



COMPOUND SEMICONDUCTOR

1997

Special Issue

Special Issue

**Reports from the Field:
The Current Status of the
Compound Semiconductor Industry**

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- Applications for Compound Semiconductors
- Laser Report
- Nitride News
- GaAs Update
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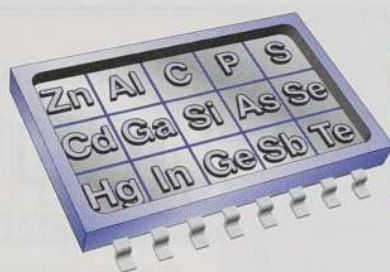
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Welcome!

This Special Issue of *Compound Semiconductor* is intended to serve two purposes. The first is to provide an overview of a variety of topics of current importance in the compound semiconductor industry. It is an exciting time in our field, and as these articles indicate, rapid progress is being made and substantial growth is occurring in several areas.

The second purpose is to provide an introduction to our magazine. The articles in this issue were selected as some of highlights from the first two volumes of *Compound Semiconductor*, a bi-monthly (6 times a year) magazine which covers new developments in III-V, II-VI and IV-IV semiconductors. Our coverage, as well as our readership, is international in scope. We cover both microelectronics and optoelectronics, and we track important news from both the production and the R&D areas.

While this Special Issue is representative of the overall quality of the editorial content in *Compound Semiconductor*, we do not have room to reprint all of our interesting articles. Regular subscribers to *Compound Semiconductor* enjoy the benefits of all of the following regular features:

- **New Devices:** a review of new products from compound semiconductor device manufacturers.
- **Device Feature:** a more in-depth analysis of a particularly interesting new optoelectronic or microelectronic device or process.
- **Research Review:** a three page report on the most interesting new compound semiconductor-related results to appear in the leading journals. Areas covered: Optoelectronic Devices, Electronic Circuits and Devices; Compound Semiconductor Materials.
- **Nitride News:** a special section of the magazine dedicated to tracking this exciting niche of the compound semiconductor industry.
- **News from Japan:** we have teamed up with a Japanese news agency to gather the latest results from the major Japanese compound semiconductor device manufacturers and research centers.
- **Portfolio:** we closely track several publicly-held companies that are active in the compound semiconductor field, reporting on both the latest news and developments as well as share price activity.
- **Patents:** a summary of compound semiconductor-related patents recently issued by the U.S. patent office.

We hope you enjoy this special issue. But more importantly, we hope that you become a regular subscriber to *Compound Semiconductor*, so that you can benefit from our excellent coverage of the industry in the future.

Sincerely,

Marie Meyer
Marie Meyer
Editor

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Compound Semiconductor is available only by paid subscription. We need the support of subscribers such as yourself to allow us to provide the high quality content that has become our hallmark.

Our editorial policies are designed to ensure that the content of each issue of *Compound Semiconductor* is fresh and interesting to a broad cross-section of the compound semiconductor industry. Most trade magazines are filled primarily with articles written by advertisers to promote their companies and products. But *Compound Semiconductor* is different - we emphasize "real news" from a variety of sources around the world, and we always strive to be useful and informative.

If you would like to stay abreast of events in the rapidly changing compound semiconductor field, then you should act today to obtain your own subscription to *Compound Semiconductor*. Prices start at as little as \$45/year (\$59 outside of the U.S.). An order form is provided for your use on page 29. If you have any questions, please contact the editor:

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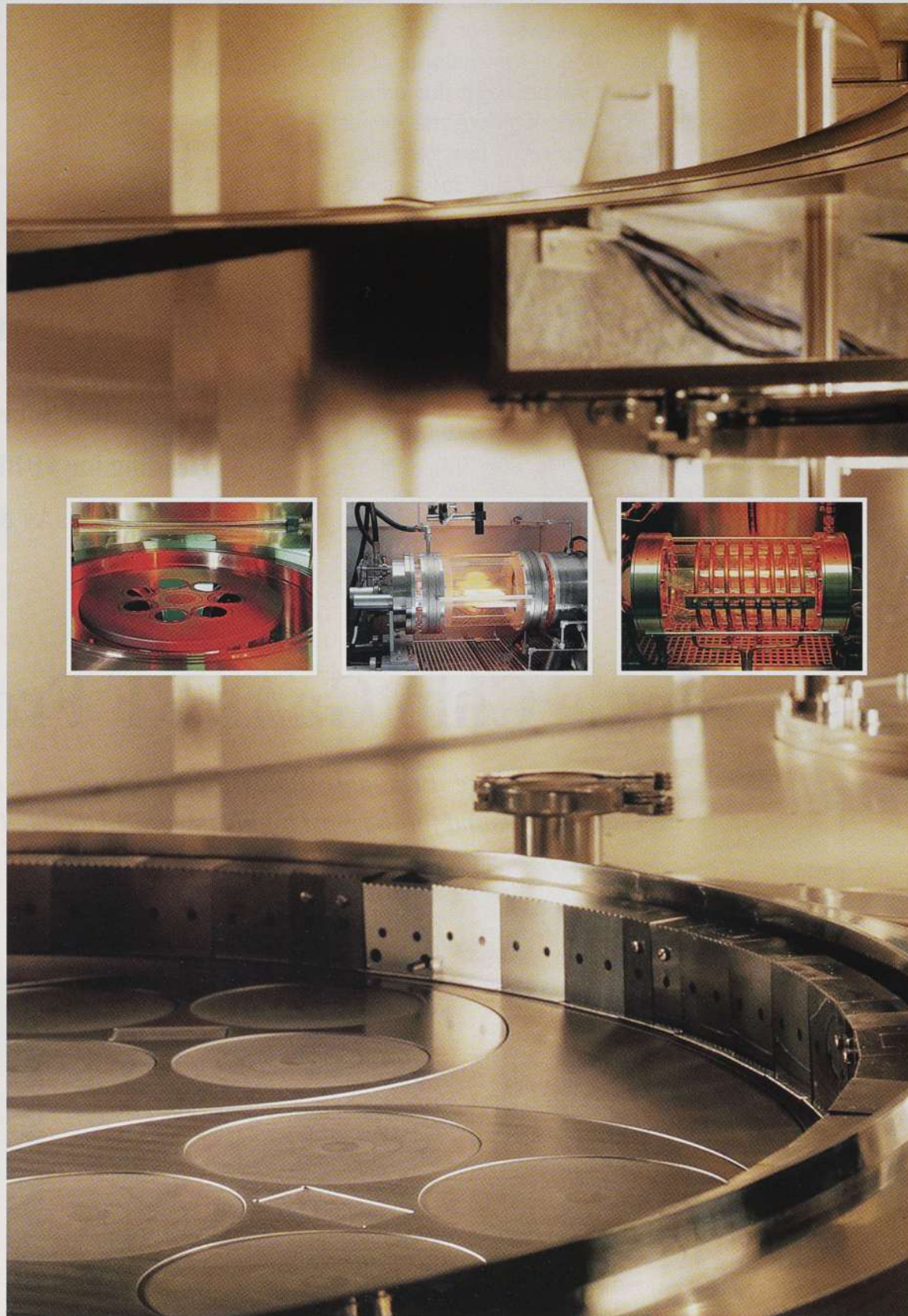
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GaAs Update

It seems that all of the news about GaAs of late has been good news. For years skeptics claimed that "GaAs is the material of the future ... and always will be". But the industry has, at last found some high volume niches. So perhaps it is time to retire that old saw.

We cannot reprint all of the GaAs articles that appeared in our first two volumes - there isn't enough room. Instead, we present here a small selection of some of the most interesting items. Much of the analysis deals with analog devices, reflecting the nature of the current market. But, beginning on page 13, we also make the point that it will be digital GaAs that propels the industry into the era of 6" processing, which may mark the beginning of the first mature stage of the industry's progress.

Also in this section:

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Single Chip GaAs RF Front End

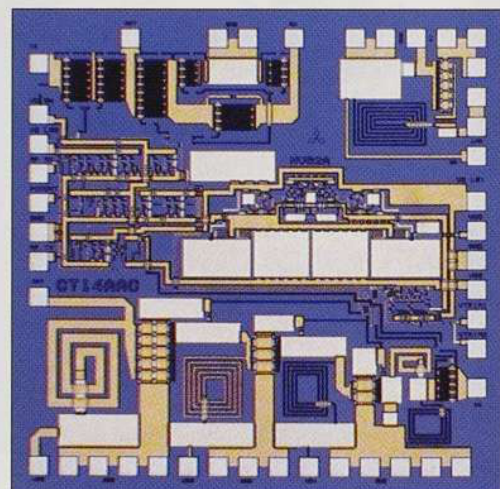
The Japanese Personal Handy-Phone System becomes the proving ground for the most highly integrated analog GaAs ICs.

Most wireless phone manufacturers build the RF front end of the handset from discrete components, meaning that the transmit/receive switch, low-noise amplifier (LNA), power amplifier and up/down converters are individual devices or, in some cases, small scale MMICs. Designers say they like this approach because it offers more design flexibility though the ability to mix different technologies and device types (i.e. both GaAs and Si, as well as Si bipolar and GaAs MESFETs and HBTs). And as long as the wireless market remains as fragmented as it currently is, with a large number of competing standards, it may be an economically advantageous approach as well, because it is difficult for the GaAs IC manufacturers to recover the development costs for more sophisticated RF chips unless they can sell large numbers of them.

The Japanese Personal Handy-Phone System (PHS) has the potential to change all

that, because it creates a high volume market for (relatively) high frequency RF transceivers, and it places a premium on size and weight. The PHS is a TDMA-based digital wireless standard operating at 1.9 GHz that is intended to fill the gap between short range cordless phones and more conventional cellular phones. PHS handsets need only relatively modest output power (10-80 mW) and are intended for stationary or walking use, primarily in dense metropolitan areas. PHS was launched in mid 1995, and by 1996 it had ~1.5 million subscribers, and it is expected to reach ~4 million by the first quarter of 1997.

Mitsubishi Electric Corporation [Hyogo, Japan] recently introduced a three chip set targeted for the PHS market. The chip set includes a GaAs IC which is a complete RF front-end, containing the LNA, power amplifier and transmit/receive switch. The chip set also includes an Intermediate Frequency Processing BiCMOS LSI which contains



Photomicrograph of the new 1.9 GHz GaAs transceiver announced in April, 1996 by Mitsubishi for use in PHS handsets.

up/down converters and phase modulation circuitry; and a Baseband Processing CMOS LSI which containing voice coding circuitry. Used with a microcontroller, the three chips provide all the main functions required in a PHS handset, reducing by half the number of chips typically required. The chips set also reduces the board size by 30%, and reduces standby power requirements to 230 μ A, thereby extending standby time. Mitsubishi will use the chips in its own phones and make them available to other manufacturers as well. Mitsubishi has already demonstrated a very small PHS handset using this chip set. When folded, the phone measures 8 x 5 x 1 cm³, and it weighs less than 100 g.

Integrated GaAs & SAGFETs

The Mitsubishi approach to GaAs RF integration in the PHS chip set represents one of the largest levels of RF complexity in any wireless phone. As described by Kazuya Yamamoto of Mitsubishi, the GaAs transceiver consists of both analog and digital circuitry. The analog portion of the chip contains the power amplifier (PA), a SPDT switch (SW), two attenuators (ATTs) for transmitting and receiving modes, and a low noise amplifier (LNA). The digital circuitry contains logic circuitry to control other circuits, as well as a negative voltage generator (NVG), which thereby enables single power supply operation. The control logic can select transmitting, receiving, or standby modes. The NVG operates only during communication - thereby cutting down on power consumption. To reduce chip size, Mitsubishi has adopted a simple SW which consists of two FETs connected in series for transmitting, and a single FET for receiving. Operating with a single 3.4 V power supply, the chip requires 171 mA while transmitting, 6.1 mA while receiving, and 4.4 mA in the standby mode. The entire chip measures 2.5 x 2.5 mm².

Unlike most GaAs device manufacturers which rely on MESFET technology, Mitsubishi has chosen to use a self-aligned gate FET (SAGFET) approach. According to Nobuyuki Kasai of Mitsubishi, "the recessed gate MESFET provides higher breakdown voltage, so these types of FETs are widely used for high power applications. However, the recessed gate FETs have poor uniformity of DC/RF performances due to the low controllability of the recess etching process - hence from the practical viewpoint of manufacturing, recessed gate FETs are a disadvantage." Therefore, Mitsubishi has gone to a

planar SAGFET process, where DC/RF uniformity is obtained by way of ion implantation, and no recess etching is required. A buried p-layer (BP) lightly doped drain (LDD) SAGFET structure is used in the implementation of the transceiver chip. A WSi/W double-layer gate structure is used to reduce gate resistance. By placing the gate closer to the source than to the drain, and using a SiO sidewalls on the edge of the gate, which are used as masks during ion implantation in order to separate the heavily doped regions away from the gate edge, gate to drain breakdown voltages as high as 20 V were obtained. Using 1.0 mm gate-length and 1.2 mm gate-width devices, a maximum output power of 24.7 dBm, corresponding to 240 mW/mm and a PAE of 54% was obtained for 1.9 GHz operation. This power density is the highest value ever reported for SAGFETs at this frequency.

