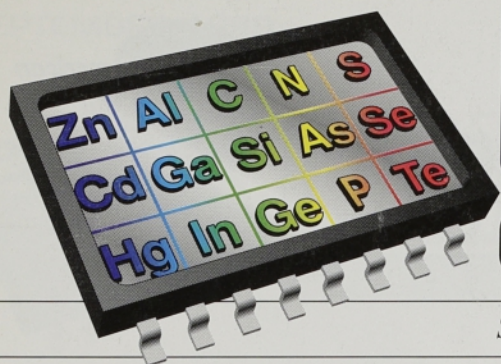




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SEMICONDUCTOR

September 1999

Volume 5 Number 7

Fourth Annual

Epitaxy Issue

- Nitride Growth by MBE
- TBAs and TBP: Alternative Precursors for MOVPE
- Control of Epitaxy for HBT Manufacturing

Also in this Issue:

CL Studies of Nitrides

QWIPs at Sanders

Profile of SDL

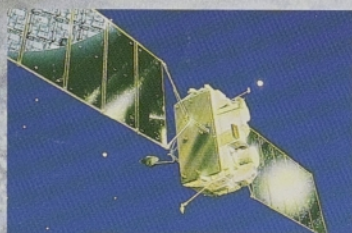
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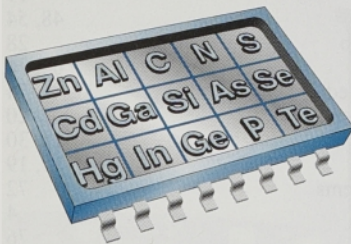
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29 TBAs and TBP - Improved Group V Sources for MOVPE

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36 Characterization and Control of Epitaxial Material for HBT Manufacturing

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48 Technology Update - Sanders' QWIPs Detect Two Colors At Once

Sanders has developed advanced quantum well infrared photodetectors capable of detecting two wavelengths simultaneously.

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SDL, known for its expertise in high power laser diodes, now generates 72% of its revenues from the optical communications market.

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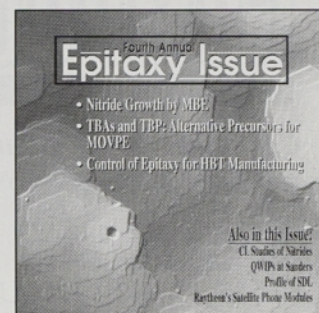
Bob Metzger discusses an impressive CMOS power amplifier. Plus, Si nanocrystal LEDs.

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Great news for investors in JDS Uniphase and SDL.



The cover photo shows an AFM micrograph of a GaN surface grown on 6H-SiC by MBE. For more on this work, see our article on the growth of nitrides by MBE, which begins on page 20. Photo courtesy of Andreas Thamm of the Paul-Drude-Institute for Solid State Electronics, Berlin.

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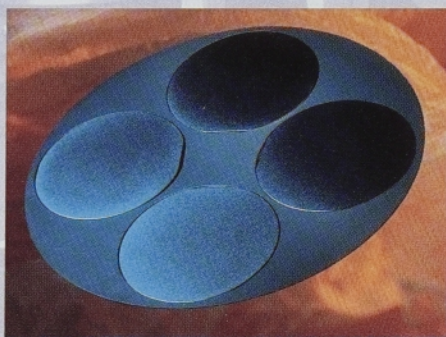
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HP Becomes Agilent

Hewlett-Packard has announced that its new, diversified technology subsidiary, which will contain HP's compound semiconductor manufacturing activities, is to be named Agilent Technologies. Headquartered in Palo Alto, CA, Agilent has 43,000 employees in more than 40 countries and will consist of HP's measurement and components businesses, including the electronic components group. These businesses contributed \$7.6 billion to HP's total 1998 revenues of \$47.1 billion. HP's computer and imaging businesses will retain the Hewlett-Packard Company name.

A registration statement has been filed with the Securities and Exchange Commission (SEC) in August for the initial public offering of Agilent common stock.

Agilent is the largest supplier of compound semiconductor devices in the world, with estimated sales around the \$1 billion mark in 1999. The new company is also the world's largest manufacturer of visible LEDs, the leading high brightness AlGaInP-based LED manufacturer, and a major supplier of nitride-based LEDs. In addition, the electronic components group designs and manufactures microwave and RF integrated circuits, LED lamps and displays, optical isolators and other opto-electronic components.

Agilent will also include the test and measurement business unit, which manufactures test equipment for semiconductors and

electronic printed-circuit boards, infrastructure for communications networks, and test and measurement equipment for the electronics industry.

Neon Replacement Lighting System Attracts HP

HP has announced its intent to acquire the rights to a lighting system that replaces neon with LEDs for decorative applications. The technology will eventually become part of the LumiLeds Lighting joint venture between HP and Royal Philips Electronics.

HP intends to license intellectual property, products and manufacturing rights to the system from an Australian company, Showers International. The neon replacement uses LEDs mounted on a linear assembly, which is sealed in a transparent or translucent extruded polycarbonate pipe. The illuminated pipes can be straight or curved, and together with other fittings the assembly can be built to follow the contours of windows, doors, roofs and other architectural features (see photo).

As replacements for neon lighting and other types of incandescent or fluorescent strip lights, LEDs offer low voltage operation which eliminates the special wiring, conduits and weather sealing required for high voltage tubes or lamps. Additionally, the polycarbonate structure is extremely robust unlike brittle glass tubing used in both neon and fluorescent lamps. LEDs are significantly more energy efficient than incandescent lamps and offer much longer lifetimes.

Existing installations manufactured by Showers International, which have used HP's LEDs, have been in operation for as long as 18 months in some cases, without the need for maintenance. An HP source described the move as part of a commitment to develop innovative new products and technologies for solid-state light sources, for applications such as architectural lighting, illuminated signs and, ultimately, area lighting. "LEDs are already replacing incandescent bulbs in automotive exterior lighting, traffic signals and a number of other specialized applications requiring reliability, efficiency and design flexibility," said the spokesperson.



HP plans to license an LED-based lighting system which could replace neon tubes for a variety of decorative applications

Tunable Lasers

An article on tunable lasers in our last issue [CS 5(6), p. 30] mistakenly attributed the manufacture of tunable near-IR diodes for the Mars Polar Lander to SpectraSensors. In fact, the lasers were developed and manufactured by NASA's Jet Propulsion Laboratory (JPL). SpectraSensors was established last year to commercialize JPL's technology in this area.

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Lucent's Optoelectronics Unit Expands Again

To accommodate the spiraling growth of the telecommunications components sector, Lucent Technologies has announced a \$30 million expansion of its Optoelectronics Division manufacturing capabilities. This expansion, the third in three years, includes a new plant with 125,000 sq. ft. of manufacturing space for the assembly and test of laser components, using Lucent's Laser 2000 assembly technology [see CS 4(7) p.16]. The new plant will be adjacent to, and nearly five times larger than, the existing optoelectronics facility at Breinigsville, PA (see photo). A further 18,000 sq. ft. will be devoted to offices and development laboratories.

Jim Dormer, Manager of Lucent's Manufacturing Realization Center (MRC), says the expansion reflects the continuing phenomenal growth of the optoelectronics industry as Internet providers search for increased communication speed and bandwidth, driving growth rates of 30% per year. "We plan to move our existing facility and newly acquired equipment into the new building in order to grow our capability to meet on-going demand," says Dormer.

The MRC was originally opened in 1997 as a 20,000 sq. ft. facility for automated assembly, test and packaging of optoelectronics components. The principal products are digital and analog cooled laser modules, particularly electroabsorptive modulated lasers (EML) and distributed feedback (DFB) lasers, for use in telecommunications, cable TV and data communications markets. The facility also produces optical sub-assemblies for use in Lucent's FastLight range of uncooled lasers. These are used in applications such as fiber-to-the-home (FTTH) or fiber-to-the-curb (FTTC) or where tight wavelength constraints can be relaxed. A forthcoming product is the Phase II Translight transponder, a 2.5 Gbps SONET/SDH-compatible transmitter/receiver integrating up to 15 discrete ICs and optoelectronic components, slated for high-volume manufacturing by mid-2000.

The original building, which received an upgrade of 10,000 sq. ft. in 1998, will be used for fiber amplifier manufacturing, and will be known as the Fiber Amplifier Center of Excellence. "Our fiber amplifier business is growing at a tremendous rate," says Dormer. "This group will be moving into the original site to accommodate their expansion."

In a concurrent project at its nearby Reading facility, Lucent will invest \$6 million to accommodate the production of next-generation PIN photodetectors and other products. The optoelectronics business occupies about 25% of the Reading site, which also houses the majority of Lucent's IC division. Most of the Lucent's optoelectronics R&D is done at Breinigsville, with other work at Bell Laboratories in Murray Hill, NJ.



Simulated view of Lucent's manufacturing site in Breinigsville, PA, showing the location of the new 125,000 sq. ft. facility for laser manufacturing.

VCSELs Used for 10 Gbps Serial Transmission Demo Over Multimode Fiber

Corning and W.L. Gore & Associates recently demonstrated serial transmission at 10 Gbps over a distance of 600 meters of multimode fiber. The test system used 850 nm VCSELs supplied by Gore, in combination with Corning's specially developed 50 μ m InfiniCor fiber.

"Bandwidth demand in local area networks [LANs] has exploded in the last few years," says Windsor Thomas, Corning's premises product line manager. "After adopting standards for gigabit transmission, the industry is now working on standards for 10 Gbps transmission. We expect this 10 Gbps solution to be very attractive economically, since it will utilize 50 μ m multimode fiber and relatively low cost 850 nm wavelength lasers, i.e. VCSELs."

"The test demonstrates that VCSELs and multimode fiber will be a solution at 10 Gbps for typical LAN distances," said Frank Peters, lead research scientist at W.L. Gore. "Gore is focused on developing technologies that deliver the lowest overall cost solution for high-data-rate transmission. There is more work to be done prior to commercialization, but this demonstration is certainly an important milestone."

In a related announcement, Corning has demonstrated transmission over a distance of 3000 m at Gigabit Ethernet speeds in the 850 nm window, using InfiniCor multimode fiber.

Meanwhile, Gore has said that it will soon be introducing the nLIGHTEN line of multi-channel parallel optic modules, featuring arrays of 850 nm VCSELs. The modules are designed for high bandwidth, short-distance data transmission, supporting data rates of more than 15 Gbps at distances of up to 300 meters along multimode fiber. Gore has an agreement with Infineon Technologies to supply interchangeable parallel optic communication modules - Infineon's products are marketed as PAROLI [see CS 5(3), p. 18].

Birdwatching

A round-up of recent satellite news

News has been mixed for several of the existing and proposed satellite "constellations". Despite the dismal failure of Iridium to attract customers, it appears that its direct competitor, Globalstar, has much better prospects. Of course, most - possibly all - of the RF components and solar cells used to manufacture the Iridium and Globalstar "birds" have already been built and shipped.

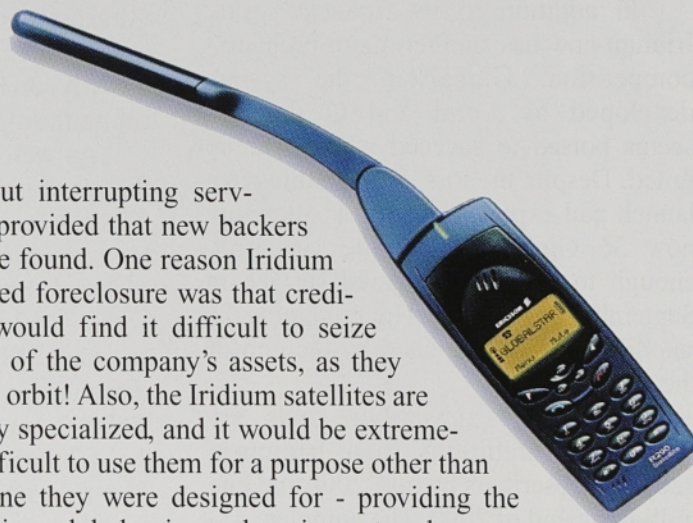
Of more interest are the future prospects for the broadband systems, including Lockheed Martin's Astrolink, Hughes' Spaceway, and Teledesic. At present, it seems that Alcatel's Skybridge system including 80 low Earth orbit satellites is on hold until regulatory approval is received.

Iridium

Iridium, the 66-satellite global voice and paging network that began service just over a year ago, filed for voluntary Chapter 11 bankruptcy protection in August after defaulting on loan payments. The move allows Iridium to try to restructure

without interrupting service - provided that new backers can be found. One reason Iridium avoided foreclosure was that creditors would find it difficult to seize many of the company's assets, as they are in orbit! Also, the Iridium satellites are highly specialized, and it would be extremely difficult to use them for a purpose other than the one they were designed for - providing the links in a global voice and paging network.

Analysts suggest that the number of Iridium subscribers is somewhere around 15,000, which is far below the target - the company originally hoped to have 500,000 subscribers by the end of 1999. Many of the system's problems stem from the price of user equipment and call rates, even though Iridium cut the suggested retail price of phones in July to "only" \$1,495, and reduced service costs by up to 65%.



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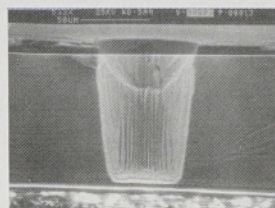
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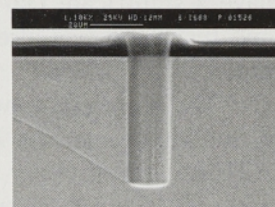
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Globalstar

In addition to its financial woes, Iridium now has another major problem - competition. Globalstar, the system developed by Loral and Qualcomm, seems poised to succeed where Iridium failed. Despite the loss of 8 satellites in a launch pad explosion last year, there are now 36 Globalstar satellites in orbit, enough to begin commercial service in September or October. The remaining 16 satellites will be launched by the end of the year.

Globalstar's subscriber goals are even more ambitious than Iridium's: 220,000 subscribers by mid-2000 and one million by end of 2000. The complete 48-satellite system will have a capacity for 7.5 million subscribers. However, there doesn't appear to be a shortage of potential subscribers; rather they are waiting for a reliable, low cost network. While Iridium has been criticized in hindsight for being "over-engineered" and "gold-plated" (although not literally), the Globalstar system is simpler and leaner. A bent pipe configuration is used to deflect the signal from the user to the nearest

ground station, while Iridium has RF links between all its satellites. Also, Globalstar is more closely integrated with terrestrial networks, and the use of CDMA technology could tie in with future third-generation (3G) systems.

As well as offering higher data rates than Iridium (7.2 kbps against 2.4 kbps), Globalstar service is likely to be much less expensive. Mobile handsets, manufactured by Qualcomm, Ericsson and Telital, are likely to sell for an initial price of around \$1,200, and are about half the size and weight of those for Iridium. Over 300,000 handsets have been ordered for the Globalstar CDMA-based network. The Ericsson R290 handset, which has already been launched (see photo, previous page), supports both GSM 900 for terrestrial networks and the Globalstar system when GSM 900 services are not available. Telital's handset is also dual-mode GSM/Globalstar, and Qualcomm is to launch a tri-mode phone offering Globalstar CDMA service together with the terrestrial CDMA and AMPS formats.

TRW Gets Payload Contract for Astrolink

TRW has received a contract to supply advanced digital satellite payloads for Astrolink, a \$3.6 billion broadband satellite system conceived by Lockheed Martin. The contract calls for TRW to design, build and provide engineering services for four satellite payloads, consisting of advanced electronics equipment, including antennas, digital processors and routers, which TRW will supply to Lockheed Martin. A spokesperson for TRW confirmed that the RF payloads will have a significant GaAs MMIC content, and that work has already begun on the project.

The Astrolink network will eventually contain as many as 9 Lockheed Martin A2100 geostationary (GEO) satellites with 12-15 year lifespan. The payload, based around Ku-band transmission, is a 4th generation system developed by TRW for Milstar. Each satellite will have a total data capacity of ~6.5 Gbps. Around 30-50 gateway Earth stations will allow customers to connect with the Astrolink system at data rates up to 110 Mbps.

"This agreement is a key element of TRW's strategy to apply our advanced payload designs to the emerging, commercial broadband satellite communications market," said Timothy Hannemann, executive VP and general manager of the TRW Space & Electronics Group. "This new market opportunity is projected to represent approximately \$300 million annually in sales for TRW over the next several years and continued sales growth thereafter."

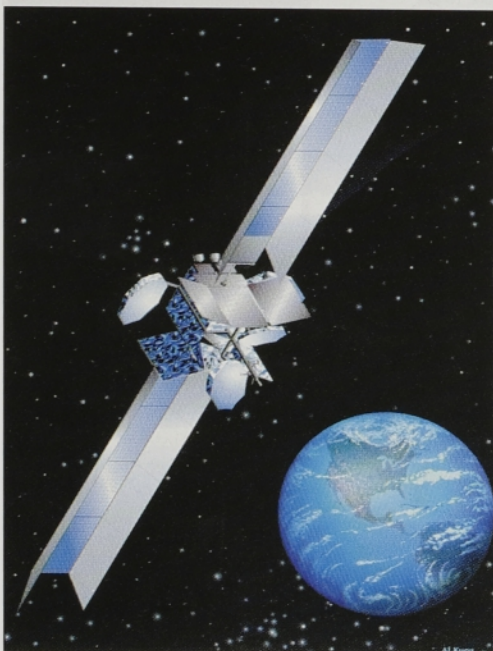
Spaceway

Hughes Electronics has invested \$1.4 billion in its own Spaceway network, which is scheduled to begin operation in North America in 2002. Spaceway will provide high bandwidth, high speed communications for broadband and multimedia applications, at uplink rates of between 16 kbps and 6 Mbps, using Ka-band transmission. The initial system will consist of two Hughes-built HS 702 geostationary (GEO) satellites (see photo), plus an in-orbit spare. User terminals with 26-inch diameter antennas will provide access to next-generation DirecPC broadband Internet services.

Teledesic

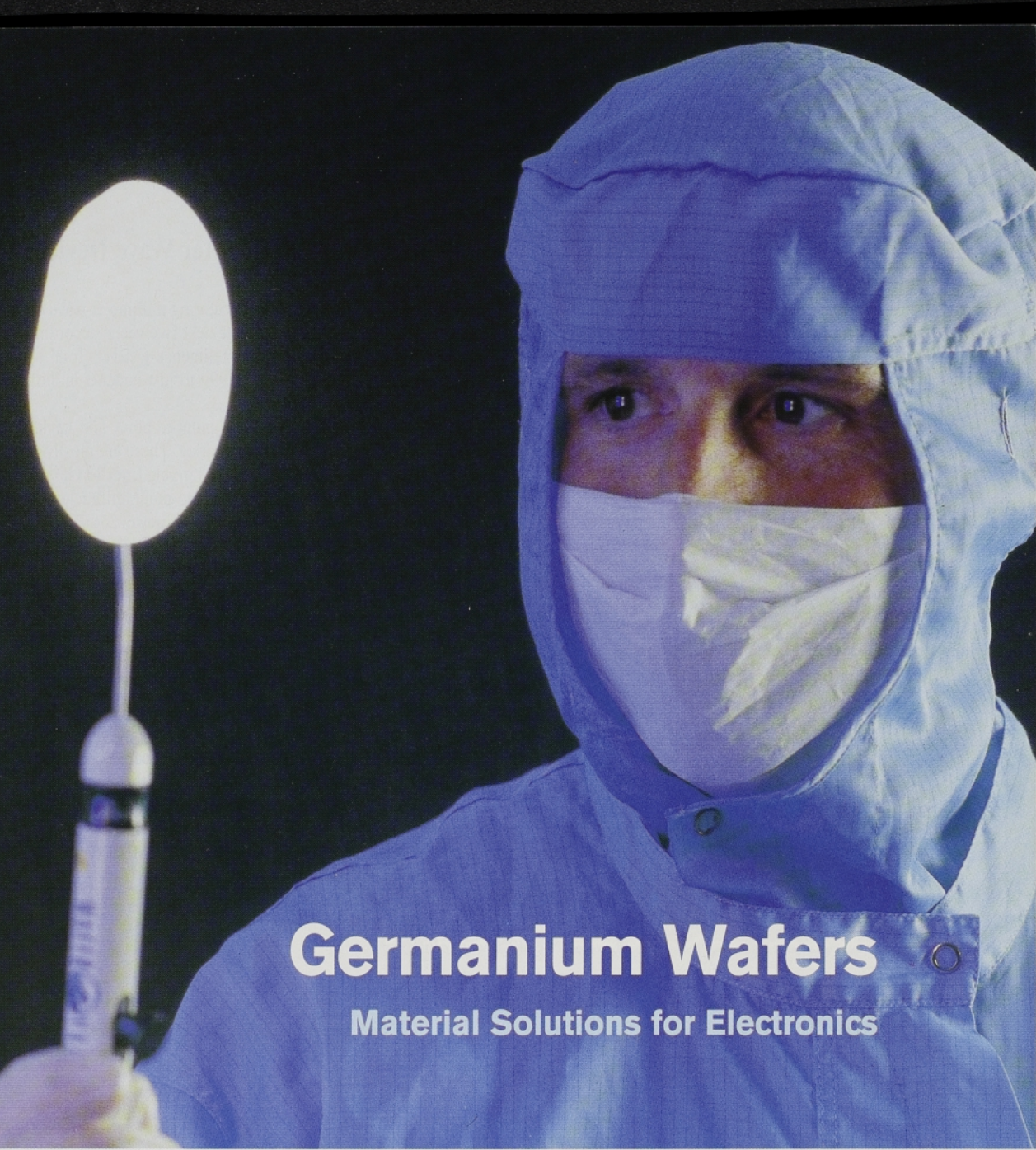
Teledesic LLC recently announced two milestones in its bid to create a broadband "Internet-in-the-Sky" system using a network of 288 low Earth orbit (LEO) satellites. The company has signed a major launch contract with Lockheed Martin that will put a significant proportion of the Teledesic spacecraft into orbit, and has also signed a system agreement with Motorola, the prime contractor for building the birds.

Teledesic is expected to take about 3 months to approve Motorola's enhanced system design plans, and the two companies will then finalize the program's list of major subcontractors. With somewhere around 300 satellites to be built, including spares, the Teledesic project is of intense interest to manufacturers of solar cells and microwave components. Privately held Teledesic has raised more than \$1.5 billion to get its network off the ground, from founders Craig McCaw and Bill Gates, as well as Motorola, a Saudi prince and Boeing.



The Hughes HS 702 satellite carries 118 high-power transponders, and is powered by multi-junction GaInP/GaAs/Ge solar cell arrays manufactured by Spectrolab, a Hughes subsidiary. The arrays provide up to 15 kW of power at end-of-life. The satellite weighs up to 5,200 kg and is 40.9 m in length.

Hughes

A person wearing a white cleanroom suit, hood, and face mask is holding a large, oval-shaped wafer. The background is dark.

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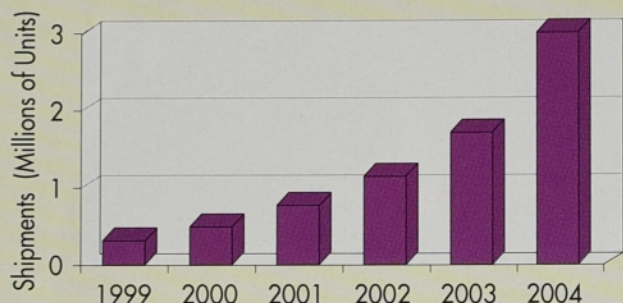
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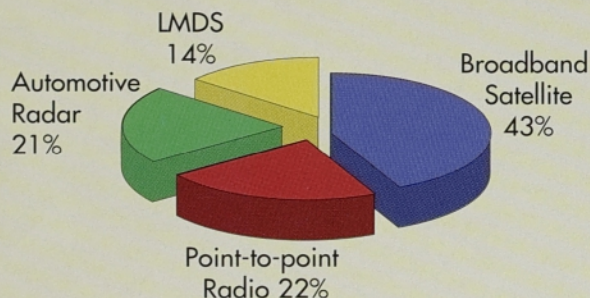
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Shipments of Millimeter-Wave End-User Equipment



ABI

Uses of Millimeter-Wave Equipment in 2004



ABI

Strong Growth for Millimeter Wave Devices

The market for end-user equipment featuring millimeter-wave components is set to grow ten-fold in the next five years, according to a new study by Allied Business Intelligence (ABI).^{*} Total shipments will grow from 314,000 units in 1999 to just under 3 million in 2004 (see graph).

At present, shipments for traditional point-to-point and backhaul applications account for over 90% of the market. These are mostly used for cellular and PCS networks, at frequencies ranging from 13 GHz to 60 GHz. ABI estimates that less than 5% of point-to-point millimeter radios shipped in 1999 will provide access to end-users, however this figure is expected to increase rapidly as more networks are built.

As shown in the chart, the largest application for millimeter-wave equipment in 2004 will be for end-user equipment to access broadband satellite services provided by systems such as Astrolink, Spaceway and Teledesic [see page 7]. The LMDS market (24, 28, 38 and 42 GHz) is also expected to grow rapidly, although many systems are likely to be point-to-point, with multiple users sharing access to a single high frequency antenna.

Automotive radar systems at 24 GHz and 77 GHz have enjoyed success on heavy goods vehicles and have recently appeared on Mercedes-Benz cars. These systems should account for 21% of the market in 2004.

The study also predicts that shipments of millimeter-wave semiconductors will be valued at \$28.1 million in 1999, with "brisk growth" expected in the oncoming years. Shipments for LMDS alone should account for around 19% of the market in 1999.

^{*} "Millimeter Wave '99" is available from ABI. TEL [1] 516 624 3113, WEB www.alliedworld.com.

Over 1 Million Cable Modems in North America

More than 1 million households in North America now have cable modem service, says Kinetic Strategies of Phoenix, AZ, and the number is expected to reach 1.6 million by the end of the year. Cable modems provide Internet and communications services by linking computers to broadband cable lines - the same lines used in many households to carry cable TV signals. A typical monthly cost for cable modem service is \$39.95, including the fee for renting the cable modem, which compares favorably with the cost of Internet access and a separate phone line for online use.

Separately, the Strategis Group (Washington, DC) predicts that there will be over 8 million cable modem subscribers by 2003. This figure will far exceed the number of users of digital subscriber line (DSL) services. Both cable modem and DSL will offer stiff competition to emerging millimeter-wave technologies, such as LMDS and broadband satellite services. Furthermore, the same report estimates that almost 11 million users will subscribe to cable telephone services by 2005.

CDMA Leads Handset Sales in US

CDMA has overtaken TDMA as the leading digital mobile phone technology in the US, according to Dataquest. In the first quarter of 1999, 3.2 million CDMA handsets were sold, compared to 2.8 million units for TDMA. "We expect CDMA to maintain its momentum and actually increase the distance between itself and competing standards in the US marketplace," says Dataquest's Matt Hoffman. As shown below, Nokia currently dominates digital handset sales in the US.

Company	Q1 '99 Market Share
Nokia	32.4
Qualcomm	14.8
Ericsson	12.7
Motorola	11.2
Audiovox	7.4

US Digital Handset Sales. Source: Dataquest.

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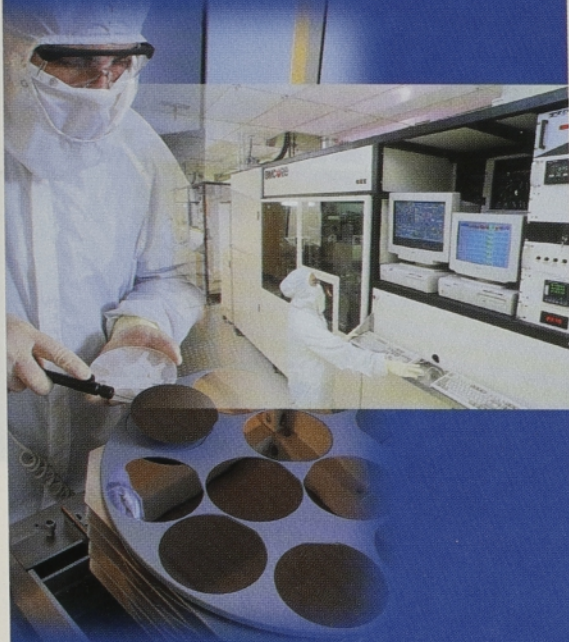
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NITRIDE NEWS

Europe's First InGaN Blue Laser

A research team led by Osram Opto Semiconductors (Regensburg, Germany) has reported the first demonstration of an InGaN-based laser in Europe. Other participants in the project sponsored by the German government were the Fraunhofer Institute for Applied Solid-State Physics in Freiburg, the Universities of Stuttgart, Braunschweig and Ulm, and Infineon Technologies.

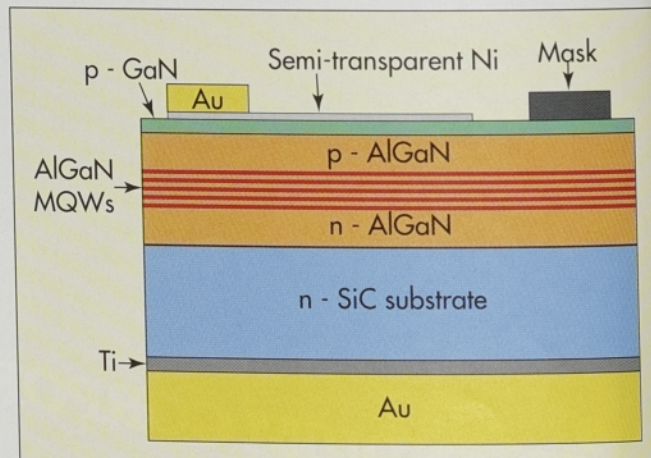
The laser structure was grown on a SiC substrate, and exhibited pulsed laser emission at room temperature. The threshold current density was below 20 kA/cm² and the turn-on voltage was 25 V. Emission was at 420 nm.

NTT Reports 346 nm Emission from AlGaN LED

GaN-based devices with emission wavelengths below the bandgap wavelength of GaN (~360 nm) are desired for applications such as chemical analysis and future high-density optical storage. UV LEDs are also required for next-generation white LEDs [see CS 5(4), p. 28]. AlGaN has a shorter bandgap wavelength than GaN, but usually shows poor optical quality, so that GaN/AlGaN quantum well heterostructures have been investigated. These structures have a high piezoelectric strain due to the large lattice mismatch, resulting in deterioration of the emission efficiency due to the spatially induced indirect transition.

Recent work by T. Nishida and colleagues from NTT's Basic Research Laboratories* has focused on the growth of strain-reduced quantum well structures grown by MOVPE on 6H-SiC substrates. Reduction of strain between wells and barriers was achieved by increasing the Al content of the well layers. The LED structure (see figure) commenced with 400 nm Si-doped Al_{0.12}Ga_{0.88}N grown directly onto SiC. The active MQW region consists of 5 repetitions of 2 nm Al_{0.08}Ga_{0.92}N wells and 2 nm Al_{0.12}Ga_{0.88}N barriers. This was followed by 400 nm Mg-doped Al_{0.12}Ga_{0.88}N, and a 10 nm p-GaN contact layer. A 15 nm semi-transparent Ni layer and gold contact were used for the p-electrode, with Ti/Au on the backside of the SiC substrate as the n-electrode.

The emission wavelength of the device was 346 nm, and the FWHM of the emission peak was 5 nm. The emission holds the same wavelength with the injection current less than 800 A/cm². A leakage current of 8 mA/cm² was observed at a reverse bias voltage of -10 V, and the forward voltage at 40 mA/cm² was 3.5 V. The emission wavelength is the shortest ever reported for nitride-based LEDs.



Structure of the 346 nm LED. The active MQW region consists of 5 repetitions of 2 nm Al_{0.08}Ga_{0.92}N wells and 2 nm Al_{0.12}Ga_{0.88}N barriers, designed to reduce piezoelectric effects. The window area is 4×10^{-5} cm².

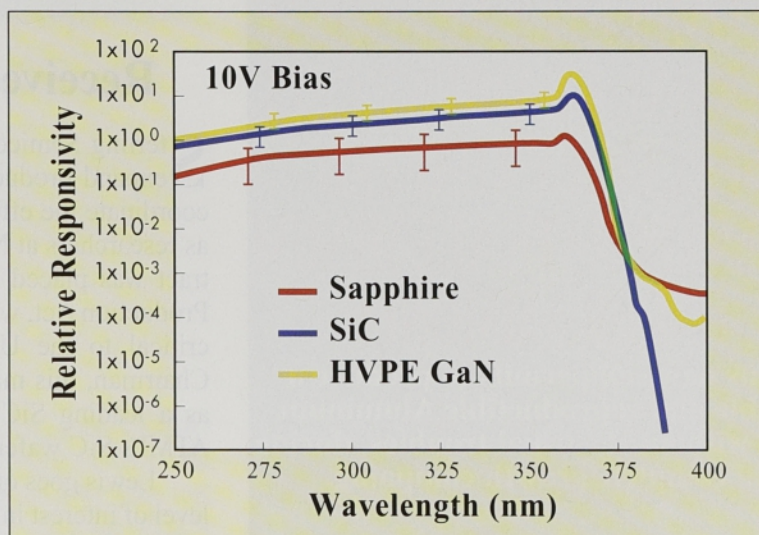
*T. Nishida and N. Kobayashi, Proc. IC Nitride Semiconductors, Montpellier, 1999, p. 90

Substrate Effects on GaN Photodetector Performance

GaN photoconductive devices are highly suited as UV photodetectors for applications such as missile detection, flame sensing and solar UV monitoring. A recent paper from ATMI described the effects on device performance of GaN detectors grown on different substrates, namely sapphire, 6H-SiC and GaN-on-sapphire grown by HVPE. Crystal quality can be significantly affected by the choice of substrate for nitride growth, causing variations in x-ray diffraction peak width and dislocation density in the epilayer.

Detectors were fabricated from GaN layers grown by MOVPE at 1100°C on the various substrates. Different nucleation procedures and GaN layer thicknesses were used with each substrate, to minimize the dislocation density and surface roughness of the GaN epilayer. The detector structure consisted of 5 µm wide interdigitated Ti/Al electrodes separated by 20 µm, with a 1 mm square active area. The relative responsivity of each detector as a function of wavelength is shown in the figure at right.

The magnitude of the responsivity and the sharpness of the wavelength cut-off vary considerably for detectors grown on different substrates. The magnitude of the response from the detectors grown on SiC and GaN-on-sapphire is 4.6 times and 7.8 times larger respectively than that of the devices grown on sapphire. The detectors grown on sapphire also have a much less sharp wavelength cut-off.



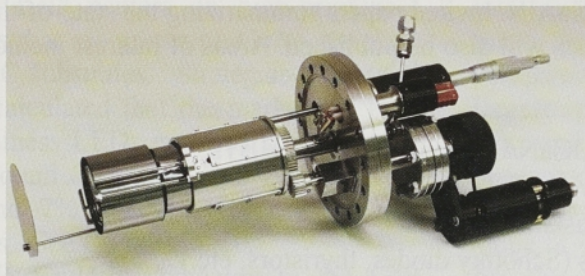
Average relative responsivity for photoconductive GaN detectors on each of the three substrates.

The device results correlate with material properties; material grown on sapphire had broader x-ray diffraction peak widths, rougher surfaces and higher dislocation densities than material grown on the other substrates. The authors postulate that the increase in responsivity for detectors fabricated from lower dislocation density material may be due to an increase in the carrier lifetime.

