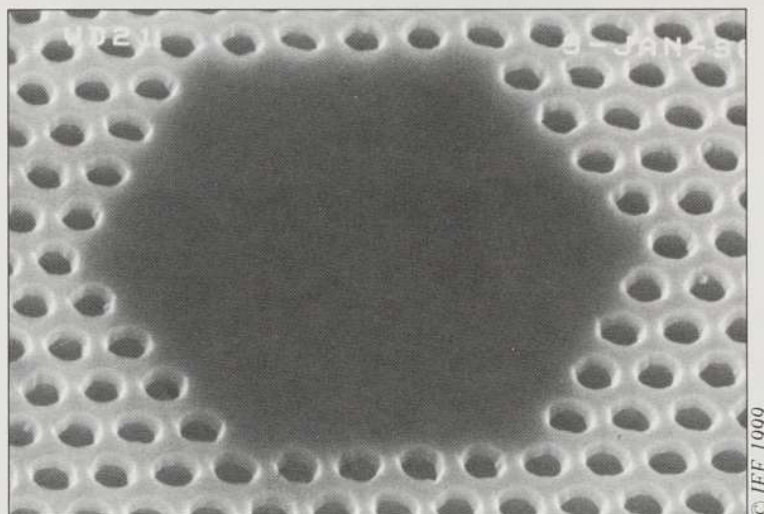
SEM photograph of optimized all-active Mach-Zehnder wavelength converter.

Photonic Bandgap Laser

R. Lee et al, Elec. Lett., 1999, 35(7), p. 569

Photonic bandgap structures modify the propagation of photons through the material from which they are fabricated, and can also fundamentally modify the spontaneous emission properties of light-emitting materials. This paper, from the **California Institute of Technology**, reports the fabrication of a photonic bandgap disk laser operating at room temperature (see figure). The structure consists of an array of holes etched through a free-standing membrane by chemically-assisted ion-beam etching. The membrane comprises an active region of six InGaAs QWs with InGaAsP barriers, within an InGaAsP waveguide with a total thickness of 150 nm. These layers were grown by MOVPE on an InP substrate; after etching the holes, the InP was etched away to leave the free-standing, air-suspended membrane.

The index contrast between the membrane and air provides strong optical confinement within the plane, resulting in a two-dimensional laser structure. The hexagonal center of the membrane, which does not contain air holes, constitutes the optical cavity. The pattern of air holes around the cavity, which constitutes the photonic bandgap structure, acts in a similar way to a distributed Bragg reflector (or a dielectric mirror). Such a mirror one would normally have quarter wavelength layers of alternating high and low refractive index materials, building up a high



SEM top view of a hexagonal membrane cavity bounded by a 2D photonic bandgap structure, formed by etching air holes through the membrane in a regular pattern.

reflectivity over several periods. The photonic bandgap structure acts as a 2-dimensional mirror, confining light within the micro-fabricated optical cavity. This type of structure is an alternative to a microdisk laser, in which optical confinement is provided by total internal reflection at the curved boundary of the semiconductor disk.

The ratio of the hole size to the lattice space (r/a) for the photonic structure was ~ 0.35 . Cavities measuring ~ 10 - $15\ \mu\text{m}$ were examined; these form a multimode cavity at the emission wavelength of $1.55\ \mu\text{m}$. The laser cavities were optically pumped nor-

mal to the membrane using a $980\ \text{nm}$ InGaAs laser with a spot size of $\sim 15\ \mu\text{m}$. Lasing was observed at room temperature normal to the membrane, in spite of the poor thermal conduction path for heat removal.

7 W CW Power from GaAsP/AlGaAs Lasers at 735 nm

A. Knauer et al, *Elec. Lett.*, 1999, 35(8), p. 638

The 700-780 nm wavelength range is important for emerging applications such as photo-dynamic therapy, high speed printing and femtosecond solid-state laser pumping. Conventional AlGaAs lasers offer limited CW output powers, as the presence of Al in the active layer reduces the maximum internal power density at the catastrophic optical mirror damage (COMD) level. The elimination of Al from the active region using (In)GaAsP quantum wells is key to improving performance. This

paper, from the **Ferdinand-Braun-Institute (FBH-Berlin), Germany**, reports lasers with record high CW output powers in the 715-735 nm range, which contain a compressively strained $\text{GaAs}_y\text{P}_{1-y}$ QW embedded in an AlGaAs waveguide. The MOCVD-grown structure consisted of a single 9 nm $\text{GaAs}_y\text{P}_{1-y}$ QW within an $\text{Al}_{0.65}\text{Ga}_{0.35}\text{As}$ waveguide layer, with $\text{Al}_{0.70}\text{Ga}_{0.30}\text{As}$ cladding layers. The value of y was 0.65 for emission at 730 nm. $100\ \mu\text{m}$ stripe broad area lasers were