Competition

The new Mitsubishi chip set will challenge another product using highly integrated GaAs circuits. PCSI, a "fabless" semiconductor manufacturer based in San Diego, CA, has been supplying PHS chip sets since 1995. The four-chip PCSI set includes CMOS and BiCMOS baseband chips, as well as two MESFET-based GaAs RF circuits fabricated by TriQuint Semiconductor. The first GaAs chip contains a power amplifier, LNA and transmit/receive switch - a chip very similar to the Mitsubishi transceiver. In addition, the PCSI chipset includes another GaAs IC which contains all up/down converter functions required for PHS. (Mitsubishi chose to implement this function in its BiCMOS baseband chip.) According to John Meyer, Vice President and General Manager of PCSI's Semiconductor Group, "we have now sold 2,000,000 PHS chip sets to Japan, and we supply 50-60% of the PHS market". A second version of the chip set, in which all the baseband functions currently done in 3 different silicon chips will be combined into one large baseband chip, is planned for later this year.

Mitsubishi announced plans to begin shipping its chip set by mid 1996, with forecasts for 300,000 sets per month by the end of the year. PCSI has demonstrated that integrated GaAs RF transceivers can not only successfully compete in the marketplace, but can actually dominate. Mitsubishi's aggressive production estimates demonstrates that they plan to recreate that experience for itself.

From our May/June 1996 issue.

Good Signs for GaAs

There was much good news for GaAs in 1996, including numerous reports of companies expanding their processing capabilities. Here are a few of the highlights:

Four new GaAs fabs are being built in the U.S. **Vitesse** is launching the industry's first 6" fab in Colorado Springs, CO. It will have a total capacity of 600 wafers a week. The company will also retain its current 4" fab in Camarillo, CA. **TriQuint Semiconductor** is moving into a larger fab in Hillsboro, OR that will up their capacity to 750 4" wafers per week. Similarly, **Anadigics** is expanding its facilities in Warren, NJ by acquiring an adjacent site to allow capacity to be doubled to around 500 4" wafers per week. And **RF MicroDevices** is building the industry's most unique GaAs fab: a plant in Greensboro, NC which will be dedicated to processing HBT circuits, with a total capacity of 500 4" wafers a week.

From our Sept/Oct 1996 issue.

OKI Electric plans to increase microwave device production by 50% to 3 million units per month by mid-1997. The company says the move is in response to strong demand in the mobile communications area, especially satellite-based services. **NEC** also recently announced plans to increase capacity for all of its compound semiconductor activities, in both the optoelectronic and microelectronics areas.

From our Nov/Dec 1996 issue.

Thomson-CSF of France and **Daimler-Benz** of Germany are teaming up for a GaAs joint venture which will be called "**United Monolithic Semiconductors**". The new company will be owned 50% by Thomson and 50% by two Daimler subsidiaries: Daimler-Benz Aerospace (DASA) and TEMIC Telefunken Microelectronic. The former GaAs production activities of Thomson-CSF Semiconductors Specifiques in Orsay and the Daimler-Benz GaAs foundry in Ulm will be merged. The "front-end" processing activities will be concentrated in Ulm, where a 4" line will be added to the existing 3" line. Back-end processing will be concentrated in Orsay, as well as the design activities, product line coordination, and marketing.

From our July/August 1996 issue.

Recent market research from Dataquest shows that **Fujitsu** and **NEC** are the world's top suppliers of GaAs ICs, with market shares of 32% and 12% respectively. Four U.S. companies occupy the next spots: **Anadigics** (6.3%), **Vitesse** (5.8%), **TriQuint** (5.6%) and **M-A/COM** (4.8%). Dataquest calculates that sales of GaAs ICs should top \$1 billion in 1996.

From our Nov/Dec 1996 issue.

TRW Advances MMIC Technology with Integrated HEMT/HBT Circuits

TRW is opening up new possibilities for GaAs MMICs with first production ready MMIC which monolithically integrates HEMTs and HBTs in the same microwave circuit. This new capability allows TRW designers to create a single chip solution which can handle both faint and strong signals by combining the low noise and high gain characteristics of HEMTs with the clean, accurate amplification capabilities of HBTs. "We've created a new family of chips which reduces the parts count for a typical integrated microwave assembly by a factor of 30 to 1," says Dave Vandervoet, vice president and general manager of TRW's Electronics Systems and Technology Division. "This breakthrough not only reduces our assembly costs, but also leads to significant improvements in the size, power consumption, and reliability of our customer's systems."

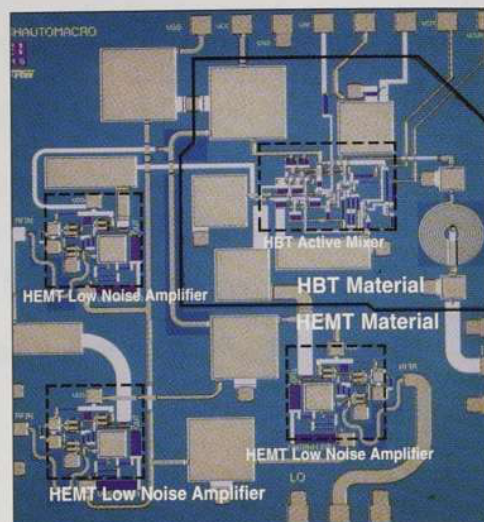
Selective Epi

The circuits are fabricated using selective MBE and a merged process technology which has been under development at TRW for the last three years. According to Dwight Streit, principal investigator for the project, "the technology has now matured to the point in which we have circuits which show clear advantages in microwave performance as compared to HEMT-only or HBT-only circuits which are then externally connected." The npn

HBT profile is grown first by solid source MBE using Be p-type doping. The wafer is then removed from the MBE system, patterned with PECVD silicon nitride in the areas where HBTs will be needed, and the unpatterned areas wet etched back down to the substrate. The wafer is then reintroduced to the MBE system, and the GaAs/InGaAs HEMT is grown. The silicon nitride overhang created by the retrograde wet HBT etch provides a clean separation between the HBT island and the HEMT region. The polycrystalline HEMT material and the silicon nitride layers are then removed. A merged device process is performed to fabricate the HEMT and HBTs, with ion implantation used for device isolation within islands, and air-bridges used for island interconnects.

A schematic of an integrated HEMT-HBT profile is shown in Figure 1. This example includes PIN and Schottky diodes which are easily been fabricated from the base-collector and collector region of the HBT. Potential applications for this new capability include single-chip transmit-receive circuits (using the HEMT to receive, the HBT to transmit, and PIN-diodes in switching functions); HEMT low-noise amplifiers that use HBT active feedback along with PIN-diode variable-gain control; and monolithic gain blocks that could combine HEMT low-noise front-ends with HBT high-linearity output stages.

From our Sept/Oct 1995 issue.



Photograph of TRW's new integrated HEMT/HBT technology, implemented as a low noise receiver chip.

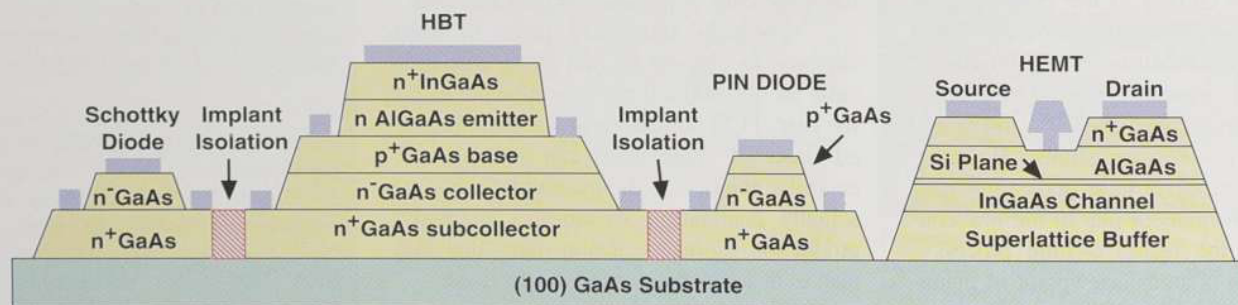


Figure 1. Schematic of integrated HEMT/HBT profiles, including PIN and Schottky diodes.

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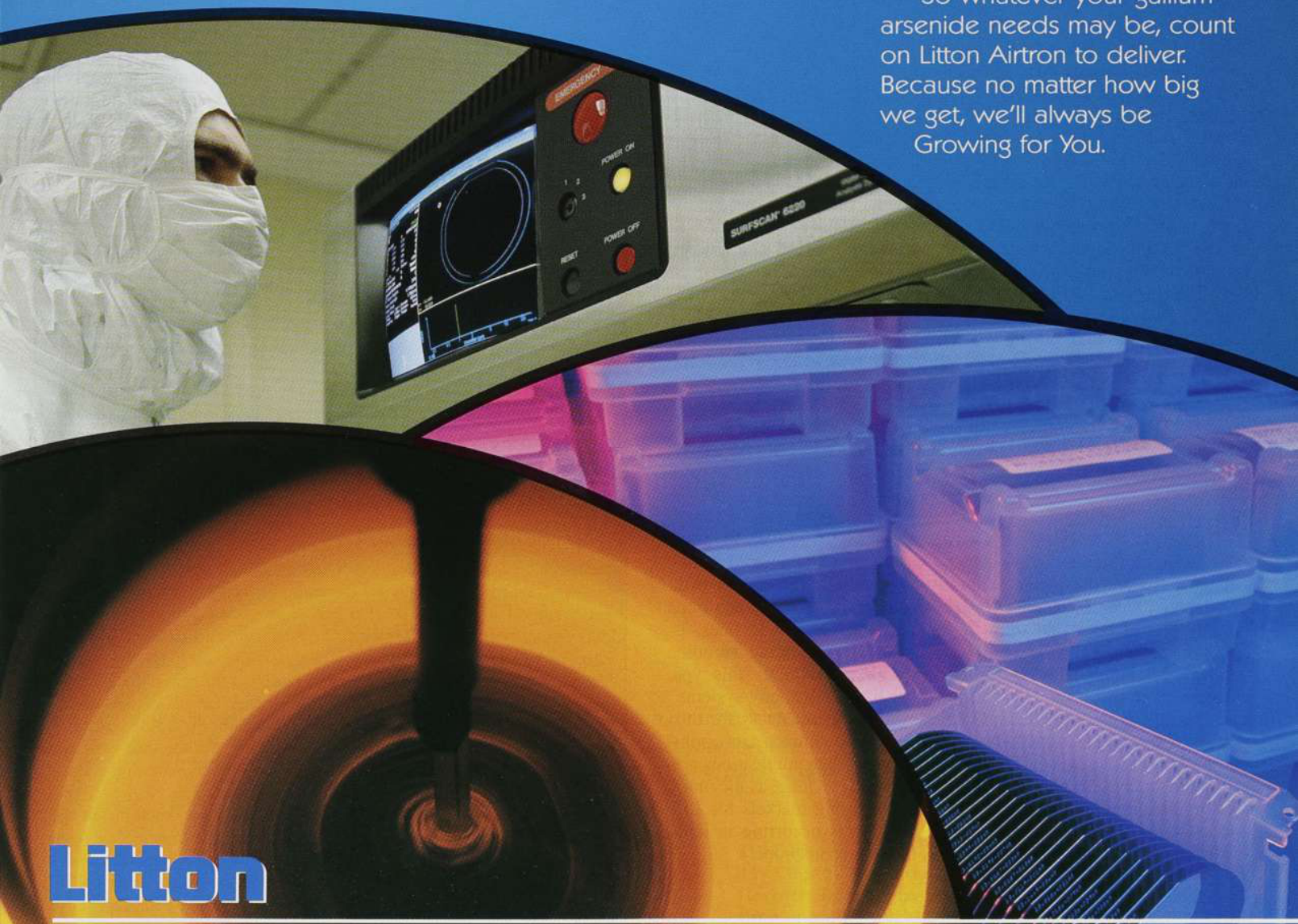
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TriQuint's GaAs Transceiver for 622 Mb/s Communications

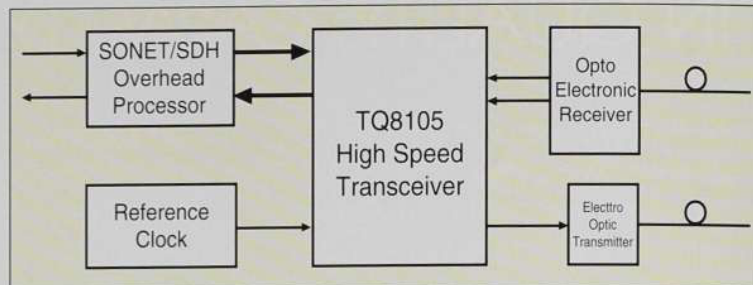
Optical communication systems require transceivers to act as links between the optics (either the laser/LED transmitter or the photodetector receiver) and the communications processing where both switching and digital signal processing takes place. The heart of a high speed data transceiver is a multiplexer/demultiplexer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

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

The TQ8105, which is fabricated on 4 inch GaAs substrates, utilizes TriQuint's new enhancement/depletion ion implanted SCFL (Source Coupled FET Logic) MESFET process. This process uses 0.6 μ m gate length transistors which exhibit f_t values of 20 GHz. Four layers of Au coupled with dielectric isolation are used for metalization, with each metal layer exhibiting a 4 μ m pitch (2 μ m line and spaces). The TQ8105 utilizes 1800 equivalent two input gates and has an area of 3.56 x 3.43 mm². It can operate with a single 5 V supply and dissipates 2.3 W.