* G. M. Smith et al, *Appl. Phys. Lett.*, 1999, 75(1), p. 25

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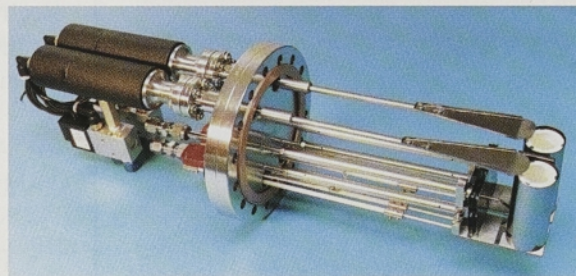
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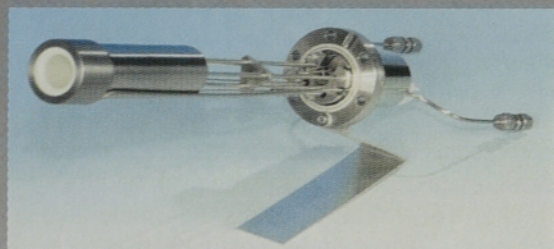
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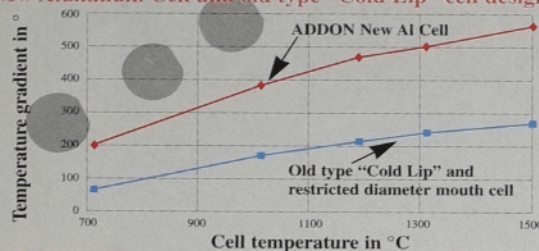
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Sterling Semiconductor Receives \$3 million Title III Contract Award

Sterling Semiconductor (Sterling, VA) has received a contract worth \$3 million to expand production capacity of SiC substrates. As prime contractor, Sterling will coordinate the efforts of subcontractors including ATMI and General Electric, as well as researchers at New York State University and Carnegie Mellon University. The contract was placed by the US Department of Defense under Title III of the Defense Production Act, which aims to maintain domestic production capacity for items that are critical to the US defense industrial base. According to Gene Lewis, Sterling's Chairman, this marks a major milestone for the company. "We have been recognized as a leading SiC substrate supplier," he says. Founded in 1996, Sterling acquired ATMI's SiC wafer operation in 1998.

Lewis goes on to describe how Sterling plans to take advantage of the current high level of interest in the SiC field. "SiC-based semiconductors are expected to enable significant new applications in power electronics and high frequency communications, in addition to the current immense contribution to blue optoelectronics," says Lewis. "From a strong base in substrate manufacturing, we plan to develop application-driven partnerships to promote the expansion of the market." Sterling intends to focus on three major tasks throughout the course of the program, namely growth of larger diameter wafers, cost reduction, and improvement of wafer quality.

IEEE Issues Call for Papers on InGaN-Based Devices

The IEEE has issued a call for papers on InGaAlN-based devices for inclusion in a special issue of the IEEE Transactions on Electron Devices. The issue is to document the rapid progress being made in InGaAlN based electronic devices, and to examine the future potential of these materials.

While wide bandgap semiconductors have been considered ideal for high power, high temperature, and high frequency electronics, the material quality was insufficient until recently to demonstrate significant performance. This has now changed with the drive, largely due to opto-electronic applications, for improved materials. The special issue will include both invited and contributed papers on electronic applications of InGaAlN. Invited papers summarizing the state-of-the-art of competitive technologies will also be published. Areas of interest include, but are not limited to:

- AlGaIn/GaN HEMTs, AlGaIn/GaN and GaN/SiC HBTs
- III-Nitride MESFETs, MOSFETs, JFETs, etc.
- Negative differential resistance devices
- Power switching devices (Schottky diodes, thyristors, etc.)
- Substrate dependent device optimization
- Polarization effects and device impacts
- Thermal management, noise performance
- Device relevant materials issues
- Carrier Transport, theory and modeling
- Sensors (UV, piezoelectric, pyro-electric, etc.)
- Radiation and elevated temperature device performance
- State-of-the-art of competitive technologies (authors to be invited by editors)

The submission deadline is April 1, 2000
with publication scheduled for March 2001.

Shipments of GaAs & InP Up, GaP Down in Japan

Shipments of GaP wafers in Japan are declining, while shipments of GaAs and InP wafers are increasing, according to recently released statistics. The data was compiled by the Japan Manufacturers' Society of Compound Semiconductor Materials (JAMS-CS), which conducts a twice-yearly survey of shipments of III-V wafers from Japanese suppliers. After posting excellent growth in fiscal year 1997, total sales by Japanese wafer companies declined 3% in fiscal 1998, to ¥ 45.2 billion (US\$ 397 million).

The decrease was due entirely to a downturn in demand for GaP wafers, which declined more than 25% between fiscal 1997 and fiscal 1998. GaP is used almost exclusively in the production of LEDs. Given that the LED business is booming, this downturn may seem surprising. However, GaP-based LEDs are usually low-to-medium brightness devices. Most of the excitement in the LED field centers on high-brightness LEDs that are grown on GaAs, sapphire or SiC substrates. Strategies Unlimited has calculated that the market for high brightness LEDs is growing at around 20% per year, compared to around 7% per year for conventional LEDs. See CS 5(3), p. 10.

Particularly damaging to the GaP market has been a steep decline in the use of green GaP-based LEDs in cell phones, where they were formerly used for dot matrix displays and back lights. Also, the JAMS-CS figures are based on the value of shipments, not quantities of wafers. Therefore, it seems like that price erosion is at least partially to blame, given that the GaP-based LED market is very mature. But the fact that

the center of gravity for the world's LED industry seems to be shifting from Japan to Taiwan (see CS 5(4), p. 24) does not appear to be a factor. The JAMS-CS members point out that a very large majority of the world's GaP wafers are produced in Japan, and therefore the Taiwanese LED manufacturers are expected to continue buying their GaP wafers from Japanese suppliers.

In contrast to the GaP situation, JAMS-CS members reported that shipments of GaAs were up 11% and shipments of InP were up 11.5% between fiscal 1997 and fiscal 1998. The figures do not distinguish between sales of semi-insulating and semi-conducting materials. However, JAMS-CS does provide a breakdown by device type. For fiscal 1998 visible LEDs were the largest application category, accounting for 49% of the total value, but their total value was down 14% compared to fiscal 1997. IR LEDs accounted for an additional 9% of total shipments, and the value for shipments for this application increased 2% compared to the previous year. The next largest application area after LEDs was ICs and discrete transistors, which accounted for 23% of the total shipments, and which saw an increase in value of 9%. The biggest increase came for the field of laser diodes, which accounted for 12% of the total and which saw an increase in total value of 13%.

Domestic shipments accounted for 63% of the total wafer shipments.

The nine members of the JAMS-CS are: Dowa Mining, Furukawa Electric, Hitachi Cable, Japan Energy, Mitsubishi Chemical, Shin-Etsu Handotai, Showa Denko, Sumitomo Electric Industries, and Sumitomo Metal Mining.

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Optoelectronics News

Mitsubishi Chemical says it will double optoelectronic product sales to more than 30 billion yen (\$245.9 million) over the next few years. The company will focus on its laser diode business. The company has already developed a high-output excitation pump laser for use in erbium doped fiber amplifiers. The laser diode can generate 80-90 mW and is ready for volume shipments. Plans call for commercializing a new pump laser with an output of more than 100 mW by spring 2000. This fall, the company will also begin to manufacture commercial quantities of 650 nm lasers for DVD and CD players.

Seven companies have established the **POF Consortium** that will try to establish a standard for plastic optical fiber (POF) interfaces for use in next-generation digital home appliances. The members are Matsushita Electric, Sony, Hitachi Cable, Toshiba, SMK, Nippon Morex, and Daiko Electric. Capable of carrying more data than copper wires and lighter and cheaper than conventional optical fiber, POF is expected to be widely used in homes. However, the current standard POF interface, which was designed to accommodate ATM (asynchronous transfer mode) standards, measures 20 x 22 x 8.5 mm, and is considered to be too large for home use. The consortium is aiming to reduce the connector to less than half in size, and hopes to entice more companies to join their effort.



Intelligent Epitaxy Technology, Inc.

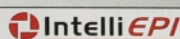
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Fujitsu Laboratories recently announced a room temperature CW quantum dot semiconductor laser operating at 1.3 μm . MBE was used to grow InP/InGaAs quantum dots on a GaAs substrate. A key feature of the process was to reduce the amount of time required to form the quantum dot layer, which resulted in increased dot density, although the dot size was reduced slightly. Fujitsu claims that the laser oscillated at a threshold current of 8 mA, a fraction of the previous record held by the University of Texas.

Hamamatsu Photonics has developed a technique to manufacture IV-VI quantum well IR lasers operating at 3-5 microns. The lead sulfide-based structure has a maximized energy gap between the clad layer and the active layer, and a 3-micron laser was oscillated at 1 KHz at -73°C . With a peak output of more than 1 mW, the lifetime was more than 5,000 hours. The company carried out a 550 million yen (\$4.5 million) development project on this topic between fiscal 1994 and 1998 (supported in part by the Japan Science and Technology Corporation).

Nitride News

Kagoshima Matsushita Electronics and Toyoda Gosei have teamed up to offer high brightness flip-chip blue and green LEDs. Conventional GaN/InGaN structures on sapphire emit light through a transparent electrode on the chip surface. Matsushita says that about half the light is lost in transmission through the electrode. The new structure uses a facedown construction where-in light is emitted through the sapphire substrate. The new devices are said to be twice as bright as conventional devices as equivalent power levels. Moreover, the submount chip - which supports the facedown LED chip - is a Zener diode or a constant voltage diode that provides around 30x higher protection against static electricity or surges. This simplifies the process of installing the LEDs into displays, appliances and other electronic systems. The viewing angle for the new LEDs is 140 degrees. The lamps are sample-priced at 200 yen (\$1.67), and a 240x240 mm color LED display is sample-priced at 250,000 yen (\$2,083).

Fujitsu Laboratories has demonstrated a room temperature CW InGaN laser on a 4H (hexagonal) SiC substrate. The 404 nm device had a threshold current of 60 mA and a threshold voltage of 8.3 V. In an experiment, the laser generated 1 mW output power and oscillated for 57 hours at 25°C . Fujitsu had previously demonstrated a CW blue laser on a 6H-SiC substrate. However, it is hoped that the use of 4H SiC might lead to lower materials costs and lower electrical resistance.

A new effort has been launched to develop **GaN-based transistors and ICs** for use in next-generation mobile communications equipment. A consortium of public, private and academic institutions recently set up a three-year R&D program. Goals include demonstrating a microwave IC and a heterojunction RF device which will operate on 50 V at 10 GHz and generate 10 W of output power.

The consortium members include the Osaka National Research Institute of the Agency of Industrial Science and Technology (AIST), Ritsumeikan University, Sharp, Matsushita Electric, NEC, and Ion Engineering Research Institute Corporation.

Microelectronics News

Japan's Ministry of Posts and Telecommunications (MPT) is asking the world's regulatory bodies to set aside part of the electromagnetic spectrum for an interesting project. Known as the "Stratosphere Platform Project" it consists of networks of balloons hovering in stationary patterns 20 km above the earth's surface. They will be used to relay voice and data traffic, much in the same way that satellites do. According to the MPT, a portion of the 47 GHz spectrum that is already allocated to fixed wireless systems will interfere with transmissions to and from the "airship stations". To overcome this problem, the MPT is proposing that a portion of the spectrum be reserved exclusively for this purpose. A study group convened by the MPT has concluded that all of Japan could be covered by as few as 20 balloons.

Mitsubishi Electric has developed three high-output GaAs FETs for use in cellular phone and base station amplifiers. The leadless SMD (surface mount device) structure, on which the FETs are based, helps reduce the footprint by more than 75% compared to conventional FETs. The new devices measure 4.2 x 4.0 x 1.1 mm. They are sample-priced at 1,000-2,000 yen (\$8.40-16.81).

Mitsubishi has also developed an ultra-compact GaAs power amplifier module which operates on 3.2 V. For use in CDMA handsets, the AO1384 is housed in a 7.5 x 7.5 x 1.7 mm package, 56% smaller in size and in footprint than conventional modules. The company began shipping samples in August. The sample price is 2,000 yen (\$16.67). Mitsubishi plans to launch commercial production at 500,000 units per month.

NEC has prototyped a power FET for use in next-generation communica-

tions devices. The device has an embedded voltage control circuit that can adjust voltage levels from 3.5V to 1.0V depending on distance between a mobile unit and a base station. The device uses a heavily-doped AlGaAs active layer which reduces resistance to about $1/4$ the level of conventional microwave amplifiers. The company says that the power FET will allow handsets to remain operational 2-4x longer than those using conventional power FETs.

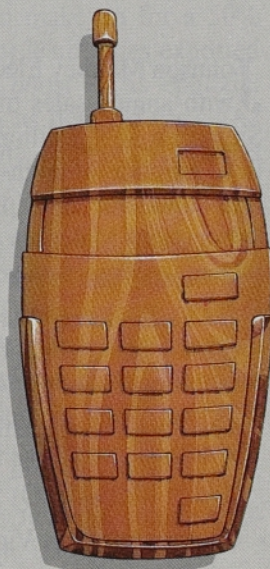
Research News

The Femtosecond Technology Research Association (FESTA) reports that it has successfully integrated all-optical switches on a chip, paving the way for reduction in size of terabit-per-second optical communications systems. Two symmetrical Mach-Zehnder (SMZ) all-optical switches, each measuring 25.0 x 0.5 mm, are created on a 50x50 mm chip carrier on which quartz waveguides and optical fiber fixation V-shaped grooves are integrated using chemical vapor deposition. In the center of the waveguides lies a non-linear waveguide made of InGaAsP. The prototype achieves a switching speed of 670 femtoseconds.

Professor Iga's group of the Tokyo Institute of Technology has prototyped a InP surface-emitting laser with a simplified structure. The prototype has a tunnel junction-based NPN structure with negative electrodes on both sides. The device also incorporates a current bottleneck structure, which is created with a selectively destroyed tunnel junction. The group has already observed pulsed operation at room temperature.

Tottori University has developed a highly sensitive ZnSe optical detector, which outperforms conventional silicon-based detectors by 50-100% in the 0.45-micron band. This performance level will help double the recording capacity of CDs and optical disks, and will be able to detect optical signals that are about $1/10$ the intensity of optical signals detectable with conventional devices.

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Allied Signal Acquires Johnson Matthey Electronics

Johnson Matthey Electronics, a division of Johnson Matthey Plc. with annual sales of \$670 million, has been bought by Allied Signal for \$655 million. JME, headquartered in Eden Prairie, MN is a supplier of high-technology materials and services to the semiconductor and microelectronics industries. JME's Wafer Fabrication Materials Group (WFMG) contains several areas related to compound semiconductors;

- JME's Spokane-based operation is a leading supplier of single crystal materials for infrared and optoelectronic applications, including InSb, GaSb, CdZnTe and HgTe substrates.
- The Spokane operation also produces a wide range of high purity metals, including Cd, Te, Sb, Hg, Sn, Zn, Al, B, Cu, Pb and Ag, as well as B₂O₃ for encapsulants.
- Crystar, based in Victoria, BC (Canada) is a major supplier of sapphire substrates for growth of nitride-based materials and devices.

Dowa Builds New Gallium Plant...

Dowa Semiconductor reports that it has completed construction of a new ultra-pure gallium refining plant and begun shipping samples. Capable of producing 6N (99.9999%) pure gallium, the 1.5 billion yen (\$12.6 million) facility has an annual output capacity of 100 tons, doubling the company's capacity. Commercial production is scheduled to begin in the second half of fiscal 1999. Dowa claims a 40% share of the Japanese market and a 27% share of the global market for gallium.

...and Rhodia Sells Gallium Business

Rhodia, the former chemical unit of Rhone Poulenc, has announced that GEO Specialty Chemicals (Cleveland, OH) will acquire its gallium business. The deal is expected to be completed by early September. The sale encompasses Rhodia's complete gallium business, including the manufacturing facilities in Stade, Germany and Salindres, France. Rhodia is expected to pursue its focus on core specialty chemicals. Its sales from gallium amounted to \$16 million last year.

George Ahern, GEO's CEO said: "The company has sought acquisition opportunities in specialty metal-based markets for some time, and we intend to build around this acquisition and broaden the scope of our activities."

Furukawa to Produce More Arsenic

Furukawa Company has announced plans to expand its capacity to produce high-purity metal arsenic for GaAs production. To meet a projected increase in demand, Furukawa intends to increase its present production capacity of 6.3 tons per month by around 30% to 9 tons per month. It aims to use 60% of this output to supply domestic manufacturers. The company is targeting an increase in annual turnover from the electronic materials business sector from its current level of 7.5 billion yen level to 10 billion yen in the next few years.

Aixtron Builds New Site, Reports Asian Reactor Sales

Aixtron has laid the foundations for a new production plant in Herzogenrath, near its original plant in Aachen, Germany. The new site, occupying 90,000 sq. ft., is for MOCVD reactor assembly. Aixtron plans a ten-fold production capacity increase in the long term.

The company has also announced recent reactor sales in Taiwan and Japan. United Epitaxy Company (Hsinchu, Taiwan) has ordered an AIX 200 planetary reactor with a capacity of 6 x 2-inch wafers, intended for the growth of AlGaInN-based optoelectronic devices. AIX 2400 planetary reactors have been ordered by Seiko Epson (Japan) for the growth of GaAs/GaAlAs, and by Canare Electric, a Japanese company specializing in cables and connectors.

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. If you missed out on that edition, but would like to be included in 1999, please contact us.

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Riber Reports Reactor Sales

Riber recently received an order for two MBE 6000 multi-wafer production systems from epiwafer vendor Picogiga. Two other MBE 6000 systems have been sold in the United States, to TRW and RFMD. The MBE 6000 is capable of growth on four 6" or nine 4" wafers, and is designed for large-scale production of electronic and optoelectronic device structures such as MESFETs, PHEMTs, HBTs and lasers.

New Systems for SiGe CVD, ICP Etching

Ulvac has introduced its first SiGe UHV CVD system. The V8-50LLC-EPI is a vertical vacuum heating furnace, and is said to be the first vertical batch type system that has been developed. It is capable of an hourly throughput of 12 wafers, and a more advanced model capable of processing 20 wafers per hour is in development. The EPI sells for 250 million yen (\$2.0 million), and Ulvac plans to ship five units the first year. The company forecasts that the market will reach 6 billion yen (\$48.8 million) in 2005 and is aiming for a 50% share of the market.

Samco International has developed an ICP (induction coupled plasma) dry etching system for use in compound semiconductor and GMR head processes. The system controls a special coil three-dimensionally to adjust the distribution of sheet plasmas on a plane and generate stable high-density plasmas efficiently. Available for commercial use, the system sells for 120 million yen (\$983,600). The company plans to sell 15 units annually.

Japanese Epiwafer Vendors Address Changing Markets

Hitachi Cable says it plans to beef up its compound semiconductor business in order to make up for a 50% drop in sales of LOC (lead-on-chip) leadframes exported to Korea. The company plans to boost GaAs epitaxial wafer production capacity by 50% as demand for GaAs semiconductors from cellular phone component makers continues to grow.

Showa Denko has decided to shift the focus of its compound semiconductor business to cellular handset and optical communications devices. The company's current mainstay product is LEDs, but it intends by 2002 to have sales of GaAs and InP epitaxial wafers account for about 50% of its compound semiconductor sales, nearly a twofold increase from 1998. Plans call for installing new epitaxial wafer production equipment at its Chichibu plant and strengthening joint development with communications equipment maker to reduce the lead time.

The company recently began sample-shipping AlInGaP epiwafers for communications laser diodes in Japan and photo detector epitaxial wafers in the US. Showa Denko is aiming to boost compound semiconductor sales to 20 billion yen (\$163.9 million) in fiscal 2002, up 70% from fiscal 1999.

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Nitride Growth by MBE

All commercial nitride device production currently uses MOVPE-grown material. We ask if there are any fundamental reasons why MBE can't look forward to the same success.

RICHARD DIXON and TIM WHITAKER

The growth of GaN-based epitaxial device structures such as LEDs, UV photodetectors and lasers is dominated by MOVPE. While companies such as Nichia, Cree, Osram and Hewlett-Packard are all producing MOVPE-grown nitride-based LEDs by the million, we have yet to see the first commercial nitride device grown by MBE. However, the wait may be over soon; SVT Associates has plans to introduce MBE-grown UV photodetectors shortly. Additionally, a number of groups have reported very encouraging results with MBE-grown devices, including excellent mobilities from HEMT epilayers, which suggest that MBE should not be written off by the nitride community.

"There is a fairly pessimistic view around the world about the performance of MBE for nitrides," says Alistair Kean of Sharp Laboratories of Europe Ltd. (Oxford, UK). "However, I

think that once both the growth process and technology are optimized then MBE will be well-suited for growing all kinds of nitride devices."

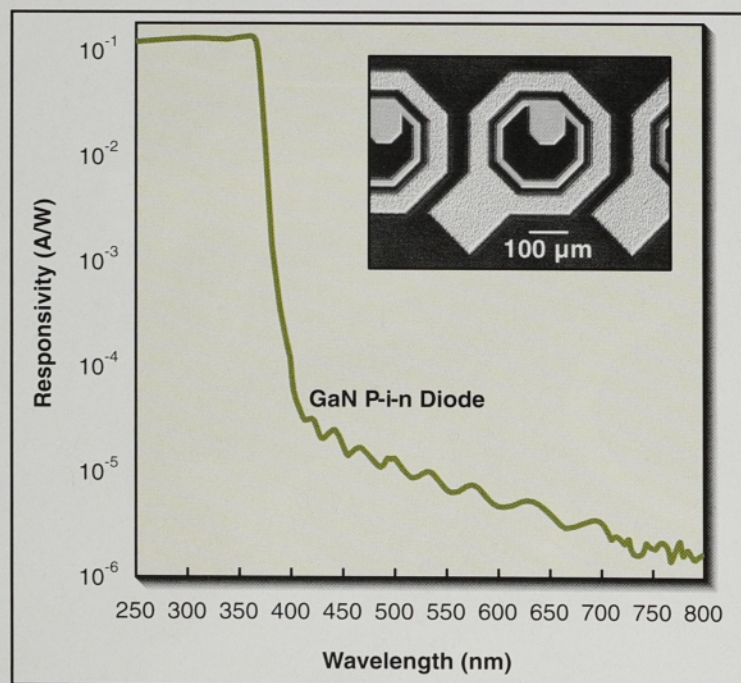
Coming Soon — MBE-Grown Devices from SVT Associates

At present, the only commercial supplier of MBE-grown GaN-based epitaxial wafers is SVT Associates. "We provide GaN epiwafers on 2- and 3-inch diameter sapphire, which are grown using atomic nitrogen produced from an RF plasma source developed in-house," says Jim Van Hove. "We have provided wafers to various industrial and academic groups for a variety of uses, including etching, ohmic contact development, and optical characterization."

SVT Associates has developed UV GaN photodiodes with a high response and excellent UV/visible rejection ratio (see Figure 1), along with solar blind AlGaIn detectors with a cut-off at 275 nm. These seem likely to become the first commercially available MBE-grown nitride devices. "We are currently providing high response GaN and AlGaIn UV detectors in packaged form for beta-site testing," says Van Hove. "These will be available in packaged form in the next 3 months."

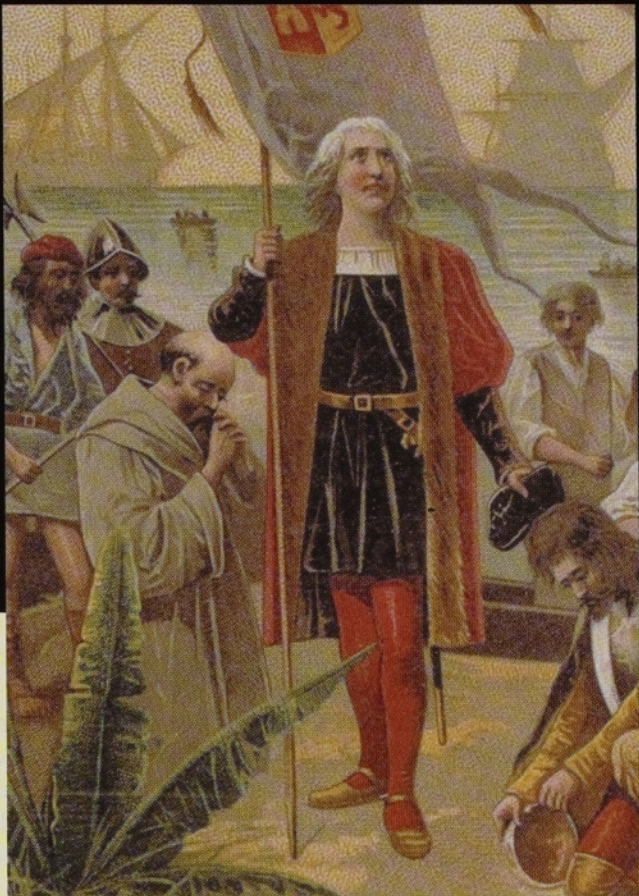
The Source of the Problem

According to Van Hove, MBE can offer a number of potential advantages and improvements over MOVPE, in areas such as layer uniformity, composition and doping control, interface abruptness and reduced growth temperature. So why does MOVPE have such a big lead over MBE? The fundamental reason concerns the difficulty of getting nitrogen-containing species to the growth surface in MBE. While MOVPE growth of nitrides generally uses ammonia as the N-source, many MBE reactors do not have a sufficiently fast pumping system to handle a high gas load. Also, high growth temperatures are used in MOVPE to dissociate ammonia, but these are not appropriate in MBE, as they can compromise the UHV environment in addition to causing the group III species to desorb from the growth surface. Even so, ammonia has been successfully used in gas-source MBE, and other molecular precursors such as dimethylhydrazine are used,



SVT Associates

Figure 1. SEM image (inset) of one element of a linear array from a UV pin photovoltaic detector made by SVT. Fabricated from n- and p-type GaN, the detector exhibits a peak photo-response at 365 nm and is designed for flame sensing, combustion control and analytical equipment applications.



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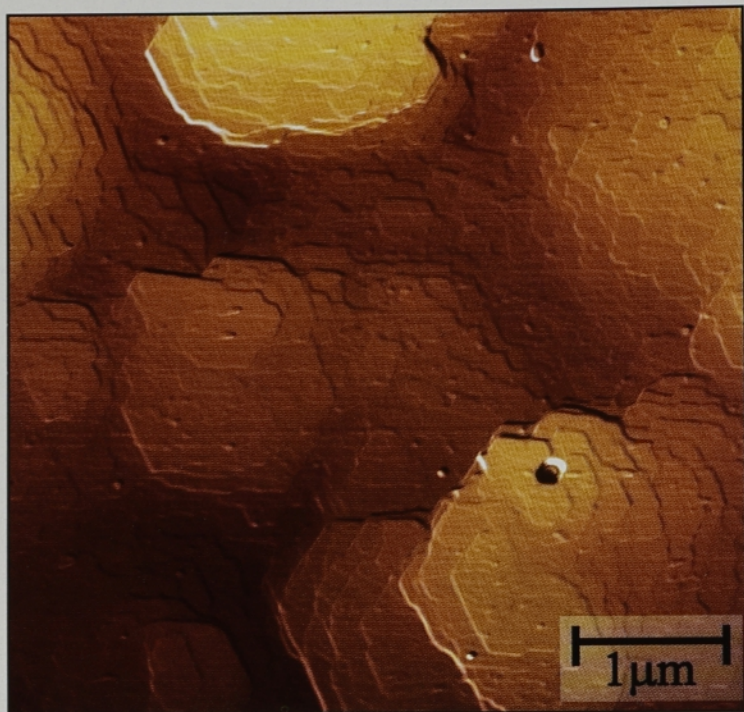


Figure 2. AFM micrograph showing the surface morphology of a 1 μm thick GaN layer grown by reactive MBE directly onto a SiC substrate. The peak to valley height is 15 nm, and the rms roughness of 1 $\times$ 1 μm sections is 0.7 nm. Surface roughness increases the luminescence width of subsequently grown quantum wells and can localize carriers, reducing the luminescence efficiency.

particularly for the growth of InGaNAs alloys.

The problem of obtaining a suitable source of atomic nitrogen species at the growth surface has largely been resolved by the development of RF, DC and electron cyclotron resonance (ECR) plasma sources. In simple terms, these dissociate stable nitrogen (N_2) molecules to form highly active atomic nitrogen radicals.

While allowing lower temperatures to be used, in the past growth using plasma-assisted sources has suffered from ion damage, contamination by sputtering effects, a lack of reproducibility and low growth rates. To reduce this, Theodore Moustakas and his group at Boston University have developed an aperture solenoid source that significantly reduces the effects of ion damage, and has used it to make a GaN homojunction LED entirely by MBE [1].

Another approach to this problem has been to use 'reactive' ammonia. Markus Kamp of the University of Ulm (Germany) delivered uncracked ammonia to the surface using a high-temperature gas injector [2]. Decomposition takes place at the growth surface, typically at around 750°C for GaN, by the dissociation of NH_3 into molecular N_2 and H_2 , and subsequent catalytic reactions with Ga ($2\text{Ga} + 2\text{NH}_3 \rightarrow 2\text{GaN} + 3\text{H}_2$). For this reason, Kamp has also called this on-surface cracking (OSC).

The presence of hydrogen, and the coupling of the surface stoichiometry to both the Ga flux and substrate temperature, distinguishes growth with reactive ammonia from the plasma-assisted RF approach — the situation is more akin to conventional MBE or to MOVPE. [OSC has also led to growth rates of around 1 $\mu\text{m}/\text{h}$, which is comparable to those of MOVPE, says Kamp.]

Andreas Thamm [3] from Berlin's Paul Drude Institute for Solid State Electronics has found that using reactive ammonia as the source can produce excellent step-flow growth by MBE (Figure 2). This is achieved, he says, by in situ control of the stoichiometry monitored by the 2×2 reconstruction. Growing 1 μm GaN directly onto a 6-H SiC substrate, he was able to produce high quality surfaces, which he attributes to this growth optimization and to the presence of hydrogen at the growth front.

Jim Van Hove of SVT Associates points out that growth rates in excess of 1 $\mu\text{m}/\text{hour}$ can now be achieved in MBE using both ammonia and RF-plasma sources, although 1 $\mu\text{m}/\text{h}$ remains the typically-chosen rate. "I prefer RF-plasma, because we have more experience in that technique," he says. Alistair Kean of Sharp notes that the efficient use of ammonia is one of the major advantages of gas-source MBE growth. "Our growth technique uses at least 100 times less ammonia than a CVD process," he says. "This has obvious implications in terms of source usage and environmental pollution."

Ga-rich Growth

The highly-reactive nitrogen species makes GaN RF plasma MBE distinctly different to MBE of conventional III-V semiconductors, says Markus Kamp. "The atomic nitrogen supplied in the case of plasma MBE is so reactive that it reacts directly with every species on the surface, a situation quite different to the common MBE growth mode," he says. This implies different growth modes since with plasma MBE, good results are only reported for Ga-stable conditions.

Using Ga-stable growth conditions, the Ga flux is in excess and the growth rate is limited by the N-flux. This is very different to GaAs MBE, which is usually done under As-stable conditions. "The effect of the V/III ratio on the crystal properties of GaN is dramatic, and even a short period of group V-terminated growth results in unrecoverable damage to the optical and electrical layer qualities," says Kamp.

As a result, a lot of time has been spent on this issue. Working in Jim Speck's group at the University of California at Santa Barbara (UCSB), Eric Tarsa and Ben Heying have looked at the morphology and structure of RF plasma-assisted MBE growth of GaN films as a function of Ga/N ratio [4]. Using homoepitaxy on MOVPE-grown GaN to isolate the effects of nucleation layers and the type of nitrogen source, they note that the structure and morphology of MBE GaN is extremely sensitive to III-V ratio during growth at 650°C. Rough morphologies and columnar structures were observed, resulting from a slight excess of N (i.e. N-stable growth), initiated by stacking faults.

However, by moving to slightly Ga stable conditions (i.e. excess Ga), layers of comparable quality to the MOVPE 'template' layer were possible. Under N-stable conditions (equivalent to a Ga-terminated surface), the high density of available dangling N bonds reduces Ga adatom mobility by surface diffusion. This causes quenched growth, and leads to roughening and the characteristic columnar structure.

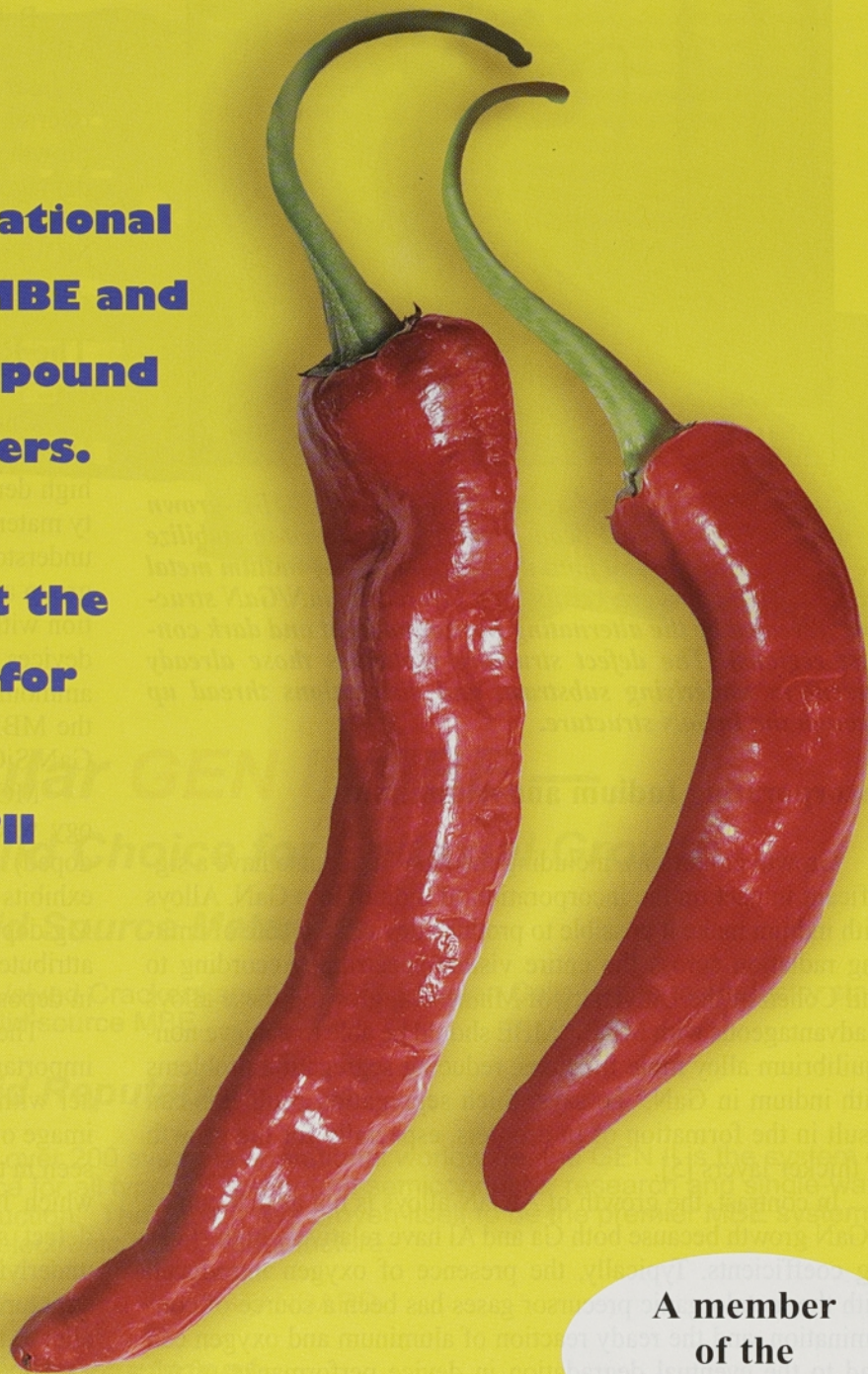
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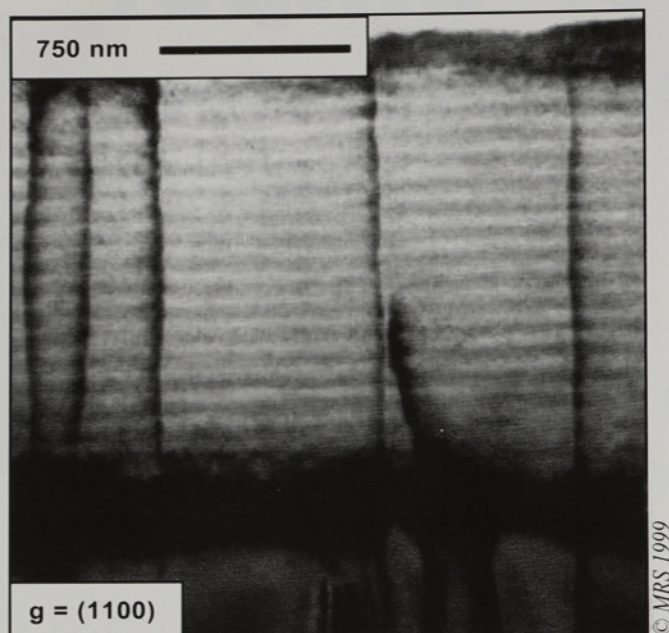


Figure 3. TEM cross-section image of MBE-grown InGaN/GaN. Modulated beam growth is employed to stabilize the growing surface and limit the precipitation of indium metal droplets. This approach results in a layered InGaN/GaN structure (revealed by the alternating horizontal light and dark contrast regions). The defect structure replicates those already present in underlying substrate, and dislocations thread up through the InGaN structure.