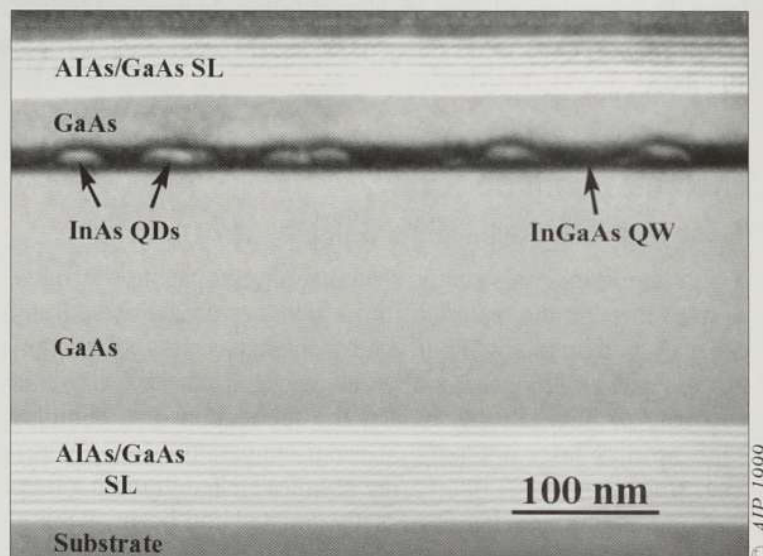
fabricated. For 2 mm long AR/HR (2%/90%) facet-coated devices, a threshold current of 375 mA, slope efficiency of 1.26 W/A, CW output power of 7 W and wallplug efficiency of 50% were recorded for 735 nm devices. The calculated power density at the 7 W level was $8.8\ \text{MW}/\text{cm}^2$. Reliability measurements at 0.5 W and 25°C suggest lifetimes in excess of 10^4 hours. The 718 nm device with a $60\ \mu\text{m}$ strip width had an output power, limited by COMD, of $\sim 2.5\ \text{W}$.

1.3 μm Quantum Dot Emitters Grown on GaAs

V. Ustinov et al, *Appl. Phys. Lett.*, 1999, 74(19), p. 2815

The interest in optical transmission at $1.3\ \mu\text{m}$ is promoting the search for an alternative to InGaAsP/InP-based emitters. These suffer from poor high temperature performance, due to insufficient electron confinement in the active region, and also use more expensive InP substrates. Directions for developing GaAs-based emitters include N-based quaternary materials (i.e. GaInNAs), and InGaAs quantum dots. This paper, from the **Ioffe Institute, Russia, and the Technical University of Berlin, Germany**, describes a method to reduce the energy of the optical transition of an InGaAs quantum dot by decreasing the bandgap of the surrounding matrix. InAs quantum dots (QDs) are placed within an external, strained InGaAs QW, which allows control of the QD emission wavelength by varying the InGaAs composition.

Structures were grown by MBE on GaAs and consisted of an InAs QD array within an InGaAs QW, which was placed into a $0.12\ \mu\text{m}$ GaAs layer, and confined by AlAs/GaAs superlattices (see photo). The InAs mole fraction and the QW width were varied in the 0.1-0.3 nm and 10-4 nm ranges respectively. Room temperature PL with varying In content showed that a decrease in the bandgap of the InGaAs matrix (increasing In composition) resulted in a red shift of the PL line. The PL peak position reaches $1.3\ \mu\text{m}$, with an FWHM value of 50 meV, for the 4 nm



Cross-sectional TEM showing an InAs quantum dot array in a $10\ \text{nm}$ $\text{In}_{0.12}\text{Ga}_{0.88}\text{As}$ quantum well.

$\text{In}_{0.3}\text{Ga}_{0.7}\text{As}$ QW. A $1.33\ \mu\text{m}$ PL peak was observed from a vertical optical microcavity containing an InAs/InGaAs QD active region, suggesting this approach could also be suitable for fabricating $1.3\ \mu\text{m}$ VCSELs.