Markets

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



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

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

The future direction for these transceivers is at higher data rates, the next being OC-48 at 2.5 Gb/s. Turudic says, "we are not currently producing large volumes of 2.5 Gb/s parts because the demand is simply not there yet. When there is a significant enough market, we will migrate up to 2.5 Gb/s." He believes that the technology is available and ready to used - as soon as the market develops.

From our March/April 1996 issue.

Vitesse Sticks with Digital GaAs

Vitesse Semiconductor [Camarillo, CA] should have been rattled by the demise of the GaAs supercomputer business - but it wasn't. In 1993 the majority of their revenue came from the computer market. Three years later that segment had all but disappeared, but nevertheless company-wide revenues more than doubled (>\$40 million in 1996) on the strength of Vitesse's telecommunications business. The company is very satisfied with these turns of events, especially given that the forecast for the amount of data that will be transmitted over phone lines is forecast to quintuple over the next 12 - 15 years.

Data transmission is much more demanding than voice communications, creating bottlenecks for the phone company and the local network administrator. Vitesse believes that it can solve the problems with GaAs ICs that deliver 2 to 4 times the speed of silicon with half the power consumption, at a comparable price. Of course, at one point it looked like GaAs would be the solution to supercomputer bottlenecks as well, but it was eclipsed by silicon parallel processing. But Vitesse CEO Lou Tomasetta doesn't think history will repeat itself this time. The difference, as he sees it, is that in supercomputers the key to the cost of the system was not the number of channels used, but the cost of the circuits. But in telecommunications, the use of multiple channels is rarely practical, because most of the cost of a communication link lies in setting up the connection. Therefore the customer is highly motivated to move the maximum amount of data through each channel, and is, within reason, less sensitive to the cost of the circuits in it.

Vitesse still manufactures ASICs for computers and automated test equipment. But the majority of their internal investment is directed toward developing standard products for communications. And why not? That market segment is currently growing for them at around 70% per year, which is certainly more than enough to make up for the demise of the GaAs supercomputer.

From our Sept/Oct 1996 issue.

¹ Synchronous Optical Network/Synchronous Digital Hierarchy.

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

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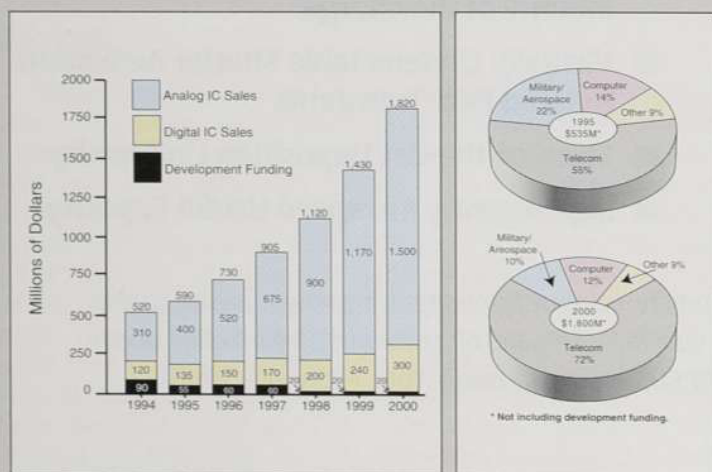
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The Forecast for GaAs Integrated Circuits

Four market research firms offer their views on growth in the GaAs IC market by the year 2000

Anyone who remembers the too-good-to-be-true 1980's predictions for GaAs is likely to approach the subject of forecasting with a bit of trepidation. But professional market forecasting can be indispensable, and even the biggest skeptic may have his curiosity stirred by the fact that several consulting firms are once again painting a rosy picture for GaAs's future. Is it time to shrug off the previous bad experience and start looking at the bar charts and graphs again?

We recently had the opportunity to discuss the forecast for the GaAs IC market with four US market research firms. The following is a brief summary of their views. Each firm has addressed the topic differently, and therefore their results should not be compared or contrasted. But if you look at the subject as a whole, what emerges is picture of industry which is poised to enjoy growth in the coming years, although opinions about the extent of that growth vary, ranging from "solid" to "spectacular".



© Integrated Circuits Engineering 1995

ICE's forecast for the worldwide merchant GaAs IC market. Right: Breakdown of the merchant GaAs IC market by application. Source: Integrated Circuits Engineering.

\$1 Billion by '98

Integrated Circuit Engineering Corporation (ICE) evaluates the GaAs IC market as part of its annual "Mid-Term" report on the status and forecast of the entire IC industry. Their figures are derived by analyzing both external sales and internal consumption for the merchant fabs. In contrast, all of the production from the captive fabs is excluded. For these purposes, a "captive" fab is defined as any company which delivers less than 25% of its production to the open market. While there are not many companies which fall into this category, those that do are notable - Hewlett-Packard and IBM are good examples.

ICE valued the worldwide GaAs IC market at \$535 million in 1995. They predict that it will pass the \$1 billion mark in 1998, and will reach \$1.8 billion by 2000. ICE calculates a 23% compound annual growth rate (CAGR) for the GaAs IC industry between 1994 and 2000, with most of that growth driven by analog ICs (30% CAGR, compared to 17% for digital).

ICE's Bill McClean cites the "booming" market for communications equipment as the driving force behind GaAs's growth. He believes there is reason "considerable" concern about the demand for digital GaAs ICs, but he thinks that high volume use of analog GaAs ICs in 2 GHz and higher wireless communications is "almost guaranteed". McClean goes on to say that "analog GaAs ICs have even done fairly well at penetrating 800 MHz-type applications", and continued success at lower frequencies is one factor in ICE's calculations.

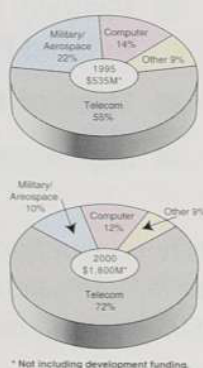
ICE includes developmental funding - such as the MIMIC and MAFET programs - in its definition of the market. However, that portion of the market will decline significantly beginning this year. ICE also predicts a declining role for military and aerospace applications among end users, with the difference to be made up by telecommunications.

Digital Wireless

Kenneth W. Taylor & Associates specializes in strategic information for the digital wireless communications (DWC) industry. They track GaAs ICs only insofar as they are used in DWC; digital GaAs ICs and analog GaAs ICs used in analog communications are not included in their forecasts. Company president Ken Taylor believes this approach is appropriate for his opportunity-identification-based consultancy because "DWC is going to be the most important growth sector for the GaAs industry". Both captive and merchant GaAs IC production for the DWC are included.

Taylor calculates that the market for GaAs ICs in DWC recently doubled, growing from \$72 million in 1994 to \$177 million in 1995, and that it will continue to grow rapidly reaching an estimated \$2.2 billion in the year 2000. This corresponds to an impressive 76.2% CAGR. He also predicts that the market will be dominated by "planar" structures (JFETs, MESFETs), but "heterostructure" circuits (HFETs, MODFETs, HEMTs and HBTs) will gain ground toward the end of the forecast period.

According to Taylor, his firm's methodology focuses on "total business forecasting". When preparing their forecast they first analyzed 17 major applications of the DWC industry as a whole, and then calculated GaAs's role within it. Given their robust forecast for GaAs, it is not surprising to learn that the firm believes that the entire DWC industry has reached the "take-off" point. They predict that the number of DWC terminals in operation worldwide will increase from 34.5 million in 1994 to 585 million by 2000. Taylor's firm believes that there are key DWC applications other than telecommunications that will fuel



demand for GaAs circuits. For example, he predicts that the largest of all DWC applications will be radio frequency identification (RFID) transponders, accounting for 47.2% of all DWC terminals in the year 2000. RFID applications include security, toll collection ("smart highways") and industrial process controls.

GaAs for Mobile Communications

Another view on the wireless market is provided by Electronic Trend Publications, an independent market research firm specializing in computer, semiconductor and telecommunications markets. They recently analyzed the semiconductor content in a number of mobile communication products, including pagers, analog and digital cellular phones, analog and digital cordless phones, and WLANs. They forecast that the total market for all RF/IF circuits (GaAs and Si) for these applications will increase from \$611 million in 1993 to \$1.7 billion in 2000 (a CAGR of 15.8%).

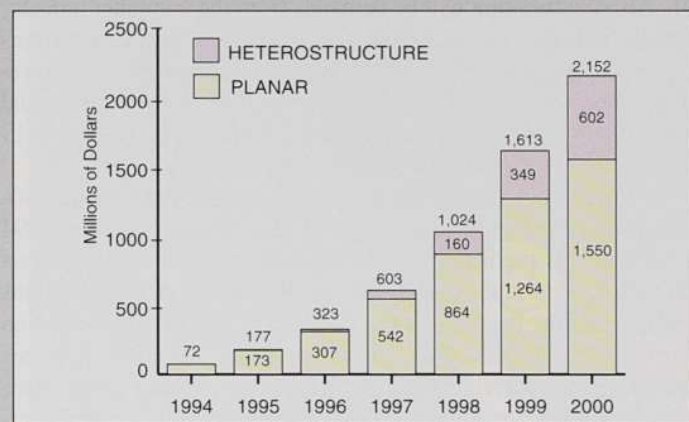
What does that mean for GaAs? Forecasting is by nature an inexact science, at best. Not surprisingly, Electronic Trend acknowledges that when one moves beyond asking "how much RF?" and begins to ask "how much GaAs?", the margin for error increases. As Murray Disman, Electronic Trend's chief investigator on this project, says: "the markets for the RF/IF functions can be defined fairly accurately. However, partitioning these functions into specific types of semiconductors and ICs is highly dependent on a number of different factors. There are numerous ways to partition the circuitry for the same application, and the selection of either bipolar silicon or GaAs IC technology is not always a clear or obvious choice. The key deciding factors should be, as always, total cost of manufacture, size, and power consumption. However, the experiences and prejudices of the equipment designer and the capabilities and overall directions taken by the semiconductor producer are also important factors in this decision."

Disman goes on to explain that in his view the primary drawback to the use of GaAs, as compared with Si, has been the high cost resulting from lower yields and the high cost of wafer material. "But both of these factors become less important for smaller-size chips. In this case, a large part of the cost is determined by assembly, packaging, and testing. The cost of integrated RF functions in GaAs is therefore not significantly more than the bipolar silicon equivalent, except for the power amplifier. But in this case, GaAs is often a clear winner on performance, as GaAs power amplifiers are generally more efficient than silicon devices, and have better linearity. The disparity in efficiency grows as the operating frequency increases and, obviously, becomes more important to the total power budget in applications requiring higher power levels."

With these and other factors in mind, Electronic Trend has ventured an estimate of the market for GaAs MMICs as compared to Si in mobile communications. For this purpose power amplifiers and T/R switches have been included in the MMIC category, since these parts contain more than a single transistor. GaAs's projected market share by the year 2000 is estimated at 62.5%, which, according to Electronic Trend, should have a value of approximately \$600 million. That same market is estimated to be approximately \$75 million for 1995.