Incorporating Indium and Aluminum

Growth conditions, including the III/V ratio, also have a significant impact on the incorporation of indium into GaN. Alloys with indium make it possible to produce devices capable of emitting radiation across the entire visible spectrum. According to Phil Cohen of the University of Minnesota, growing these alloys is advantageous with MBE. "MBE should be able to achieve non-equilibrium alloy mole fractions, reducing segregation problems with indium in GaN," he says. Such segregation problems can result in the formation of In droplets, especially for the growth of thicker layers [5].

In contrast, the growth of AlGaIn alloys is not as difficult as InGaIn growth because both Ga and Al have relatively high sticking coefficients. Typically, the presence of oxygen introduced with the metalorganic precursor gases has been a source of contamination, and the ready reaction of aluminum and oxygen can lead to the eventual degradation in device performance of Al-containing optoelectronic devices. MBE is generally assumed to result in lower levels of unintentionally-incorporated O.

Dopants and Impurities

The incorporation of dopants has been an important factor in the development of nitrides. For a long time it was thought impossible to grow p-type GaN by MOVPE due to the formation of neutral Mg-H complexes. However, it was found that annealing in

nitrogen removes hydrogen and activates the dopants. This was a crucial step in enabling the growth of p-n junction LEDs [6].

In plasma-assisted MBE growth, the absence of hydrogen alleviates the need to anneal samples, and room temperature hole concentrations of around $3 \times 10^{18} \text{ cm}^{-3}$, comparable to MOVPE, have been achieved.

But the reduced requirement for processing could make MBE more suited to the growth of final p-type contacting layers in laser diodes, says Sven Einfeldt of the University of Bremen (Germany). If p-type conductivity can be achieved without post-growth annealing, this simplifies device processing and reduces damage to underlying layers. "A solution would be the MBE growth of heavily-doped GaN:Mg as a contact layer on top of MOVPE-grown laser diodes," he says.

The Role of Dislocations in Optoelectronic Devices

One of the most remarkable features of nitride-based optoelectronic devices is the fact that they work at all, considering the high density of dislocations contained in even the highest quality material. The role played by these dislocations is still not fully understood, and was recently investigated by Jan Schetzina's group at North Carolina State University (NCSU) in collaboration with Cree Research [7]. The paper compared optoelectronic devices grown by MBE and MOVPE. The MOVPE growth used ammonia as the group V source and sapphire substrates, while the MBE system used an RF plasma source, and pre-nucleated GaN/SiC substrates.

MOVPE-grown GaN has a smooth and featureless morphology when viewed by SEM for undoped, n-type or p-type (Mg-doped) material. In contrast, undoped or n-type MBE-grown GaN exhibits what the authors describe as a 'wormy' structure, while Mg-doped material reveals a faceted surface structure. This they attribute to the pre-existing dislocation structure and difficulties in depositing Mg at the high pressures required for growth.

The presence of hydrogen in MOVPE growth plays several important roles, the paper reports. Hydrogen was found to interact with the dislocations. Figure 3 shows a TEM cross-section image of MBE-grown InGaIn/GaN layers. (The layered structure seen in the image arises from the use of modulated beam growth which limits the precipitation of indium metal droplets.) The defect structure in the epilayers replicates the defects in the underlying substrate. In MBE-grown InGaIn-based LED test structures, these dislocations act as shorting pathways lying parallel to the diode junction.

In the case of MOVPE growth, the dissociation of ammonia provides hydrogen at the growth surface. The key result is that even though threading dislocations are still present in MOVPE grown material, it appears that hydrogen passivates the dislocations, rendering them electrically neutral. The same effect cannot be achieved by adding hydrogen to the nitrogen plasma in MBE.

For a device, the result is a difference of two orders of magnitude in the forward current required for luminescence from MBE and MOVPE grown LEDs to be clearly visible at room temperature. The values were 50 mA for the MBE-grown structure and 0.5 mA for MOVPE-grown material. MBE-grown diodes also

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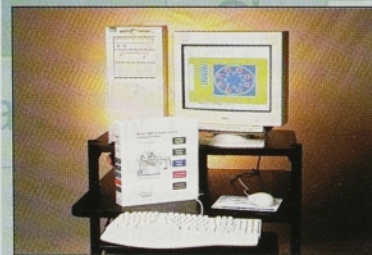
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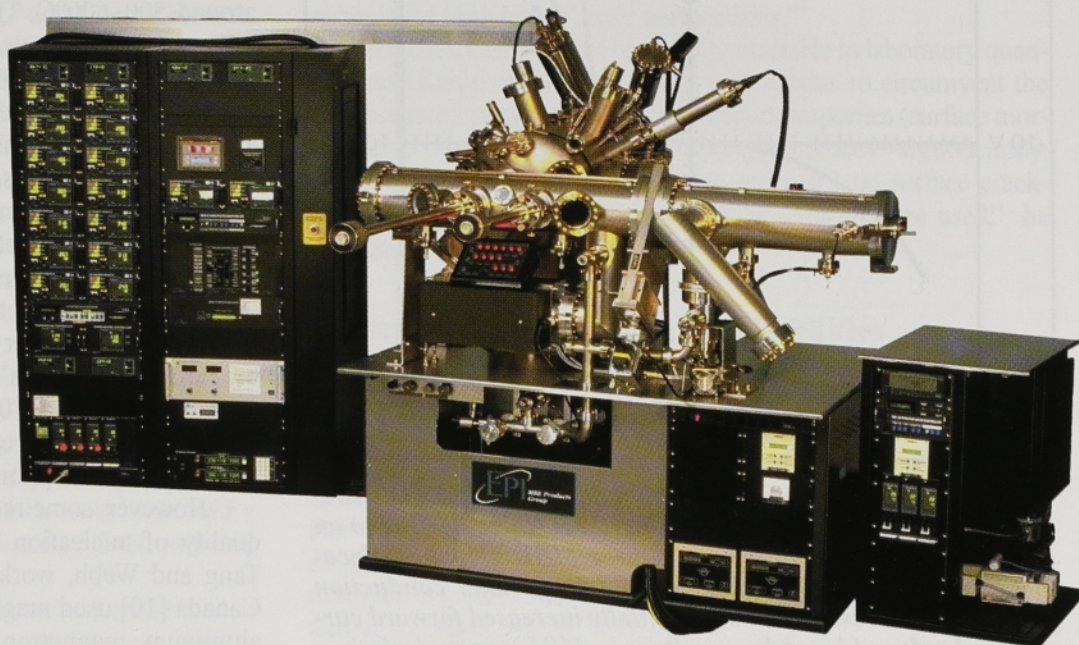
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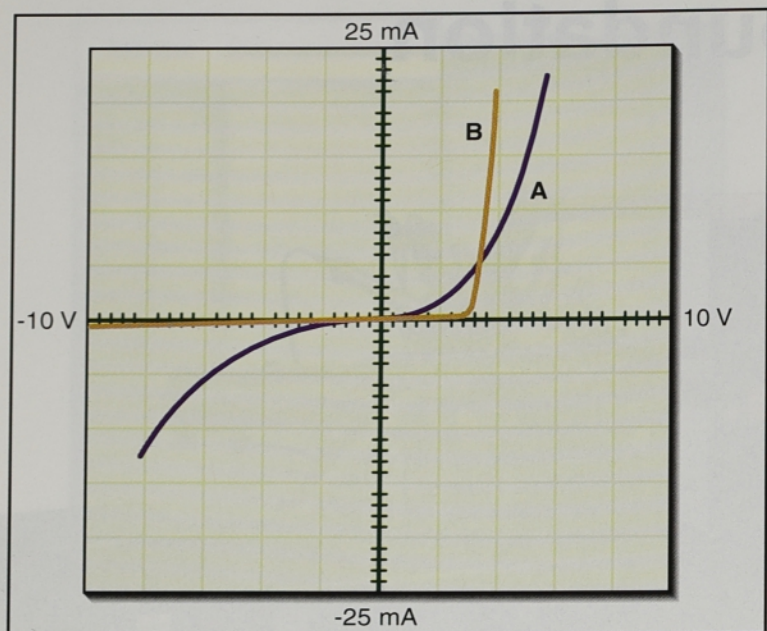


Figure 4. *I-V curves for an InGaN quantum well LED structure grown by MBE (trace A) and MOCVD (trace B). Due to an absence of hydrogen in plasma source MBE growth, dislocations are not passivated and can act as parallel conduction pathways. This results in a substantially increased forward current and reduced breakdown voltage in MBE-grown devices.*

show a comparatively low reverse breakdown voltage (Figure 4). The NCSU/Cree paper concludes that the presence of shorting dislocations severely limits the suitability of MBE-grown vertical transport bipolar devices for optoelectronic applications.

Even so, there has been some success with the growth of GaN and InGaN-based devices. Infineon Technologies' (formerly Siemens) work on MBE-grown InGaN for blue and green LEDs is one example. Robert Averbeck of MBE group says that the company started to study the MBE growth of GaN back in 1995, reporting processed devices with green electroluminescence which exhibited more light output than conventional green GaP:N LEDs [8]. Later work has focused on the improvement of material quality, he says, such as producing orders of magnitude higher PL intensities for InGaN, and hole concentrations for GaN:Mg of 10^{18} cm^{-3} . "The work hasn't been applied because Infineon's LED production process uses MOVPE," says Averbeck, adding that the InGaN work has only recently been made public due to patent issues [9]. "Infineon is now also concentrating on MBE-grown structures for GaN-based electronics," he says.

Substrates and Nucleation Layers

Substrates are a big issue for nitride growth. Due to the lack of a suitable, low lattice mismatch substrate, sapphire and SiC are used; sapphire is cheaper, but SiC is conductive, leading to easier contacting and simpler device geometries for LEDs and other devices [CS 5(5), p.15]. Both materials have a large lattice mismatch to GaN (13% for sapphire, 4% for SiC), resulting in a large number of dislocations in GaN epilayers.

To improve material quality in MOVPE growth, nucleation or buffer layers are used. Their quality is critical to the final quality of the layers, as the lattice mismatch-induced dislocations are 'remembered' during growth of subsequent layers. Typically, 20–30 nm of either AlN or GaN is grown at a temperature of around 500–600°C. The result is a thin film consisting of crystalline and amorphous regions. The substrate is then heated to the growth temperature for GaN (in excess of 900°C), resulting in recrystallization of the buffer and lateral overgrowth. This lateral growth mechanism ensures that dislocations are initiated only at the coalescence points of largely-spaced grains in the overgrowth material as it grows on top of the nucleation layer. The bigger the grains, the less nucleation sites for dislocations.

However, at the lower growth temperatures typically employed by MBE, the quasi-lateral overgrowth of the GaN nucleation layer observed in MOVPE growth doesn't occur, and the buffer layer doesn't work as well. Thus, MBE films typically contain around $1 \times 10^{10} \text{ cm}^{-2}$ dislocations, compared to $1 \times 10^8 \text{ cm}^{-2}$ for MOVPE layers. As Jim Van Hove puts it, "The proper MBE buffer on sapphire is still being developed."

However, some recent developments have been made on the quality of nucleation buffers using a modified form of MBE. Tang and Webb, working at the National Research Council in Canada [10] used magnetic sputter epitaxy (MSE), a high-purity aluminum magnetron sputter cathode, in combination with ammonia-source MBE to first grow the low-temperature AlN nucleation layer.

The authors obtained room temperature electron mobilities for GaN of $550 \text{ cm}^2/\text{V s}$. While this is lower than that available from MOVPE devices (the highest is $900 \text{ cm}^2/\text{V s}$), this is almost twice that previously obtained with MBE-grown GaN. The authors concluded that this result showed that with the MBE technique, the type of defects affecting the electron mobility can be reduced significantly, as they have been with MOVPE.

Templates

To circumvent the problems associated with the nucleation layer in MBE, many researchers have investigated GaN homoepitaxy on 'templates'. These consist of GaN layers, 1–20 μm thick, grown by HVPE or MOVPE on sapphire or SiC. Templates are available from several commercial sources. According to Sven Einfeldt, lower dislocation densities are possible because, in the same way as MOVPE, MBE growth only reproduces the defect structure of the template and does not introduce additional defects.

Ben Heying of UCSB has used these templates to grow high mobility HEMT structures [4]. "We can get films with comparable quality to the underlying MOVPE layer if we grow under the correct conditions," he says. "The idea is that eventually GaN substrates will be commercially available, and when that happens MBE will be better suited for growing layers for certain devices."

LEO by MBE

Lateral epitaxial overgrowth (LEO) has been successful in improving GaN material quality for subsequent device growth. In

LEO, GaN is grown on a template consisting of a SiO_2 or SiN mask which is patterned to expose the underlying GaN. In the overgrown regions, defects extend vertically through the window regions but do not extend laterally over the mask regions, resulting in low defect density material above the mask.

Zhonghai Yu and colleagues at NCSU and Cree Research [11] have compared this approach for growth on both SiC and sapphire substrates using MBE and MOVPE. In contrast to the MOVPE-grown materials, which showed single crystal GaN areas over the SiN mask stripes, high dislocation densities and randomly oriented columnar structures appeared in MBE material in the mask areas. Yu concludes that this relates to the limited range of available active nitrogen species from the plasma sources for MBE growth of GaN at temperatures up to 1000°C . MBE cannot be used to obtain low dislocation density GaN by the LEO technique, he says.

However, Phil Cohen's group at the University of Minnesota has demonstrated pendeo-epitaxy [see CS 5(2), p.16] using MBE. In this technique, a pattern is etched in a GaN layer to expose the underlying substrate. Overgrowth occurs from the top and side facets of the GaN pillar. Mike Hoyt's work indicated a 3:1 lateral to vertical growth ratio of good quality GaN, initiated from side-walls using MBE [12].

These are encouraging results, says Cohen, and could lead to a high-quality nucleation layer for subsequent device growth. "For device structures that are best achieved by MBE, this approach would be an alternative to purchasing epitaxial substrates, or growing and transferring MOVPE-grown LEO samples," he says.

Homoepitaxial Growth on GaN Substrates

Of course, the ideal substrate for GaN growth is GaN. This would eliminate the need for nucleation layers, resolve growth mode problems, reduce dislocations due to the lack of lattice mismatch, and improve processing steps, such as facet cleaving to form mirrors for lasers. A conducting substrate such as GaN is highly advantageous for high temperature electronics.

Currently, only small area GaN substrates are available for research purposes. The leading group in this field is the High Pressure Research Center at the Polish Academy of Sciences in Warszawa, Poland, which grows GaN crystals from atomic nitrogen dissolved in a Ga melt at 1600°C , under an N_2 pressure of 20 kbar [13]. Although only small samples measuring $10 \times 10 \text{ mm}^2$ are presently available, the dislocation density is extremely low, at around $10^3\text{--}10^5 \text{ cm}^{-2}$.

Markus Kamp (Ulm University, Germany) has used these substrates to grow a number of devices, including the first InGaN/GaN double heterostructure LEDs grown by MOVPE on bulk crystal substrates [14]. His group has also investigated ammonia MBE growth, and noted that very high quality material (a PL linewidth with a FWHM of 0.5 meV) with dislocation densities in the $10^2\text{--}10^3 \text{ cm}^{-2}$ range was possible.

Kamp has obtained the best results from MOVPE, which he reports exhibits a PL linewidth below 0.1 meV [15]. "These advances in material quality can be attributed to our improve-

ments in crystal preparation, rather to differences between ammonia MBE and MOVPE," he says. However, as only small pieces of GaN substrate are available at present, Kamp comments: "Even if the effort needed to make these substrates is probably too high for mass products such as LEDs, it might be worth it for high power laser applications."

However, GaN substrates are only available in laboratory quantities and Kamp maintains that using templates to circumvent the initial steps of growth improves all epilayer properties (surface morphologies, optical, and electrical properties) significantly. "Particularly with GaN growth using ammonia on-surface cracking, MBE can be as good as MOVPE if templates are used," he concludes.

Electronic Devices — Record Mobilities

Although offering many attractive features for high frequency, high power and high temperature operation, electronic nitride-based devices have yet to enter production, irrespective of the epitaxial growth technique. In contrast to LEDs, the high dislocation density is highly detrimental to device performance, since dislocations act as scattering sites for carriers and reduce the mobility. As noted above, growing on templates improves the situation for MBE and MOVPE.



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$\text{Al}_{0.12}\text{Ga}_{0.88}\text{N}/\text{GaN}$ 2DEG heterostructures. The structures were grown by RF plasma MBE using a GaN-on-sapphire template. Hall mobility values of 14,500 cm^2/Vs at 77 K and 20,000 cm^2/Vs at 12 K were reported, and low temperature (13 K) mobilities greater than 50,000 cm^2/Vs are now possible by MBE, according to UCSB's Ben Heying [17]. Both values are records for this material system. The highest mobility recorded for a similar structure grown by MOVPE was 9000 cm^2/Vs at 77 K.

Elsass concludes that the high degree of thickness, interface, and impurity control provided by MBE growth can improve the quality of the AlGaIn/GaN interface compared to MOVPE. He also suggests that the lower impurity levels in MBE-grown material could be a reason for increased mobility. Oxygen in particular is known to be highly detrimental to the performance of devices with Al-containing layers.

SVT Associates has collaborated with Daimler Chrysler to produce high performance AlGaIn/GaN HEMTs (Figure 5), including a device with a breakdown voltage of 410 V [18]. More recently, a device with a gate length of 0.2 μm demonstrated an f_{max} of 78 GHz and an f_t of 45 GHz [19]. Also, SVT Associates worked with the University of Florida, Sandia and Bell Labs to produce one of the first nitride-based HBTs [20]. The device was grown by MBE on top of a highly resistive undoped GaN layer grown by MOVPE.

The Future of MBE

The results described above clearly suggest that MBE has a great deal of potential for the growth of certain types of nitride-based devices. SVT is close to commercialization of MBE-grown photodetectors, which they say demonstrate performance that is at least as good as those grown elsewhere by MOVPE. Excellent mobilities and high power, high frequency properties have been demonstrated for HEMT structures, and layers with high optical

quality can also be grown provided that high dislocation densities can be avoided.

The issue of substrates and dislocation densities is key for MBE-grown devices. In the absence of high quality MBE-grown buffer layers, GaN templates grown by MOVPE or HVPE provide a good solution. As well as supplying these templates, several companies are working on methods to remove the GaN films from the underlying substrate to yield free-standing GaN. However, progress in finding a route to bulk single crystal GaN remains extremely slow.

Phil Cohen is of the opinion that MOVPE enjoys a big lead over MBE mainly because more effort has been put into it. "Not all the growth problems have been solved by MOVPE," he says. Choosing lasers as an example, he notes that most GaN-based blue laser structures are grown by MOVPE, but only one company, Nichia, has really got the MOVPE growth process under control at the moment. "Nichia knows how to make lasers with 10,000 hours of operation, but the rest of the world is struggling to keep pace. I think it relates to the fact that the MOVPE process is difficult to control. This is where the in-situ diagnostic tools of MBE [e.g. desorption mass spectroscopy and RHEED] can be helpful, as they allow the growth process to be better understood, and ultimately, to be portable."

But is it possible that MOVPE's lead is so great that MBE will never be able to catch up? It is highly doubtful that MBE will ever make inroads into LED production. Lasers could be a different matter, but only if good substrates become readily available. However, MBE does have very good prospects for photodetectors and for electronic devices.

As more effort is expended on nitride growth by MBE, it seems that the lead currently enjoyed by MOVPE may soon start to diminish.

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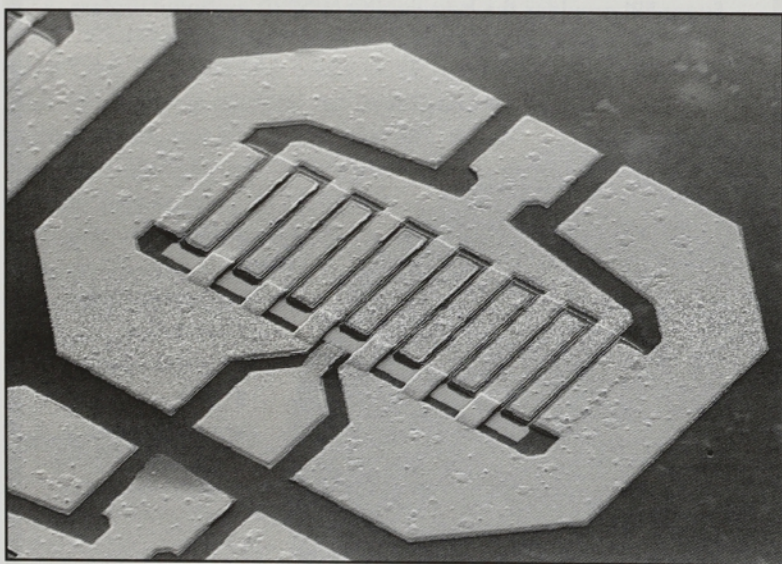


Figure 5. SEM image of an MBE-grown AlGaIn-on-sapphire HEMT fabricated by SVT Associates. GaN-based devices show promise in applications for high power transistors operating up to temperatures of 400°C.

SVT Associates

TBAs and TBP — Improved Group V Sources for MOVPE

The use of TBAs and TBP as replacements for the traditional MOVPE Group V precursors — arsine and phosphine — can offer enhanced material quality and device performance, in addition to improved safety.

WOLFGANG STOLZ* AND TIM WHITAKER
*Philipps-University, Marburg, Germany

In the last decade, many research programs have investigated alternative group V sources as substitutes for the traditional III-V epitaxy precursors arsine (AsH_3) and phosphine (PH_3). Initially, the main concern was the extremely high toxicity of AsH_3 and PH_3 and the danger posed by rapid spreading in the event of a leak of these compressed gases. Associated with these properties are the high cost of storage, process safety monitoring and waste treatment, along with environmental concerns.

More recently, it has become clear that some Group V alternatives have improved decomposition characteristics, allowing the use of lower growth temperatures and lower V/III ratios. In turn, this can lead to improved layer homogeneity, improved device characteristics and the possibility of novel device structures.

The most successful alternatives to the hydrides AsH_3 and PH_3 are tertiarybutylarsine (TBAs) and tertiarybutylphosphine (TBP). Structurally, these molecules are similar to the hydrides, except that one H atom is replaced with a bulky tertiarybutyl group. This makes TBAs and TBP much less toxic than the hydrides, and also means that the compounds are liquids at room temperature, significantly reducing the risk of widespread contamination in the event of a leak. Furthermore, TBAs and TBP decompose at much lower temperatures than AsH_3 and PH_3 , permitting the use of lower substrate temperatures and V/III ratios. The higher efficiency of TBAs and TBP reduces the amount of source material required, cuts the amount of As and P in the pumping system (thereby increasing reactor uptime), and also reduces the amount of waste material produced.

TBAs and TBP only recently became available with sufficient purity to be considered for use in production, and are still expensive compared to standard starting materials. However, this higher cost is offset by a variety of benefits.

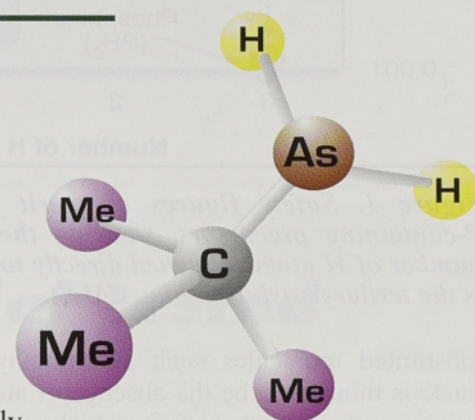
Safety in MOVPE

According to several studies, the acute toxicity of As- and P-hydrides is directly linked to the number of As-H and P-H functions in the source molecule. Substituting one H-function in the molecule by an organic alkyl group (e.g. methyl, tertiarybutyl) reduces the toxicity and the vapor pressure of the compound by about one order of magnitude. Both these properties are of key importance for the safety of epitaxial growth processes. Highly toxic materials are obviously undesirable, while a high vapor pressure increases the risk of a wide spreading of the compound in case of an accidental leak. A safety figure of merit can be defined by the equation below. The LC_{50} value represents toxicity, where the higher the LC_{50} value the lower the toxicity of the respective compound.¹

$$\text{Figure of Merit} = \frac{\text{LC}_{50}}{\text{Vapor Pressure @ } 20^\circ\text{C}}$$

This figure of merit is displayed in Figure 1 for various As- and P-compounds. The substitution of only one H-function by a tertiarybutyl group leads to an improvement in safety by three to four orders of magnitude for TBAs and TBP as compared to AsH_3 and PH_3 . Additional substitution of H-functions improves the safety even further. However, this occurs at the expense of increased intrinsic carbon incorporation, particularly from fully

¹ LC_{50} represents the concentration of a chemical that is lethal for 50% of a representative animal population after exposure for a time of typically 4 hours.



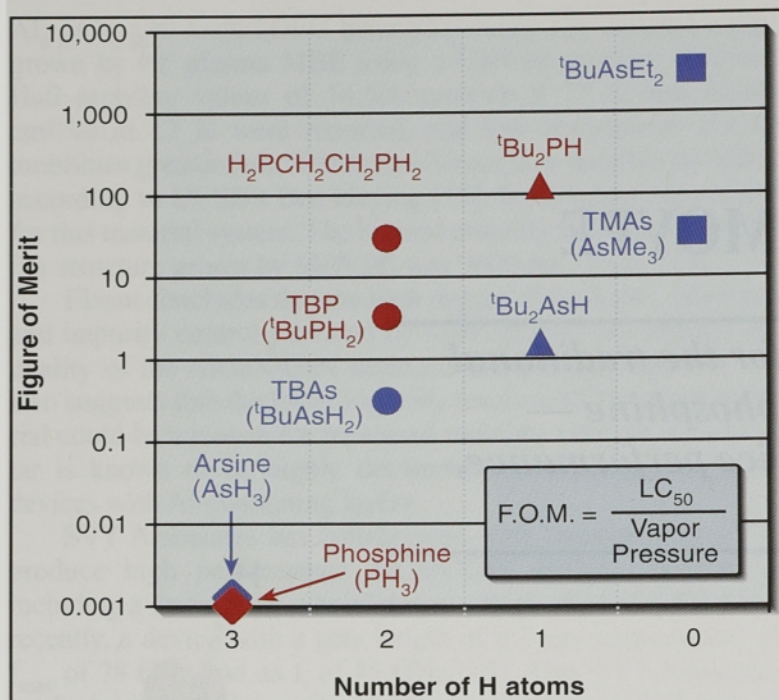


Figure 1. Safety figures of merit for various As- and P-containing precursors, showing the correlation with the number of H atoms attached directly to the As or P atom (*t*Bu is the tertiarybutyl group i.e. CMe_3).

substituted molecules such as trimethylarsenic (TMAs). The cause is thought to be the absence of atomic hydrogen or AsH_x species at the growth surface, which act to remove alkyl species during growth with arsine or TBAs. Considering both toxicity and C incorporation, TBAs and TBP represent the optimal replacements for arsine and phosphine respectively, and have been widely evaluated in both research labs and industrial development and production.

Decomposition Characteristics

A number of research groups have established that TBAs and TBP begin to decompose at significantly lower temperatures than AsH_3 and PH_3 [see Figure 2]. These values ensure that TBAs and TBP possess improved growth efficiencies compared to the respective hydride gases, allowing a reduction in growth temperature and V/III ratio. This allows improved compositional control and improved layer homogeneity, particularly for quaternary material systems such as GaInAsP/InP . In addition, the reduction in V/III ratio, which can be as low as 2–5 $\times$ for GaInAs , and 10–20 $\times$ for InP and GaInAsP at 610°C, results in a drastic reduction in waste material. This improves the up time of the vacuum system, the pumps and the scrubber system, and significantly reduces maintenance requirements.

Both 1.3 μm and 1.55 μm telecommunication laser diodes as well as pin-detector and FET structures with excellent device characteristics have been demonstrated using TBAs and/or TBP [1, 2, 3]. Uniphase Netherlands (formerly Philips Optoelectronics) has a number of development programs that use TBAs and TBP in the growth of telecommunication lasers.

Andre van Geelen reports that several production reactors currently using AsH_3 and PH_3 are equipped with the necessary lines for TBAs and TBP, and that these new precursors can be “switched on” when the development program is completed. “The most important advantage of TBAs and TBP is their low decomposition temperatures, which enable lower growth temperatures and a more uniform material composition,” says van Geelen. “The low V/III ratios significantly reduce the amount of As and P in the pumping system, leading to less downtime and maintenance, which is a clear advantage in a production environment.”

Eberhard Veuhoff of Infineon Technologies (formerly Siemens Semiconductors) sees a number of advantages inherent in using TBAs and TBP for the production of photonic devices by MOVPE. “We see the main advantages in reduced safety risks, reduced ecological risks due to the lower toxicity, and reduced production costs due to the lower costs for storage and waste management and due to more efficient use of these precursors,” he says.

Supply Situation and Cost

The demand for TBAs and TBP has increased drastically in recent years, and the worldwide market in 1999 is estimated to be around 300–400 kg. This already represents a significant percentage of the total Group V source market. The total amount of arsine and phosphine consumed for III-V epitaxy is estimated to about 20,000–25,000 kg per year at present. Due to the improved thermal decomposition characteristics of TBAs and TBP, the V/III ratio can be reduced by a factor of about 3–40, depending on the material system, the device structure and the epitaxial equipment. Assuming an average V/III ratio improvement factor of 10 and taking into account the different molecular weights, the TBAs/TBP market represents a “hydride equivalent” of about 2,000 kg, or around 10% of the group V market for III-V epitaxy by MOVPE.

Several suppliers, Epichem/Air Products (UK/USA), Furukawa (Japan) and Mochem (Germany), offer both TBAs and TBP, while Shin-Etsu Chemical (Japan) supplies only TBP. Due to the complexity of the chemical processes involved in synthesizing and purifying these materials, production quality sources have only recently become available — at a price reflecting the current market demand of only 300–400 kg.

“The TBAs/TBP purchasing costs are still relatively high today,” says Infineon’s Eberhard Veuhoff. “However, one can beat these costs by the more efficient use of TBAs/TBP (i.e. high cracking efficiency, low V/III ratio) and by using these precursors only in certain parts of multilayer device structures, for example growing just the active N-containing region of a GaInNAs laser structure with TBAs.”

“The more dominant costs are in the qualification process,” continues Veuhoff. “Switching from standard hydrides to alternative precursors in an established production process makes a new qualification process necessary, which is quite expensive and time-consuming.” Of course, TBAs and TBP can be incorporated into a new process from the outset, and Veuhoff says that

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Infineon is currently evaluating such a process. "We think that these precursors will play an important role in device production in the future," he says.

In some cases, it appears that the only obstacle to using TBAs/TBP may have been the price of the precursors at the time they were evaluated. For example, Tecstar, one of the leading manufacturers of III-V solar cells, does not use TBAs or TBP in production. "The main reason is cost," says Tecstar's Frank Ho. "Growth of large area GaInP/GaAs solar cells in multiwafer production reactors uses a great deal of As and P, and TBAs and TBP are too expensive."

According to Andre van Geelen of Uniphase, the availability of these precursors is still very limited and there is a clear supply bottleneck. "In addition, the price of TBAs and TBP is still much too high," he says. "Comparing TBAs and AsH₃, we see that TBAs is still a factor of five more expensive than AsH₃, even including other benefits such as less scrubber and pumping maintenance. A few years ago the material quality was a big issue, but I think that the quality is currently comparable to that of AsH₃ and PH₃."

With respect to the supply situation, Arnd Greiling of Mochem admits, "We have seen a drastic increase in demand in the last two years, resulting in excessively long delivery times for our customers. Therefore, Mochem has significantly increased its production capacity in the first quarter of 1999. At present, we are building up further stock capacity of TBAs and TBP, and have eliminated the supply bottleneck."

Greiling also envisages that the price of these materials can be expected to fall. "The selling price of TBAs and TBP is directly related to the amount of material sold," he explains. "If overall consumption continues to increase as it has over the last two years, the production costs of TBAs and TBP, and thus the market price, can be significantly reduced. This is particularly true for large-scale industrial users based on just-in-time delivery contracts."

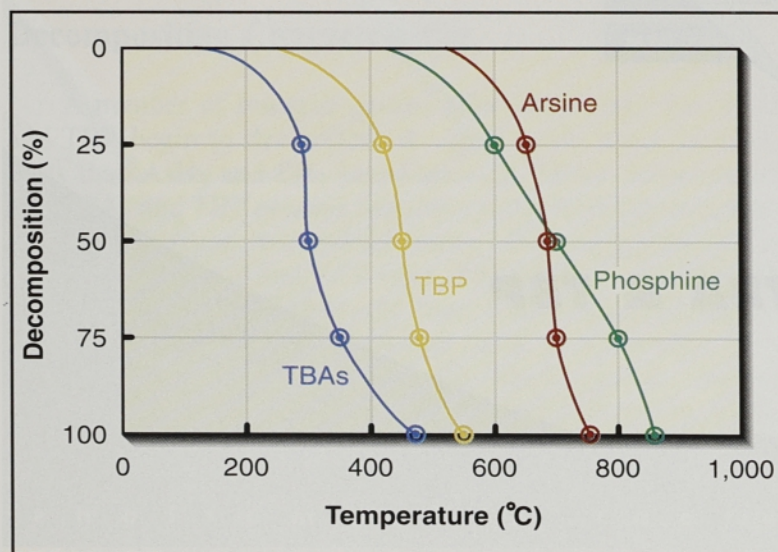


Figure 2. Decomposition temperatures of standard hydride gases (arsine, phosphine) and alternative liquid precursors (TBAs, TBP). Data courtesy of Epichem Ltd.

Improved Device Performance, Novel Materials

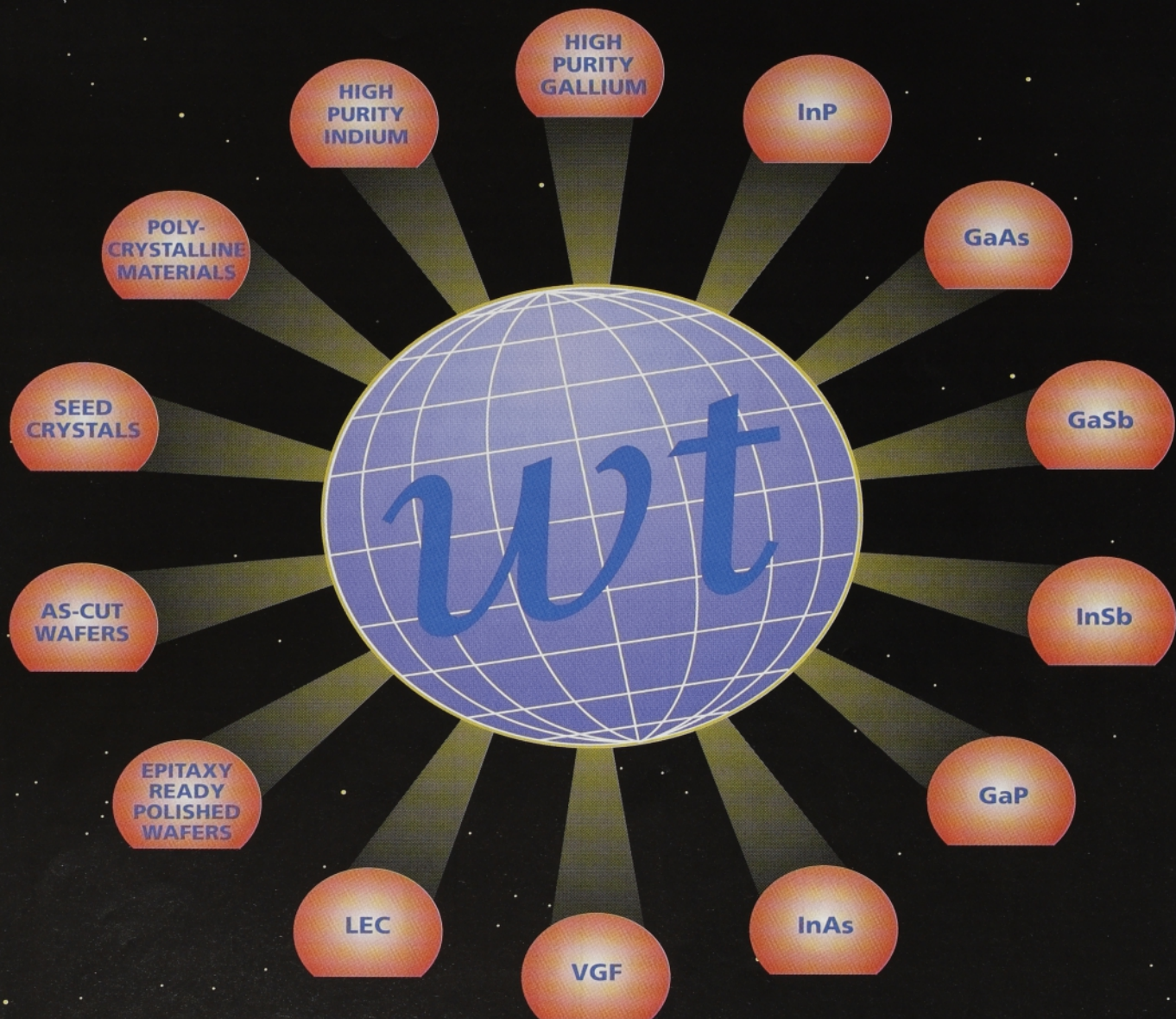
Features associated with the use of TBAs and TBP, such as lower growth temperatures and V/III ratios, offer improvements to existing devices along with the opportunity to develop novel device structures. For example, most regrowth processes, particularly those involving grating structures for lasers, could benefit from the use of reduced growth temperatures. As one example, Figure 3 shows an SEM micrograph of the overgrowth process of a grating structure in the GaInP waveguide layer in DBR laser sequence by p-AlGaAs using TBAs [4]. Due to the low overgrowth temperature of 660°C and the stabilization of the grating by TBP, the grating structure is preserved. This leads to excellent DBR laser characteristics: single mode output at 1.06 μm , with a CW power of 75 mW at 25°C and a threshold current density of 100 A/cm².