QDs in the InGaAs matrix are typically 20 nm across and 5-6 nm in height, which is larger than InAs islands in a GaAs matrix. This increased QD size is thought to contribute to the increase in emission wavelength - a similar effect has been postulated for InN dots in InGaN-based LEDs [see CS 5(4), p. 18].



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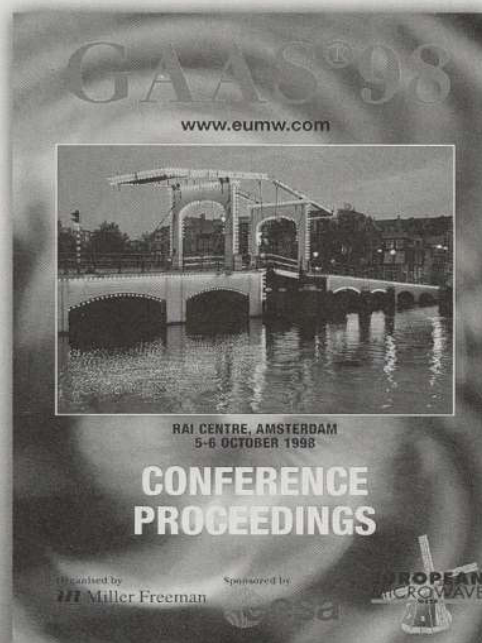
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Mr Ali Fazal – *Nokia Mobile Phones, USA*
Dr Aiden Higgins – *Rockwell Science Centre, USA*
Dr Charles Huang – *VP Anadigics, USA*
Dr. M Rocchi – *Philips, France*

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In & Out

MARIE MEYER

Our Portfolio lost one member but gained another during the last week of May.

The new member is IQE plc, which began trading on the EASDAQ exchange in Belgium on May 28. The company was formed on May 4 by the merger of Epitaxial Products International, Ltd. (EPI) and Quantum Epitaxial Designs, Incorporated (QED). The two companies had combined annual sales of \$30 million in 1998, and are growing at approximately 35% per year. IQE bills itself as "the world's leading 'pure play' merchant epitaxial supplier".

The EASDAQ is the European stock market for small-cap companies, based in Brussels. Modeled after the U.S. NASDAQ exchange, the EASDAQ uses a multiple market maker system which allows trading and settlement across the European Union. Trading is available in 13 European countries. Approximately 45 companies are currently listed.

Slightly more than 20% of the IQE's shares were offered in the IPO, which was valued at \$40 million. IQE was expected to net around \$31 million from the transaction.

For more on IQE, see page x.

SLI Delisted from NASDAQ

The exiting member of the Portfolio is Semiconductor Laser International, which was delisted from the NASDAQ on May 26 for failure to meet the exchange's minimum requirements for share price and tangible asset value. SLI stock has been consistently trading below \$1 since mid-August, and trading at about 50 cents or below since mid-December. The company will now be traded only in the "over-the-counter" (OTC) markets, greatly restricting its liquidity.

This event will further erode SLI's image. As we reported previously, the company is currently under investigation by the SEC and the U.S. Attorney's office for possible violations of securities regulations (CS (5)(1), p. 62).

SLI President and CEO Geoff Burnham, in announcing the delisting, held out the possibility that the company would be able to return to NASDAQ after taking steps to bring it into compliance with exchange regulations. Shareholders will be asked to approve a reverse stock split at the company's annual meeting in mid-June. If adopted, this measure will consolidate the number of shares from

12.2 million to 1.74 million and thereby boost the price of each share - although the actual value of the company would not be changed.

Burnham also said that although he was "disappointed" about the delisting, he remains optimistic about SLI, and he hopes to attract additional outside financing.

Since it was founded in 1993, SLI has posted a cumulative loss of \$18 million, with a \$1 million loss in its most recently completed quarter. At their peak, shares in SLI traded as high as \$10 - see chart, next page.