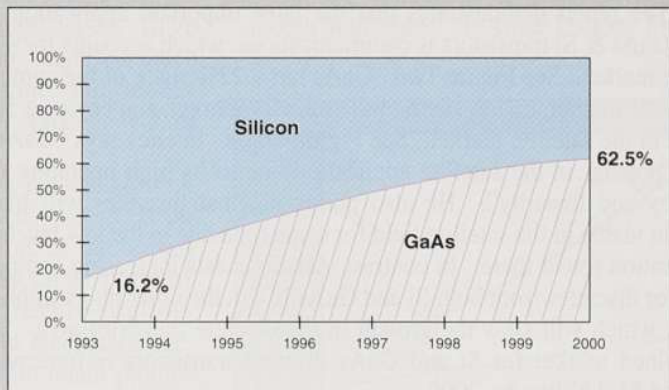
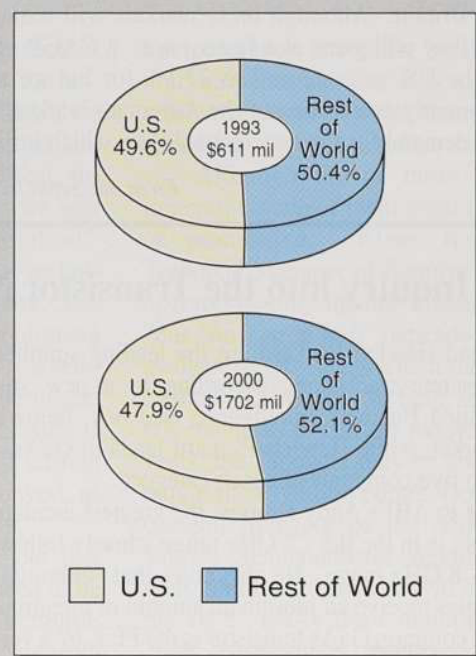
US Manufacturers Lead the Way

The Information Network [Williamsburg, VA] predicts that the worldwide market - merchant and captive - for digital GaAs devices will grow from \$123 million in 1994 to \$333 million in 1999 - a CAGR of 22.1%. According to Robert Castellano, the firm's president, the market for digital GaAs will be driven by fiber optic telecom-



© Kenneth W. Taylor & Associates 1995

The forecast for the worldwide digital wireless communications GaAs IC market. Source: Kenneth W. Taylor & Associates



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Top: Forecast of the market for all RF/IF Circuits (GaAs and Si) for mobile communications applications. Bottom: Segmentation of the market for MMICs in mobile communications between GaAs and Si. Source: Electronic Trend Publications.

munications and data networking in applications such as SONET and FDDI. Also contributing will be demands from the computer industry for use in high-end supercomputers, workstations, and general purpose compute engines. Growth of a more impressive nature is forecast for analog/microwave GaAs ICs. Their value - both merchant and captive - is forecasted to increase from \$292 million in 1994 to \$919 million in 1999 - a CAGR of 25.8%.

The Information Network has also analyzed the market on a geographical basis. The US commanded the largest share in 1994 (51.1%), and it is predicted to hold the lead throughout the forecast period. Castellano notes that in the recent past military applications have accounted for the bulk of the US market, but now that position has decreased to around 25%, and will continue to shrink. He sees telecoms, the new driving force in the US, as moving along three fronts: GaAs ICs for long haul technologies over fiber; the ever-expanding wireless market, including cellular, set-top boxes, and LANs as well as ID tags, tolls, and GPS; and the demand for GaAs in direct-broadcast satellite. Castellano goes on to say that the driving force in the development of GaAs ICs in Japan will come from communications and consumer applications. The same trends will be evident in Europe, with some contributions from the weapons industries in France and Britain. Although these markets will remain smaller than the US's, they will grow at a faster pace: a CAGR of 22.3% is predicted for the US, as compared to 27.1% for Europe and Japan. This due to the early emergence of the American market, as well as generally high demand for the new technologies which utilize GaAs.

From our Sept/Oct 1995 issue

Discrete Inquiry into the Transistor Market

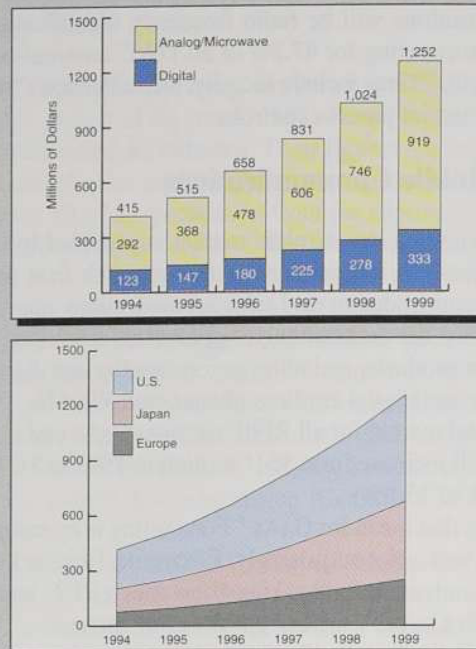
Motorola and Hewlett-Packard are the leading suppliers of Si and GaAs discrete transistors, according to a new study recently released by Allied Business Intelligence (see box, below). Motorola tops the Si market, while Hewlett-Packard leads in GaAs. See Figure One for the top five companies in each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

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

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

From our July/August 1996 issue

"Semiconductors and Amps: Global Markets, Applications and Competitors: 1995 to 2000 Analysis", published by Allied Business Intelligence, Inc., 202 Townsend Square, Oyster Bay, NY 11771-2339 USA, TEL [1] 516 624 3113, FAX [1] 516 624 3115, Web www.alliedworld.com. Published April, 1996, 229 pages, 97 figures, \$2,800.



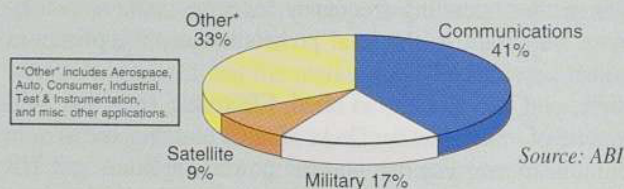
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Top: The Information Network's forecast for the worldwide GaAs IC market. Bottom: Breakdown of the GaAs IC market by geographic area. Source: The Information Network

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

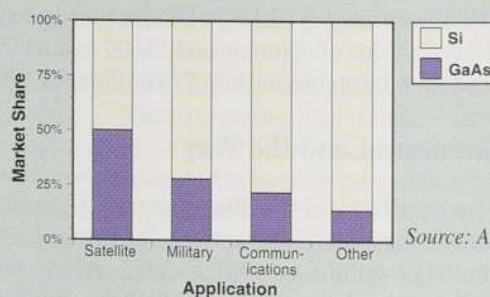
Source: ABI

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



Source: ABI

Figure Two: The market for discrete transistors by application.

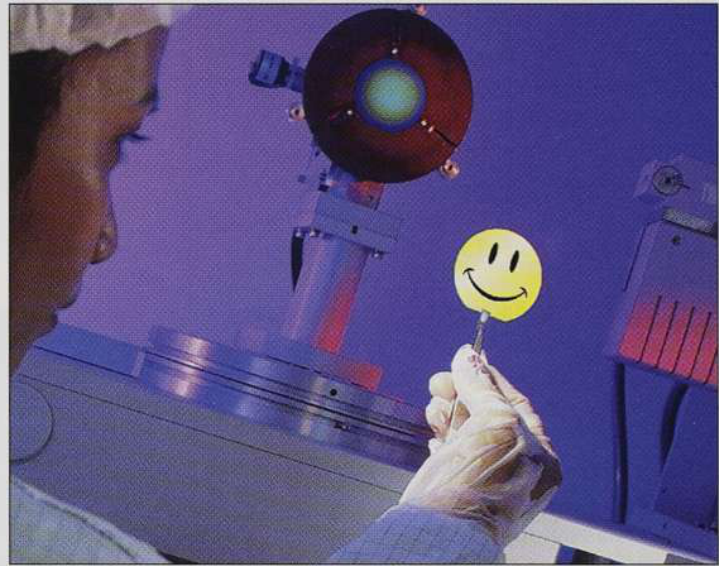


Source: ABI

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

Trends in Wafer Sizes

Look for 6" GaAs to make its debut in 1998



It is a well known fact that compound semiconductors are 2 - 4 generations behind silicon wafers, and given the enormous differences in volume, this is not surprising. Nevertheless, as the silicon industry prepares its new 300mm standard, one begins to wonder when the compound semiconductor industry will begin to migrate to the next generation of GaAs and InP wafer sizes.

Of the fifty or so GaAs processing lines in the world, about one-quarter were running 4" wafers (in 1996). As is shown in Figure 1, most of today's consumption of semi-insulating GaAs is in the form of 3" wafers. But consumption of 4" GaAs will become dominant over the next two years, as several Japanese fabs are said to be planning conversion from 3" to 4". Production runs of 6" GaAs wafers will debut - albeit in small quantities - around 1998. None of the world's GaAs fabs currently have a 6" line in operation¹; but if current market conditions persist, a few will be commissioned before the turn of the century, beginning in 1998.

Semi-Insulating GaAs: 6" by 1998

Anadigics has been rather slow to convert to 4" wafers - in fact, they were still doing some 3" processing in 1996. Charles Huang, Executive Vice President at Anadigics, attrib-

utes the delay to previously insufficient demand. However, he says that now "the levels of demand are greatly increased, and if we could, we would like to skip 4" altogether and go straight to 6". But we cannot do that, for technical, not business, reasons. So we will have to wait for those issues to be resolved." Like many others, he identifies the key technical issues as reliable supplies of quality, consistent 6" wafers, and processing equipment which has a demonstrated capability for handling 6" GaAs wafers. Looking to the future, Huang says that "the sooner 6" processing is available, the better for everyone. If current demand patterns hold out, we'll convert as soon as the technical issues are solved."

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

An obvious prerequisite for scaling-up is a reliable supply of quality 6" wafers, at the right price. It appears that all of the leading substrate suppliers are at work on the problem. Mechanical 6" samples are readily available, but there are some important technical issues that remain to be dealt with to attain production quality material. S. Sawada of Sumitomo Electric summarizes the key issues in 6" GaAs production as dislocation densities resulting from increased thermal stress in the growth process, and higher residual strain than in 4" crystals, which can cause problems with slip

line generation and wafer breakage. In addition, he points out that it is more difficult to achieve the desired wafer flatness and surface cleanliness in large diameter samples.

Although all of these problems are important, none of them seem insurmountable or prohibitive. Klaus Jurgen Schoepf, Technical Manager of Siemens' GaAs Device operation, sums up the situation as follows: "our conversion to 6" depends heavily on the availability of wafers which meet our specifications. Those that we have seen now would not enable us to convert today. But, within 2 years, the suppliers may be able to fulfill our requirements." Bob Nunn, Vice President and General Manager of the ASIC Division at Vitesse Semiconductor reports that Vitesse feels confident that there will be a viable supply of 6" GaAs from multiple suppliers by 1998. Many other fab managers agree, but it is probably unrealistic to expect a perfectly smooth transition: JoAnne Dalton, Product

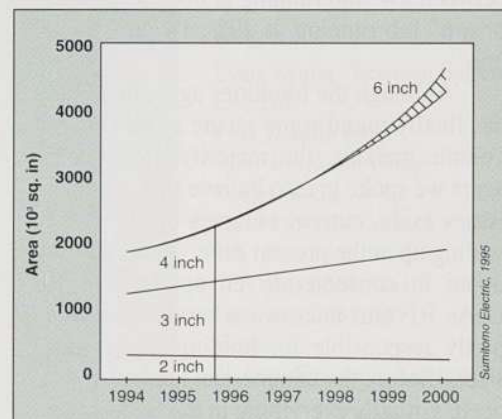


Figure 1. The worldwide market for semi-insulating GaAs by substrate size.

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

Manager of M/A-COM's GaAs Materials Group, points out that none of the vendors can completely refine their products until at least one device manufacturer has begun consistently running 6" wafers on production equipment. She says, "We can develop the product up to a point, but until our customers start processing the wafers and identify what the manufacturing issues are, we can't get the feedback that we need to further our development."

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

Die Size and Volume

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

Although the foundries agree that GaAs has finally found some secure niches in high volume markets, the majority of the managers we spoke to also believe that, technical issues aside, current volumes do not justify scaling up at the present time. Ironically, the boom in consumer-driven applications for GaAs RF and microwave products may be partly responsible for holding down wafer sizes. Before the commercial markets developed, virtually everything in the GaAs industry was driven by military applications. Filling orders for defense systems usually

Major GaAs Device Manufacturers

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

Source: Magus Research, from in the Second Edition (1996) of *GaAs Electronic Materials and Devices*, published by Elsevier Advanced Technology.