"In our laboratories, we have shown that strained GaInAsP/InP MQW lasers produced with TBAs/TBP have characteristics comparable to our standard devices, where AsH₃ and PH₃ are used," says Infineon's Eberhard Veuhoff. "Even for Al-containing compounds we obtained the same material properties as with standard hydrides in the initial AlGaInP test structures, revealing the high quality of alternative precursors today. The material quality of the grown structures, however, depends on the precursor supplier. Currently, we are taking advantage of the low temperatures associated with growth using TBAs for the development of GaInNAs/GaAs laser structures."

Quaternary Nitrides

The GaInNAs material system, which can be grown lattice-matched or slightly strained on GaAs substrates, can be used to realize GaAs-based lasers emitting at 1.3 μm due to extreme band gap bowing [see CS 4(5), p. 30]. Strong electron confinement in these devices is expected to lead to improved high temperature device performance compared to InP-based structures, for both edge- and vertical-emitting devices. The MOVPE growth of GaInNAs is facilitated by the use of TBAs rather than arsine and by replacing ammonia with the liquid N-source 1,1-dimethylhydrazine (UDMH₂). The low decomposition temperatures of these precursors compared to the hydride alternatives (i.e. AsH₃, NH₃) allow growth of high quality material at temperatures as low as 500°C [5]. Crucially, this allows nitrogen concentrations in excess of 3%, leading to longer wavelength emission. Philipps-University has demonstrated GaInNAs/GaAs MQW structures with room temperature luminescence emission at 1.55 μm [6]. Recently, low threshold current densities of 0.7 kA/cm² were obtained for SQW edge-emitting lasers emitting at 1.28 μm [7]. Also, the first optically pumped VCSELs with excellent dynamic properties have been demonstrated in the GaInNAs material system, using the TBAs for the entire growth sequence including the AlAs/GaAs DBR stacks [8].

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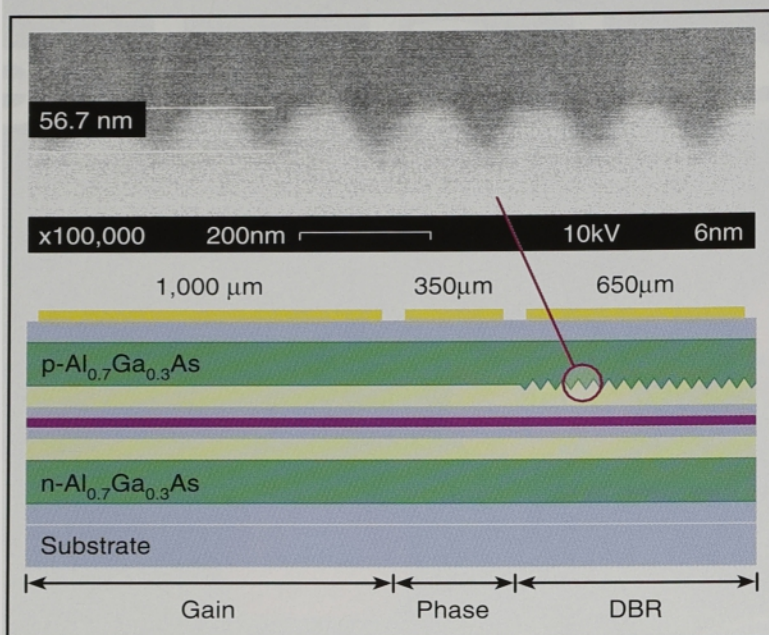


Figure 3. (bottom) Structure of a 1060 nm DBR laser, containing a single InGaAs QW in GaAs, with InGaP cladding layers. Growth up to the p-InGaP waveguide was carried out using AsH₃ and PH₃. (top) SEM micrograph showing the DBR grating in InGaP, overgrown with AlGaAs at 660°C using TBAs. From [4].

Heterojunction Bipolar Transistors

In epilayers that require high doping concentrations, low growth temperatures offer a distinct advantage in order to achieve both abrupt doping profiles and high doping levels. These characteristics are very important for base layers in HBTs and for tunnel junctions in tandem solar cells. In some instances of HBT growth using hydride gases, the base layer is grown at a lower temperature than the rest of the structure in order to achieve the desired doping profile. Use of TBAs and TBP offers the opportunity to simplify the deposition process by growing the entire epilayer at low temperature.

TBP is used as the primary phosphorous source in Kopin's production HBT process, according to Dave Davito. The device structure contains an GaInP emitter layer, which is the only P-containing epilayer. Phosphine is also qualified for the production process, but is found to be less efficient than TBP. "Since we grow thin layers of GaInP, the source lasts us quite a long time," says Davito. "Although TBP is more expensive than phosphine, the properties of TBP allow us to use smaller amounts of TBP relative to phosphine, making the cost of using TBP lower. Furthermore, we have cleaner systems using TBP, because of the lower volumes of phosphorous decomposed in the reactor."

High Al-Content Materials Using TBAs and TBP

Using TBAs and TBP, significant reductions in the concentrations of residual impurities, particularly oxygen, have been achieved in Al-containing materials. In addition, TBAs

offers other distinct advantages for the growth of AlGaAs compared to AsH₃. Growth of high quality AlGaAs epilayers using AsH₃ requires substrate temperatures in excess of 700°C and high V/III-ratios. The high temperature encourages desorption of Al-methoxide groups, thought to be the main source of O in MOVPE growth using TMAI as the Al precursor. The high V/III ratio limits the incorporation of O-containing species and also getters C-containing methyl groups. As shown in Figure 3, O-incorporation in Al_{0.85}Ga_{0.15}As grown with AsH₃ is strongly dependent on V/III ratio and substrate temperature [9].

For TBAs, the O-incorporation behavior is completely different [10]. Figure 4 also shows that for TBAs-grown material, the lowest O level (and thus the highest optical quality) is achieved at 625°C, and is almost independent of V/III ratio. However, C-incorporation decreases with increasing V/III ratio, using either AsH₃ or TBAs. This is because a high group V flux provides more AsH_x species and H atoms that remove (getter) C-containing methyl species from the surface. Since a high V/III ratio is not required in order to limit O-incorporation using TBAs, the incorporation of C in AlGaAs can be controlled by varying the V/III ratio, for intentional p-type doping. Doping levels up to the high 10¹⁸/cm³ doping range are accessible by choosing the appropriate V/III ratio. As an example, high quality, AlGaAs:C layers have been grown at low temperature for use as the p-type current-spreading layers in visible AlGaInP-based LED structures. Because of the low growth temperature of 625°C, the doping profiles in the active LED layer are no longer altered by overgrowth of the thick current spreading layer. In addition, the very low V/III ratio of 2.5 for growth using TBAs also drastically reduces the amount of waste material for this process.

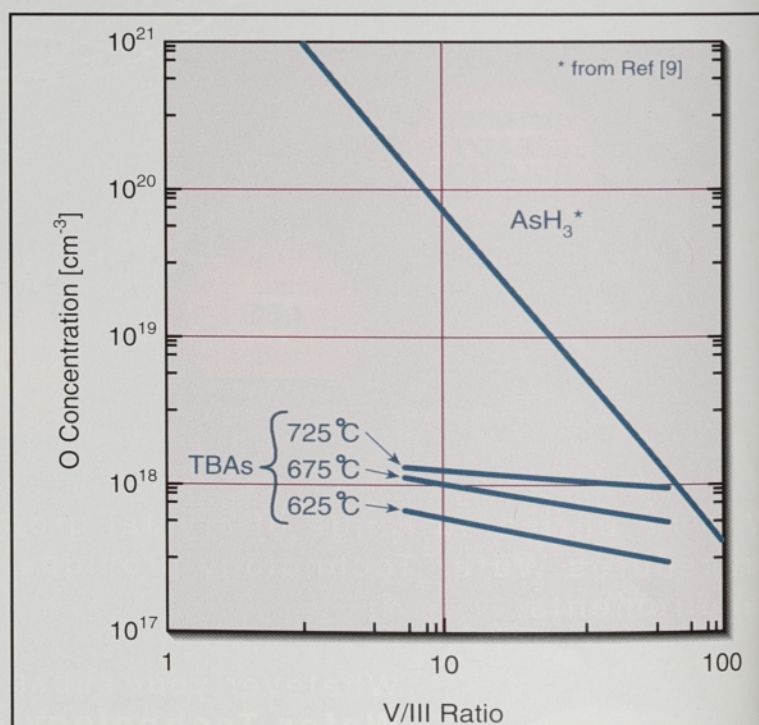


Figure 4. Oxygen concentration in (Al_{0.85}Ga_{0.15})As grown using TBAs or arsine, obtained by calibrated SIMS investigations. From [10].

The improved device characteristics of TBAs-grown (AlGa)As at a low growth temperature of 625°C is underlined by the successful realization of a GaAs solar cell structure with a C-doped p-Al_{0.85}Ga_{0.15}As window layer, which demonstrated a conversion efficiency of 24.2% under AM1.5 illumination [11]. The entire layer structure was grown using TBAs at 625°C, using a V/III ratio of 10–20 for GaAs and of 2.5 for AlGaAs. In the same reactor system, the V/III ratio for hydride growth would be about 100 for GaAs and 200 for AlGaAs.

In a similar way, recent improvements in TBP quality have lead to high quality AlGaInP layer structures, which are used for high brightness visible LED and laser diode structures. These improvements are manifested by calibrated SIMS analysis of O on (Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P layer structures applied as high Al-content barrier material in the above-mentioned devices. For a wide range of growth parameters (temperatures and V/III ratios) the O-incorporation is below the SIMS detection limit of $1 \times 10^{17} \text{ cm}^{-3}$, as shown in Figure 5 [12]. This low incorporation of O in AlGaInP leads to a drastic increase in the luminescence efficiency of AlGaInP double heterostructures grown using TBP for visible LED applications. These results confirm Eberhard Veuhoff's comments that high quality AlGaInP test structures can be achieved with currently available high quality TBP.

In conclusion, recent improvements in the quality of commercially available TBAs and TBP have resulted in consequent improvements in the quality of high Al-content AlGaAs and AlGaInP structures grown using these compounds. It is expected that with further increase in demand the purchasing costs of

TBAs and TBP will be reduced. The use of these alternative materials as replacements for the highly toxic hydride gases can offer enhanced material quality and device performance in addition to improved safety. Therefore, it is anticipated that these compounds will increase their future share of the III-V MOVPE source market, provided that manufacturers can continue to reduce prices and ensure consistent supplies for high volume manufacturers.

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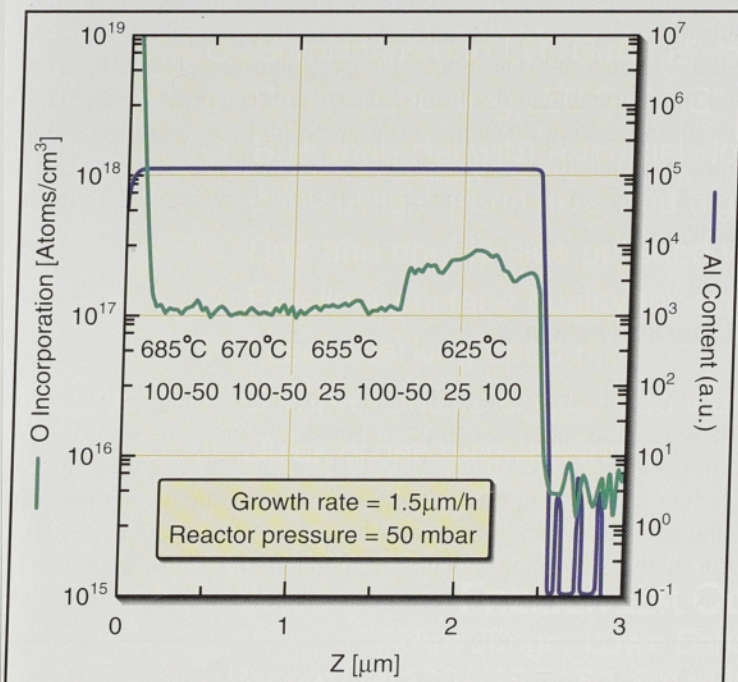


Figure 5. SIMS profile of (Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P grown using TBP. The oxygen concentration is at or below the SIMS detection limit ($\sim 10^{17} \text{ cm}^{-3}$) except for layers grown at 625°C. From [12].

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Characterization and Control of Epitaxial Material for HBT Manufacturing¹

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Nortel Networks,
Ottawa, Canada

For several years, Nortel Networks has manufactured GaAs HBTs with lattice-matched GaInP emitters exhibiting cut-off frequencies in excess of 60 GHz. They are used in high speed digital and analog ICs, including multiplexers, modulator drivers, pre-amplifiers, error correction and demultiplexers, for Nortel Networks' OC-192 (10 Gb/s) fiber-optic telecommunications systems. GaInP emitters are preferred over the more traditional AlGaAs because of greatly improved reliability, as well as better device characteristics and easier processing, including features such as a selective dry etch to the emitter layer. Extensive reliability tests have shown that the devices and circuits meet stringent telecommunications requirements, with median times to failure in excess of 10^8 hours under normal maximum operating conditions [1].

Manufacturability of such an advanced technology, in particular the ability to obtain high yield, requires precise and reproducible epitaxy. This goal is accomplished by providing fast turnaround characterization of epitaxial growth using an extensive toolkit of analytical techniques. Thickness, composition, and

doping levels throughout the structure are monitored on all wafers, as well as on some special calibration wafers, using a variety of techniques. The value of optical characterization in particular has been recognized for some time because of its precision and non-destructive nature [2].

Epitaxy

Epitaxial growth for our standard device consists of a $0.3\text{ }\mu\text{m}$ thick n^+ sub-collector, a $0.4\text{ }\mu\text{m}$ thick collector, a $0.05\text{ }\mu\text{m}$ thick p^+ base, a $0.05\text{ }\mu\text{m}$ thick GaInP n -type emitter, and a $0.2\text{ }\mu\text{m}$ thick n^+ emitter cap layer. The doping levels are $5 \times 10^{18}\text{ cm}^{-3}$ for the sub-collector and emitter cap, $3 \times 10^{16}\text{ cm}^{-3}$ for the collector, $4 \times 10^{19}\text{ cm}^{-3}$ for the base, and $4 \times 10^{17}\text{ cm}^{-3}$ for the emitter. The n -type dopant is silicon and the base dopant is carbon.

Epitaxial material is routinely grown in-house on 4-inch substrates by MOCVD and chemical beam epitaxy (CBE). MOCVD material is also obtained from an external vendor.² The use of epitaxial material from different sources proves extremely useful in tracking down and differentiating between process and epitaxy issues in the final product. Parameter targets are fine-tuned to reflect the systematic differences between wafers from different sources.

Characterization

An extensive toolkit of characterization techniques has been assembled to monitor epitaxial growth of GaAs and GaInP layers for HBT fabrication. Every HBT epiwafer is sent for resistivity measurement to monitor the highly conductive emitter cap and sub-collector regions, for particle count measurements, and for analysis by photorefectance modulation spectroscopy (PR). PR measurements provide rapid feedback on composition and

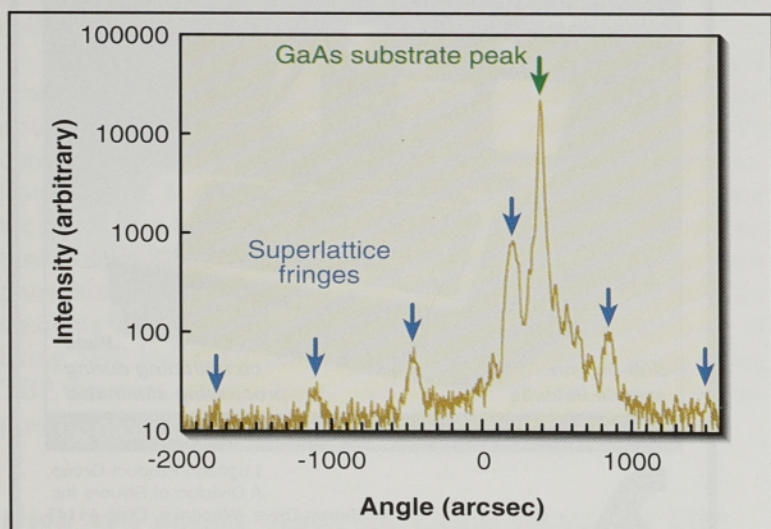


Figure 1. X-ray rocks curve from a full HBT structure. The peaks surrounding the intense narrow substrate peak are the result of the InAs/GaAs superlattice in the subcollector.

¹ 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.

² The external vendor for MOCVD-grown HBT epiwafers is Kopin.

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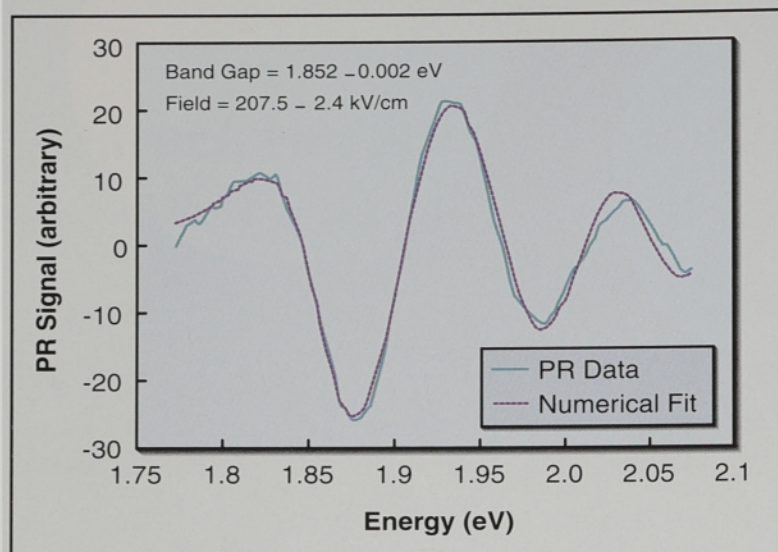


Figure 2. PR spectrum for the GaInP emitter near the emitter/base junction. The data are shown by the solid line, while the numerical fit is given by the dashed line. The parameters extracted from the fit are $E_g = 1.852$ eV and electric field = 207.5 kV/cm.

PR measurements provide rapid feedback on composition and GaAs doping levels.

Selected wafers are analyzed destructively using secondary ion mass spectroscopy (SIMS) and scanning electron microscopy (SEM) in order to determine layer thicknesses and (SIMS only) composition and doping.

Our in-house MOCVD wafers include an 8 period 5 Å InAs / 295 Å GaAs superlattice grown into the first 2400 Å of the sub-collector. The superlattice period is measured by x-ray diffraction (XRD) and acts as a growth rate and uniformity monitor. A typical rocking curve is shown in Figure 1. The peaks surrounding the intense narrow substrate peak are the result of the InAs/GaAs superlattice in the subcollector. Spacing between fringe peaks is inversely proportional to the combined InAs and GaAs layer thickness in the superlattice.

Special calibration wafers are also produced that consist of a thick (0.5–2.0 μm) GaInP layer on a GaAs wafer. These contain enough ternary material to enable photoluminescence (PL), Hall effect, and XRD measurements of bandgap, activated dopant concentrations, and lattice matching, respectively. Similar analysis is carried out on C-doped GaAs calibration samples.

Finally, PL, PR, and XRD correlate GaInP ordering with reactor-to-reactor variations in material properties. This toolkit not only measures all important growth parameters, but also pro-

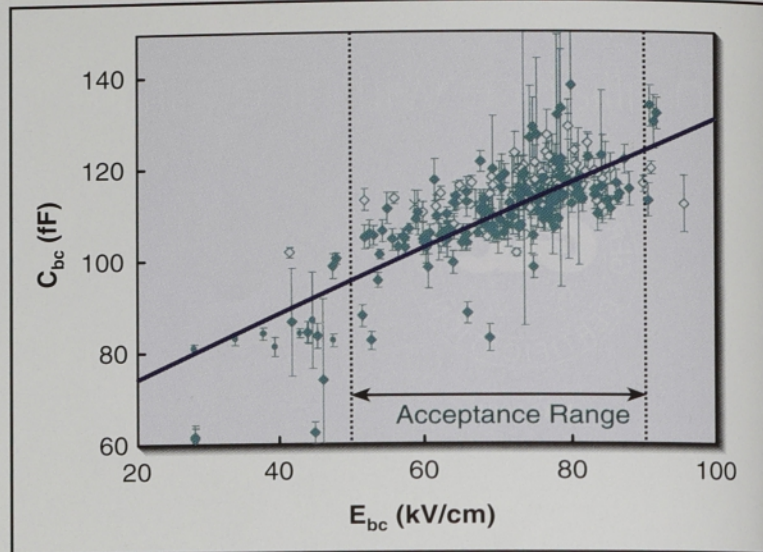


Figure 3. Correlation between base-collector capacitance measured on finished devices, and the base-collector electric field as measured by PR after epitaxial growth.

vides some redundancy to check measurement consistency, a basis for statistical process control (SPC), and correlations with device characteristics.

Photoreflectance

Photoreflectance (PR) is a non-destructive optical spectroscopic technique that provides a precise measure of transition energy and electric field in semiconductors. The dependence of optical reflectivity on illumination intensity provides insight into the dielectric function and hence into the material properties. PR is particularly sensitive at surfaces, junctions, or interfaces, and requires the presence of a (built-in or externally applied) electric field.

A typical PR spectrum for the GaInP emitter region (near the emitter/base junction) is illustrated in Figure 2. The spectral line shape is fit numerically to a theoretical expression in order to extract energy gap and electric field [4]. This procedure accounts for contributions from transitions to all three valence bands (i.e. those from the heavy hole, light hole, and split-off bands). The GaAs portion of the PR spectrum arises mainly from the collector near the base/collector junction. Since the band gap of GaAs can be assumed, a somewhat simpler analysis is used here to obtain the electric field in the collector.

The uncertainties in the extracted parameters are summarized in Table I, together with the consequent accuracy for determination of the related physical properties of the semiconductor. To obtain the accuracy values, Vegard's Law is assumed for band gap, while the emitter and collector electric fields are assumed to vary as the square root of dopant concentration. In all cases the accuracy obtained is much smaller than the acceptance range of the particular property.

We have correlated PR measurements with device characteristics. For example, Figure 3 shows a plot of base-collector

Table I

Accuracy of Photoreflectance Measurements

Parameter	Uncertainty	Property	Accuracy
Band gap	3 meV	GaInP composition	0.002
Emitter field	4 kV/cm	Emitter doping	$4 \times 10^{15} \text{cm}^{-3}$
Collector field	8 kV/cm	Collector doping	$2 \times 10^{15} \text{cm}^{-3}$

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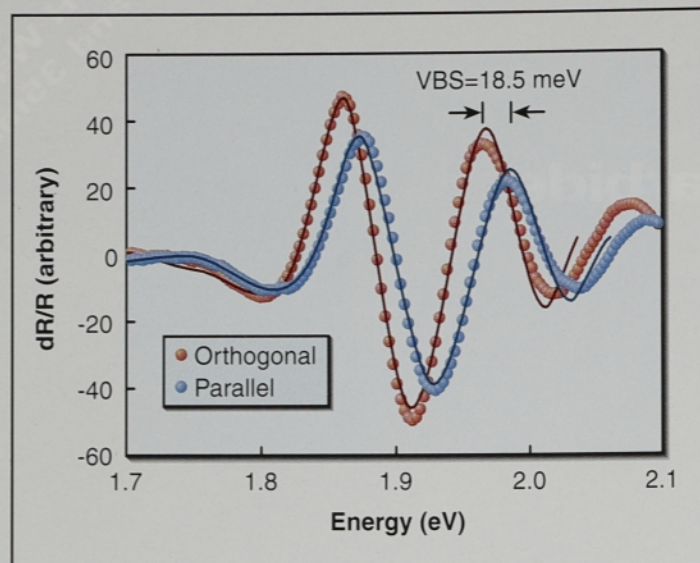


Figure 4. PR spectra for the same sample, with the incident polarized parallel and orthogonal to the $[110]$ direction. The points show the measurements, while the fits are given by solid and dashed lines. The average band gap was 1.85 eV.

capacitance measured on finished devices, compared with the base-collector field (E_{bc}) extracted from PR analysis after epitaxial growth. The acceptable range of E_{bc} values is 50–90 kV/cm.

Bandgap Centering

The bandgap obtained from PR (or from PL) does not depend solely on the composition. GaInP in particular can expe-

rience atomic ordering within the Ga-In sublattice [5]. As the order parameter η varies from fully disordered ($\eta = 0$) towards fully ordered ($\eta = 1$), where the Ga and In atoms are on alternate planes of the sublattice, there is a band gap reduction (BGR) from 1.915 eV to ~1.44 eV [6]. At the same time, valence band splitting (VBS, the anisotropy between the $[110]$ and $[1\bar{1}0]$ directions) increases from 0 to ~60 meV.

If the PR signal is measured with the incident light polarized first along the $[110]$ and then along the $[1\bar{1}0]$ directions, the difference in band gap between the two directions gives the VBS, which we then use to determine the degree of ordering [7]. Figure 4 shows the difference between two spectra taken on the same MOCVD-grown sample, but with light polarized in orthogonal directions. The VBS is 18.5 meV, which indicates an order parameter η of 0.39. The corresponding BGR is then predicted to be 75 meV, very close to the observed value of 70 meV.

We also grow HBT structures by CBE. When the polarized PR technique was applied to a CBE wafer, the VBS was only 7 meV, corresponding to $\eta = 0.23$. The equivalent theoretical BGR is 25 meV, which again agrees well with the observed reduction of 20 meV. These results imply that we are growing lattice-matched material, since, within our uncertainties, we can account for the BGR through ordering alone. Figure 5 shows selected area diffraction patterns (SADPs) from $[100]$ -oriented samples of our GaInP layers grown by MOCVD and CBE, as well as from a similar structure grown by MOCVD by an external supplier.

All three SADPs contain the fundamental diffraction spots expected for a zinc-blende material. In the case of the Nortel MOCVD sample, and to a lesser extent the external sample, additional intensity is observed at $\frac{1}{2}(\bar{1}11)$, $\frac{1}{2}(311)$, $\frac{1}{2}(331)$ and

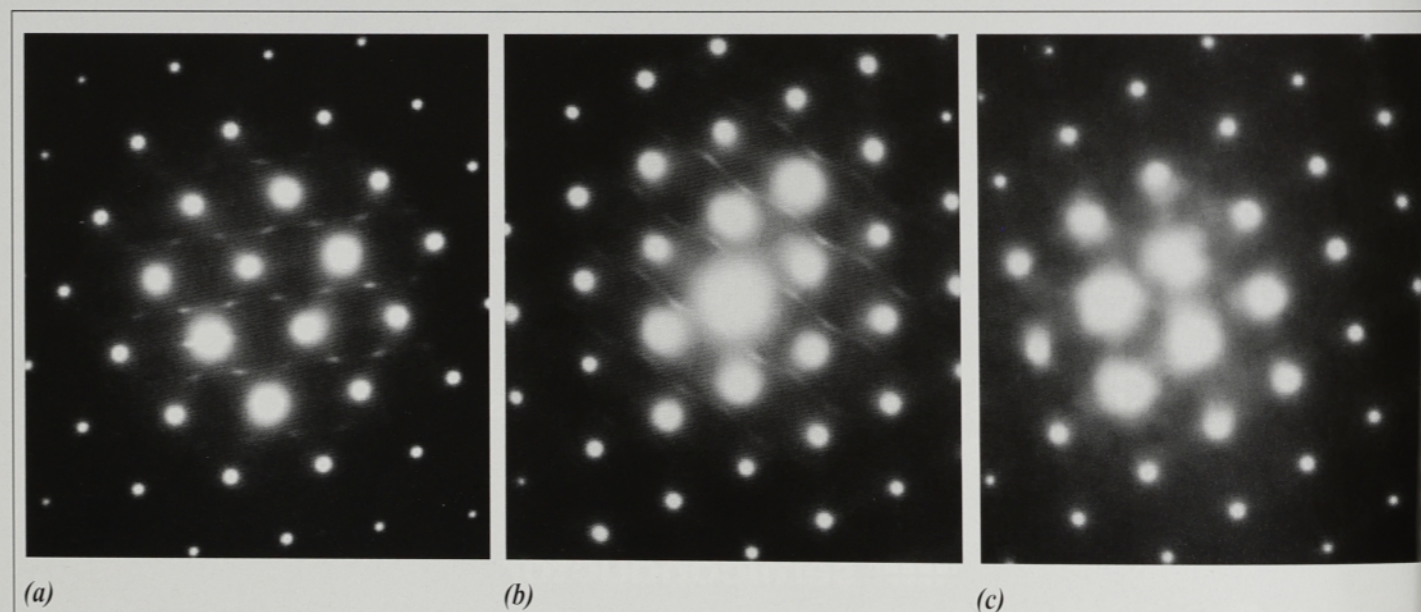


Figure 5. Selective area diffraction patterns of GaInP emitter regions, taken with a transmission electron microscope. The three samples are from material grown by (a) MOCVD at Nortel, (b) MOCVD at an external supplier, and (c) CBE at Nortel. Superlattice diffraction spots (halfway between the bright spots) are clearly seen in the MOCVD sample from Nortel, while a much longer exposure was required to make them visible in the MOCVD grown externally. They cannot be seen at all in the CBE sample.

higher order sites. These spots, and the absence of similar intensity in the corresponding [110] patterns, is representative of "Cu-Pt-type" atomic ordering [8]. Diffraction spots due to ordering are not observed in the CBE sample, corresponding to the lower degree of order (η) in this material, as indicated by the polarized PR results.

Degrees of Ordering

Because the band gap of GaInP depends on the degree of ordering, which in turn depends on the deposition equipment and growth conditions even when all material is lattice matched, we cannot have a single target specification for band gap. For example, we have a difference of 30 meV between the targets for our MOCVD and CBE material.

In order to confirm the validity of this approach, we must directly measure the degree of lattice matching for our GaInP and compare it with band gap over a reasonable range of compositions. We use XRD to measure lattice mismatch and then plot that against PL bandgap. By interpolating to zero mismatch we can directly compare the centre points for each method.

Plotted in Figure 6 are data for Nortel MOCVD, CBE, and externally grown material. Bulk GaInP samples are typically produced after source or system changes to guarantee material compliance and system calibration. These samples are 0.5–2.0 μm thick and doped with 4×10^{17} Si/cm³. An XRD measurement will return a precise measurement of epi mismatch which, assuming Vegard's Law, can then be converted to a Ga composition fraction. Note that coherent GaInP layers, lattice-matched to GaAs, contain 51.1% Ga. Plotting these data along with room temperature PL, the composition for the three sources of material are compared. The increasing target PL bandgaps at zero mismatch of 1.851 eV, 1.897 eV, and 1.899 eV for MOCVD (Nortel), MOCVD (external), and CBE correspond to the decreasing degree of order observed by PR and TEM.

Carbon-doped GaAs base Material

Without the aid of SIMS or some sort of large area device process, the determination of a correctly doped base is elusive. Therefore it is prudent to produce a bulk carbon-doped GaAs calibration sample from time to time. Nortel has performed resistivity, XRD, SIMS and Hall measurements on these samples to help guarantee consistent material quality.

Highly carbon-doped ($[C] > 4 \times 10^{18} \text{ cm}^{-3}$) GaAs is a pseudomorphic material due to the lattice contraction caused by the small carbon atom on the group V lattice site. In addition, a relative lattice expansion is caused by the presence of hydrogen, which is (suspected to be) chemically bonded to carbon. Care must be taken to appropriately anneal the sample to remove hydrogen prior to analysis. The effect of annealing p-GaAs is a relative shift to higher strain for a given total amount of carbon.

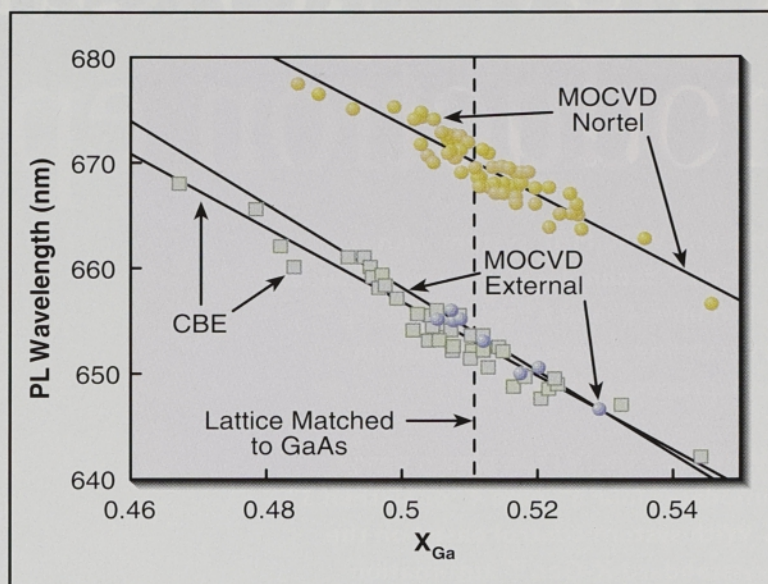


Figure 6. Bulk GaInP sample correlation for material grown in-house (MOCVD Nortel, CBE) and externally (MOCVD external). InGaP composition is determined from XRD measurements of lattice mismatch.

The active carbon concentration (from Hall measurements) and total carbon concentration (measured by SIMS) in the lattice can be correlated with XRD measurements of lattice mismatch. To simplify p-GaAs calibration measurements, it is possible to use the above correlation to XRD data along with sheet resistance to ensure proper layer thickness and doping level. If this calibration procedure is used between batches of runs, we can guarantee HBT material compliance to spec.