Company	Symbol	Exchange	Closing Price May 28	52 Week Low	52 Week High	Market Cap (\$M)	P/E Ratio
GaAs ICs							
Alpha Ind.	AHAA	NASDAQ	32.38	5.75	47.50	516	26
Anadigics	ANAD	NASDAQ	24.00	4.63	28.00	355	-
Celeritek	CLTK	NASDAQ	5.38	2.50	8.38	39	-
Conexant	CNXT	NASDAQ	38.88	13.00	45.00	3,755	n.a.
RFMD	RFMD	NASDAQ	39.75	5.25	68.00	1,558	39
TriQuint	TQNT	NASDAQ	36.25	11.00	39.88	346	30
Vitesse	VTSS	NASDAQ	55.56	17.13	59.00	1,422	72
Optoelectronics							
APA Optics	APAT	NASDAQ	6.25	4.00	10.00	53	-
Coherent	COHR	NASDAQ	15.88	7.50	23.25	380	27
Cree	CREE	NASDAQ	55.13	10.50	60.63	799	73
Ortel	ORTL	NASDAQ	11.44	6.00	20.25	136	-
SDL	SDLI	NASDAQ	89.50	8.13	127.00	1,311	+
Uniphase	UNPH	NASDAQ	131.75	31.25	148.00	5,323	-
Uniroyal Tech.	UTCI	NASDAQ	9.38	7.25	10.88	112	23
Materials and Equipment							
ATMI	ATMI	NASDAQ	22.25	10.88	31.00	495	-
AXT	AXTI	NASDAQ	19.75	5.25	27.00	318	47
Emcore	EMKR	NASDAQ	20.88	6.00	28.75	197	-
Kopin	KOPN	NASDAQ	15.63	11.38	24.88	244	-
PlasmaTherm	PTIS	NASDAQ	2.56	2.06	9.00	32	-
Spire	SPIR	NASDAQ	3.31	2.25	6.75	11	-
European Companies (Currency data in Euros)							
Aixtron	AIX	Neur Mkt.	212	92	235	1058	+
IQE plc	IQEP	Easdaq	12.57	12.09	12.57	166	n.a.
Picogiga	PICO	N. Marche	10.77	9.99	44.52	17	40

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

Financials

The following is a summary of the first quarter financial results that weren't available in time for our previous issue:

Aixtron reported that revenues for the first quarter increased 16.1% to Euro 16.6 million. (US\$17.7 million), while net income grew 26 percent to Euro 1.9 million. (US\$2.0 million). In that period, the company booked Euro 16.9 million (US\$18.0 million) in new orders for MOCVD equipment, and at March 31 Aixtron's backlog stood at Euro 50.7 million. (US\$54.1 million), 76% higher than it was in the year-ago period.

Alpha Industries reported that net income for the quarter was \$8.5 million, compared with \$3.7 million for the same period last year. Excluding a tax benefit of \$3.3 million recorded in the quarter, net income was 42%. Sales were \$34.3 million, compared with \$31.9 million for the same period last year. The company's Wireless Semiconductors segment had sales of \$19.5 million and generated \$2.7 million in operating profit at a 45% gross margin. Application Specific Products had sales of \$7.5 million and generated \$2.1 million in operating profit at a 49% gross margin. Ceramic Products had sales of \$7.3 million and generated \$0.8 million in operating profit at a 37% gross margin.

On May 26 Alpha announced that it would offer 3.0 million shares of its common stock to the public at a price of \$35.00 per share. Proceeds from the offering are to be used for working capital and other general corporate purposes, which may include the purchase of equipment, the expansion of facilities and potential acquisitions.

For the first quarter **Celeritek** reported revenues of \$10.1 million, compared with revenues of \$15.8 million for the same quarter 1998. The company reported a net loss of \$2.0 million, compared with net income of \$812,000 for the same period a year ago.

Tamer Hussein, president and chief executive officer, said the company has had a very difficult time as of late in the radio/satellite products area, but it has continued its strategy of making signifi-

cant investments in semiconductor and transceiver development and production processes. "These investments are beginning to pay off," he said. Sales of semiconductor products were up 24% and 53% respectively over the year-ago period and the prior quarter. But Hussein said that these gains, "while extremely positive", were not enough to offset the dramatic change in radio/satellite demand. Celeritek's radio/satellite business has declined 61% over the past twelve months, while defense sales dropped 12%.

Emcore reported that their revenues for the quarter ended March 31, increased 59% to \$16.1 million, which is a record for the company. The company reported a net loss of \$2.9 million compared to a net loss of \$5.8 million in the previous quarter. Emcore's backlog on March 31 was \$43.8 million, up approximately 5% from December 31, 1998, and up 68% from September 30, 1998. The current backlog value is also a record for the company.