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GaAs Substrates:

- ▶ epi-ready SI and SC
- ▶ 2", 3", 100 mm and 150 mm
- ▶ all variety of orientations

InP Substrates:

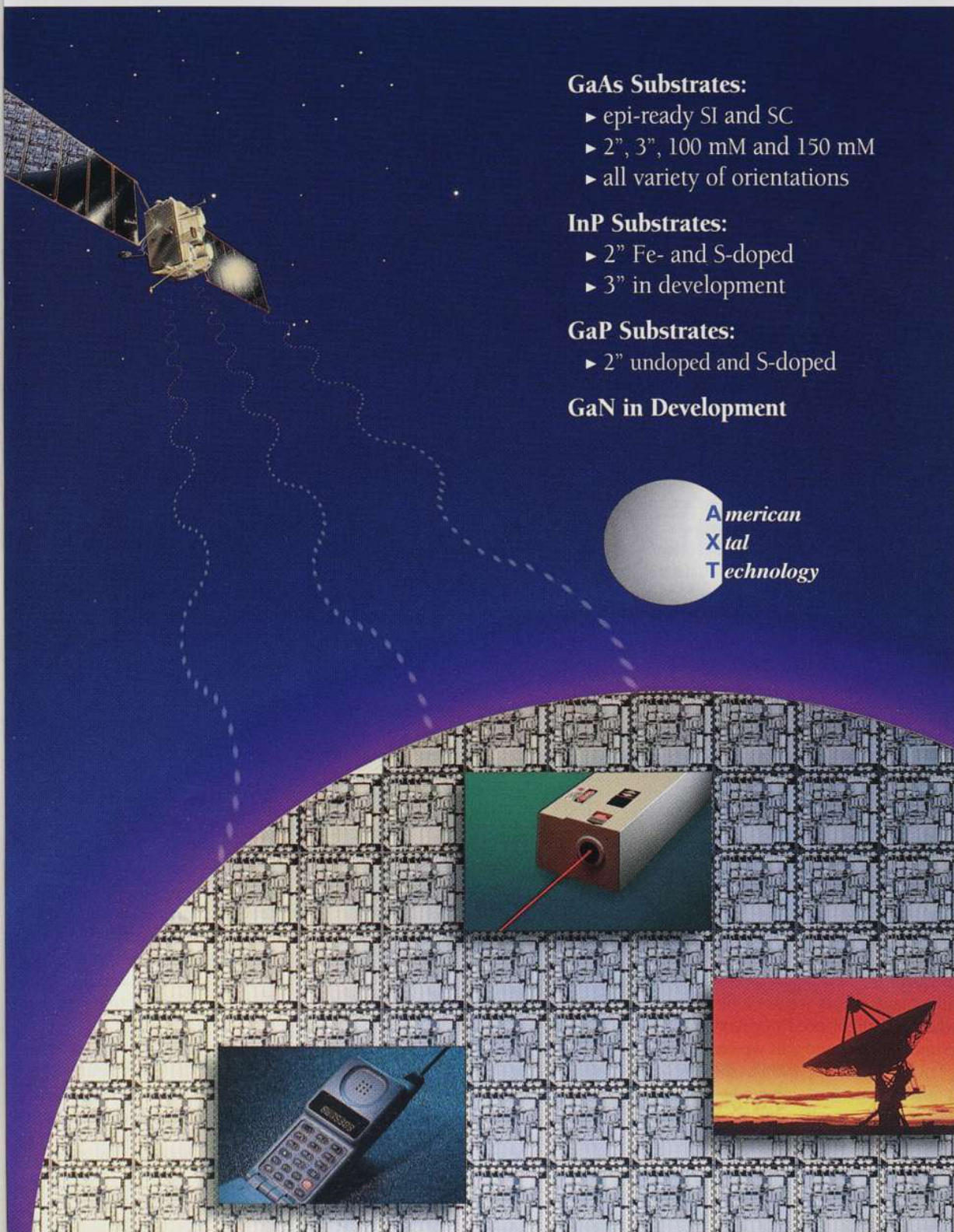
- ▶ 2" Fe- and S-doped
- ▶ 3" in development

GaP Substrates:

- ▶ 2" undoped and S-doped

GaN in Development

American
Xtal
Technology



meant high frequency, high power circuits which required big die sizes. But the current markets for wireless handsets require lower performance devices with lower levels of integration - or even discretes. As Jim Oakes of Raytheon says, "the move from military to commercial markets has driven up our volume, but driven down our die sizes, which means that we can get a lot more out of a 4" wafer".

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

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

M/A-COM probably found the best possible solution to its capacity problems when it acquired the defunct Cray Computer facility in Colorado in 1995. Rick Hess reports "We were thinking a lot harder about 6" before the Cray acquisition! That was an excellent way to increase our capacity, and it was less expensive and less painful than a 6" conversion. Unfortunately, that was probably a once-in-a-lifetime opportunity." So what lies ahead? Hess states "like many others we are looking at the 1998 time frame as the point when we might need our next capacity increase...but we won't scale-up until we are sure that we can actually fill a 6" fab." Others, including TriQuint, also see 1998 as the "earliest possible" conversion date, but it appears that no company has set out a firm time table - with one exception. The overall mood is one of cau-

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

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

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

equipment available. According to Nunn, "leading edge semiconductor equipment is becoming hard to find at the 4" level". And, perhaps most importantly, strong growth in sales (up 25% over the past 15 months and 35% over the last two quarters) is creating a capacity shortage at Vitesse's current fab. Nunn reports that "we've grown to the point where we will be over capacity at our current fab by the end of 1998. We believe that the most effective solution to the problem is to begin construction on a new facility for 6" processing." If they adhere to their timetable, Vitesse seems certain to be the first company to convert to 6 inch.

Are We Lagging Behind?

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

The state-of-the-art standards in silicon are tailored to the demands of microprocessor and memory chips. The goals in the digital arena are to produce the fastest, smallest and most tightly packed transistors, operating at the highest possible speed, and performing the

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greatest number of logic operations in a given time. Digital technology "pushes the envelope" to accommodate smaller transistor dimensions on wafers of constantly increasing diameter. Therefore it is not surprising that Vitesse, whose product line is 95% digital, would be the first GaAs fab to scale-up to 6".

But again, Vitesse is the exception to the rule. The majority of GaAs fabs produce mostly or only analog devices. If you look at their counterparts in the silicon industry, you will see little interest in those 200mm and 300mm wafers. As Larry Sample, Design Vice President of Micrel Semiconductor puts it, "the high-performance silicon analog manufacturers are quite comfortable using wafer sizes that our digital colleagues abandoned years ago". In the analog side of the business, he says, "circuit cleverness is more the aim than component size or circuit density." Analog devices have to accommodate an often bewildering array of conditions. At the most basic level, digital circuits do pretty much one thing: turn transistors on or off under software or firmware control. They are required to respond to only a minimum set of conditions in order to execute these tasks. Analog circuits, on the other hand, have to respond to a host of different electrical occurrences and must accommodate a wide spectrum of voltage, current and frequency conditions. Consider, for example, the large number of standards currently in use in the wireless communications industry. Therefore for both silicon and GaAs analog device manufacturers one can expect to find a larger variety of solutions, each which sells over a long period of time but in small quantities compared to digital silicon circuits. This has the effect of holding down volume demands and enhancing the attraction of processing on smaller wafers.

Indium Phosphide

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

Although the annual market value of InP-based devices is >\$1 billion, the market for InP wafers is tiny. The worldwide market in 1993 (the last year for which complete figures are available) was just \$18 million. In that year 80% of the world's InP consumption

(183,200 sq. in.) was for optoelectronic devices, and >90% of the wafers consumed were 2".

The dominant position of optoelectronics in InP consumption has a negative effect on the development of InP-based microelectronics. 3" is generally considered to be the minimum size for even modest volume production, but InP is not easy to grow, and 3" semi-insulating InP wafer technology is very immature. In addition, many customers want high quality, "epi-ready" surface finishes, which adds to the complexity of the problem. At the same time, wafer manufacturers are under pressure from their optoelectronics customers to improve quality and reduce costs of their 2" semi-conducting products. Consider the disparity between the alternatives: (a) InP optoelectronics, a well established and growing industry which generates steady demand for 2" semi-conducting wafers based on mature crystal growth technology requiring only incremental improvements to satisfy customer requirements; or (b) InP microelectronics, a nascent market niche with an as yet undetermined future, generating low and unpredictable demand and requiring significant investment in crystal growth technology. Is it any wonder that the substrate vendors might prefer the lower risk course described in (a)?

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

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

From our March/April 1996 issue.

U.S. Getting Ready for a Semi-Insulating InP Program

If current funding projections hold out, in the spring of 1997 the U.S. Air Force, through Wright Laboratory at Wright-Patterson AFB, will award a contract or contract(s) aimed at improving the availability of high-quality, large surface area semi-insulating indium phosphide substrates. The details of program are currently being mapped out under the authority of Title III of the Defense Production Act, which allows the U.S. government to offer appropriate incentives to develop and expand the productive capacities of domestic sources for critical components and resources essential for the execution of the national security strategy.

Title III was used previously to improve the domestic supply of semi-insulating GaAs wafers, an effort which met with considerable success. Less money will be available this time - around \$4 million is anticipated - and there is more work to be done, so comparable results are not likely. However, the program does have the potential to significantly impact the future development of InP microelectronics, given that the high price and inconsistent quality of the current supplies of InP substrates are a major complaint of virtually every researcher working in the field.

The stated objectives of the project are "to improve the quality, size, consistency and availability of (semi-insulating) InP substrates while concurrently reducing the cost". This translates into a primary focus on reproducible, consistent, and less expensive 3" wafers, but the program is also looking ahead to 4" wafers as well. The project will consist of one phase lasting approximately 30 months. At a recent conference for potential bidders on the project, the Title III contracting officers made it clear that the \$4 million may be divided between two bidders. They also report that the criteria for the success of the program will be "the creation of a domestic, financially-viable provider of semi-insulating InP material, committed to continuous improvement".

Proposals will likely be due in early January 1997. A maximum of two awards is planned.

From our Nov/Dec 1996 issue.

Laser Report

The variety of topics that can be assembled under the heading of "Semiconductor Lasers" is astonishing. Therefore the following pages contain a mixture of articles on devices and technologies in varying stages of production, development and research, with applications in a number of different areas. But we must acknowledge that the most interesting laser story of all - the drive toward a commercially viable GaN-based short-wavelength laser diode - is not covered in detail here at all. The reason? The rate of progress in this area is so rapid that anything news item from our first two volumes already hopelessly out of date. But we do classify it as the top laser R & D development of 1996, in the story which begins on page 20.

Also in this section:

- ▶ **Highlights of Semiconductor Laser Research in 1996- page 20**
- ▶ **DVD Lasers- page 22**
- ▶ **Laser News from Japan - page 23**
- ▶ **The Market for InP Laser Diodes - page 24**

Honeywell Micro Switch Offers VCSELs as Catalog Items

Honeywell's Micro Switch Division [Freeport, IL] has begun offering 850 nm VCSELs in TO-46 packages. This is believed to be the first instance of VCSELs being offered as discrete components. The devices will be fabricated at Micro Switch's Dallas, TX facility.

Honeywell is widely recognized as a leader in switching and sensing technology, and the Micro Switch Division is one of the two largest manufacturers of LANs for datacom, and is already engaged in the manufacture of LEDs for fiber optic communications. This new product announcement marks their first foray into the laser diodes area.

Honeywell's marketing message for VCSELs is simple and direct: "All the desirable features of an LED with the benefits of a laser diode." Characteristics include:

- Low drive current requirements (5 to 15 mA);
- Low EMI/RFI
- High coupled power (> 1 mW typical);
- High reliability (MTTF > 10⁷ hours); and
- Wide bandwidth (f_c > 10 GHz).

Other selling features of the new device will be familiar to anyone who has been tracking VCSEL development: a symmetrical beam, low coherence, and a narrow beam angle. Another feature is stability of operating characteristics with temperature (see figure), which Honeywell says "potentially allows operation without continuous photodiode feedback control", which would simplify drive circuit design.

The new device, which is called the HFE 4080-321, is intended for high-speed data communications. Data rates can vary from DC to above 2 GB/s depending upon the application. Honeywell says that it is specifically designed to interface with 50 micron and 62.5 micron multi-mode fiber, and that while larger fiber sizes are possible, "essentially of the VCSEL power can be coupled into even the 50 micron fiber if necessary".

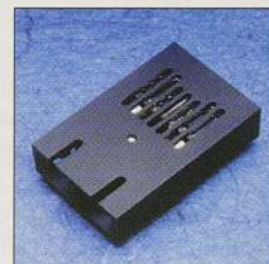
Technically speaking, this is not the first instance of VCSELs being commercialized. Hewlett-Packard recently began offering a

VCSEL-based transceiver for gigabit+ data links handling multimedia information. Similarly, Motorola offers a series of optical interconnects which they call the "Optobus family" that are based on 850 nm VCSELs combined with high performance ICs on a multi-chip module. However, it does appear that Honeywell is the first company to make VCSELs available as standard catalog items available from stock. List price in the U.S. is \$24 per piece.