Acknowledgements

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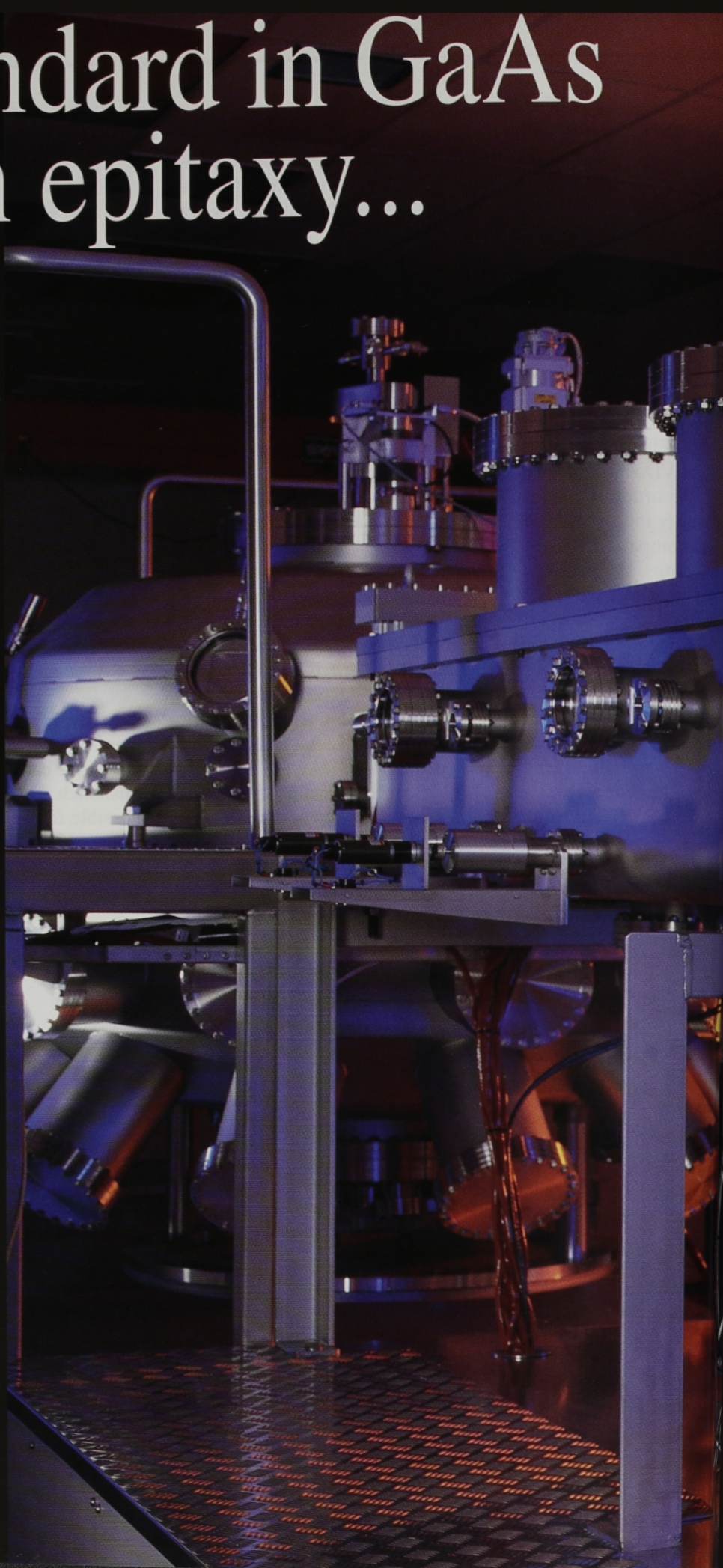
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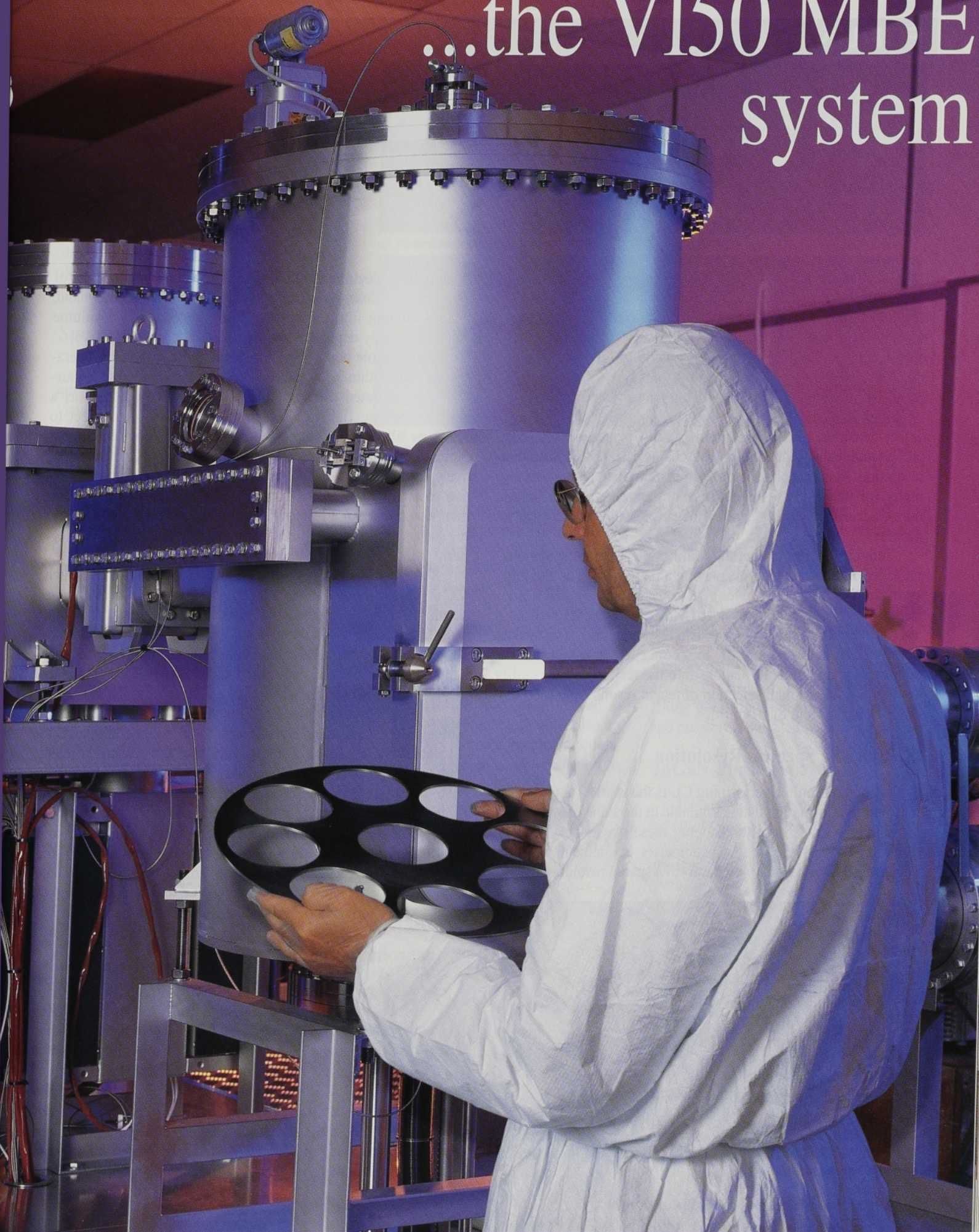
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Cathodoluminescence Studies of III-Nitrides

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Regular readers of *Compound Semiconductor* magazine will be familiar with the ever-expanding market for optoelectronics, which is needed to satisfy the world's insatiable appetite for increased information storage capacity, communications, and displays. Although a familiar story to many, the speed of progress in growth, fabrication and applications of group-III nitrides has taken many people by surprise.

As these novel materials are complex and often contain high defect densities, greater demand has been placed on scanning probe techniques to provide optical characterization with spatial resolution. Accurate characterization is more than just producing pretty (or not-so pretty) pictures. With complex growth procedures, accurate feedback, even if negative, can prove critical to progress.

Judging by recent literature and conference presentations, cathodoluminescence (CL) is playing a major role. The flexibility of the electron probe gives rise to easy focusing and a high depth of field compared to near-field techniques, as well as a useful injection source for wide bandgap materials. This article briefly introduces some of the concepts involved in CL microscopy, and aims to demonstrate the technique's versatility by highlighting a small selection of recent results from top laboratories in the field of III-nitrides.

Spatial and Spectral Resolution

A key reason for performing CL is the spatial- and spectral-resolution information that is available in the same experiment. It is therefore worth briefly recapping these two issues. An SEM spot size is, at best, a few nanometers in diameter, and this determines the secondary electron (SE) spatial resolution. This is

because these electrons originate from the top few nanometers of material, very close to the electron beam spot. On the other hand, photons ranging from X-rays to CL are generated in a volume which is strongly dependent on the accelerating voltage (kV).

Electron-hole pair generation occurs within the CL generation volume within a few picoseconds (ps). Like a crowded airport, the generated carriers end up either moving about (as a result of electric fields or diffusion effects), or are subject to delays or alternative routings, (non-radiative recombination or captured by traps). Leaving the airport analogy, CL is, collectively, the UV, visible or IR photons generated as a result of radiative recombination of electron hole pairs which exit the specimen; those that don't (up to 95%) are re-absorbed on the way to the surface or on the way back after suffering total internal reflection.

The depth of the pear shaped generation volume in which CL is created follows the relationship $z \sim (kV)^{1.7}$, where z is the depth. To a first approximation, this also represents the width, and therefore a pre-diffusion lower limit of the CL spatial resolution. Reducing the accelerating voltage from 30 to 3 kV reduces z by a factor of 50, and hence the CL spatial resolution is highly dependent on the chosen accelerating voltage.

The spectroscopy side of CL is similar to PL experiments, although the luminescence can be in short supply compared to PL due to the small stimulated volume. For this reason, efficient light collection and coupling to dispersive elements and sensitive, cooled detectors becomes important. Now is not the time to panic! CL is relatively straightforward, especially for bright luminescent materials. However, the experimental configuration and variables are important as they can determine the validity of the experiment, i.e. where the electron hole pairs are generated, where radiative recombination may occur, and whether the photons survive to reach the outside world for detection.

Panchromatic Images

In a review of ICNS-3 (third Nitride Semiconductor Conference, July 1999) in Montpellier, Professor Monemar joked that theoreticians have started predicting states in the band gap to match experimental evidence of non-radiative recombination at dislocations! As proof, Sugahara et al [1] recorded SEM CL and TEM images from low dislocation density GaN, showing that individual dislocations act as non-radiative recombination centers. The strength of these results lay in finding the same individual dislocations in the SEM and TEM after transferring between instruments, as shown in Figure 1. The TEM specimen

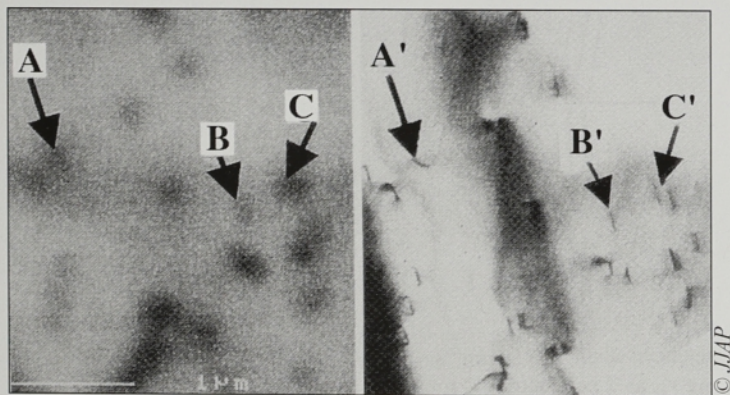


Figure 1. Matching SEM CL and TEM image of the same individual dislocations in GaN [1].

enhanced the SEM CL spatial resolution as a result of its very small sampling volume, and thus restricted the size of the material available to participate in luminescence. Also, a difference in the darkness of the CL spots depended on dislocation separation. This was interpreted as proof of a short diffusion length (~ 50 nm), a value which was the typical distance distinguishing those neighboring dislocations which acted strongly in tandem (C), to those which were isolated and therefore acted less strongly (A, B).

Spectroscopic Images

Monochromatic imaging is very quick and powerful. The images can be viewed in sequence, or alternatively overlaid with different colors to show spectral luminescence features in one image. Researchers at Linköping University have been pursuing HVPE growth of GaN on sapphire to achieve relatively thick, uniform films. Sequential monochromatic CL images close to the band gap (with 1 nm bandpass) are shown in Figure 2. Areas showing small blue-shifted luminescence are interpreted as being associated with strongly degenerate n-type material. The high energy tail of the CL spectrum from certain areas is modeled [2], quantifying the carrier concentration to be in the range 10^{18} - 10^{19} cm³.

In plan view, the triangular features seen in cross-section are almost hexagonal. Two images recorded at 355 nm (blue tint) and 356 nm (green tint) are overlaid in Figure 3b. The center of the defect is highly degenerate compared to the area close to the rim, which shows stronger excitonic luminescence.

Alternatively, a specialized mode of CL, sometimes termed CLWI or CL wavelength imaging, can record spectroscopy at each image pixel. This technique is also powerful but can be very time consuming [3,4]. Bertram et al have recently published beautiful CLWI images (see Figure 4) which characterize cross-sections of epitaxial layer overgrown (ELOG) structures. Micro-Raman confirms and quantifies some of the results, which highlight the significant differences in impurity and carrier concentration, as well as the stress state between overgrown areas on top of the

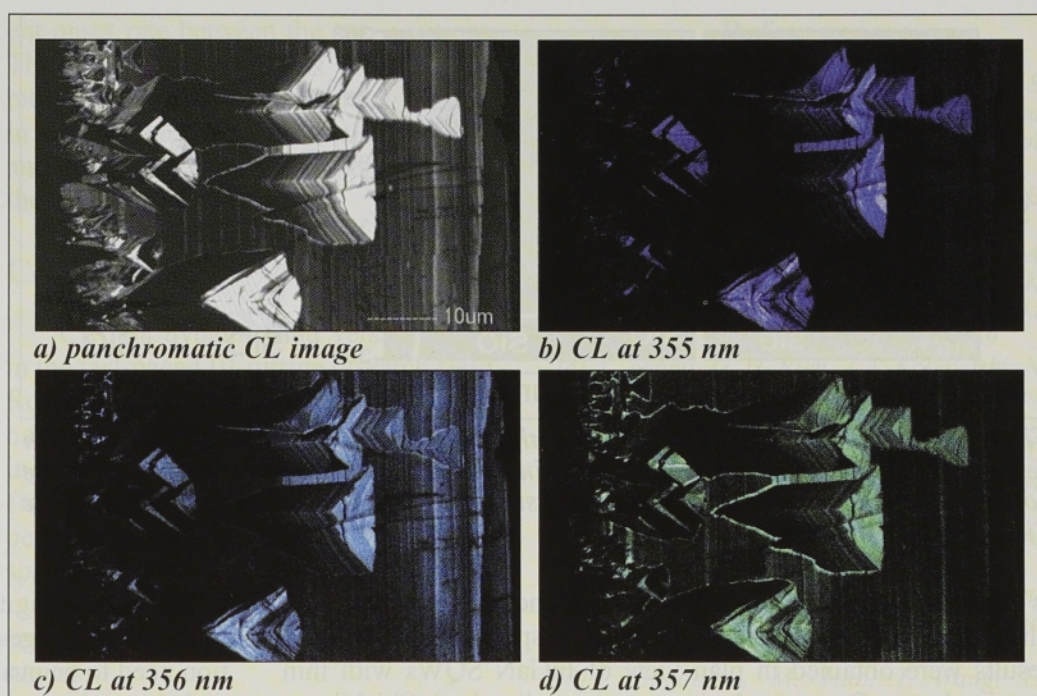


Figure 2. Panchromatic and false color CL images of cross sections of HVPE GaN.

SiO₂ stripes and the coherently grown region between the stripes. Of note are the significant differences in the GaN CL spectra between 354 nm and 364 nm (when recorded at 5K) from regions microns apart, which are due to the complex growth and relaxation mechanisms.

Quantum Dots

Quantum dots may prove critical in causing a low threshold current for lasing action in nitride-based heterostructures, and much research is being conducted in this field. Although high density dots are difficult to resolve (especially in capped material), much can be deduced from comparing spot to raster-mode spectra. At Lund University, CL was recently record-

ed from individual uncapped GaN dots grown on AlGaIn [5]. The luminescence was found to be weaker than expected with a strong size-intensity correlation, but virtually no color variation (~ 2 meV). The dot CL was believed to be dominated by carrier injection at the dot rather than diffusion of remote carriers to the dot (as in other material systems). Also unexpected, the FWHM was not a function of the filling of dot states but integral to the dot, and possibly associated with Si impurities.

InGaIn Phase Separation

InGaIn alloys and quantum wells are the corner stone of visible light and laser emission in III-nitride materials. However, the material physics of InGaIn

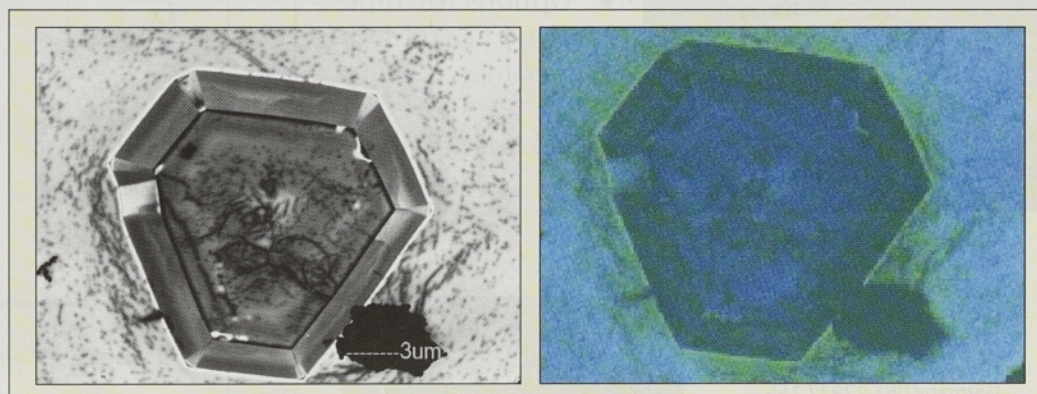


Figure 3. Plan view panchromatic and overlaid (355 nm blue and 356 nm green) CL images of HVPE GaN.

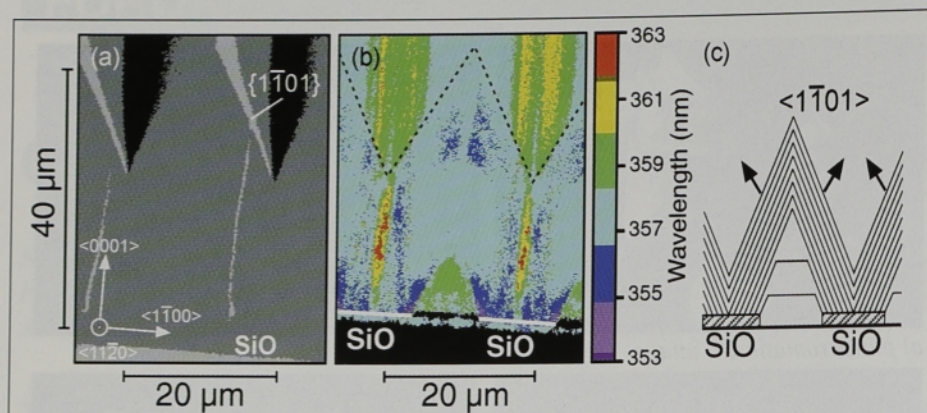


Figure 4. a) SE image and b) CL wavelength image (CLWI). The two different growth regions indicated in the schematic drawing are clearly visible in the CLWI - the coherently grown area between the SiO₂ stripes and the overgrown area above the SiO₂ stripes (region of coalescence).

is still much debated because of the tendency of the material to phase-separate during growth. Key high spatial resolution CL results were obtained in plan view of InGaN SQWs with thin capping layers. For example, in separate studies, both Chichibu et al [6] and Ponce et al [7] noted a large reduction in the CL FWHM between spot and raster-mode spectra. Furthermore, spot-mode spectra often consisted of multiple sharp emission peaks corresponding to several nanoscale structures having different band gap energies.

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High resolution spectroscopic CL imaging has illustrated the importance of threading dislocations in the mechanism leading to compositional fluctuations in InGaN quantum wells [8]. Dislocations with screw components were found to be associated with minute regions of higher indium concentration. Also striking are the recent CL images of InGaN quantum wells grown homoepitaxially on low dislocation density GaN. No comparable phase contrast features are evident, further emphasizing the role of dislocations as a driving force for localized In-rich and In-deficient areas.

In plan view SEM CL studies, increasing the accelerating voltage is a versatile way of increasing the depth penetration. However, correct interpretation of images requires care as both generation and absorption need to be evaluated. Fleischer et al [9] modeled generation and absorption profiles in GaN material. A comparison of a predicted accelerating voltage dependence of the band-edge blue (2.8 eV) and yellow emission (centered at 2.2 eV) for a homogeneous specimen with those actually recorded prove the yellow luminescence to increase with depth.

Depth profiling and Beam-Induced Changes

With characterization techniques, a general rule is to avoid beam-induced changes to specimens, e.g. by reducing the electron beam flux. This rule exists because interpretation is easier if the 'goal posts' are stationary! In unpublished work by the present author, InGaN SQW luminescence showed intriguing beam-induced changes when recorded at 5 K using a CCD camera for fast spectroscopy, as shown in Figure 5. The initial CL peak intensity reduced quickly, while a second peak, blue-shifted by 11 nm, grew in its place. This effect was persistent and is still not understood.

Longer timespan electron beam irradiation experiments on n-doped GaN have been published [10]. Under continuous irradiation

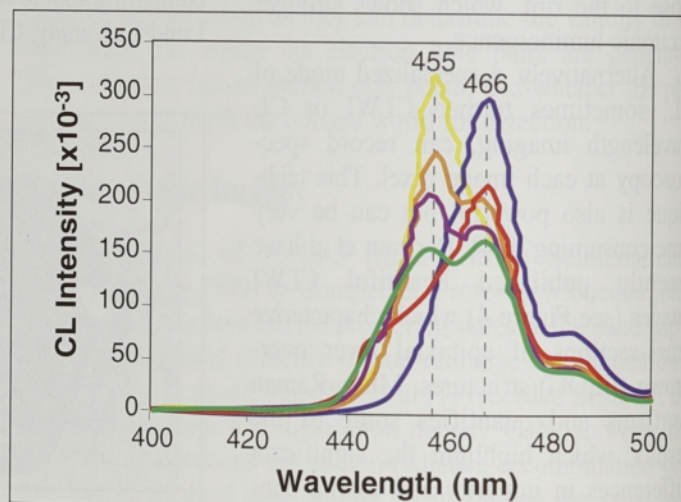


Figure 5. Six CL spectra obtained from a SQW InGaN, recorded in sequence as a function of irradiation time at 5 K.

diation, complex and different changes in the Donor Bound Exciton, Donor Acceptor Pair, and blue and yellow mid-gap luminescence states were recorded and were explained by electromigration of O_N^+ and H^+ . The filling of traps beneath the stationary electron beam spot created an electric field which induced diffusion of charged species. The diffusion of oxygen was corroborated with wavelength dispersive X-ray data. Either as a result of limited study or (more likely) under-reporting, not enough is known about the effects of the electron beam.

Time Resolved CL

Using time-correlated single-photon counting with a fast beam blanker, impressive time-resolved CL can be achieved. For example Zhang et al [4] have studied carrier relaxation in InGaN SQWs with a time resolution of ~ 100 ps. The CL showed different transients between a bright exciton localization center and a dark boundary, and also a differ-

ent onset rate between the two positions. These were interpreted as showing non-radiative recombination reducing lifetime in the boundary region, and also diffusion and drift to the InN-rich centers, delaying the transient slightly.

Conclusions

CL is a dynamic and versatile asset in the fast-paced III-nitride research field. Recently, a reduction in defect densities has meant laboratories now admit to having defects (in their specimens) in the first place! Progress will most likely occur with increased emphasis on high spatial resolution (TEM CL) and time resolved work, with perhaps greater emphasis on results from combined techniques.

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Sanders' QWIPs Detect Two Colors At Once

TIM WHITAKER

Infrared imaging, widely used by the military, is now finding many uses in the commercial world, such as predictive maintenance, industrial process control, medical imaging, search and rescue, enhanced vision systems for pilots, and research and development. The highest resolution IR imaging cameras are still fabricated using mercury cadmium telluride (MCT) focal plane arrays. In recent years, QWIPs — quantum well infrared photodetectors — have emerged to challenge MCT devices. These detectors, fabricated from multi-quantum well III-V heterostructures, are now commercially available from Sanders, a Lockheed Martin company, and from QWIP Technologies.¹

According to Tom Faska, Department Manager for QWIPs development at Sanders in Nashua, NH, single color QWIP arrays are available on a commercial basis, in both 320×256 and 640×480 formats. The QWIPs group is part of the Integrated Optoelectronics directorate within Sanders. Inframetrics (Billerica, MA), which was recently bought by FLIR Systems, has already incorporated QWIP detector manufactured by Sanders into demonstration versions of the MilCAM handheld camera.

Using the advanced growth and fabrication processes available through its GaAs foundry, Sanders routinely fabricates 320×256 single color QWIP focal plane arrays for detection in the long-wave IR² region at $8.6 \mu\text{m}$. The detectors

demonstrate >99.5% pixel operability, <3% uncorrected non-uniformity, and a fill factor of 87%. The median noise equivalent temperature difference (NETD—the minimum temperature change in a scene required to produce a signal equal to the rms noise) is less than 20 mK. Figure 1 shows the excellent image quality available using this QWIP detector.

Two Color QWIPs

During epitaxial growth, it is possible to fabricate QWIPs (and MCT detectors) with two separate sections, each tuned to detect a different wavelength. Sanders was first to fabricate 2-color, 256×256 QWIP focal plane arrays in each of four important combinations — LW/LW, MW/LW, NIR/LW and MW/MW — with simultaneous integration. This means that the signals from the two colors can be measured at the same time, rather than alternately. "Vertical stacking of the QWIP detectors gives spatial registration of the signals, and simultaneous integration gives temporal registration," explains Tom Faska. "This is very important for 2-color detection and provides much better absolute temperature measurement capability." Although a single-color detector records the radiant emittance of a target, the temperature cannot be deduced because the target's emissivity is unknown. A 2-color detector gives 2

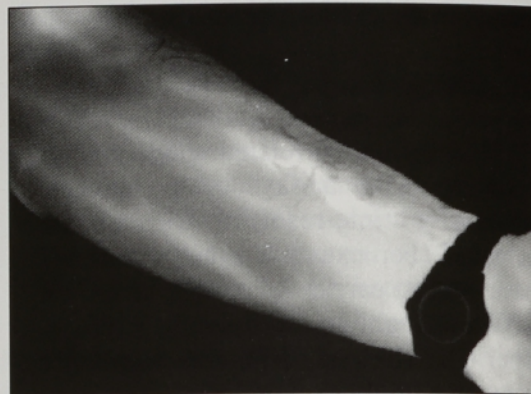


Figure 1. Image from a 320×256 LW QWIP focal plane array with a noise equivalent temperature difference of less than 20 mK.

points on wavelength-emittance curve, allowing a semi-absolute temperature measurement to be made.

The various types of 2-color detector were developed by Sanders for military applications. "The LW/LW detector was developed for a BMDO [Ballistic Missile Defense Organization] strategic interceptor program," says Faska. "For example, the 2-color QWIP is able to differentiate between a missile and its exhaust plume, which have widely different temperatures." The MW/MW device was developed to improve clutter rejection in missile warning systems. "There is a great deal of solar reflection in the mid-wave IR region," explains Faska. "By processing two signals at different wavelengths, the false alarm rate can be reduced dramatically."

Sanders plans to commercialize the 2-color MW/LW technology next year and will provide focal plane arrays or integrated assemblies to camera manufacturers, for applications such as industrial process control where semi-absolute temperature measurements are valuable.

¹ QWIP Technologies was formed recently as a joint venture between Rainbow Group of Companies and ViaSpace Technologies. ViaSpace holds the exclusive license from CalTech to manufacture QWIP detectors based on technology developed at NASA's Jet Propulsion Laboratory (JPL).

² Long-wave infrared (LWIR or LW) usually refers to the $8\text{--}14 \mu\text{m}$ band. Mid-wave IR (MWIR or MW) is $3\text{--}5 \mu\text{m}$, near IR (NIR) is $\sim 0.9\text{--}1.7 \mu\text{m}$.

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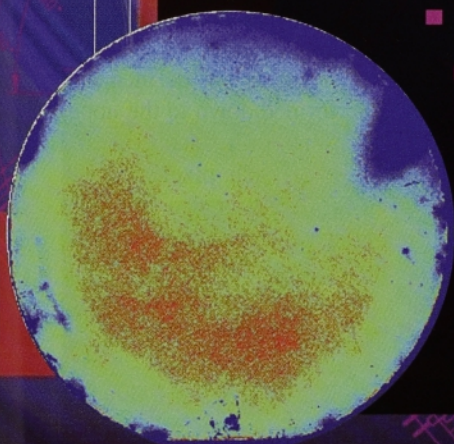


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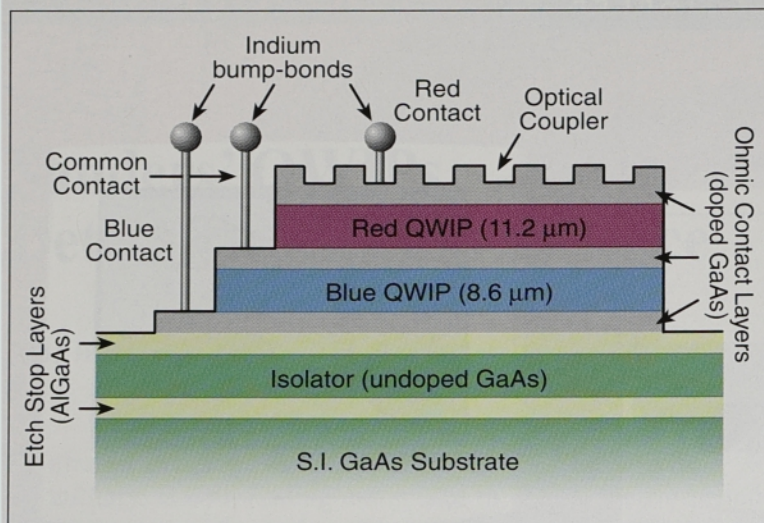


Figure 2. Schematic showing the structure of a 2-color stacked QWIP with contacts to all three ohmic-contact layers. The top etch stop layer allows electrical and optical isolation between all pixels. The isolator layer provides physical support for the pixels in the array. Indium bump-bonds, one at each contact (blue, red, common) are used to bond the detector array to a CMOS read-out IC. The bottom etch stop layer facilitates substrate removal after hybridization. Radiation enters the detector from below (as drawn here). The optical coupler scatters internally reflected light to increase coupling with the quantum wells.

QWIP Design and Manufacturing

QWIPs with a peak detection wavelength exceeding $6.5\ \mu\text{m}$ are fabricated in the GaAs/AlGaAs material system, using MBE-grown multilayer heterostructures. One reason for the success of QWIPs is the control afforded by MBE growth of GaAs/AlGaAs multilayers, compared to the difficulties of working with MCT. Also, a number of standard GaAs wafer-level processes, such as stepper lithogra-

phy and dry etching, can be used to provide high uniformity and reproducibility.

"Mercury cadmium telluride detectors have higher quantum efficiency and therefore higher performance than QWIPs," says Tom Faska. "The big disadvantages with MCT are problems with uniformity and manufacturability, while these are strong points for QWIPs. In the commercial arena and in some military applications where ultimate performance is not required, QWIPs have a big advantage in terms of cost."

Generally, GaAs/AlGaAs QWIPs are multi-quantum-well

heterostructures containing doped GaAs wells separated by barriers of bulk AlGaAs (in the case of bound-quasibound devices) or a GaAs/AlGaAs superlattice (for mini-band transport devices). In both device types, an incoming photon excites an electron from a ground state deep within the quantum well, to an excited state resonant with the bottom of an energy continuum or a miniband. The electron is swept out along the miniband or continuum by an externally applied electric field, producing a photocurrent.

The spectral response (peak position and width) of the QWIP is controlled by the GaAs well width and the barrier composition. The use of strained InGaAs in the QWs allows wavelengths as short as $\sim 4.0\ \mu\text{m}$ to be detected, while shorter wavelengths require the use of InGaAs/InAlAs lattice-matched to InP.

Fabrication of 2-Color QWIP Focal Plane Arrays

Devices capable of simultaneously detecting two separate wavelengths can be fabricated by vertical stacking of the different QWIP layers during epitaxial

growth. Separate bias voltages can be applied to each QWIP simultaneously via the doped contact layers that separate the MQW detector heterostructures.

Sanders has demonstrated several types of 2-color QWIP array, and the fabrication of a LW/LW device with peaks at $11.2\ \mu\text{m}$ and $8.6\ \mu\text{m}$ is described here. The device epilayers were grown by MBE on 3-inch semi-insulating GaAs substrates. An undoped GaAs layer (called an isolator) was grown between two AlGaAs etch stop layers, followed by an ohmic contact layer of doped GaAs. Next, the two QWIP heterostructures were grown, separated by another ohmic contact layer, with the $11.2\ \mu\text{m}$ structure (red QWIP) grown above the $8.6\ \mu\text{m}$ structure (blue QWIP). Each QWIP is a 20-period GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ MQW stack in which the thickness of the Si-doped GaAs QWs and the Al composition (x) of the undoped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers ($\sim 550\text{--}600\ \text{\AA}$ thick) is adjusted to yield the desired peak position and spectral width. A top contact layer completes the structure, shown in Figure 2.

Due to quantum selection rules, the QWs can only absorb radiation with a polarization component perpendicular to the growth direction. To increase scattering of normally-incident radiation, which is not absorbed, the top surface is patterned with a regular 2D optical coupler, using reactive ion etching. A 256×256 pixel array (pitch = $40\ \mu\text{m} \times 40\ \mu\text{m}$, pixel size = $39\ \mu\text{m} \times 39\ \mu\text{m}$) was defined, and etching was performed down to the upper etch stop layer to ensure electrical and optical isolation of each pixel from its neighbors. Each pixel was also etched to allow metal contacts to be attached to the different ohmic contact layers.

Indium bumps, 3 per pixel, were placed on the metal contact pads (see Figure 3). The wafer was diced, and suitable 256×256 arrays were In bump-bonded to the matching read-out IC. After this hybridization step, the substrate was removed by a $\text{SF}_6/\text{SiCl}_4$ backside dry etch through to the bottom AlGaAs etch stop layer. This is necessary to reduce optical crosstalk between pixels, and also to reduce thermal stress. Typical operating temperatures for QWIP detectors are in the region of $40\text{--}100\ \text{K}$, and the silicon ROIC and III-V detector have very different thermal expansion coefficients.

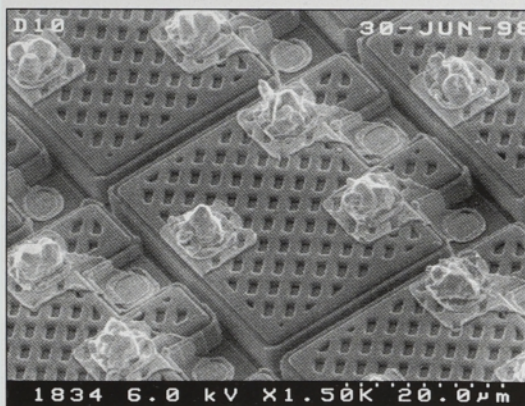


Figure 3. Section of a 2-color QWIP focal plane array after indium bump deposition, ready for hybridization to a CMOS read-out IC.

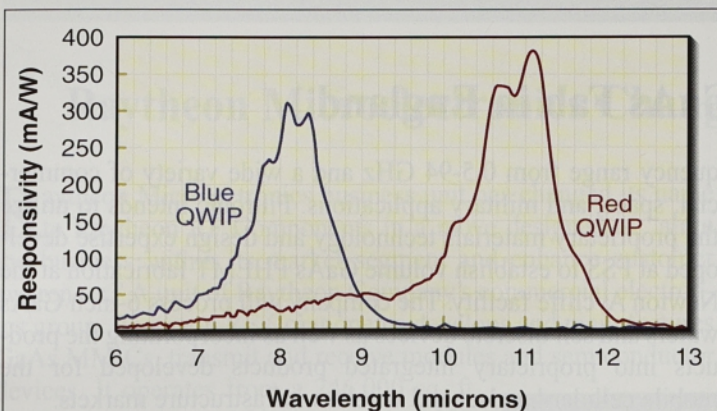


Figure 4. Typical responsivity spectra at 40 K and a common bias of 1.5 V, recorded simultaneously for two QWIPs in the same pixel.

able to apply the same bias to both colors. As shown in Figure 4, the responsivity of both QWIPs is around 300–350 mA/W under these conditions. The peak conversion efficiency approaches 5% for the blue QWIP and 7% for the red QWIP.

The peak quantum efficiency for each of the 20-period QWIPs was estimated to be ~10%. In comparison, a normal 1-color QWIP with twice the number of periods has a QE of around 20%, showing that the complex 2-color processing has not compromised the electrical or optical quality of either color in the 2-color device.