Kopin reported first quarter revenue of \$6.7 million, compared to \$5.5 million for the same period last year, an increase of 3%. Net income was \$205,867, compared to a net loss of \$611,025 for the comparable period last year. Product revenues in the first quarter increased 28% to \$6.0 million. Virtually all of the product revenue came from shipments of the company's GaAs epiwafer products, which were up 34%.

Spire reported revenues of \$3.8 million for the first quarter, compared with \$4.4 million for the quarter ended March 31, 1998. Net was \$149,000 compared to net income of \$17,000 for the same quarter of 1998.

Commenting on the results, Roger G. Little, chairman and president, said, cost reduction efforts put in place in late 1998 and early 1999 helped to minimize the loss and allowed the company to reduce its bank debt by \$300,000 over the quarter. Regarding the

company's compound semiconductor activities, Little noted that Spire Optoelectronics announced the availability of its III-V epitaxial growth and processing facilities, together with technical support, to start-up companies and to research and development organizations of larger companies. "Interest in the company's VCSEL wafers continued to be high. We also introduced on-line quotation requests for optoelectronics products via Spire's corporate web site," he said.

Spire recently announced that it had retained the services of an investment banking firm to advise the company on how to best deal with its three lines of business - photovoltaics, optoelectronics, and bio-medical. "These options may include joint ventures, a merger or the sale of a product line or a business," Little said.

Uniroyal Technology Corporation reported that net income for the first quarter was \$1.1 million, exceeding analyst's estimates by approx. 20%. Howard R. Curd, Chairman and Chief Executive Officer, said, "We are pleased with the overall progress at each of our business segments. We are making significant investment expenditures this year in a number of divisions. We believe the long-term benefits of these investments will be substantial." Curd also commented, "The Company has embarked upon a strategy of repositioning itself into higher growth segments targeted to enhance shareholder value." One such segment is optoelectronics, where the Company is investing in a new manufacturing facility to produce high brightness LEDs.



July

41st Electronic Materials Conference (EMC)

June 30-July 2
University of California,
Santa Barbara
<http://www.tms.org/Meetings/Specialty/EMC99/EMC99.html>

European Conf. on High Temperature Electronics (HITEN '99)

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July 5-9
Montpellier, France
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6th Int'l Workshop on Femtosecond Technology (FST '99)

July 13-15
Chiba, Japan
<http://www.festa.or.jp/meeting/fst99-e.html>

1999 Integrated Photonics Research Topical Meeting (IPR '99)

July 19-21
Santa Barbara, CA
<http://www.osa.org>

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

July 27-30
Tsukuba, Japan
<http://solid.pe.titech.ac.jp/cbe-7>

August

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

August 1-6
Tucson, Arizona
<http://www.aml.arizona.edu/aacg>

1999 International Microwave and Optoelectronics Conference (IMOC '99)

August 9-12
Rio de Janeiro, Brazil
<http://www.mc21.fee.unicamp.br/imoc99/>

1999 International Symposium on Compound Semiconductors (ISCS '99)

August 22-26
Berlin, Germany
Contact: ISCS '99 Secretary
ISCS99@pdi-berlin.de

September

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

September 6-7
Aachen, Germany
Abstract Deadline: July 2
<http://www.iht.rwth-aachen.de/miomd.html>

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

September 13-17
Miyagi, Japan
Contact: Prof S. Zaima
zaima@alice.xtal.nagoya-u.ac.jp

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

September 26-28
Minneapolis, Minnesota
Contact: Janice Jopke
jjopke@aol.com

October

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

October
Las Vegas, Nevada
Contact: Jay Morreale
jmorreal@newyork.palisades.org

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

October 4-8,
Munich, Germany
<http://www.eumw.com>

18th North American MBE Conference (NAMBE-18)

October 10-13
Banff, Canada
<http://www.nrc.ca/confserv/NAMBE99>

Int'l Conference on Silicon Carbide and Related Materials (ICSCRM '99)

October 10-15
Research Triangle Park, NC
<http://www.icscrm99.ncsu.edu/>

21st Annual GaAs IC Symposium

October 17-20
Monterey, CA
<http://www.gaasic.org>

196th Meeting of the Electrochemical Society

October 17-22
Honolulu, Hawaii
ecs@electrochem.org
<http://www.electrochem.org/meetings/196/symp.html>