From our Nov/Dec 1996 issue.

HP Launches VCSEL-Based Transceiver

Hewlett-Packard has introduced its next-generation multimode transceiver which enables multimode fiber transceivers to achieve gigabit+ data-rate performance on links up to 500 meters. It is targeted toward applications such as full-motion video and other multimedia-information transmissions. This new product is unique in that the light source is a 850 nm VCSEL. The VCSEL is driven by a custom Si bipolar IC that converts differential positive electron-coupled logic (PECL) signals into an analog drive current. HP says that the new transceiver will be priced "between the costs of high-speed 1300 nm LED transceivers at \$70 and 1300 nm laser transceiver products at \$400". The company hopes that the low cost (as compared to models using edge emitting lasers) will pave the way for a number of emerging applications for gigabit-rate data links, including mass storage and computer system input/output channels, high-speed peripheral interfaces, and computer networking equipment. Volume production is targeted for the second half of 1996.

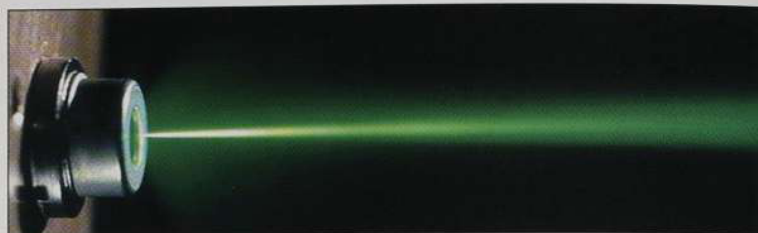


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From our May/June 1996 issue.

Semiconductor Lasers: 1996 was a Banner Year

GARY W. WICKS



One of 1996's highlights: a 515 nm ZnSe-based laser with a lifetime exceeding 100 hours from Sony Corporation.

The past year was quite remarkable year in the field of semiconductor laser research and development. New records were set for both long and short wavelength performance, and low thresholds and high efficiencies. In addition, new and potentially significant lasing materials have been established, and there were even reports on new types of lasing transitions. In short, there has been an unusually high level of significant achievement over the past twelve months. To commemorate these events, here is an overview of some of the highlights of laser diode research in 1996.

Short Wavelengths

Undoubtedly the biggest story of the year has been the emergence of GaN-based lasers. Shuji Nakamura and co-workers of Nichia Chemical Industries [Tokushima, Japan] started the year off with a bang with their January 15 paper¹ demonstrating the first nitride-based laser diode. This first device used an InGaN strained multi-quantum well active region in a GaN core with AlGaIn clads grown on (0001) sapphire by MOCVD. Since this orientation of sapphire does not cleave along planes perpendicular to the surface, laser facets were etched by reactive ion beam etching. With high reflectivity coatings on the facets, the device lased at a violet wavelength of 417 nm under pulsed conditions at room temperature with a threshold current density, J_{th} , of 4 kA/cm² and a threshold voltage, V_{th} , of 34 V. Both J_{th} and V_{th} were fairly high by diode laser standards, but understandable for a first result. Not only was this the first report of a nitride-based diode laser but, at the time, it also represented the shortest wavelength ever by a semiconductor laser. Since then, however, Akasaki and co-workers of Meijo University [Nagoya, Japan] have achieved UV lasing in these GaN-based materials². Nitride lasers continued prominently in the news all year as incremental improvements were made. The most recent

report showed that V_{th} had dropped to 11 V, through improved ohmic contacts, and pulsed lasing up to a temperature of 70°C and continuous (cw) lasing up to T=-40°C had been achieved. It appears that room temperature operation under cw conditions will likely be achieved very soon.

The II-VI material system was the first to provide a shortwave length, bluish-green laser diode. Now, however, it seems almost forgotten due to the enormous level of interest in nitride compounds. Nevertheless, a remarkable leap forward was recorded in this area researchers from Sony Corporation announced in February that they had produced a green ZnSe-based diode laser that operated cw at room temperature with a lifetime of 100 hours³. The previous best mark for a II-VI laser had been just 4.5 hours. The Sony laser had a ZnCdSe quantum well active layer and lased in the green at a wavelength of 515 nm. Sony's data over the last few years shows that lifetime is increasing each year by an order of magnitude, which suggests that their target for commercialization, 10,000 hours, is not far away.

Long Wavelengths

Short wavelength lasers attracted the most attention in 1996, but there was also some considerable activity at longer wavelengths. Researchers developing laser diodes for infra-red wavelengths longer than 3 μ m reported a variety of new record performance levels, new lasing materials, and, most interestingly, new lasing transitions.

The traditional approaches, which use lead salt or antimonide materials, are still going strong, and new benchmarks for operating temperature and power were established this past year. The new state-of-the-art in IV-VI lead salt lasers was established in a report from Laser Photonics [Andover, MA] of a cw 4.4 μ m PbTe laser operating at temperatures up to 223K⁴. This work represented the high-

est cw operating temperature of any type of mid-IR diode laser. In the III-V antimonide area, researchers at MIT Lincoln Labs reported quantum well InAsSb/InAlAsSb diodes that lase at 3.5 μ m. These devices now operate cw up to T = 175K and pulsed up to 250K. At 80 K these devices emit 215 mW/facet⁵, which is a new power record for cw power beyond 2.2 μ m wavelengths.

But 1996 also provided clear evidence that the lead salts and antimonides are going to face stiff competition from a relatively new direction. Until recently, all semiconductor lasers, regardless of their operating wavelength, relied upon direct band-to-band transitions in bulk material or analogous transitions in type I quantum wells. But rapid progress has been reported this year in mid-IR lasers based on new types of transitions. The most notable examples of these new types of lasers are the quantum cascade laser and the type II quantum well laser. Quantum cascade lasers operate on transitions within the conduction subbands of multiple quantum wells and have been pioneered by Bell Laboratories. Operation above room temperature was recently reported⁶ for the first time for a quantum cascade laser emitting at 5 μ m in the pulsed mode, and up to T=140 K cw operation. The other new development, the type II quantum wells, involve spatially indirect transitions between neighboring quantum wells. Reports were made in 1996 of type II quantum well lasers in GaInSb/InAs which operate pulsed at 250 K at 3.2 μ m⁷. While these new types of lasers are still in the experimental stage, they appear to offer the prospect of more robust construction and higher temperature operation than is possible with the materials which have been used up to this point.

Dr. Wicks is a Professor at The Institute of Optics at the University of Rochester, and is the Optoelectronics Editor for Compound Semiconductor

Materials for Red and Near-IR

In the red and near IR, the lasing materials are already mature and highly efficient. Nonetheless, materials improvements continued in 1996 with the further development of aluminum-free lasers. In these structures, the conventional material for the cladding and core, AlGaAs, is replaced with phosphorus-containing alloys such as GaInP and GaInAsP. Lifetime, reliability and high power benefits involve reduced reactivity to oxygen. University of Wisconsin [Madison] researchers have recently reported an aluminum-free laser operating at 980 nm that has a record cw wallplug efficiency of 66%⁸.

Additional research in near-IR lasing materials involved quantum dots constructed of strained InAs islands grown on GaAs. The islands grow naturally by MBE if the appropriate growth temperature is selected - no high resolution processing is required. Several groups have reported lasers constructed of one or more layers of quantum dots inserted into the core of an otherwise conventional AlGaAs-based laser⁹. The interest in quantum dot lasers is based on several theoretically predicted advantages. Ideal quantum dot lasers are expected to exhibit lower thresholds, higher differential gains, higher modulation speeds and less temperature sensitivity (high T_0). It's too early to tell with these preliminary devices whether such advantages will actually be realized. Size fluctuation in the quantum dots may be one factor that limits their usefulness.

VCSELs

The most popular topic in the area of device design is definitely vertical cavity surface emitting lasers (VCSELs), which are being enthusiastically pursued for optical communication and optical interconnects. They have circular beams and low thresholds, are amenable to 2-D integration and on-wafer testing. 1996 saw the first aggressive commercialization of VCSELs. For example, Hewlett-Packard is offering a transceiver for multi-mode fiber optic data links that uses a 850 nm VCSEL as the light source, and Honeywell Microswitch has begun selling VCSELs as standard catalog items.

Most of the R&D news regarding VCSELs has involved the pursuit of low threshold devices, wavelength tunable devices and efforts to develop VCSELs that operate at longer wavelengths. The latter goal is both particularly challenging and important. Most

of the VCSEL work done to date has been on GaAs, and has therefore involved the 0.7 to 1.1 μm region - but most telecommunications applications will require operation at 1.3/1.55 μm . Traditionally this has meant that the device must be fabricated from the InP materi-

more recent demonstrations of mastery over the GaN system. Is it too much to expect that there are still more materials systems waiting to be exploited? There have been recent reports of two new possibilities. For example, mixed nitride/arsenide structures, which have the potential to extend the range of wavelengths than can be accessed by diodes grown on GaAs (See CS 2 (6), p. 39). Also, there is an argument that the addition of thallium to the traditional III-V materials might have a similar effect on InP-based lasers. (See CS 2 (6), p. 34). The practical value of these proposals remains to be proven, but their potential is intriguing.

R&D of semiconductor lasers flourished in 1996. The excitement surrounding the blue nitride lasers seems to have spread to the entire field. And as there are no signs yet of a slow down, look for the rapid progress to continue in 1997.

Editor's Note: Since this article first appeared in our November/December 1996 issue, Nichia Chemical has reached another milestone: room temperature CW operation of a GaN laser.

1996 Semiconductor Laser Highlights

- ◆ **1st GaN Laser** - Nichia Chemical
- ◆ **Shortest Wavelength Laser** - Meijo University
- ◆ **100+ Hour CW Room Temperature Operation of a 515 nm Laser** - Sony
- ◆ **Highest Temperature CW Operation (223K) of a Mid-IR Laser (4.4 μm)** - Laser Photonics
- ◆ **Highest CW Power (215 mW/facet) for a Mid-IR Laser (2.2 μm)** - MIT Lincoln Labs
- ◆ **1st Room Temperature or Higher Operation of a Quantum Cascade Laser** - Bell Labs
- ◆ **Pulsed Operation of a Type II Quantum Well Laser** - Multiple
- ◆ **Al-free Laser with Record CW Wallplug Efficiency (66%)** - University of Wisconsin
- ◆ **Quantum Dot Lasers** - Multiple
- ◆ **Long Wavelength VCSELs (>1.3 μm)** - Multiple

References

als system. Unfortunately, the InP-based materials do not provide the large refractive index difference needed to produce the high quality mirrors that VCSELs require. However, recent work has shown that the use of air gaps alternating with InP may improve performance¹⁰. Another promising approach, demonstrated by the University of California at Santa Barbara and Hewlett-Packard, involves fusing an InP-based active layer between mirror stacks constructed from GaAs-based materials which have the requisite index of refraction¹¹. Lasing wavelengths around 1.55 μm have been achieved using this technique.

Looking Ahead

It has been 35 years since the concept of stimulated emission of photons due to recombination across a p-n junction was first proposed, and next year will mark the 35th anniversary of the first working semiconductor laser diode. Looking back across that period, one sees a steady accumulation of new capabilities. Many of those breakthroughs were enabled by the harnessing of a new materials system, beginning with GaAs/AlGaAs, then the InP-based materials, on up to the

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DVD Laser Update

With the launch of the first DVD players approaching quickly, much of the recent compound semiconductor news from Japan has been related to laser diodes for optical pick-ups. The DVD standard will require 635 - 650 nm AlGaInP diodes as compared to 780 nm AlGaAs diodes which are used in the current generation of CD players. Typical output power for the read-only versions will be ~5 mW. Interestingly, the roadmap for developing the DVD standard calls for an erasable version to be available in 1 - 2 years time. It is known that such a product would require much higher power diodes (around 35 mW), but many other details regarding it have not yet been worked out.

Another, rather important, detail which remains unknown is the size of the market for DVDs. The current market for the CD-format is around 100 million units, $\pm 20\%$, depending upon your source. But the experts disagree about the forecast for DVD players. The low estimate is 50 million units/year by the year 2000, while the high estimate is twice that.

Between the two of them, Sony and Sanyo are believed to control around 70% of the market for optical pickups for these applications. Last summer Sanyo announced it was expanding its annual optical pick-up business to 55 million units by 1998, up from 45 million scheduled for 1996. The company estimates that they hold a 30% market share. Production of DVD lasers at Sanyo, is expected to reach 500,000 units a month by March 1997. Current production consists of a 645 nm, 5 mW read-only model, and the company is sampling a 635 nm, 30 mW read/write model.