After hybridization to an ROIC, initial 2-color FPAs showed a pixel operability for each color of >97%, compared to the value of >99.5% routinely achieved for single-color QWIPs. Early arrays were incompletely thinned, and the ~30 μm thick residual substrate was thought to induce thermal stress. The NETD value was 24 mK for the blue QWIP and 35 mK for the red QWIP. The difference was assigned to the poor transmission properties of the optics in the 11.2 μm band.

Both MW/LW and MW/MW 256 $\times$ 256 QWIP focal plane arrays have also been fabricated at Sanders. The MW/LW device consisted of an 8.6 μm (LW) GaAs/AlGaAs QWIP on top of a 4.7 μm (MW) strained InGaAs/GaAs/AlGaAs heterostructure. The fabrication process allowed fill factors of 85% and 80% for the MW and LW detectors. The first focal plane arrays with this configuration had an operability in excess of 97%, an NETD value better 35 mK, and excellent imagery

in each color (see Figure 5).

Large format (640 $\times$ 512) 2-color QWIPs are now being developed in all three wavelength combinations: MW/LW, MW/LW and MW/MW.

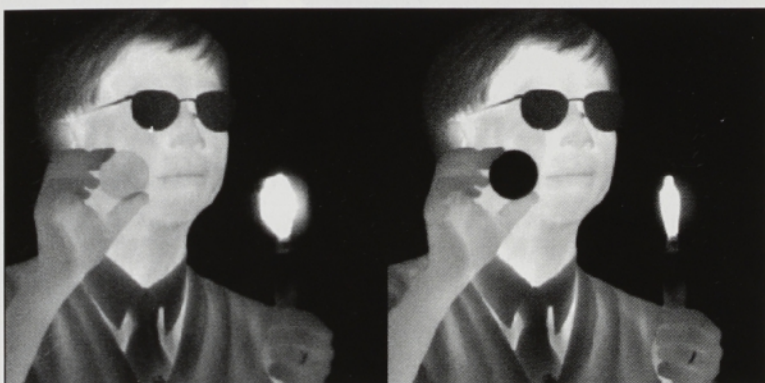


Figure 5. Simultaneous images from a 256 $\times$ 256 MW/LW QWIP focal plane array. Note the appearance of the filter and the soldering iron in the two bands.

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2-Color Performance

The performance of the LW/LW 2-color QWIP was measured, on a single pixel test device, at a temperature of 40 K, and at an operating bias of +1.5 V applied to the common contact. The bias across each QWIP can be adjusted separately, although it is desirable

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Filtronic Plans 6-Inch GaAs Fab in England

Filtronic plc, the UK-based parent of Filtronic Solid State, has announced plans to build a new 6-inch GaAs fab at Newton Aycliffe, County Durham, England. The fab will occupy a 310,000 sq. ft. facility, including a 100,000 sq. ft. Class 10 clean room, which was originally built by Fujitsu for silicon DRAM manufacturing. The agreement to purchase the facility from Fujitsu is conditional upon Filtronic receiving financial assistance from the UK government.

Filtronic, a world leader in microwave technology and supplier of cellular handset and base station components, already operates a 3-inch GaAs fab at its US subsidiary, Filtronic Solid State (FSS). This facility, in Santa Clara, was acquired from Litton in October 1998. Standard products include MMICs, FETs and Gunn Diodes in both GaAs and InP covering the fre-

quency range from 0.5-94 GHz and a wide variety of commercial, space, and military applications. Filtronic intends to utilize the proprietary materials technology and design expertise developed at FSS to establish volume GaAs PHEMT fabrication at the Newton Aycliffe facility. The company will process 6-inch GaAs wafers and sell discrete devices as well as incorporating the products into proprietary integrated products developed for the mobile cellular handset and wireless infrastructure markets.

"We are delighted to agree terms with Fujitsu for the acquisition of such a high quality facility, which will rank amongst the first and largest 6-inch GaAs foundries in the world," says David Rhodes, Executive Chairman of Filtronic plc. "I believe that GaAs will have the same impact on the information technology and communications revolution as silicon has had in the past."

RFMD to Build Second GaAs HBT Fab

Not content with expanding its existing GaAs HBT fab to handle 50,000 4-inch wafers per year, RFMD has announced plans to build a second fab capable of producing four times that

volume. The new fab will be located near RFMD's existing facility in Greensboro, NC, and will be constructed in two phases. The first phase will be completed in late 2000, and will provide a full capacity output equivalent to 60,000 four-inch wafers per year.

The second phase should be completed late in 2001 and will bring the total capacity of the new fab to the equivalent of around 210,000 four-inch wafers per year. According to a company spokesperson, the new fab will allow RFMD to expand capacity for current customers, address new customers and markets, reduce product costs and enhance the company's competitive position. The cost of the 130,000 square foot facility will be approximately \$250 million. Financial incentives from city, county and state governments played a part in RFMD's decision to locate the facility in Greensboro.

Anadigics 6-inch Fab Commences Production

In late July, Anadigics announced that its top two customers have accepted and will receive production shipments of key high volume products from its newly completed 6-inch GaAs fab (Fab 2). Anadigics announced plans for the world's first 6-inch GaAs analog fab in December of last year. It accelerated the development of the 6-inch fab in order to lower cost structures, improve efficiency, and increase capacity. "This world-class facility enables Anadigics to better serve the needs of our customers by delivering high quality products with shorter time to market," comments Bami Bastani, president and CEO. The new facility is currently being used for GaAs MESFET and PHEMT processing. In addition, Anadigics is developing in-house HBT manufacturing capabilities, which the company plans to implement in Fab 2.



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Raytheon Microelectronics Changes Name, Introduces HBT Products

Raytheon Microelectronics business unit has changed its name to Raytheon RF Components in a move designed to "align the business within its market segment and enhance customer awareness." A unit of Raytheon Company's commercial electronics group, Raytheon RF Components develops and manufactures GaAs MMICs, transmit and receive modules and semiconductor devices. It operates from a 246,000 sq. ft. facility in Andover, MA, opened in 1988, and produces fully assembled and tested microwave circuits for use in commercial wireless products, advanced military radars and satellite-based communication systems.

The company has recently focused a great deal of attention on mobile phone MMICs as a key high volume market for its products. "Our strategy to become a leading component supplier to the wireless marketplace," says Charles Krumm, Raytheon RF Components' general manager. Sources say that Raytheon's GaAs wafer fabs are currently producing over 500,000 ICs per week. Raytheon recently introduced its first HBT-based ICs and modules for mobile phone handsets (see below), which join an extensive line of PHEMT-based power amplifier products. The company also introduced its first base station power amplifiers, again based on PHEMTs. Raytheon's product line for this market also contains a series of MESFET-based driver amplifiers and upconverters.



HBT and Base Station Products

Raytheon has transitioned its advanced HBT-based power amplifier circuits to high volume production for mobile phone handsets, joining an ever-growing list of companies manufacturing HBT-based ICs. "These products provide better performance at lower cost, which is what our customers have demanded," says Charles Krumm. The new components operate at 3.5 V, and include a matched PA module for the cellular frequency band, providing a PAE of 60% in the AMPS mode and 35% in the CDMA mode, and a matched PA module for PCS, featuring a PAE of 35% at P_{out} of 29 dBm. Raytheon has also introduced its first base station power amplifiers. The PHEMT-based products provide highly linear and efficient sources for cellular/PCS wireless local loop transmitters, and micro- and pico-cell base station transmitters. Two of the products are 2 W linear output power components with a PAE of 25%, for use as a driver stage for wireless base stations or as the output stage for micro- and pico-cell base stations. The other products are 5 W components, also offering 25% PAE. Several dual-band multimode power amplifiers have also been added to Raytheon's line-up of PHEMT-based handset PAs.



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Sanders Supplies Mm-Wave Transceivers for Missile System

Sanders, a Lockheed Martin Company, has received an award valued at \$43 million for continued production of millimeter-wave transceivers for the Longbow Hellfire missile system. Sanders will build 4,200 Ka-band transceivers based on GaAs MMICs for Lockheed Martin Millimeter-wave Technologies, Inc. The transceiver is installed in the sensor head of the missile, where it transmits and receives signals to detect and track targets, and relays information to the missile seeker for additional tracking, guidance and engagement. Deliveries are scheduled to begin in April 2000 and will be completed in February 2002. Sanders has already produced more than 1,000 Longbow Hellfire transceivers under earlier contracts. The Longbow Hellfire missile system is deployed on U.S. Army AH-64D helicopters and will be installed on United Kingdom Army WAH-64 Apache helicopters.

Vitesse Gets ISO9001 Certification, Partners with ASIC Design House

Vitesse Semiconductor recently received certification to the ISO9001:1994 standard for its Pierre Lamond fabrication facility in Colorado Springs, CO. The certification covers Vitesse's design center, support functions and the world's first production 6-inch GaAs wafer fab.

In other news, a German company, ht-Mikroelektronik GmbH, has become the first authorized Vitesse ASIC design house. An independent IC design house with offices in Duisburg and Dortmund, ht-Mikroelektronik will assist with Vitesse ASIC design activities throughout Europe. The company will utilize Vitesse's H-GaAs technology and foundry to produce the ASIC designs, and will retain the ownership and selling rights of the ASICs. ht-Mikroelektronik has 30 employees, and supports all levels of an IC design project, including concept specification, design entry, simulation, layout, test program development and prototype evaluation.

RFMD Reports 100 million PAs Shipped, Healthy Handset Sales

RFMD recently announced the shipment of its 100 millionth power amplifier. The company stated that its GaAs HBT technology accounts for a significant proportion of PAs sold for cellular, CDMA and GSM. Other wireless applications using RFMD PAs include point-of-sale terminals, wireless meter reading equipment and wireless security systems.

The company is continuing to experience significant growth in sales of its silicon- and GaAs HBT-based RFICs to Korean handset manufacturers. The company reports that shipments to

"The Lighter Side of Fabrication"

A closer look inside a 72" wafer fab



Ron Smith

"I don't know what happened, it just fell off the wand!"

major customers in Korea, including LGIC, Hyundai and Samsung, have increased 104% from fiscal 1998 to fiscal 1999. Over half of the 30 million CDMA subscribers worldwide reside in the Asia Pacific region.

RFICs manufactured by RFMD are designed into the CDMA mobile phones of two major Korean handset manufacturers. Hyundai Electronics will purchase low-noise amplifiers, mixers, upconverters and PAs for several CDMA handsets for the domestic Korean market and for export.

The new dual-mode LGC-330W cellular phones manufactured by LG Information & Communications, Ltd. (LGIC), will include two key RFMD components. "For the past several years, RFMD has been a major provider of RF technology to LGIC. Our components are currently used in many different CDMA handsets," says RFMD's Jerry Neal. LGIC was one of the first companies to commercialize CDMA technology, and has manufactured over 4 million CDMA handsets to date.

Several key RFMD components have been designed into new CDMA cellular phones manufactured by NEC America. The Digital Talk Max 3100 and 3200 phones were created specifically for the North American market. In Europe, Bosch Telecom has designed RFMD's 3 volt GaAs HBT power amplifiers into its new dual-band GSM 900/1800 handsets. According to Bosch, the GSM 909, GSM 909S and GSM 509 handsets are the smallest dual band phones currently available on the market, and have talk times of up to 14.24 hours.

Dasa Steps Up Investment in Microwave Component Production*

DaimlerChrysler Aerospace (Dasa) is expanding its production plant in Ulm, Germany, which manufactures microwave/millimeter-wave transmit/receive (T/R) modules, to a capacity of 60,000 a year by 2002. The T/R modules, based on GaAs MMICs, are instrumental in high-power microwave applications such as commercial and military telecommunications, and active phased-array radars for airborne, naval and land-based platforms.

Dasa wants to mass-produce these components for several military programs, including the Airborne Multi-role Solid-state Active array Radar (AMSAR) for fighter aircraft being developed by a consortium including Dasa, Marconi (UK) and Thomson-CSF (France). The radar is to enter series production around 2005 and will incorporate at least 1,000 X-band T/R modules per unit.

Other prospective military programs include millimeter-wave seekers for both the SMart 155 mm artillery round and the STN Atlas Taifun combat drone. Also on the drawing board are the COBRA artillery locating radar, the active jamming part of the Eurofighter Defensive Aids SubSystem (DASS), and the

radar and missile seeker for the planned MEADS surface-to-air missile system.

Commercial and Military Targets

Clearly, the future of sensor technology in the defense industry is dependent on companies being able to set up competitive and cost-effective production of T/R modules in the 10-100 GHz frequency range. Such a capacity could also address some of the growing number of commercial markets for this technology. Potential markets for high frequency T/R modules include 77 GHz anti-collision radar for autonomous cruise control systems in cars, and 5.8 GHz, 24 GHz and 61 GHz radar sensors for industrial process control (see box). Communications markets include multimedia satellites, and point-to-point and point-to-multi-point radio link systems at 18-64 GHz for cellular radio infrastructures.

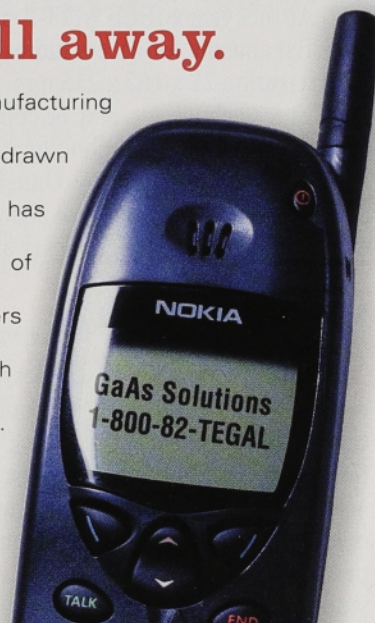
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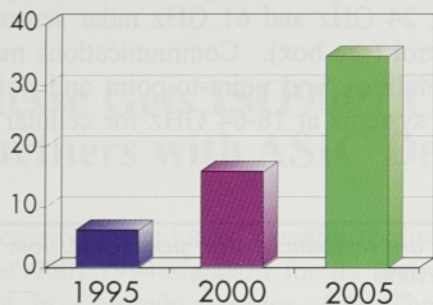
Due largely to the declining cost of microwave components in recent years, microwave radar technology has now become a viable technology for industrial process level measurement. Accurate and repeatable level measurement in industrial environments has always been a difficult problem, not least due to the wide variation in properties of the materials to be measured, and the different sizes, shapes and configurations of the containers. Different measure-

ment techniques have proved more suited to certain environments than to others. Microwave radar, which permits contact-free measurement that is largely unaffected by variations in pressure, temperature and vapor space, has been a suitable but expensive solution for many years. Now that FMCW radar modules are available at substantially reduced cost compared to several years ago, the market for this type of gauge is expected to accelerate, as shown in the graph.

Rosemount Inc. (Eden Prairie, MN) manufactures 25 GHz FMCW radar level gauges, using microwave modules from Daimler Chrysler (see photo). The gauge can be used in a variety of industrial process environments to measure levels with an accuracy of ± 3 mm. Sophisticated signal processing allows false targets to be avoided and levels to be tracked reliably, while the utilization of frequencies as high as 25 GHz offers a narrow beamwidth, making the measurements less susceptible to obstruction.

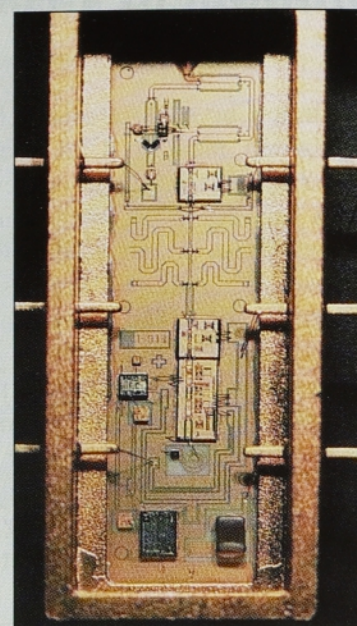
[For more on Rosemount's radar gauge, see J. Keilb and M. Pulkrabek, *IEEE MTT-S Digest* 1999, p. 281.]

Worldwide Sales of Microwave Level Gauges (thousands)



Rosemount

Rosemount's estimate of the number of microwave radar level gauges sold per year, throughout the world.



Rosemount/Daimler Chrysler

A 25 GHz FMCW radar module, manufactured by Daimler Chrysler, used in Rosemount's industrial process level gauge.

At this year's IEEE MTT-S meeting, Dasa announced a 58 GHz flat antenna for access radios in GSM networks. The antenna, measuring 25 x 167 x 215 mm, is manufactured in metal-plated plastic technology, and is compatible with Dasa's 58 GHz transceiver front-end technology, which is based on a GaAs MMIC chipset supplied by United Monolithic Semiconductors (UMS - see below). Dasa also showed a 28 GHz integrated front-end combining antenna, diplexer and LO-filter.

M5-Services

Dasa's plant in Ulm carries out design, development and manufacturing of modules in the microwave and millimeter-wave frequency bands (1-100 GHz). The company offers "M5-Services" (Microwave / MilliMeterwave Module - Engineering, Manufacturing & Services) for high volume manufacturing of complete modules according to customer specifications. Design or design support for MMICs up to 100 GHz is available, along with first pilot series manufacturing of MMICs in cooperation with an external or in-house foundry (i.e. UMS). Special packaging and assembly service for RF applications are provided together with concurrent engineering support for high volume manufacturing of RF front-ends up to 100 GHz in the highly automated "Microwave Factory."

Dasa and UMS

In 1996, Dasa's GaAs MMIC capabilities and facilities in Ulm were incorporated into United Monolithic Semiconductors (UMS), the independent joint venture between Thomson-CSF, Dasa and Temic. UMS designs and manufactures GaAs MMICs fabricated on a number of processes including MESFET, PHEMT, Schottky diode and HBT, and offers a foundry service for most of these technologies. The company uses the former Dasa facility in Ulm, Germany for front-end wafer processing, and the former Thomson-CSF fab in Orsay, France, for design, back-end processing and testing. The commercial headquarters of UMS are located in Orsay.

The Ulm facility has two wafer processing lines; a 3-inch line with a capacity of 5,000 wafers per year and a 4-inch line with a 10,000 wafer annual capacity. "By the end of 1999, all processes will be run using 4-inch wafers," says Heinrich Dämbkes, President of UMS. "A transition to 6-inch wafers is of course on our technology roadmap. However, we do not see an urgent requirement at present."

"Today, UMS is a leader for radiolink MMICs in the 20-60 GHz frequency range, and is rapidly expanding its product family," says Heinrich Dämbkes. "Furthermore, UMS is the only company to offer complete MMIC solutions for automotive

radar, deliverable off-the-shelf."

Back-end processing at Orsay includes backside wafer processing, on-wafer measurements and dicing and visual inspection of the components.

More than 10 automatic test stations, including a high volume handler/tester enable the full characterization of components in the 0.1-100 GHz range.

Chipset for 60GHz Radio Link Applications

UMS now offers a complete MMIC chipset, designed in collaboration with Dasa, for radio link system requirements at 60 GHz. The chipset consists of;

- **CHX2093:** a cascadable, by 3 frequency multiplier. Converts a signal at 9-10 GHz at an input level of 5 dBm to an output signal of 27-30 GHz with 3 dBm output power. Manufactured using a 0.25 μ m gate length PHEMT process.
- **CHX2190:** a by 2 multiplier, matched to the CHX2093 x3 multiplier performance, delivering 1 dBm output power in the 56-60 GHz frequency range.

Manufactured using a 0.15 μ m gate length PHEMT process.

- **CHS2190a:** a wideband monolithic diode-based reflective switch, exhibiting 30 dB isolation and 1.5 dB insertion loss from 50-60 GHz. Manufactured using a 1 μ m gate length Schottky diode process.
- **CHA2157:** a two stage, 55-60 GHz low noise amplifier and medium power amplifier, with a noise figure below 3.5 dB, a gain of 10-12 dB, and an output power of about 15 dBm. Manufactured using a 0.15 μ m gate length PHEMT process.

Ericsson Order for TriQuint

Ericsson has selected TriQuint Semiconductor's TQ9222 dual band TDMA downconverter for use in its dual band TDMA phones. The Ericsson 788 phone uses the TQ9222 to achieve one of the industry's smallest form factor phones with long standby time and excellent performance. "TriQuint has been a major provider of RFICs to Ericsson for several years," says Rupert Prince, TriQuint's director of wireless components marketing. "The selection of the TQ9222 for the receiver in the 788 phone confirms TriQuint as a provider of leading edge solutions for 2nd- and 3rd-generation cellular phone standards." The TQ9222 is a monolithic, 3V receiver integrated circuit designed specifically for dual band, IS136 (TDMA) standard cellular phones.

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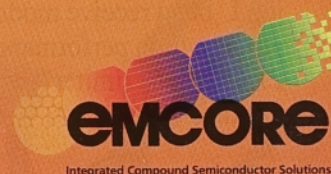
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High Performance L-Band Ball Grid Array Power and Receive Amplifier Module Set for Satellite Phone Handsets

D. COVEYOU, S. TRULLI, E. GRAY, and J. FONTNEAU
 Raytheon RF Components
 Andover, Massachusetts

Packaging is becoming an increasingly important topic in the GaAs IC industry. For low frequency products, wireless handset manufacturers are providing the impetus for change. Each new generation of mobile phones is smaller, lighter and more feature-laden than the previous, and must sell for a lower price. Corresponding improvements in RF engineering are required to keep pace. In fact, better RF design can deliver big pay-offs for the OEM. For example, a single integrated RF module can replace 20–30 discrete components on a phone's circuit board, translating into lower direct costs as well as higher yields and increased factory throughput, due to the reduction of the number of components that must be procured, tracked and assembled. Handset performance can also be enhanced by reducing RF losses in the package interconnection or in lossy dielectric mediums.

Recent activity at Raytheon RF Components has demonstrated for the first time that Ball Grid Array (BGA) technology is suitable for application to high-volume handset applications. BGA has been used for many years for ASICs and other DC applications, but there have been few public demonstrations of its use in RF chips. However, we believe — and have demonstrated — that BGA can be used to minimize board area while providing a low cost solution.

The BGA technology was applied, in a large-volume manufacturing environment, to the production of a low cost RF front-end module set for high performance handsets used in L band TDMA satellite phone systems. In one small package (see photo) we combined a highly linear and efficient 8W power amplifier module containing four parallel combined PHEMT power MMICs, 30 dB gain driver amplifier, adaptive power control coupler, harmonic filtering and an isolator. A companion L-band receive module has also been developed which integrates a high performance low noise amplifier, transmit/receive PIN switch, limiter and harmonic filter into a ceramic BGA package.

Thus, we have achieved a two-module solution for a RF front end. Over 200,000 of these modules have already been produced.

Power Amplifier Electrical Design

The power amplifier module is designed as shown in Figure 1. A multi-layer ceramic loaded laminate board acts as the package base as well as the RF substrate. Raytheon's GaAs 0.5um power PHEMT MMIC devices operating at a drain voltage of 7–8 volts are the common building block of the design. A three stage Driver MMIC amplifier provides 30 dB of gain with greater than 40 dB of adjacent channel power (ACP)*. Four parallel combined power MMIC devices are tuned to trade output power, linearity and efficiency. An off-chip output match is used to minimize loss and maximize efficiency. The devices are sized to accommodate the 2.8 dB peak to average ratio of a QPSK modulated waveform. Each final amp MMIC chip operates approximately 3 dB backed off from its full power capability. The module, therefore, which is

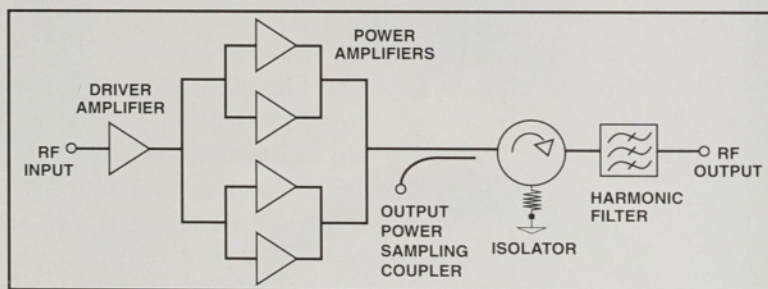


Figure 1. Power Amplifier Block Diagram

*ACP is measured in a 41 kHz BW both in band and at the adjacent channel 41 kHz away.

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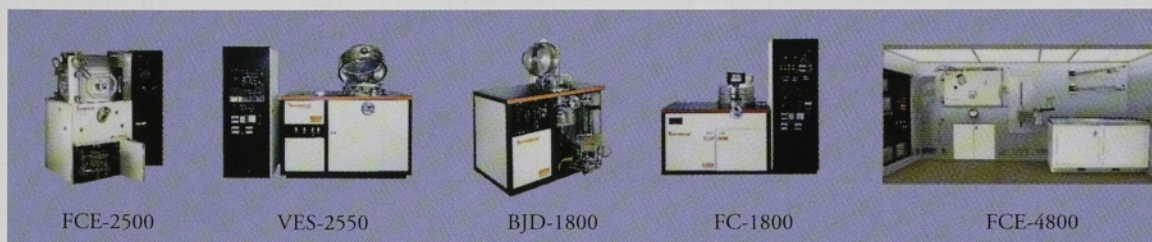
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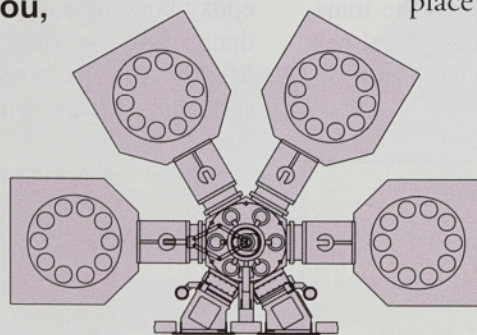
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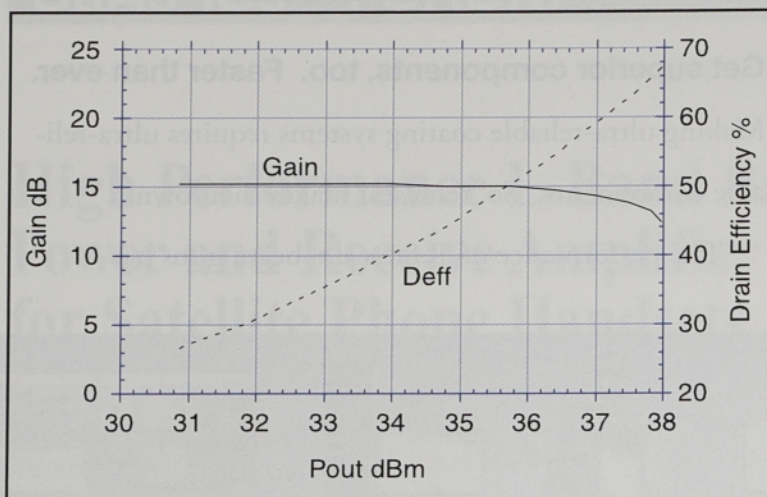


Figure 2. PA Performance (Final Stage)

designed for 8W of linear output actually has a 16W P1dB single tone power capability. Figure 2 shows the typical single tone gain and efficiency of one of the final stage MMIC devices.

Distributed microstrip and stripline power combiners minimize loss in the output circuit. A 24 dB adaptive power control stripline coupler provides a very low loss means of sampling the output power of the module. An isolator in the module provides a constant match to the power amps independent of the antenna match presented. Finally, a stripline filter minimizes the transmitted harmonic levels. A summary of the modules typical performance is shown in Table 1 while Figure 3 shows a typical gain, PAE and linearity curve of the module.

Table 1. Typical Electrical Performance

Frequency	1621 MHz
Duty Cycle	10%
Rated Output Power	8W
ACP at rated power	37 dB
Gain	43 dB
PAE	35%

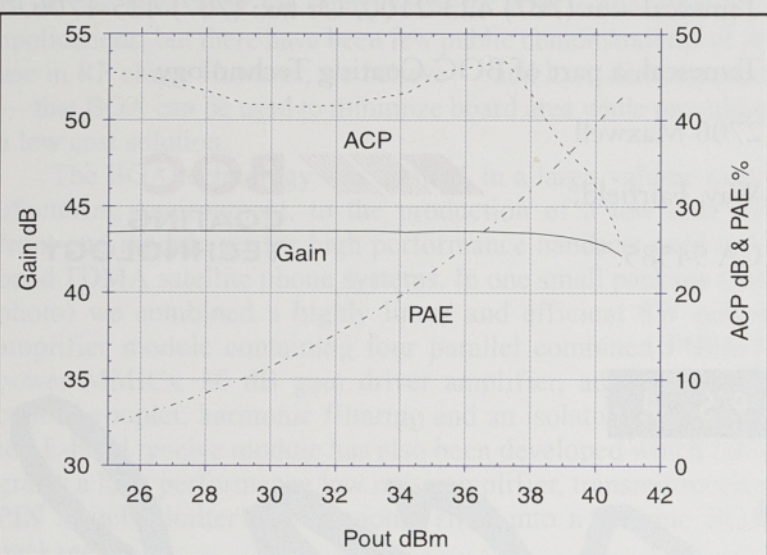


Figure 3. PA Performance (Module)

Power Amplifier Package Technology

The Power Amplifier Module uses BGA package technology providing all RF, DC and thermal connections through an array of solder balls on the bottom side of the part as shown in Figure 4.

The package is constructed of a multi-layer ceramic-loaded resin system that provides a controlled and temperature stable dielectric. Copper conductors are used throughout to maintain low IR loss and excellent thermal distribution. High density fields of copper barreled vias are located directly under the MMIC amplifier devices. The vias conduct heat directly to the large copper backside ground plane and to the tin-lead eutectic solder balls. This architecture provides an excellent thermal shunt to the copper heatsink on the mother board within the phone assembly. The thermal impedance from the package itself contributes less than 6°C to the device junction temperature.

The leadless BGA provides optimum distribution of I/Os as well as minimizing module outline. The solderball locations are defined not by the module backside metal but by the use of solder mask polymer. The balls themselves are formed of 0.020 inch diameter Sn63 solder on 0.050 inch (1.27 mm) pitch.

RF shielding and environmental protection are provided by epoxy bonding a stainless steel lid to a grounded first layer conductor ring that runs the full periphery of the Power Amplifier Module. Internal construction of the module utilizes both SMT style and chip and wire construction.

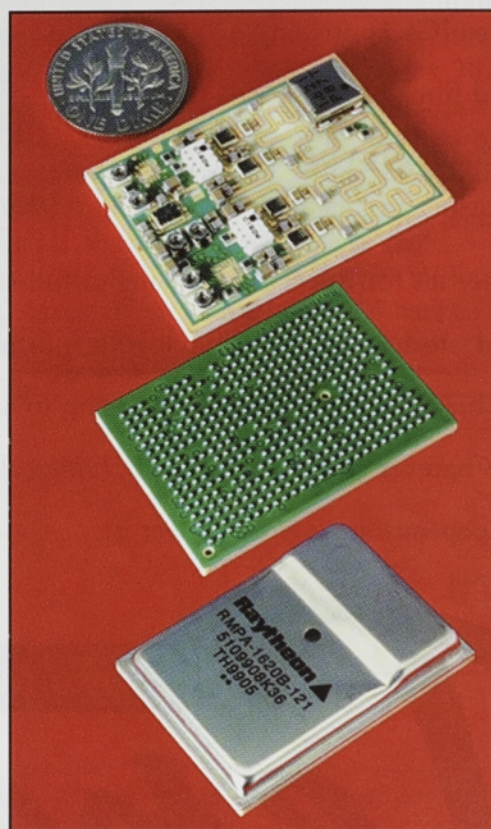


Figure 4. Power Amplifier

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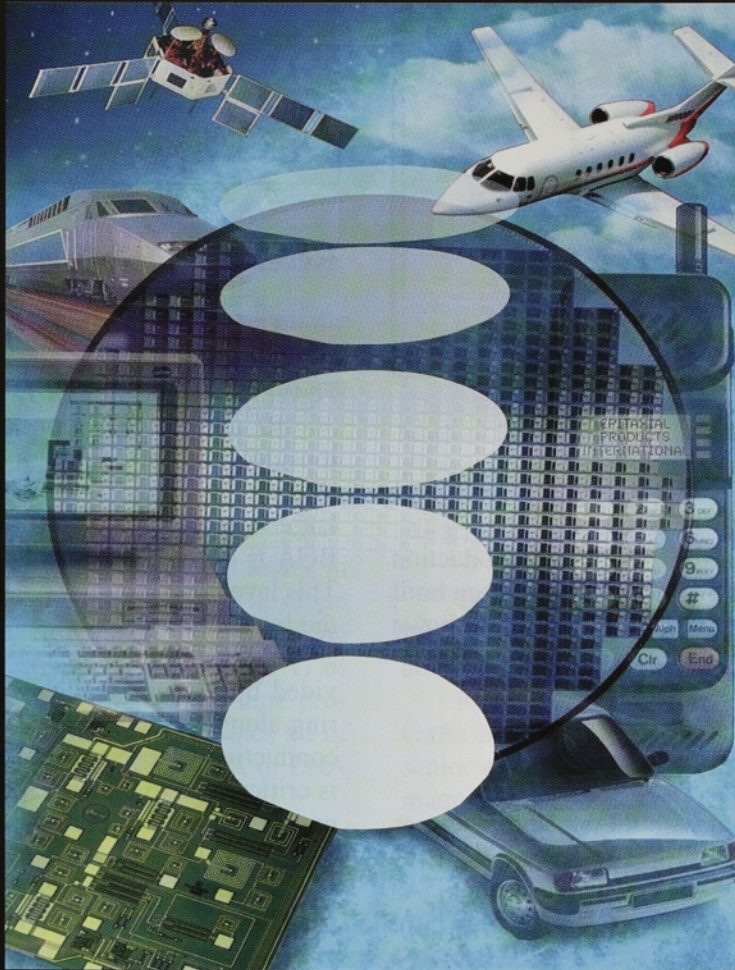
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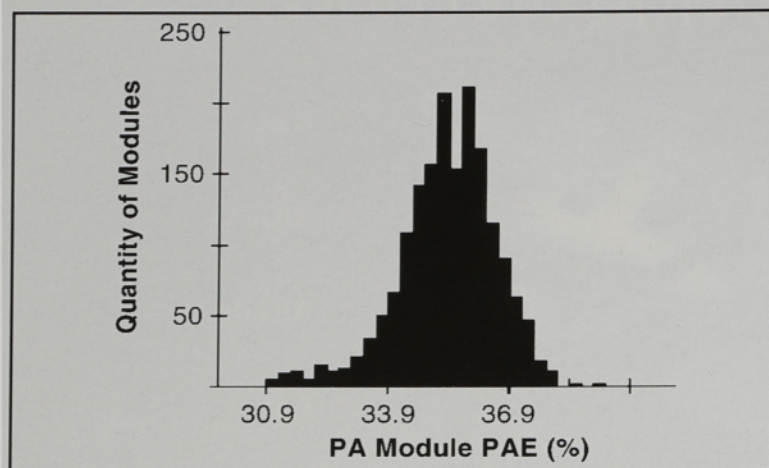


Figure 5. PA Performance (PAE)

Production Performance

The module has been designed for volume production processes and testing. Over 200,000 PA modules have been built with a typical distribution of 7V performance for PAE as shown in Figure 5.

Receive Module Electrical Design

The Receive Module is designed with the block diagram as shown in Figure 6.

The Receive Module contains Raytheon's 0.25um GaAs PHEMT MMIC low noise devices operating at 2.8V, which have a device Fmin of 0.2 dB at L-Band. The two stage self biased LNA MMIC operates with a 2.8V supply without the need of a negative voltage in the module. An off chip input match provides for an amplifier noise figure of 0.7 dB. A PIN diode transmit/receive switch is designed for 8W pulsed operation into a worst case short circuit and has a typical insertion loss of 0.45 dB. Greater than 18 dB harmonic rejection is obtained with onboard filtering. A limiter is also designed into this module to protect the LNA from destruction due to inband RF power up to 30 dBm. The transmit or receive mode can be selected or disabled through 3V control logic signals. All functions are combined together in this module to minimize interconnection losses. A summary of the modules typical performance is shown in Table 2.