46th National American Vacuum Society (AVS) Symposium

October 25-29
Seattle, Washington
<http://www.vacuum.org>

November

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

November 1-5
Kyoto, Japan
<http://fujita.kuee.kyotou.ac.jp/26kyoto/>

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

November
London, UK
Contact: Ali Rezazadeh
ali.rezazadeh@kcl.ac.uk

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

November 8-11
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Abstract Deadline: July 2
<http://www.ieee.org/society/leos/>

December

1999 Fall MRS Meeting

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Boston, MA
Abstract Deadline: June 21
<http://www.mrs.org/meetings/fall99/>

1999 IEEE International Electron Devices Meeting (IEDM)

December 5-8
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Abstract Deadline: September 15, 1999
phyllism@widerkehr.com

2000

Photonics West

January 23-28
San Jose, CA
Abstract Deadline: June 28, 1999
<http://www.spie.org>

Optical Fiber Conference

March 7-12
Baltimore, MD
Abstract Deadline: September 8, 1999
<http://www.osa.org>

GaAs Manufacturing Technology (GaAs MAN-TECH)

May 1-4
Washington, DC
<http://www.gaasmantech.org>

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>

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

June 5-9
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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.*

Join our team of bright and enterprising employees, and help propel Lasertron into the next century as a world leader in the manufacture of optoelectronic components for fiber-optic communications. Lasertron offers a dynamic, stimulating, and rewarding work environment for talented and energetic individuals with innovative ideas and the drive to succeed in a rapidly advancing industry.

MBE Engineer

Join a high visibility team responsible for the growth and characterization of advance quantum well structures for high-power semiconductor laser diode products in a fast paced manufacturing and development environment. Assist with the growth of epitaxial layers by MBE and provide support for the maintenance and upkeep of UHV systems. Requires a BS in Material Science or equivalent, 5 years experience with high vacuum systems, strong computer skills and the ability to work independently. Knowledge of semiconductor characterization and fabrication methods is a plus.

Lasertron is an equal opportunity employer offering a competitive salary and excellent benefits. Please send resume with salary requirements via mail or e-mail to:



Lasertron, Inc.

Human Resources
Job Code RP1958
Lasertron, Inc., 11 Oak Park, Bedford, MA 01730-1440.
FAX (781) 280-3301
E-Mail: QLASER_EMPLOYMENT@QLASER.COM

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Production Effusion Cells for
Multiwafer MBE

High Performance Components To Make the Most of Your MBE System

For over a decade, EPI has led the MBE industry in offering innovative designs and breakthrough technologies specifically to enhance and optimize the performance of new and existing MBE systems. Ongoing development programs continually enhance existing products as well as create new products to meet the increasing demands of the compound semiconductor research and production marketplace.

Since each element has unique evaporation characteristics, EPI designs effusion cells, crackers, and valved crackers that are specifically tailored to optimize the performance of any MBE system. Examples of EPI's technological advancements include:

■ SUMO™

This novel approach to effusion cell design enhances material quality by reducing Ga related oval defects while increasing useful capacity which allows users to maximize system up-time.

■ UNI-Bulb™

The leak-free, one-piece PBN bulb, in conjunction with the water-cooled coaxial RF coil, provides the most efficient RF source for nitrogen available today. Previous problems associated with low GaN growth rates in MBE have been addressed with demonstrated results of 1.0 $\mu\text{m/hr}$.

■ Valved Crackers

Installed in the most reputable universities, research labs, and production epi facilities worldwide and are considered to be the industry standard. Valved crackers are utilized by users who need precise group V control in the demanding area of GaInAsP quaternary growth. In addition, users benefit from the ease of calibration and large useful capacity.

■ Corrosive Series Valved Cracker

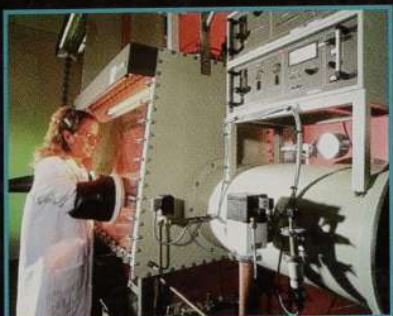
Specifically designed for corrosive elements such as antimony and tellurium. The novel PBN crucible and valve mechanism has proven to provide the capabilities to grow complex structures not previously possible with conventional sources.

Please contact EPI to discuss your growth and deposition needs or visit EPI's web site at www.epimbe.com.

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