Not to be outdone, Sony announced that it is raising semiconductor laser production. The company is spending around \$100 million to install a new assembly line at its subsidiary Sony Shiraishi Semiconductor, which will allow it to raise output by 40% to 5 million units/month. The company says that it hopes to have 60% of the market for optical pickups by the end of fiscal 1997.

Four other companies also announced new DVD laser developments. Matsushita reported that it has launched production of read-only DVD lasers and that it is developing a high temperature read/write DVD laser. While its relative position in the optical pick-up market is not clear, Matsushita is likely to be a leading manufacturer of complete DVD systems. The production model is a 650 nm, 5 mW self-pulsating laser that will

be used in players produced by Matsushita and will also be sold to other manufacturers. Production is currently "tens of thousands" units per month, and is expected to reach 200,000 units per month by the end of the year. The new read/write model, which is described as being "close to development", is said to be capable of operating at over 30 mW for 1,000 hours at 60°C, and is expected to have a life span of 5,000 - 10,000 hours. According to a Matsushita press release, the high temperature, long life operation is made possible by coating the laser's edge with silicon hydride film which absorbs less light.

NEC has announced that it has developed and started sample-shipping a DVD-ROM semiconductor laser that operates at 70°C, with plans to produce 50,000 units monthly. NEC, which earlier unveiled a 635 nm laser that operated at 60°C, reports that it has optimized the MQW active layer structure to develop a 650 nm, 5 mW laser that operates as higher temperatures, targeting PC-use DVD-ROM drives and DVD-based car navigation systems. An 85°C model will be brought to market one year from now. NEC plans to produce 200,000 DVD lasers per month late this year and expand output to 950,000 units in fiscal 1997.

Rohm announced in July of 1996 that it has begun sample-shipping DVD read-only lasers. The company has developed a single-mode 650 nm AlGaAs laser with an output of 5 mW based on its CD/CD-ROM laser technology that uses MBE to grow the epitaxial layers. The current device can operate at up to 60°C, and the company plans to raise the operating temperature to 75°C by early next year in order to develop the DVD-ROM market. Rohm also plans to unveil a multi-mode, 5 mW, 650 nm AlGaInP MQW semiconductor laser by November.

And, rounding-out the new announcements, Sharp reports that it is ready to mass-produce both 650- and 635-nm DVD lasers. The company says that its DVD lasers are guaranteed to operate for 10,000 hours and withstand high temperatures of up to 60-70°C. The company is currently sample-shipping 5 mW lasers for DVD-ROM and 30 mW lasers for DVD-RAM. Sharp now has a DVD laser production capacity of 500,000 units per month and will be able to produce 1 million units monthly from this fall. The company has spent about 2 billion yen (\$18.5 million) on existing semiconductor laser lines to produce DVD lasers.

From our Sept/Oct 1996 issue.

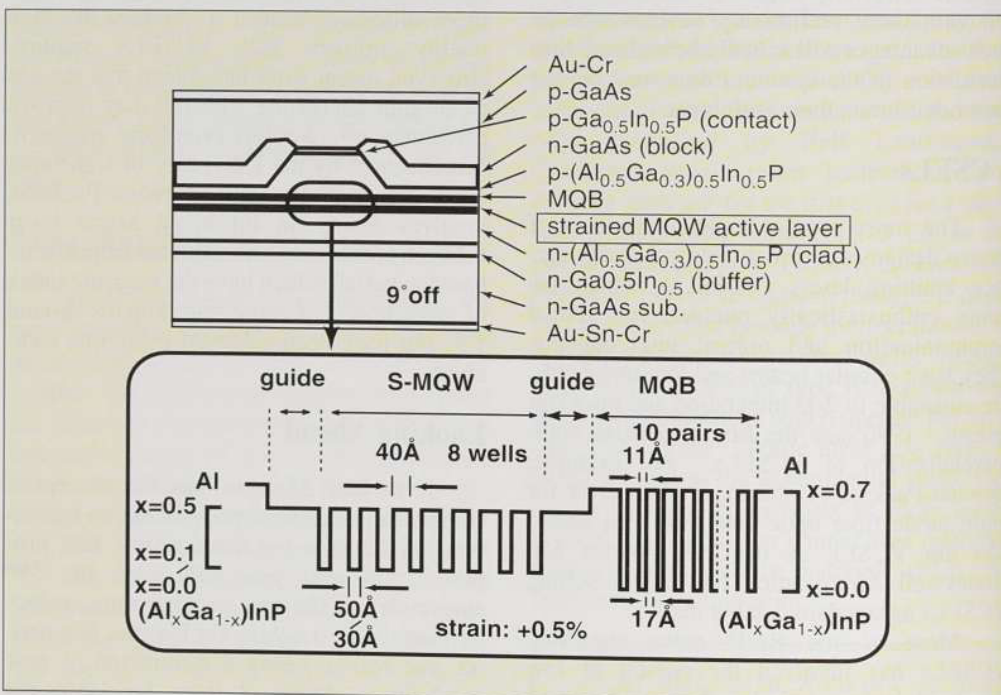


Figure 1 - A typical AlGaInP-based red laser suitable for DVD applications, incorporating both a strained MQW structure as well as a MQB confinement enhancing structure. Courtesy of Sanyo Electric Company [Osaka, Japan].

Sharp Doubling Semiconductor Laser Production

Sharp has announced that it will double semiconductor laser production from the current 5 to 10 million units per month by the end of fiscal 1997. The company says that the focus of its efforts will be on the production of 635-650nm semiconductor lasers for DVD, CD and MD (Mini-Disk) players. Sharp plans to invest about Y10 billion (\$91.7 mil) in its optical device division and expand the investment to Y20 billion (\$183.5 mil) in fiscal 1997. The company also reports a growing demand for its hologram laser, which integrates a signal detection photo diode and a laser.

Several companies are announcing plans to ramp up semiconductor laser production in anticipation of the successful launch of the new DVD optical disk technology. Sharp's announcement mirrors similar production forecasts released by Sony and Sanyo, among others. The DVD standard will require 635 - 650 nm AlGaInP diodes as compared to the 780 nm AlGaAs diodes which are used in the current generation of CD players.

From our Nov/Dec 1996 issue

NEC Sets Optical Device Target

NEC is aiming to double optical device sales to 40 billion yen (\$370 million) by 2000. The company, which provides various devices for optical communications and information systems including laser diodes, photodiodes and optical switches, says it plans to aggressively develop new products, lower costs and expand its distribution channels toward this goal.

From our Sept./Oct 1996 issue.

Nitrogen/GaInP Compound for Laser Diodes

Hitachi and the Real World Computing Program (RWCP), a MITI-initiated research organization, have jointly developed a new semiconductor material which mixes nitrogen with GaInP grown on a GaAs substrate. The joint research group has created a laser sample which uses the new material in the active layer. The device continuously oscillated at 1.2 micron at room temperature. They report that the laser is relatively unaffected by temperature changes, and it is suitable for uncooled operation. According to a MITI spokesperson, adding nitrogen as a matrix material increases the energy gap between the active and cladding layers, making the laser more resistant to changes in temperature and allowing higher temperature operation.

From our Sept./Oct 1996 issue.

Nitride Laser #3

In September researchers from Toshiba became the third group to announce the successful operation of a GaN-based laser diode, following Nichia Chemical and Meijo University. Toshiba reported that it had demonstrated a room temperature pulsed-mode 417nm laser diode fabricated from a GaN/AlGaIn MQW structure grown by MOCVD on sapphire. Processing included what the company described as "a new technology for cleaving the GaN crystal grown on the C-face sapphire substrate and assuring a smooth surface." Most of Nichia's work to date has involved dry etching of the facets, and conventional wisdom says that sapphire is not amenable to cleaving. However, Toshiba believes that it is progressing toward a more manufacturing-friendly process.

From our Nov/Dec 1996 issue.

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The Growing Market for Indium Phosphide Laser Diodes

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

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

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

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

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

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

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

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

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

From our March/April 1996 issue.

"Worldwide Markets for Fiber Optic Single-Mode Transmitter and Receiver Components", KMI Corporation, America's Cup Avenue at 31 Bridge Street, Newport, RI 02820 USA. TEL [1] 401 849 6771, FAX [1] 401 847 5866.

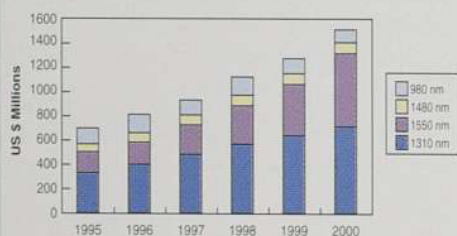


Figure 1. Worldwide market forecast for laser diodes used in fiber optics.

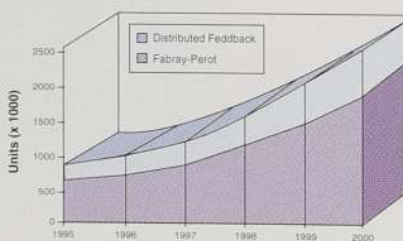


Figure 2. Worldwide forecast for fiberoptic laser diodes, number of units required.

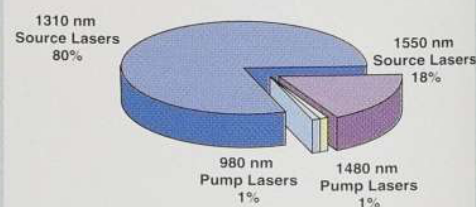


Figure 3. Worldwide market for fiberoptic laser diodes by wavelength, unit quantities, 1995

Nitride News

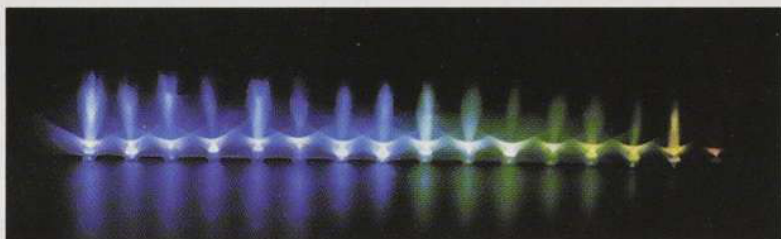
When thinking about recent activity in the field of III-V Nitride materials, the word "frenzy" comes to mind. Over 40% of our subscribers indicate that at least part of their work involves this materials system - putting it almost on par with InP, which has had a very big headstart.

It is, therefore, not surprising that we have a regular section in the magazine dedicated to this field. Earlier in this Special Issue we referenced Nichia's nitride laser breakthrough (page 20); the following is just a few of the other interesting items that appeared in our "Nitride News" department in our first two volumes.

Also in this section:

- ▶ **European Nitrides - page 26**
- ▶ **Progress in GaN Homoepitaxy - page 26**
- ▶ **White Light LEDs - page 28**
- ▶ **Surface Mount Blue and Green LEDs - page 28**
- ▶ **UV Detectors - page 33**

Nitride LEDs from Nichia



Nichia Chemical

Shown above is the range of LEDs that Nichia Chemical Industries have successfully fabricated from the GaN material system. At the far left is a violet LED with a peak wavelength of 400 nm; at the far right is an orange LED with a peak wavelength of 600 nm. According to Nichia's Shuji Nakamura, all of these LEDs were fabricated from GaN with single quantum well (SQW) InGaN active layers. The indium mole fraction is varied between 0.2 and 0.7 to change the peak wavelength from the blue region toward the yellow region. A noticeable decrease in intensity occurs at the longer wavelengths, likely due to decreasing crystal quality in the InGaN, caused by lattice mismatch and the difference in thermal expansion coefficients between the well and the barrier layers.

Nichia's first blue and blue-green LEDs were fabricated from InGaN/AlGaIn double-heterostructure (DH) layers. Although they provided high-power light output (> 1 cd), they had a broad emission spectrum (FWHM = 70 nm) with the light output ranging from the violet to the yellow-orange spectral region, making the output appear "whitish-blue" to the human eye. Greatly improved performance, in terms of both color purity and intensity, have been achieved using the SQW structures. For example, the FWHM for blue LEDs (450 nm) has been reduced to 20 nm, with brightness up to 2 cd; while green LEDs (520 nm) with FWHM = 30 nm and luminous intensity of 12 cd have also been reported. Popular applications for these devices, such as full color displays, are well known; but, according to Nakamura, it is also time to begin thinking about for the production of white LED lamps for use in place of incandescent light bulbs or fluorescent lamps. Nakamura also reports that, at present, Nichia is not working on commercialization of the yellow LEDs, in favor of concentrating on the blue and green devices.