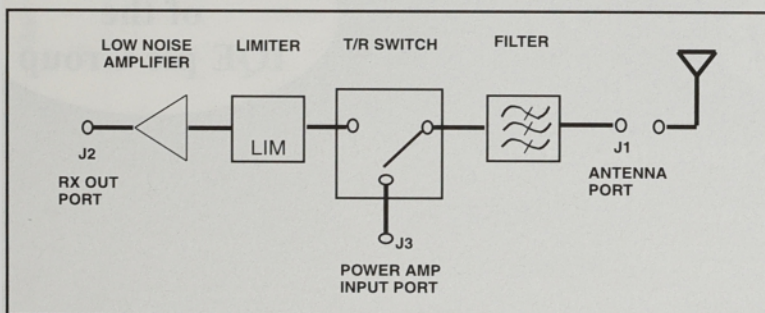


Figure 6. Receive Module Block Diagram

Table 2. Receive Module Performance

Noise figure (LNA, Limiter, Switch, and Filter)	1.5 dB
Receive gain	24 dB
Receive IIP	32 dBm
Receive current	26 mA
Transmit switch loss	0.45 dB

Receive Module Mechanical

The Receive Amplifier Module is a single layer ceramic BGA architecture that utilizes similar construction ideas as the Power Amplifier Module as shown in Figure 7.

RF and DC transitions are made directly from the thick film topside conductor through filled vias to a tin lead solderable backside conductor. Again, as in the Power Amplifier Module, a large area ground plane is provided on the backside and the BGA is defined by openings in a thick film glassy outer layer. This layer also provides a moisture tight seal in conjunction with the lid.

Environmental protection and electrical shielding are provided by a stainless steel lid bonded to a grounded conductor ring along the periphery of the topside ceramic. The electrically conductive adhesive used has a low modulus characteristic that is critical due to the large coefficient of thermal expansion mismatch between the ceramic (6.7ppm/°C) and the lid (17.2ppm/°C).

Although this Receive Amplifier Module has a relatively small, 0.25 square inch footprint, thermally induced stress due to thermal expansion mismatch between the module and the mother board are of greater concern here than in the Power Amplifier Module because of CTE mismatch between FR4 and the alumina base. To ensure high reliability against thermally induced stresses from this thermal expansion mismatch, the Receive

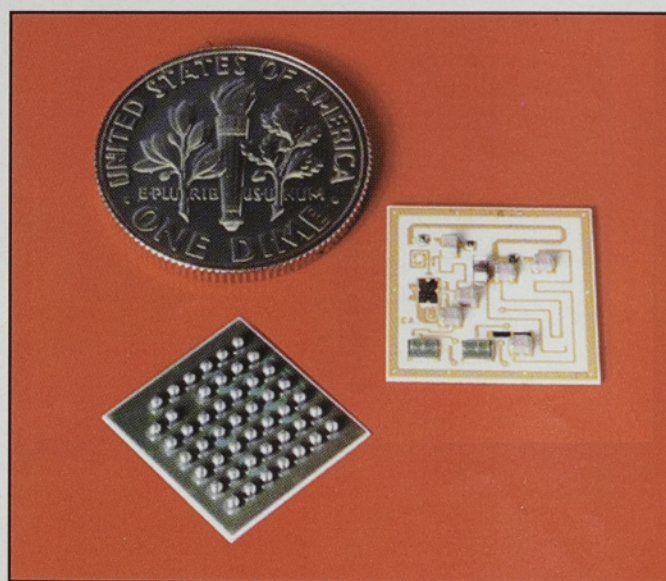


Figure 7. Receive Amplifier Module

Amplifier Module utilizes non-collapsible high temperature 90/10 PbSn solder balls of 0.035 inch diameter that are soldered to the ceramic base of the Receive Module with Sn 62. The additional height and material characteristics of the 90/10 solder balls aid in decoupling stress between the ceramic and the FR4. Due to the increased ball volume, the pitch on the BGA for the Receive Amplifier Module is 1.5 mm versus the 1.27 mm of the Power Amplifier Module.

Receive Module Production Performance

The Receive Module has also been designed for volume production processes and testing. Over 200,000 modules have been built with a typical distribution of performance for noise figure shown in Figure 8.

Conclusions

Handset performance is often degraded due to RF losses in the package interconnection, lossy mediums or the discrete nature of the components which make up the required matching circuitry following a highly efficient power amplifier (PA) or prior to a low noise amplifier (LNA). A low cost volume producible module set has been designed which incorporates all of the RF circuitry between the antenna and the MMIC PA or LNA onto a single low loss substrate.

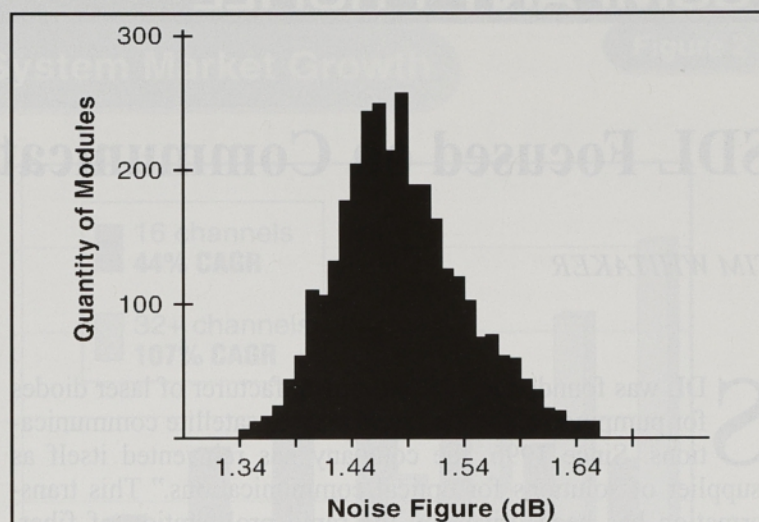


Figure 8. Receive Module Noise Figure

Acknowledgments

The authors would like to thank Rob Kincaid, Dan Donoghue, Jim Martin, Tom Noll, and Chris Caron for their valuable contribution to the success of this module development.

Raytheon RF Components is a leading supplier of advanced GaAs MMICs for the wireless marketplace. Dave Coveyou is a senior engineer within the module design group. For more information please visit Raytheon's web site at raytheon.com/micro.

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SDL Focused on Communications

TIM WHITAKER

SDL was founded in 1983 as a manufacturer of laser diodes for pumping solid state lasers and for satellite communications. Since 1996, the company has reinvented itself as "supplier of solutions for optical communications." This transformation has been driven by the rapid proliferation of fiber-optic networks, and in particular the rise of dense wave-division multiplexing (DWDM). SDL's revenue from the DWDM market increased by 109% from 1997 to 1998, and major contracts were signed with Lucent, Corning and Alcatel. The various optical communications markets accounted for 72% of SDL's revenues in the first quarter of 1999 (see Figure 1), and this share is expected to continue to grow. Other markets for SDL's high power laser diodes, such as printing, medicine and materials processing, accounted for the remaining 28% of revenues [for more on these areas, see CS 5(2), p. 24]. In the printing market, SDL has recently received major orders from Panasonic, Polaroid and Kodak, and also acquired Polaroid's fiber laser business.

Components for DWDM

SDL's major product for this market is the 980 nm pump laser, which provides the optical pumping in erbium-doped fiber amplifiers (EDFAs). The company also manufactures fiber Bragg gratings to lock the wavelength and provide flat gain across the EDFA window. SDL's individual 980 nm pump modules provide up to 170 mW of kink-free optical power, with higher power versions expected soon. The development of EDFAs, which permit amplification of optical signals without the need for an optical-electronic conversion, was vital for the introduction of low cost, long distance optical networks and for making DWDM a viable proposition. In turn, the DWDM market is now driving the demand for 980 nm pump lasers. "Over the last 12 months (to April 1999), the continuing build-out of DWDM fiber optic systems for long-haul terrestrial and undersea applications has more than doubled demand for our 980 nm pump module products," says Don Scifres, SDL's chairman and CEO.

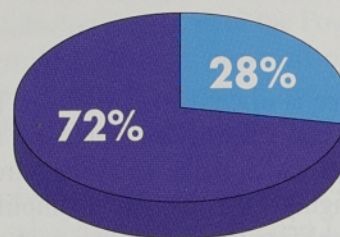
There are several reasons for this. Firstly, the number of DWDM networks is growing rapidly, as shown in Figure 2. Secondly, the number of channels is also on the rise, which means that the optical amplifier has to provide more power in order to amplify every transmission channel equally. The need to spread the optical pump power across up to 80 channels or more means that several pump lasers are commonly used in each amplifier. One of SDL's more recent product introductions is a multiplexed 500 mW pump source. This uses wavelength-multiplexing techniques to combine the outputs of 4 Bragg grating-

SDL's Q1 '99 Revenues

Figure 1

Optical Communications

Telecom
Undersea
CATV
Metro
Satellite



Other Key Markets

Printing
Materials Processing
Medical
Instruments

stabilized modules with output wavelengths at 970, 975, 980 and 985 nm.

In addition to 980 nm pump lasers, fiber Bragg gratings and modules, SDL has also introduced 1455 and 1480 nm Raman fiber lasers (see box, page 66). The range of DWDM building blocks has been enhanced by the acquisition of IOC, a leading manufacturer of lithium niobate modulators (see below). SDL is currently undertaking research in InP-based 1310 and 1550 nm source lasers, with no firm plans to move into production.

Manufacturing Facilities

Recent expansions at SDL have resulted in a 4-fold increase in capacity in the last 12 months. Average yields for 980 nm chip production increased three-fold compared to the previous laser manufacturing line. Combined with a new wafer fab capacity increase, these yield improvements helped SDL boost its production capacity to over 100,000 chips per year in 1998. The total chip capacity is expected to double again in 2000.

SDL's wholly owned subsidiary, SDL Optics, is in the process of expanding the manufacturing space at its facility in Victoria, BC, Canada. At 41,000 square feet the new facility will have almost double the space of the current facility, which is used to manufacture 980 nm pump modules and fiber Bragg gratings. "The increasing need for bandwidth due to data traffic over the current telecom network is driving the need for expansion," says Greg Dougherty, president of SDL Optics and COO of SDL, Inc. "The demand is playing to our strengths. Our high power, grating-stabilized pumps are enabling the growth of DWDM from 16 channels per fiber to between 40 and 80 channels." SDL expects to start shipping products from the new facility by the fourth quarter of 1999.

Partnerships, Contracts and Acquisitions

In February, SDL and **Alcatel** announced a four-year partnership to deliver 980 nm pump modules for undersea networks. Alcatel's Optronics group will manufacture pump modules using chips obtained exclusively from SDL. Due to the nature and inaccessibility of the undersea environment, EDFAs (and the pump lasers they contain) are required to demonstrate exceptional reliability. 1480 nm pump lasers are a more mature technology and were used exclusively in submarine EDFAs until recently. However, replacing 1480 nm pumps with 980 nm lasers significantly reduces amplifier noise in the system, which is crucial for the very long transmission distances in undersea systems. Despite being deployed for several years in Alcatel's optical amplifiers in terrestrial systems, SDL's lasers have only recently demonstrated sufficient reliability for undersea applications. The modules have output powers of 100 mW and an operating temperature range from 0-43°C. Under these conditions, the predicted failure rate has been demonstrated at less than 1% over 25 years of operation. Jean-Marie Vansteenkiste, Alcatel Optronics' chairman and CEO, said, "We believe that our module, with the SDL chip, offers the best combination of high power and submarine reliability in the industry [and] that this pump module will now enable deployment of 32 channel undersea DWDM systems." SDL also reports that a new pump chip, expected to have a 50% increase in output power with no degradation in reliability, should enter into full qualification in the fourth quarter of 1999, with shipments for terrestrial deployment planned in early 2000.

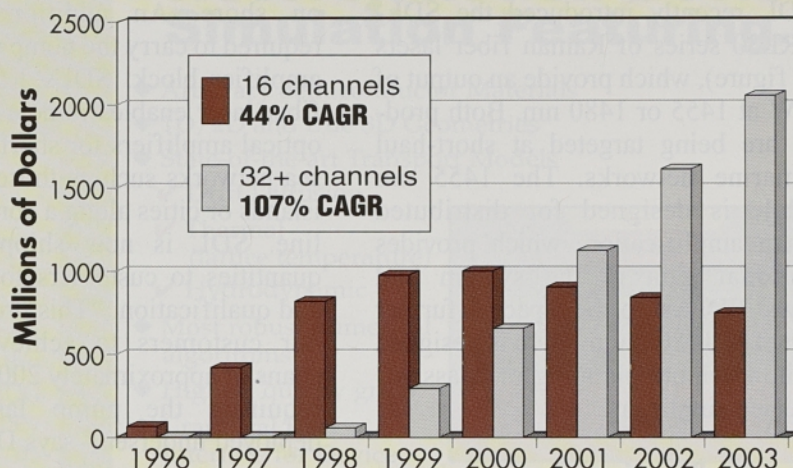
Also in February of this year, SDL acquired **Polaroid's** fiber laser business, including all physical assets and intellectual property, for \$5 million. As part of deal, SDL will supply advanced fiber laser subsystems to Polaroid's graphic imaging division.

In April, SDL entered into an 18-month supply agreement with **Corning** to be the primary supplier of 980 nm pump modules that will supply optical power for a variety of Corning's optical fiber amplifiers. Corning claims to be the world's largest manufacturer of EDFAs.

In May, SDL announced that it had secured orders from the **Eastman Kodak Co.** for the supply of fiber-coupled laser diodes for use in Kodak's market-leading "Approval" line of digital color proofing systems for the graphic arts market. The orders total approximately \$9 million and extend over a period of up to two years. The Approval system uses an array of fiber-coupled laser diodes to create color images directly from digital computer files. These color images are excellent representations of the images produced by offset printing presses and they are used by commercial printers to qualify (or "prove") the digital data before going to press. Digital color proofing systems are key to enabling

DWDM System Market Growth

Figure 2



a fully digital pre-press sequence. SDL and Kodak have worked closely together for many years to develop very high-performance laser sources for several of Kodak's graphic arts imaging systems. Last year, SDL received a contract to supply fiber-cou-

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Raman Fiber Lasers

SDL recently introduced the SDL-RL30 series of Raman fiber lasers (see figure), which provide an output of 1.5 W at 1455 or 1480 nm. Both products are being targeted at short-haul submarine networks. The 1455 nm module is designed for distributed Raman amplification, which provides additional gain in the system and allows EDFAs to be spaced further apart. The 1480 nm module is designed to allow remote pumping of "passive" undersea amplifiers.

- **Remote Pumping:** One way to get around the stringent reliability requirements for the lasers in undersea EDFA modules is to replace the conventional EDFA with a "passive" erbium-doped fiber block. With a sufficiently high power source, it is possible to pump the undersea amplifier remotely, using a 1480 nm source at the network terminal

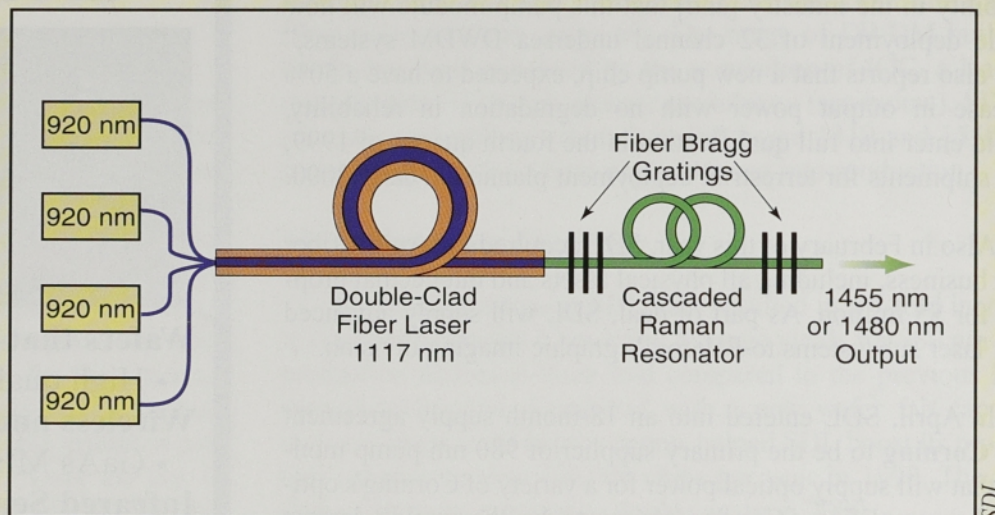
on shore. An additional fiber is required to carry the pump output to the amplifier block. SDL's 1.5 W Raman fiber laser enables remote pumping of optical amplifiers for short haul undersea networks such as those connecting islands or cities along a common coastline. SDL is now shipping sample quantities to customers for evaluation and qualification. "This product allows our customers to achieve undersea spans of approximately 200 km without requiring the pump lasers to be deployed undersea," says Don Scifres.

- **Distributed Raman amplification:** In EDFAs, as the name implies, gain is provided by a section of erbium-doped fiber. In contrast, distributed Raman amplification uses the standard 1550 nm transmission fiber to provide gain. The Raman shift of silica fiber is about 13 THz above the pump wavelength. For

transmission at 1550 nm, Raman amplification occurs when the fiber is pumped with very high optical power at approximately 1455 nm. Using a pump source in excess of 1 W at the receive terminal, the transmission fiber itself provides additional gain of up to 15 dB, equivalent to approximately 100 km of extra transmission distance between amplifiers. In Raman amplification the gain is spread out, or distributed, throughout the fiber and also allows amplification between 1300 and 1650 nm, thereby supporting a greater number of wavelength channels. With an EDFA, amplification occurs in a single discrete amplifier module and within a fixed wavelength region. SDL is now shipping initial production quantities of its SDL-RL30-1455 product to a major telecommunications company for field deployment, and other telecommunications companies are evaluating the product.

pled diodes for Panasonic's "Dry Plotter" digital prepress system, which writes the image directly from computer files onto a printing plate or film. The SDL-2300-L2 series diodes deliver up to 0.6 CW into 0.12 NA from a 100 μ m core diameter fiber pigtail at a wavelength of 830 nm.

SDL has now completed the acquisition of IOC, a UK-based manufacturer of 2.5 Gbps and 10 Gbps LiNbO₃ modulators for long-haul transmission systems. "Following the acquisition of IOC, we are able to provide our existing customers with more elements of their DWDM solutions, while leveraging the increasing market for 10 Gbps products," says Scifres. IOC has a current capacity of around 20,000 units, and will now be known as SDL Integrated Optics.



SDL's RL30 series Raman fiber lasers provide up to 1.5 W of single mode output at 1455 or 1480 nm, for Raman applications or remote pumping respectively. Several 920 nm multimode diode laser pump sources are used, each with an output power on the order of 1 W. The diodes pump an ytterbium-doped double-clad fiber laser that delivers high optical power into a single-mode fiber at ~1110 nm. This output is fed into a cascaded Raman resonator cavity with a low loss fiber Bragg grating. Successive Raman shifts result in the desired output wavelength. The 920 nm diodes have an estimated FIT rate of 1500 FIT at 1.0 W P_{out} and 25°C, and 2000 FIT at 1.2 W P_{out} and 25°C.

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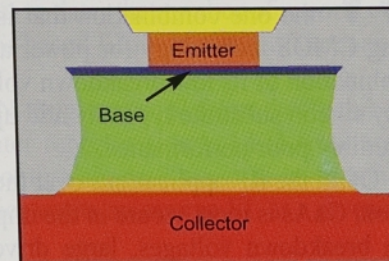
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CMOS Power Amplifier

ROBERT A. METZGER



When one considers the myriad of technologies and components that can be used in RF front-end applications, the one combination that is rarely proposed is that of using CMOS technology for power amplifier applications. The combination of its low breakdown voltage, low current drive and lossy silicon substrate typically add up to a power amplifier with incredibly poor performance.

Of all the RF applications over the important 800-1900 MHz region, GaAs is most secure in the implementation of PAs, where high breakdown voltages, large drive currents (in part due to superior carrier mobilities) and high resistivity substrates make it ideal for such applications.

But not all in the CMOS silicon world are ready to surrender the PA territory to GaAs. King-Chun Tsai and Paul Gray at the University of California, Berkeley [1] have designed and fabricated a 1.9 GHz, 1 W CMOS power amplifier implemented in a 0.35 μm , single-poly, five-layer metal CMOS process, which operates with a power added efficiency (PAE) of 48%.

Those are GaAs-like numbers.

How did they do it?

The first trick that they pulled out of their bag was to design the amplifier for Class-E operation (see Figure 1). In this mode, the input signal V_{in} toggles the switch periodically with an approximate 50% duty cycle. When the switch is on, a linearly increasing current is built up through the inductor, and when turned off, the current is steered into the capacitor, causing the voltage across the switch, V_s , to rise. The bandpass filter then selectively passes the fundamental component of V_s to the load, creating a sinusoidal output that is synchronized in phase and frequency to the input - making this mode of operation well-suited for both Gaussian minimum shift keying (GMSK) and Gaussian

frequency shift keying (GFSK) modulated input signals used in GSM and DECT standards. For Class-E operation, when the CMOS transistor is turned on, it is operating in the triode regime, such that it behaves as a simple resistor, therefore enabling modeling and analysis of the Class-E power amplifier to be viewed as a circuit which toggles between two linear LRC networks.

In principle, the switch voltage and the switch current are never simultaneously non-zero, as a result of which the switch is ideally loss-less, and all the power from the dc supply is delivered to the RF output. Of course, for high-speed operation, the switch transition time can become a significant fraction of a signal period, and it is at such moments that power losses will occur.

Since the input provides only timing information in Class-E operation, the output power cannot be controlled through the input as is normally done in linear power amplifiers. Instead, output power control is implemented through a variable supply, in which the output power is proportional to V_{DD}^2 (Figure 1).

In order to reduce substrate effects, and minimize the impact of the CMOS device's intrinsic low breakdown voltages, the power amplifier is implemented in a fully differential configuration. In this arrangement, current is discharged to ground twice per cycle, thereby expelling the substrate noise component from the desired signal frequency to twice the signal frequency, and resulting in reduced interference. In addition, the current passing through each switch in a differential configuration is lower than in a single-ended counterpart, thereby allowing a smaller transistor to be used. Another approach to current reduction is using mode locking, in which a self-oscillating circuit is coupled and forced to run at the same frequency as an input signal, thereby resulting in a substantial reduction in the input driving requirement. The down side to mode locking is that the power amplifi-

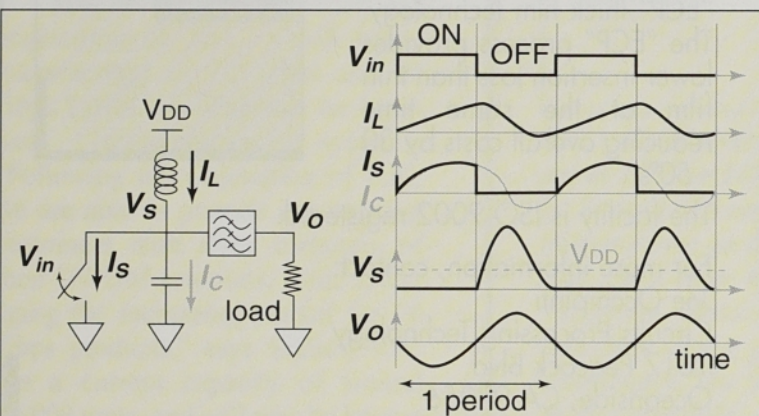


Figure 1. In high-speed operation, the switching transition time of a power amplifier can become a significant fraction of a signal period. During these transitions, the switch voltage and current may be simultaneously non-zero causing potential power drop - a loss that Class-E power amplifiers are designed to minimize.

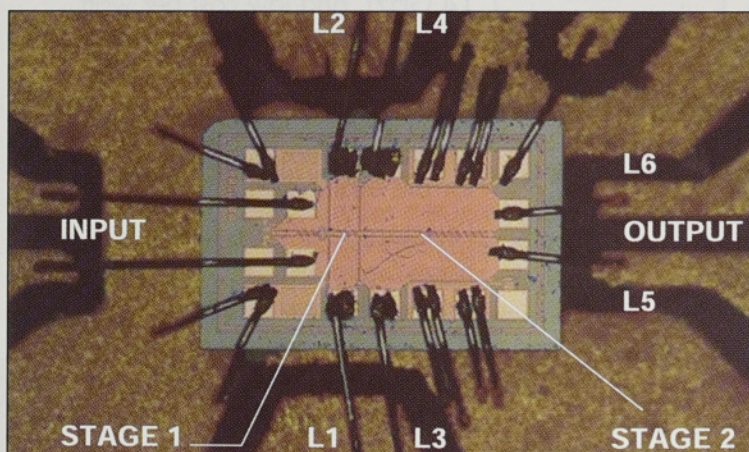


Figure 2. Photograph showing the chip-on-board assembly, a mounting technology that integrates the bare die directly to the PCB. The 0.35 μm five-layer metal layer CMOS chip is 1.0 x 0.6 mm² including bonding pads.

Si-Nanocrystal LED

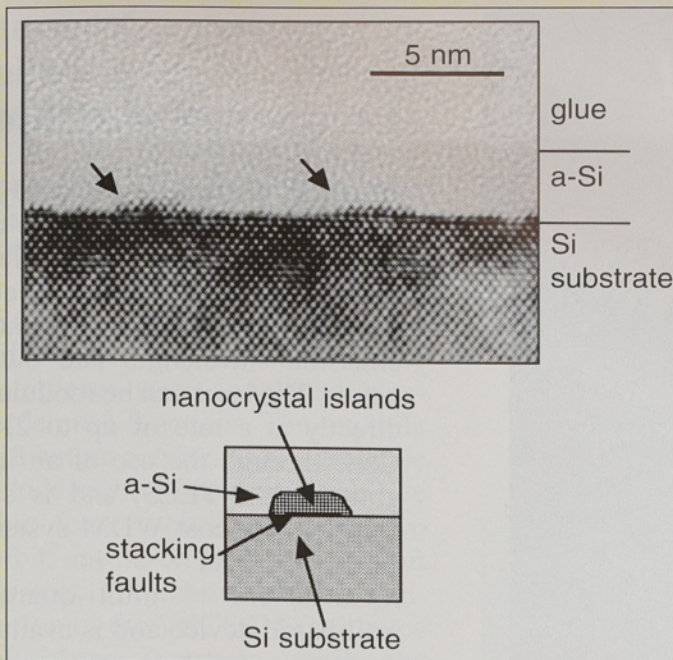
LEDs that can be monolithically integrated into Si ICs are highly desirable, and recently, Si-based nanostructures have been studied for their light-emitting characteristics. These nanostructures have feature sizes that increase the probability of radiative recombination for excitons as a result of the quantum confinement effect. Highly efficient visible PL has been reported from such Si nanocrystal structures, but to date, the number of reports of electroluminescence (EL) from Si-based LEDs is small in comparison.

In this work, S. Fujita and N. Sugiyama [1] from the Toshiba Research and Development Center report a simple LED structure consisting of Schottky contacts onto a single 3 nm *a*-Si layer containing Si nanocrystals. The device emits an orange EL at a reverse bias voltage of 5 V.

The LED structure was formed by depositing molecular beams of Si (from disilane cracked in a graphite heater) onto a 6-inch, low-resistivity p-type Si wafer. The two active layers deposited in the investigation, one 3 nm thick and the second 18 nm, were subsequently annealed at 700°C for 1 and 3 min, respectively, in nitrogen and/or oxygen gas to partially convert the *a*-Si into nanocrystals. Titanium-gold contacts were added on the top and bottom to form an LED device with the relatively small dimensions of 0.1 x 0.1 mm².

For the 18 nm layer, no visible electroluminescence was observed, but the 3 nm layer exhibited electroluminescence at room temperature. Meanwhile, photoluminescence measurements revealed a peak photon energy for this emission at 1.9 eV. In order to determine the possible origins of the electroluminescence, high resolution electron microscopy images were obtained from cross-section samples (see figure), which revealed that the device contained 2-3 nm-wide nanocrystalline islands with a height of 1 nm. From this, it was proposed that the electroluminescence originates from the confinement effect of the Si nanocrystals in the thin *a*-Si layer, with electrons that contribute to the radiative recombination confined in either the Si nanocrystal/*a*-Si or p-type Si/Si nanocrystal interface. Mechanistically, the electroluminescence was thought to originate from avalanche breakdown when the relatively large reverse bias of 5 V is applied.

The authors conclude that the operating reverse bias for visible electroluminescence could be reduced to around 4 to 4.5 V - low enough for integration with a standard Si bipolar transistor. In addition, increasing the size of the device (which is at least 30 times smaller than that of currently available visible emitters) and incorporating more quantum confinement layers should lead to stronger visible emission.



High resolution TEM image showing the interfaces of a Si nanocrystal LED. The arrows indicate nanocrystalline islands formed at a temperature of 700°C for 1 min in the *a*-Si layer. Stacking faults are present at the Si/*a*-Si interface.

er can only operate within a certain frequency range, but for a part designed for a specific standard, this is not a real problem.

The real problem is with the inductors.

High-Q inductors are critical in the design of high PAE amplifiers in which a large amount of current circulates in a tuned LC network - requiring inductors that carry substantial direct current. Standard CMOS processes cannot support such inductors. This power amplifier has been built using two stages; each stage requires an inductor with a low inductance value of 0.37 nH. For this device, these inductors are fabricated with bond wires. The reproducibility of such an approach can be tricky, and is probably the weakest element in this power amplifier when making the transition from university demonstration device to a commercial reality.

The final chip measures 1.0 x 0.6 mm², including bonding pads (see Figure 2). With a peak PAE of 48%, it exhibited a PAE in excess of 40% over a supply voltage of 0.8-2.0 V. The output power increased from 49 mW to 1.0 W monotonically as the supply voltage is swept from 0.6 to 2 V, and is approximately proportional to V_{DD}^2 . All this was achieved for 1900 MHz operation. As expected for CMOS, the maximum output power is limited by the peak drain voltage, which for 2 V operation is estimated to be 5 V, approaching the drain-gate oxide breakdown limit of the technology.

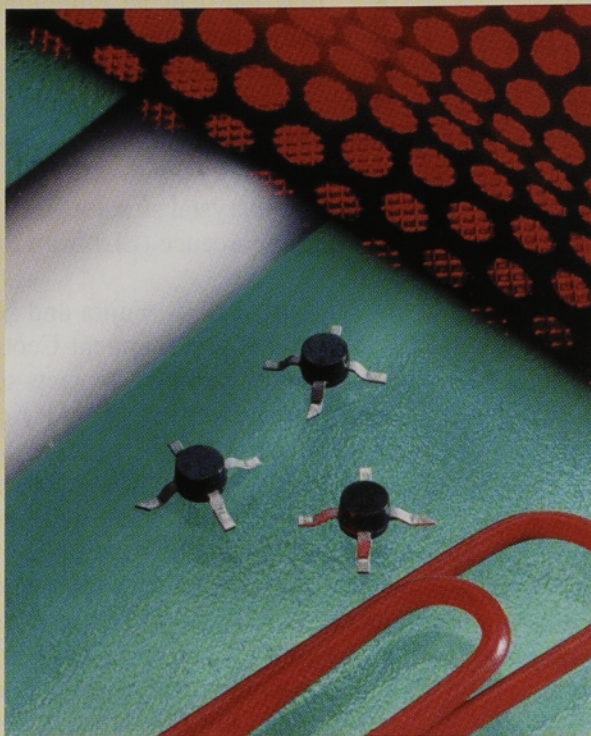
Will such an approach ever move from the laboratory to the factory? That remains to be seen. But the old argument that CMOS suffers from intrinsic limitations that will not allow it to deliver the power or power added efficiency needed for high-performance commercial RF applications should be put to rest by this demonstration.

[1] K. Tsai and P.R. Gray, "A 1.9 GHz, 1-W CMOS Class-E Power Amplifier for Wireless Communications," *IEEE J. Solid-State Circuits*, 1999, 34(7), p. 962.

[1] S. Fujita and N. Sugiyama, *Appl. Phys. Lett.* 1999, 74(2), p. 308.

Link Microtek SiGe HBT Amplifier

Basingstoke, UK. Designed for use as a power amplifier building block in wireless systems, the Link Microtek SGA 6386 is a SiGe HBT-based cascadable 50 ohm device delivering a gain of 15.4 dB at 1 GHz and 13.8 dB at 2 GHz. Targeting the frequency range DC-3 GHz for low noise amplifiers (LNAs) in cellular-, wireless-, cable television and paging systems, the linearity exhibits third order intercept point (IP3) of 34.5 dBm. At 1 and 2 GHz frequencies, the noise figures correspond to 3.8 and 4.4 dBm respectively.



AMS Optotech Cooled Laser

Munich, Germany. AMS Optotech has announced a new distributed feedback (DFB) laser with integrated thermoelectric cooling that allows a constant emission wavelength and output power. The laser can be modulated directly at a rate of up to 2.448 Gbps through the use of an integrated BIAS-TEES, and is suitable for low-cost WDM systems. The laser is an InGaAsP/InP multi-quantum well-based device and is available in varying emission wavelengths, including the 1.3 and 1.55 μm windows for data transmission, and at the 1.48 μm wavelength for monitoring applications.

Fujitsu Flexible Chip Scale Package

San Jose, CA. Fujitsu Limited and Fujitsu Microelectronics Inc. (FMI) have announced the introduction of a new enhanced chip scale package specifically designed for RF devices used in the latest generation of Japanese digital cellular telephones, which weigh only 59 g and measure 40 x 125 x 17 mm³. The company's new Bump Chip Carrier++ (BCC++) accommodates die sizes with high pin counts, is 0.8 mm thick and features a 0.5 mm terminal pitch. The center die cavity, which is attached directly to the motherboard, provides ground shield and lower inductance. The ground wire bonding is only 0.40 mm long, which stabilizes ground and also improves the thermal performance. The package can also accommodate a large die with the occupancy rate of 67 percent.

Ortel Photodiode Modules

Alhambra, CA. Ortel's models 2609C and 2611A are packaged photodiode modules with internal gain designed for use in short- and long-haul fiber optic transport systems in the 1.3 and 1.5 μm wavelength ranges, or for wave division multiplexing (WDM). These photodiodes feature an extended frequency range of up to 1 GHz and input powers of up to 3 dBm of continuous received power, or 6 dBm maximum (model 2611A only). Both devices exhibit a flat response of ± 0.5 dB, and a responsivity of less than 0.85 A/W at 1.31 μm and lower than 0.95 A/W at 1.55 μm .

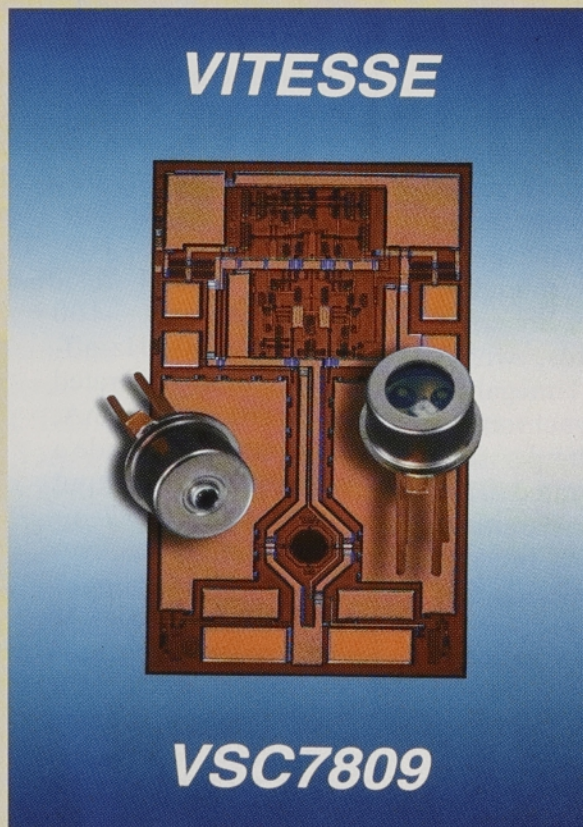
M/A-COM Announce PIN Diode Attenuators

Lowell, MA. M/A-COM has produced a new family of PIN diode-based voltage variable attenuators (VVA). The AT10-0009, AT10-0017, AT10-0019 and AT65-0008 offer an increase of 15–20 dB of third order intercept input (IP3) compared to traditional GaAs VVAs. Available in standard plastic surface mount packages, the AT10-0009, AT10-0017, and AT10-0019 devices cost \$24 each, while the AT65-0008 sells for less than \$10 each in 1,000 piece quantities.

Part Number	Frequency (MHz)	IP3 (dBm min)	Dynamic Range (dB type)	Insertion Loss (dB max)
AT10-0009	800-1000	+31	35	6.0
AT10-0017	1700-2000	+31	35	3.5
AT10-0019	50-1000	+24	42	208
AT65-0008	900-2250	+45	25	1.5

Vitesse Integrates Multiplexer and Demultiplexer

Camarillo, CA. In order to meet customer demands for an off-the-shelf high-speed video shift register, Vitesse has introduced the VSC6424, a 500 Mbps, 40-bit video shift register that integrates both the multiplexer (mux) and demultiplexer (demux) functions. The multiple shift length configurations available include eight 5-bit, eight 4-bit, five 8-bit, four 10-bit, two 16-bit, two 20-bit, one 32-bit or one 40-bit shift registers. The internal timing generation of the VSC6424 facilitates 500 Mbps operation, while the external timing generation at a speed of 250 Mbps allows compatibility with lower speed designs and previous generations of shift registers.



... And Photodetector and Transimpedance Amplifier

Vitesse has also integrated a photodetector and transimpedance amplifier (TIA). The VSC7809 is a wide-band 3.3 V device exhibiting high responsivity, sensitivity and a large optical active area intended for small form factor optoelectronic modules. Its wide bandwidth facilitates operation at 1.0 or 1.25 Gbps, making it compliant for either Fiber Channel or Gigabit Ethernet applications. In addition, the VSC7809 features a high power-supply rejection ratio (PSRR) and very low jitter, which is designed to address concerns over power supply fluctuation that affect the operation of detectors and TIAs.



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



Sponsors: IEEE Lasers and Electro-Optics Society (LEOS) and IEEE Electron Devices Society (EDS)
Conference Program and Registration Information: <http://www.ieee.leos/conferences>

ABSTRACT DUE DATE: 10 December 1999

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

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

Optoelectronics
Electron Devices
Epitaxy
Processing
Characterization and Bulk Materials

Conference Chair: Russell D. Dupuis, The University of Texas at Austin, Austin TX, USA (e-mail: dupuis@mail.utexas.edu; 512 471-0957)
Program Chair: Brad Boos, Naval Research Laboratory, Washington DC, USA (e-mail: boos@estd.nrl.navy.mil; FAX: 202 767-0455)
Publicity Chair: Joe Lorenzo, AF Research Laboratory, Hanscom AFB MA, USA (e-mail: lorenzo@maxwell.rl.plh.af.mil; FAX: 617-377-6765)

Hitachi Introduces 10 Gbps Fiber Optic Modules

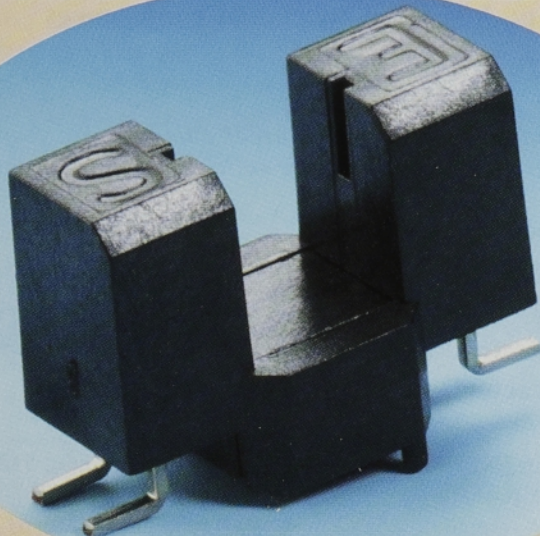
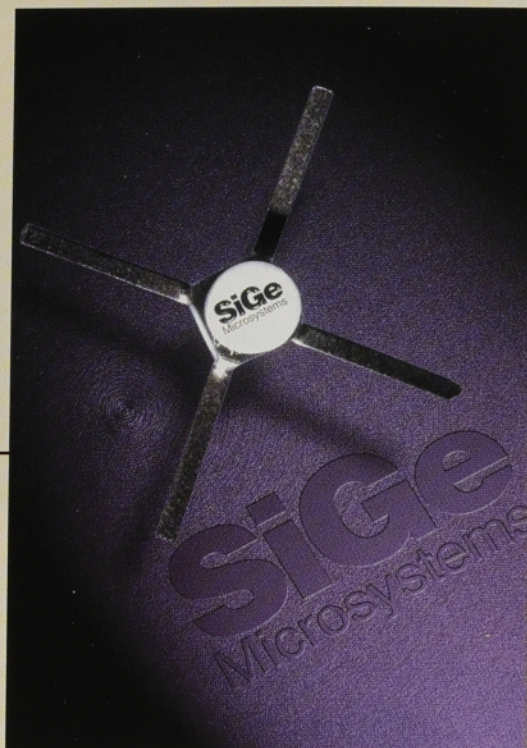
San Jose, CA. Hitachi Semiconductor (America) has announced a 10 Gbps fiber optic module for long- and short-haul signal transmission applications, such as telecommunications and data network systems. This family of laser-based transmitter and receiver modules, also available as discrete components, are compatible with SONET/SDH standards, which allows digital traffic ranging from 51 megabits (SONET) or 156 megabits (for synchronous digital hierarchy — SDH) to gigabits per second. The module includes an integrated DFB laser diode (part number LE7602), transmitters (parts TRM7033, 7043, and 7053) and InGaAs PIN-PD receivers (parts RCV7002, 7012, and 7022), with monolithically-integrated electro-absorption modulators. Applications include short-reach (2 km), intermediate reach (20 km), and long-reach (40 km) operating distances at 1.55 μm .

Fujitsu Announces FET and p-HEMT MMIC

Yamanashi, Japan. Fujitsu Quantum Devices has developed two new devices: a GaAs FET power amplifier for W-CDMA (Wideband Code Division Multiple Access System) stations, and a p-HEMT MMIC for mounting on quasi-millimeter satellites. The GaAs FET amplifier is a four-chip device operating at 2.2 GHz, with a linear gain of 12 dB and saturation power of 51.8 dBm (150 W). The power load efficiency is 35%. The two-stage p-HEMT MMIC is designed for the downlink (satellite-to-ground communication) stage of satellite communications. At an operating frequency of 18 GHz, it exhibits an efficiency of 68%, with a gain of 8.5 dB and output power of 225 mW.

SiGe Microsystems Discrete Bipolar Transistors

Ottawa, Canada. SiGe Microsystems has introduced a family of ultra-low phase noise SiGe transistors. Designers of WLAN, 3G, W-CDMA, local multipoint distribution service (LMDS), point-to-point radio, satellite, cable-modem and fiber-optic systems can anticipate higher data transfer rates due to the low phase noise provided by the HBT30 Series. At 10 GHz, these transistors exhibit typical residual phase noise of -142 dBc/Hz at 100 Hz and -160 dBc/Hz at 10 kHz off-sets. Nominally rated at 5, 10 or 20 mA, these devices provide a maximum output power of +1, +7 or +13 dBm, respectively. Supply voltages operate as low as 1 V, and versions are available in die form, SC-70 (SOT-343) and Micro-X packages.



Infineon Surface Mount Photo Interrupter

Munich, Germany. Infineon Technologies has announced a slotted photo interrupter suitable for surface mounting in sensing applications such as optoelectronic switches, counters and encoders. The SFH9500 contains a non-contact sensor featuring a 5 mm gap between the 940 nm GaAs infrared diode emitter and Si photodetector, and a slit width of 0.5 mm for increased sensing accuracy. The slotted photo interrupter features a rise and fall time of 13 and 17 μs respectively. The collector-emitter current is less than 1 mA (forward current 20 mA and collector-emitter voltage 5V), and the collector-emitter saturation voltage is lower than 0.4 V (forward current 20 mA and collector current 0.3 mA).

Microelectronic Devices and Circuits

1.6 W/mm Output Power Density MMICs

W. Marsetz et al, Elec. Lett., 1999, 35(9), p. 748

Increasing MMIC power density by using a double gate recess to increase the device breakdown voltage should reduce chip size, increase yield and reduce fabrication costs. This paper, from the **Fraunhofer Institute** (Germany), reports 0.5 μm gate length GaAs PHEMT MMICs with a power density of 1.6 W/mm at 2 GHz. The device is a T-gate $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}/\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ structure grown by MBE on GaAs. The 2DEG is supplied by pulse-doped layers on both sides of the channel resulting in a mobility of 6000 cm^2/Vs . Devices with a total gate width of 2.5 mm delivered 4 W of output under CW operation. Although the device is biased for maximum saturated output, the power at 1 dB gain compression is 2.5 W (1 W/mm). This high performance is obtained with a drain ledge of 0.9 μm , resulting in a gate-drain breakdown voltage of -27 V. Pinch off was 1 V.

Metamorphic Power HEMT with 63% PAE

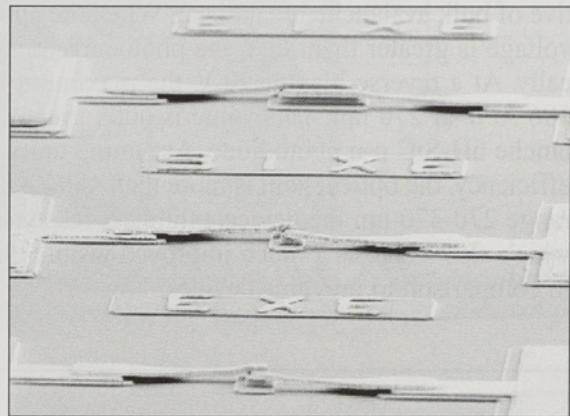
W. Contrata and N. Iwata, Electron Dev. Lett., 1999, 20(7), p. 369

$\text{InAlAs}/\text{InGaAs}$ heterojunction FETs grown on GaAs have good confinement properties and avoid process disadvantages associated with InP substrates. Surface roughening of the gate region as a result of the large substrate-epilayer mismatch can lead to device degradation. This problem can be overcome using a metamorphic buffer. This paper, from **NEC's Kansai Labs**, uses an undoped 1.65 μm thick $\text{Al}_{0.60}\text{Ga}_{0.40}\text{As}_{0.69}\text{Sb}_{0.31}$ strain relief buffer. The active area is a double-doped $\text{In}_{0.35}\text{Al}_{0.65}\text{As}/\text{In}_{0.35}\text{Ga}_{0.65}\text{As}$ structure. The result is a 1 W metamorphic power HJFET with an output power of 31.7 dBm and PAE of 63% at 950 MHz. The gate width is 12.8 mm. The maximum drain current obtained is 490 mA/mm, and the breakdown voltage is 20 V.

250 GHz InP-based Heterostructure Barrier Varactor Tripler

X. M  lique et al, Elec. Lett., 1999, 35(11), p. 938

Heterostructure barrier varactors (HBVs) take advantage of the voltage variable properties of reversed biased p-n junctions. These variable reactors (or varactors) exhibit a symmetrical capacitance-voltage characteristic that makes them attractive for power up-conversion. This paper reports improved performance InP-based $\text{InGaAs}/\text{InAlAs}/\text{AlAs}$ barrier heterostructure HBVs. Pseudomorphic growth of the step-like barrier structure provides more efficient blocking, enables greater voltage handling, and reduces self-heating. Devices consist of two stacked barriers with connecting air bridges, producing two laterally integrated diodes in series (see Figure). Tripler measurements at 250 GHz, an operating frequency higher than any previously reported, revealed a maximum efficiency of 12.3% for pump powers of around 60 mW. At an efficiency of 10.5%, a maximum output power of 9.5 dBm was obtained, the highest values for HBVs to date. Preliminary experiments demonstrated voltage handling as high as 40 V with a zero-bias capacitance level of 250 $\text{aF}/\mu\text{m}^2$, achieved when eight barriers were integrated in series. The authors are from the **University of Lille, Observatoire de Paris Meudon** and **Matra Marconi Space** (France), and the **European Space Research and Technology Center** (The Netherlands).



A 250 GHz InP-based heterostructure varactor tripler

Transferred-substrate HBTs with 254 GHz Cutoff Frequency

D. Mensa et al, Elec. Lett., 1999, 35(7), p. 605

This paper, from the **University of California at Santa Barbara**, reports transferred substrate HBTs with record values of both f_{max} (254 GHz) and f_{T} (233 GHz) using InGaAs-based heterostructures grown by MBE on Fe-doped Si InP substrates. The transferred substrate process allows lateral lithographic definition of the emitter and collector, with large improvements in the value of f_{max} . Vertical scaling by thinning of the layers reduces transit times, maintaining a reasonable $f_{\text{max}}/f_{\text{T}}$ ratio. The device

has a $1 \times 8 \mu\text{m}^2$ emitter contact with a $2 \times 12 \mu\text{m}^2$ collector contact. The f_{T} parameter can be improved by thinning the collector from several hundred nm to around 100 nm. The values of f_{T} of 254 GHz and f_{max} of 233 GHz were obtained using a collector-emitter voltage of 1 V and collector current of 10 mA. Increases in frequency performance are possible with further reductions in the ratio of the width of the collector finger to that of the emitter finger.

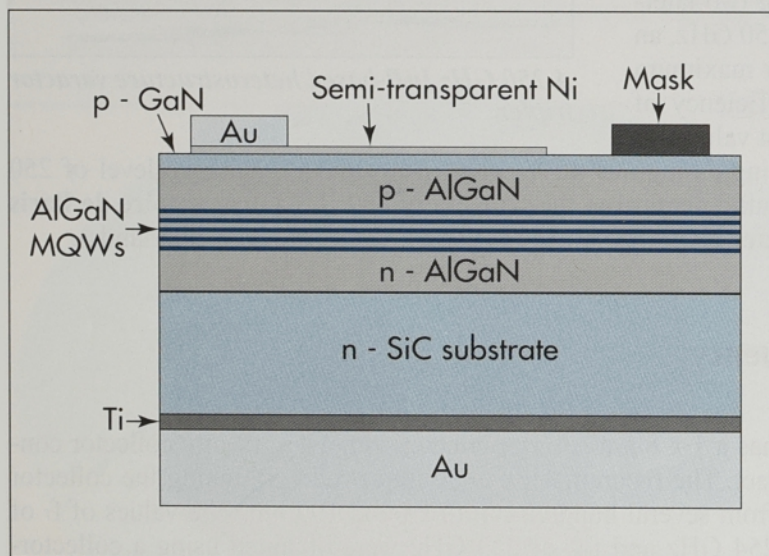
Wide Bandgap Materials and Devices

4H-SiC Visible Blind UV Avalanche Photodiode

F. Yan et al, Elec. Lett., 1999, 35(11), p. 929

SiC is an ideal material for high speed and high gain visible blind UV detectors as a result of a large ionization coefficient ratio (approximately 100) between the holes and electrons. However, it has proven difficult to fabricate SiC p-n diodes with bulk avalanche breakdown. This paper, from **Rutgers University** and **Sensors Unlimited**, reports the first fabrication of a reach-through UV avalanche photodiode (RAPD) on 4H-SiC. The device has a mesa edge termination structure, passivated with a thermal oxide, and is designed for hole-initiated impact ionization and operation up to 100 V.

The three layer epitaxial structure was grown on an n^{++} Si-face 4H-SiC substrate (see Figure). The top p^{++} layer forms the p-n junction with the n layer, which also serves as the multiplication region. The n layer is the reach-through layer, which absorbs photons and 'drags' photogenerated holes into the multiplication layer. The final device size was $85 \times 85 \mu\text{m}^2$ with an optical window of $57 \times 57 \mu\text{m}^2$. A positive temperature coefficient of $16 \text{ mV}/^\circ\text{C}$ was obtained for breakdown voltage, indicative of bulk avalanche breakdown. When the applied reverse bias voltage is greater than 85 V, the photocurrent increases dramatically. At a reverse bias of 90 V, the maximum responsivity was 106 A/W at 270 nm. This value is 600x greater than a non-avalanche 6H-SiC p-n photodiode. Assuming unity for the quantum efficiency, the optical gain is more than 480. In addition, over the range 270-370 nm the device exhibits a responsivity ratio of 20, which also suggests a much improved visible blind performance in comparison to previous devices.



Cross-section of the RAPD structure on 4H-SiC.

AlGaIn/GaN HFET with 107 GHz f_{max}

R. Li et al, IEEE Electron Device Letters, 1999, 20(7), p. 323.

AlGaIn-based HFETs have shown great promise for high power microwave applications. Problems still to be solved include the frequency response, which is limited by the carrier mobility and gate length, and can be degraded further still after production of air bridges for high power operation. This paper, from **UCLA**, **JPL** and **Epitronics**, reports an undoped channel $\text{Al}_{0.30}\text{Ga}_{0.70}\text{N}/\text{GaN}$ HFET grown on semi-insulating 4H-SiC, which is fabricated without air bridges and reaches a reported record value of f_{max} of 107 GHz. The device contains a 100 nm AlN buffer, $1.25 \mu\text{m}$ of undoped GaN, 3 nm of undoped $\text{Al}_{0.30}\text{Ga}_{0.70}\text{N}$, and a 30 nm $\text{Al}_{0.30}\text{Ga}_{0.70}\text{N}$ layer with heavy n-type doping ($\text{Si} = 1 \times 10^{19} \text{ cm}^{-3}$). The gate length was $0.2 \mu\text{m}$, and a source-drain ohmic contact resistance of $0.15 \Omega\text{-mm}$ was achieved as a result of the high Al content and n-type doping in the AlGaIn layer. In addition to the excellent frequency performance, the device exhibited a transconductance of 260 mS/mm (gate reverse bias of 3.5 V) and a saturated current density of 1.2 A/mm with an undoped channel layer.

Enhanced Mg Doping Efficiency in AlGaIn/GaN Superlattices

P. Kozodoy et al, Appl. Phys. Lett., 1999, 74(24), p. 3681

In order for GaN-based bipolar transistors to realize their potential as high power devices, the high resistance to lateral current flow in the Mg-doped p-type base must be overcome. The p-doping is limited by the deep nature of the Mg acceptor and consequent low acceptor ionization percentage, in addition to the low hole mobility in heavily Mg-doped GaN. The problem is also compounded in AlGaIn by a low doping efficiency. However, the inclusion of superlattices containing alloys with different valence band edge positions modifies the band properties - a periodic oscillation of the valence band edge has been shown to increase the number of carriers. This paper, from the **University of California at Santa Barbara**, examines the impact of differing periods of AlGaIn/GaN superlattices on the average carrier density. An $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ superlattice with equal barrier and well widths (L), and uniform Mg-doping was grown by MOCVD on sapphire to a total thickness of $0.4 \mu\text{m}$.

Room temperature Hall measurements on AlGaIn films showed that as the superlattice dimension L is increased, the measured hole concentration increases quickly from the value of a bulk $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ film of $1.7 \times 10^{17} \text{ cm}^{-3}$ to around $2.5 \times 10^{18} \text{ cm}^{-3}$, an order of magnitude increase. [cont. next page].

Optoelectronic Devices

Monolithically-Integrated 40 Gbps Optical Receiver Modules

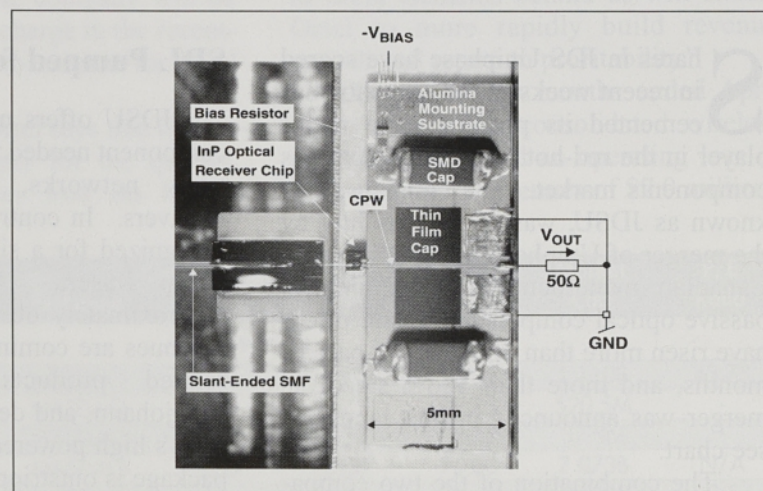
Bitter et al, Proc. InP & Rel. Mat. Conf., 1999, p. 381; Huber et al, Elec. Lett. 1999, 35(11), p. 897; Y. Baeyens et al, IEEE Photonics Tech. Lett., 1999, 11(7), p. 868

Monolithically-integrated high-speed, base-band optical receivers are required for future 40 Gbps time-division multiplexing (TDM) optical transmission systems. Bitter et al (Swiss Federal Institute of Technology and Opto Speed SA) describe a fully-packaged module system based on monolithically integrated PIN photodiodes and single heterojunction InGaAs/InP HBT transistors grown on SI InP substrates (see photo, top). The HBT devices exhibit a current cut-off frequency f_T of 70 GHz (at 5 mA collector current and collector-emitter voltage of 1.5 V) and a maximum oscillation frequency f_{max} of 160 GHz. The photodiode contains a light-sensitive area of 11 μm (diameter). At 1.55 μm , an overall conversion gain of 48 V/W, a small signal bandwidth of 30 GHz, and a clear eye opening value of 40 Gbps was observed.

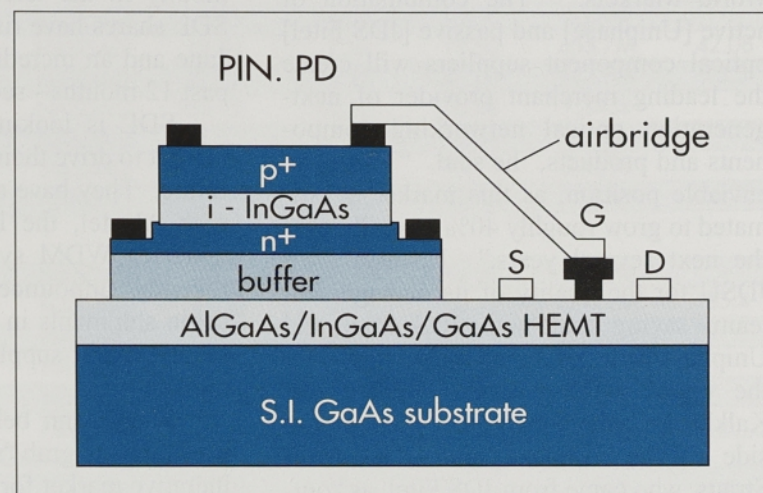
Huber et al [Swiss Federal Institute of Technology and Polytechnic of Aargau (Switzerland), plus the Fraunhofer Institute (Germany)], report a 40 Gbps photoreceiver consisting of an InGaAs pin photodiode, transimpedance amplifier and differential post-amplifier. The pin photodetector is co-integrated with the pre- and post-amplifier without additional epitaxial or processing steps, as the InGaAs base-collector junction SHBT is used as the basis of the photodiode operating at 1.55 μm . The integrated HBTs combine to achieve a f_T value of 130 GHz (at 130 kA/cm² collector current density and collector-emitter voltage of 2 V), and f_{max} of 220 GHz. The photodiode (light sensitive diameter of 9 μm) exhibited a -3 dBm bandwidth of 30 GHz, with a transimpedance gain of 3.3 k Ω .

Baeyens et al (Fraunhofer Institute) report a narrow-band 1.3-1.55 μm photoreceiver fabricated by integrating an In_{0.53}GaAs_{0.47} pin photodiode with a 0.15 μm GaAs dual-gate PHEMT. The epilayers are grown on GaAs, allowing the use of a well-established and cost-effective process. Using MBE, the

AlGaAs/InGaAs/GaAs PHEMT layers are grown first, followed by 600 nm of compositionally-graded AlInGaAs buffer layer to accommodate the strain between substrate and InGaAs photodiode layers (see figure, bottom). The HEMT had an f_T of 90 GHz and f_{max} of 150 GHz, and the top-illuminated photodetector had a light sensitive diameter of 10 μm . A 42 GHz receiver had a maximum output of -5 dBm for an optical input of -3 dBm, while a 58 GHz receiver reached -8 dBm for 0 dBm input.



Photograph of the optical receiver module. A slant-ended single mode fiber (SMF) couples the light to the top-illuminated pin photodiode.



Cross-section of InGaAs pin photodiode integrated with a GaAs PHEMT. The PHEMT is grown first, followed by a thick, compositionally-graded AlInGaAs buffer layer to accommodate mismatch between the substrate and the pin photodetector.

Mg Doping [cont.]

The maximum occurs at a superlattice period thickness of 70 Å, beyond which the hole concentration saturates and begins to decline. However, the mobility in the superlattice samples is 10 cm²/Vs, compared to 16 cm²/Vs in bulk GaN films, and electron transport across the base is impeded as a result of conduction band barriers induced by the superlattice. This problem may be partially overcome in future by the use of quaternary alloys, and AlGaN/GaN superlattices may prove useful for devices such as edge emitting- and vertical cavity lasers, which operate by hole transport only.

SDL and JDS Uniphase Investors are Beaming

The two largest pure-play telecom laser manufacturers have surpassed the GaAs IC companies as the hottest members of the Compound Semiconductor Portfolio. Can new management at Ortel lift their company to the same level?

MARIE MEYER

Shares in JDS Uniphase have soared in recent weeks as the company has cemented its position as a major player in the red-hot telecommunications components market. The company, also known as JDSU, was formed in July by the merger of Uniphase with JDS Fitel, a Canadian manufacturer specializing in passive optical components. Share prices have risen more than 400% in the past 12 months, and more than 186% since the merger was announced in late January - see chart.

The combination of the two companies makes JDSU more valuable than just the sum of its parts, according to James Jungjohann, an equity analyst at CIBC World Markets. "The combination of active [Uniphase] and passive [JDS Fitel] optical component suppliers will create the leading merchant provider of next-generation optical networking components and products," he said. "This is an enviable position, as this market is estimated to grow roughly 40% annually over the next several years." He also likes JDSU for the quality of its management team, saying that both JDS Fitel and Uniphase have "executed masterfully over the years". He describes CEO Kevin Kalkhoven, who comes from the Uniphase side of the business, and COO Jozef Straus, who came from JDS Fitel, as "out-of-the-box visionaries" who have "a market-driven mentality tied with the cardinal aspect - satisfying customer needs".

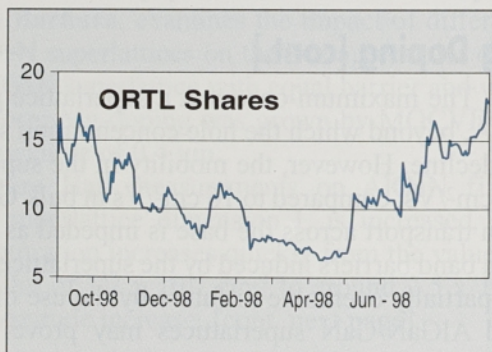
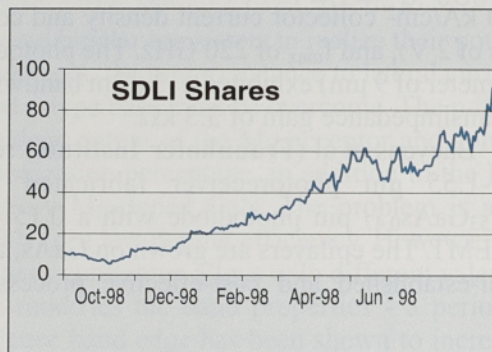
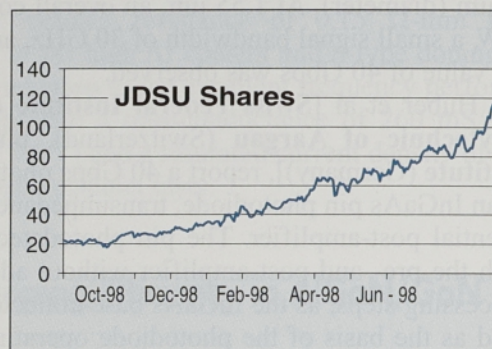
SDL Pumped for Success

JDSU offers nearly every optical component needed for telecommunications networks, except for PIN receivers. In contrast, SDL is chiefly recognized for a single product line - pump lasers. See page 64. Approximately 60% of SDL's current revenues are coming from its 980nm-related products, according to Jungjohann, and demand for the company's high powered grating-stabilized package is outstripping supply.

Being somewhat of a niche player hasn't hurt SDL. As Jungjohann points out, pumps are the hottest commodity in the telecom market today. SDL shares have risen over 70% since June and an incredible 710% over the past 12 months - see chart.

SDL is looking to the undersea market to drive their growth in the near future. They have a four year contract with Alcatel, the largest provider of undersea WDM systems. They also recently announced that they will begin shipments in fourth quarter to a second major supplier to the undersea market.

Jungjohann believes that SDL is positioned to grab "at least" 50% of the lucrative market for submarine pumps. He also expects to see SDL introduce a high powered 1550nm source laser sometime in the near future.



New Management Takes Control at Ortel

Ortel, the third "pure-play" laser company, has missed out on the tremendous run-up in share prices enjoyed by JDSU and SDL. Years ago, Ortel established a very comfortable niche for itself, making 1310nm DFB lasers for cable television networks. But the company has been late in introducing high performance 1550 products for the new generation of telecom networks. Moreover, their attempt to compete with Uniphase and SDL in the pump market met with failure, and the company withdrew from that market segment earlier this year (see CS 5(2), p. 6). At the same time Ortel has seen a 20 - 30% annual erosion in CATV laser prices. Not surprising, Ortel reported a loss for the past twelve months and is not expected to be profitable this year, either.

A new management team has been put in place in hopes of turning things around. Stephen R. Rizzone took over as President and CEO in June. He replaces Wim Selders, who has retired. Rizzone will also succeed Amnon Yariv as Chairman of the Board of Directors. Yariv, who will remain on the board, is a co-founder of the company and a well-known pioneer in laser diode development. He also holds a professorship at Cal Tech.

Rizzone was formerly the president and CEO of NetVantage Inc., a publicly traded networking company. He became available when that company merged with Cabletron Systems in September 1998. Another ex-NetVantage executive, George M. Pontiakos, has come aboard to serve as senior vice president of operations.

One of Rizzone's first moves after arriving at Ortel was to reorganize the company's marketing effort. A new position of vice president of marketing was created, and a former ETEC Systems executive, Jeff Rittichier, was chosen to fill the spot. Rizzone said the move was made to reflect "an accelerated marketing strategy".

More recently, Rizzone announced the sale Ortel's loss-making U.S. wireless operations to CI Wireless Inc, a privately-

Telecom Laser Makers at a Glance							
Company	Market Cap.*	52 Week		Past 12 Months, Actual**		Next 12 Months, Est.**	
		Low	High	Revenue	Net Income	Revenue	Net Income
JDS Uniphase	\$9.7B	\$16	\$121	\$588	\$125	\$967	\$206
SDL	\$2.5 B	\$4	\$93	\$134	\$15	\$211	\$30
Ortel	\$212 M	\$6	\$19	\$72	-\$0.68	\$79	-\$0.56

*Market Capitalization = # Shares x Current Price

**In Millions. Source: CIBC

held company based in Fort Worth, Texas. Terms of the all cash transaction were not disclosed. Ortel is also negotiating with a European buyer for the sale of its wireless operations in Sweden.

More housecleaning is on the way. Rizzone has shelved plans for a new facility and phased-out some of Ortel's low-volume products. The company will be taking a \$9.3 million charge in the recently completed quarter to account for all of the changes.

On the upside, Ortel says that it is on track to beat estimates for the quarter, reporting a narrower loss on higher

revenues. Commenting on the situation, Rizzone said "Completion of the wireless transactions is one more critical element in refocusing Ortel on its core technologies in order to capture a more significant share of the considerable growth opportunities available to us in the telecommunications and cable industries. Putting all of these elements behind us will enable Ortel to more rapidly build revenue growth and return to profitability."

For the twelve months ended April 30, 1999, Ortel's consolidated wireless operations recorded an operating loss of \$3.3 million on revenues of \$7.0 million.

Company	Symbol	Exchange	Closing Price	52 Week		Market Cap	P/E Ratio
			Aug 30	Low	High		
GaAs ICs							
Alpha Ind.	AHAA	NASDAQ	57.28	5.75	58.06	1.110B	43.73
Anadigics	ANAD	NASDAQ	35.00	4.63	39.25	520.5M	-
Celeritek	CLTK	NASDAQ	5.13	2.50	7.13	37.8M	-
Conexant	CNXT	NASDAQ	72.56	13.00	75.00	7.073B	N/A
RFMD	RFMD	NASDAQ	42.94	3.06	48.50	3.401B	82.57
TriQuint	TQNT	NASDAQ	51.00	7.31	56.50	743.0M	55.04
Vitesse	VTSS	NASDAQ	66.94	17.13	74.50	5.136B	78.75
Optoelectronics							
APA Optics	APAT	NASDAQ	6.50	4.00	10.00	55.3M	-
Coherent	COHR	NASDAQ	18.94	7.50	19.50	455.7M	42.08
Cree	CREE	NASDAQ	32.25	5.25	41.00	943.6M	73.3
JDS Uniphase	JDSU	NASDAQ	105.72	15.63	120.88	9,343B	-
Ortel	ORTL	NASDAQ	17.75	6.00	18.44	212.6M	-
SDL	SDLI	NASDAQ	78.69	4.06	92.75	2.459B	+
Uniroyal Tech.	UTCI	NASDAQ	10	7.25	12.63	120.8M	26.32
Materials and Equipment							
ATMI	ATMI	NASDAQ	32.00	11.25	36.63	835.5M	+
AXT	AXTI	NASDAQ	24.38	5.25	36.19	396.0M	55.4
Emcore	EMKR	NASDAQ	18.56	6.00	28.75	176.3M	-
Kopin	KOPN	NASDAQ	36.5	11.38	40.75	453.1M	-
PlasmaTherm	PTIS	NASDAQ	3.31	2.06	5.00	37.2M	-
Spire	SPIR	NASDAQ	3.81	2.25	5.69	12.4M	-
European Companies (Currency data in Euros)							
Aixtron	AIX	Neur Mkt.	97.00	30.7	97.00	1.45B	+
IQE plc	IQEP	Easdaq	13.31	11.58	13.31	176M	87
Picogiga	PICO	N. Marche	15.7	9.91	26.8	24.7M	32

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

October

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/>

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

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

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

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

December

1999 Fall MRS Meeting

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

1999 IEEE International Electron Devices Meeting (IEDM)

December 5-8
Washington, DC
Contact: Ms Phyllis Mahoney
phyllism@widerkehr.com

Jan-Feb 2000

Photonics West

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

Strategies in Light: Business Opportunities in LEDs

February 10-11
San Francisco, CA
http://www.strategies-u.com/op/op_strategiesinlight.html

March-April 2000

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

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

Optical Fiber Conference

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

MRS Spring Meeting

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

May 2000

GaAs Manufacturing Technology (GaAs MANTECH)

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

16th European Photovoltaic Solar Energy Conf

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

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>

June-July 2000

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

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

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

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

4th European GaN Workshop

July 2-5
Nottingham, England
Abstract Deadline: March 1, 2000
enquiries@global-meeting.co.uk

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

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

Sept 2000

Int'l Conf on Microwave and Millimeter Wave Technology

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

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

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

28th IEEE PV Specialists Conference (PVSC)

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

Int'l Workshop on Nitride Semiconductors (IWN2000)

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

Oct-Dec 2000

Advanced Semiconductor Devices And Microsystems (ASDAM)

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

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

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

2000 Asia-Pacific Microwave Conf (APMC 2000)

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

Conference Organizers: Please send details of your events to: tim.whitaker@compsem.com

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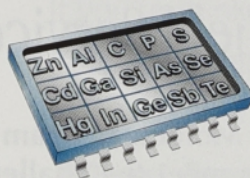
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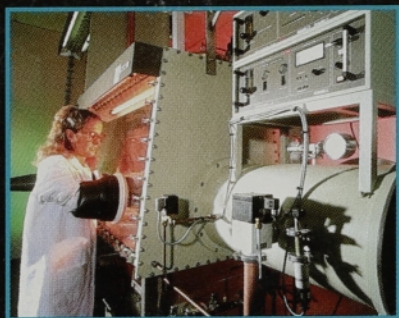
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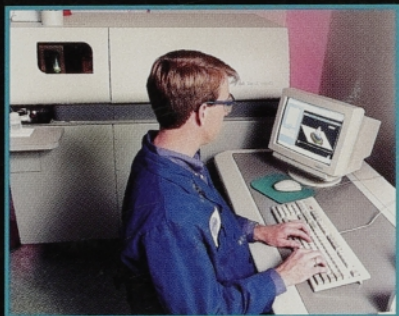
Argon	< 20 ppb	Oxygen	<100 ppb
Carbon Dioxide	<100 ppb	THC (as Methane)	< 50 ppb
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