From our Nov/Dec 1995 issue.

Blue LED #4

Sanyo Electric has announced that it has developed a blue LED, and that its subsidiary Tottori Sanyo Electric will produce and market blue LEDs lamps from October 1996 and bring full-color (red-green-blue) LED displays to market in the spring of 1997. This would make Sanyo the fourth company to enter the blue LED market, behind Cree Research, Nichia Chemical, and Matsushita/Panasonic. No details, such as active layer materials and performance specifications, are available at this time, but the company says that the newly-developed blue LED is brighter than those from Cree and Nichia, and has a comparable life span. A company spokesperson also reports that Sanyo will now focus on the development of a blue semiconductor laser.

From our Sept/Oct 1995 issue.

Samsung to Pursue Blue LEDs

It appears that Samsung's name should be added to the growing roster of companies that are pursuing, or planning to pursue, the blue LED market. The evidence for this proposition comes by way of MOCVD equipment manufacturer Emcore, which recently announced what it calls a "multi-million dollar multiple system order" from Samsung. According to Emcore, the order consisted of "a number" of new systems which "will be used to expand Samsung's production line in Kiehung, Korea to enable the manufacture of GaN blue LED's at present with an eye toward laser devices in the future". A possible schedule for introducing the devices to the market was not given.

From our Sept/Oct 1995 issue.

Europe's Status in Group III-Nitrides

Markus Kamp
University of Ulm
Ulm, Germany

The First European GaN Workshop (EGW-1), held in Rigi, Switzerland June 2-4, 1996 provided a unique opportunity to review the status of Group III-Nitride activities in Europe. The workshop, which was the first European meeting dedicated to Group III-Nitrides, attracted 140 attendees, 64 contributed presentations, and three invited talks.

The following statistics on the workshop can be used to help analyze Europe's relative position in this field. Seven categories (substrates, growth, characterization, alloys, doping, processing & devices) are used to describe activities in GaN research.

Attendees of EGW-1 enjoyed eight European talks (16%) on substrates and twelve talks on growth (24%). No talks from Europe were particularly on alloys. Twenty-one contributions (42%) were presented on characterization, two presentations (4%) dealt with doping issues. Five talks (10%) were given on processing and only two European contributions (4%) were on devices. The remaining 14 talks were contributed by non-European researchers. By way of comparison, it is interesting to note that the first MRS symposium on Group III-Nitrides (held last fall in Boston, MA - see CS 2(1), p. 41) had a significantly lower number of talks on substrates (3%), whereas there was a notably higher proportion (17%) of contributions on devices. All other topics at that meeting found comparable attention.

Europe, and especially Eastern Europe, has a strong background in crystal growth, and has produced powerful techniques such as the Czochralski method. Today, the group headed by Prof. S. Porowski at Unipress (Polish Academy of Sciences) is leading the field in GaN substrates (see box). As a further general trend concerning substrates, SiC seems to be less popular in Europe than in the USA. The exceptions to this rule are for obvious reasons: the Cree Eastern European Division and the Ioffe Institute (St. Petersburg, Russia).

The European device activities still suffer from the belated beginning of GaN research in

Europe. Whereas the number of American and Japanese companies which are developing or offering GaN based devices (LEDs, FETs, detectors) is increasing, there is still very little real device activity in Europe. Serious efforts occur at many places, but only Siemens (Germany) and the University of Nottingham (UK) reported electroluminescence from GaN pn homojunctions. Both of these reports were based on MBE-grown material. Since the electroluminescence is still weak, these structures are not yet good enough to yield commercial products. At the University of Stuttgart (Germany), researchers have succeeded in optical pumping of a GaN/InGaN DFB laser. Although this is not a real device, it does prove the good quality of the underlying structure.

The two "real" device talks at EGW-1 were both contributed by the Ioffe-

Institute/Cree EED collaboration. This group is active in GaN on SiC. Using HVPE they succeeded in the direct growth of GaN on SiC without the otherwise mandatory low temperature nucleation layer. Chlorine gas is assumed to play the key role in achieving the direct growth with reasonable quality. Since the GaN/SiC interface is conductive, they can employ vertical current transport through the substrate. Currently various heterosystems on SiC (AlGaIn/GaN/SiC, AlGaIn/SiC, GaN/SiC), where SiC acts partly as substrate, and partly as heteromaterial, are being reported.

The European contributions on characterization of GaN have been strong since Prof. B. Monemar of the University of Linköping (Sweden) started optical characterization some 25 years ago. His well-regarded work on photoluminescence includes excitonic studies,

Progress in GaN Homoepitaxy

For a long time researchers struggled to grow high quality GaAs on Si substrates. Eventually, this work was all but abandoned because it was not possible to reduce the dislocation densities below 10^5 - 10^6 cm⁻² due to the lattice mismatch of 4%. In GaN growth on sapphire substrates one has to cope with a 16% lattice mismatch, yielding dislocation densities as high as 10^9 - 10^{10} cm⁻². However, Shuji Nakamura of Nichia Chemical has certainly proved that LEDs and lasers can be produced nonetheless.

In spite of Nichia's outstanding results, there is a consensus that a better substrate material could improve the performance of most devices. The ideal substrate would be conductive (in contrast to sapphire), thereby allowing current injection through the substrate. It should also be highly heat conductive, to facilitate high power applications. Additionally, the crystal structure as well as the lattice constant and thermal expansion coefficient should be the

same as the epitaxially grown layers, to allow the cleaving of laser facets and 2-dimensional epitaxial growth without dislocations.

Obviously, all of this can be achieved only in case of homoepitaxy, where GaN materials are grown on a GaN substrate. Happily, progress is being made toward that goal. With the outstanding work performed at the Polish Unipress Center in Warsaw, the group around Prof. Porowski for the first time has produced GaN substrates in useful sizes - up to 9 x 9 mm with thickness around 0.5 mm. Employing a high pressure (15000 bar), high temperature (1600°C) method they obtained GaN platelets from seeded or unseeded Ga melts under N₂ pressure. These crystals reveal dislocation densities in the 10^2 cm⁻² range, whereas a high number of point defects still causes background carrier concentration of 10^{19} cm⁻³.

The maximum achievable size is currently equipment limited, and Prof. Porowski presented an impressive plot at EGW-1 showing an

strain dependence and time-resolved PL of undoped and doped GaN. Besides him, Prof. B. Meyer (formerly Univ. Munich, now Univ. Giessen) and Dr. U. Kaufmann (Fraunhofer IAF) performed well-respected studies on deep levels and excitonic transitions. Serious work on electrical and optical characterization is done at Ciudad University (Spain), within the cooperation of the European LAQUANI project.

So far, there are only a few companies in Europe which are interested in production of GaN-based devices. The major interest of European companies is a blue LED, where both Siemens and Temic (both German) have research projects. Temic, a subsidiary of Daimler-Benz, has publicly announced that it plans to enter the blue LED market with a GaN on SiC product - see CS 2(4), p. 25. Siemens, which is a major player in the worldwide LED market is also quite serious about GaN, and has invested heavily in a cooperation with Cree, giving Siemens access to their GaN/SiC LED technology. (See CS 2(1), p. 14.) Thompson-CSF (France) is working on photodetectors. Philips (Netherlands) has projects on lasers, but conducts research in the United States. On the other hand, several non-European companies have research activities in Europe, including Cree (mentioned earlier), IBM (IBM Zurich) and Sharp (Sharp Research in Oxford, England).

Beside companies interested in GaN-based devices, there are several European equipment manufacturers. Certain companies produce general-purpose semiconductor equipment which can also be applied to GaN, such as x-ray diffractometers, PL & Hall systems, etc. Beyond that, there is equipment particularly dedicated to GaN. In Europe this includes systems from MOVPE manufacturers Aixtron (Germany) and Thomas Swan (UK) and MBE system manufacturers VG Semicon (UK) and Riber (France) and MBE component manufacturer Oxford Applied Research (UK). Vendor interest in the nitride field was revealed by the strong participation in the exhibit at EGW-1 - almost 20 companies, or roughly one for every eight attendees!

Today, almost every major European country has nation funding projects in the GaN field. However, most of these projects started very late. For example, the first significant German project on GaN was launched two years ago. Aside from the different national projects there is one single GaN project of the European Community - the ESSPRIT project LAQUANI, mentioned earlier, which is dedicated to laser quality material with one focus being the development of suitable substrates.

Europe has some 150 groups working on GaN, with efforts ranging from basic physical investigations to unconventional applications (e.g. carrier injectors to organic LEDs). It is

impossible to make mention of every group. However, to complete the overview the theoretical work by V. Fiorentini of the University of Cagliari (Italy) and J. W. Orton of the University of Nottingham (UK) has to be mentioned, as well as the activities at universities in Montpellier (France), Stuttgart (Germany), Munich (Germany) and at CNRS Valbonne (France) and the Fraunhofer IAF and PDI Berlin (both German).

In summary, GaN activities in Europe started late (except for the area of characterization) and are still behind the status achieved in Japan and the United States. Up to now, Europe has achieved reasonable results on GaN growth and excellent research on characterization, and very notable work on GaN substrates from Unipress in Poland. But, there have been no commercial devices so far. However, at several European facilities GaN growth is succeeding to a point where the first devices can be expected soon.

The GaN activities in Europe will continue - and so will the European GaN Workshop. EGW-2 is being planned for June, 1997 by Prof. J.P. Faurie of CNRS-Valbonne. At that time we might expect some device work and will be able to see if Europe is managing to catch up with Japan and the US in the emerging field of GaN.

From our Sept/Oct 1996 issue.

almost exponential increase in size with time (See Figure One.) So far the crystals, which usually have a rough N terminated and a smooth Ga terminated surface, have been used unpolished. With MOVPE excellent optical properties have been achieved on these substrates (Pakula et al.), where PL linewidths down to 0.6 meV have been reported at 4K. Recent results

obtained at the University of Ulm (Germany) revealed record PL linewidths of 0.5 meV on MBE grown homoepitaxial layers (See Figure Two). This work, in which ammonia was used as the N source in an on-surface-cracking approach, revealed that MBE can deliver high quality GaN layers at fairly low growth temperatures ($\sim 750^\circ\text{C}$). However, so far it remains to

be shown that homoepitaxial growth of ternary alloys will also be significantly improved in spite of the lattice mismatch or if stress compensated structures have to be employed. Nevertheless, it seems likely that if the GaN crystal size and availability can be further improved, it will have a major impact on many aspects of the development of GaN technology.



Figure One: Progress at Unipress in increasing GaN crystal size. Crystal area doubles every 3-4 months.

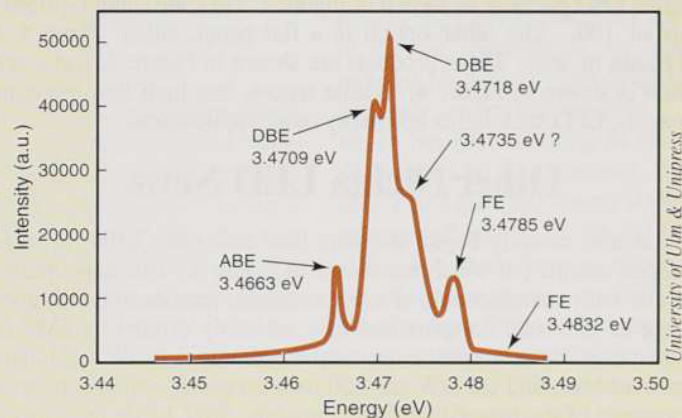


Figure Two: PL spectrum of GaN homoepitaxy grown by MBE. Spectrum taken at 4.2K, excitation 1 mW, HeCd.

White Light Burning Bright at Familiar Site

Nichia Chemical establishes another "first" with the release of a white light LED

Nichia Chemical has announced that it is ready to begin volume production of a highly efficient white LED lamp. The new device combines a blue GaN LED with a yttrium aluminum garnet (YAG) fluorescent layer to emit white light. One lamp has the brightness of 5 lumen per 1W; two units of the lamp will be brighter than a typical "dome light" inside a car. Samples of the new lamps are shown in Figure 1. The actual color of the emission is indicated on the CIE Chromaticity Diagram in Figure 2. Nichia's standard LED products (blue, green and bluish green) are shown for comparison, as are the "traditional" III-V light emitters, GaP, AlInGaP, and AlGaAs.

Nichia has become famous in the compound semiconductor industry because of the pioneering work in shortwavelength optoelectronics conducted by its head of R&D, Shuji Nakamura. But before Nakamura unleashed his GaN juggernaut in 1993, the company was well-known in other circles as the world's largest independent supplier of phosphors for color television picture tubes. Thus there is a neat symmetry to this new development, as it brings together Nichia's traditional area of expertise with its newest capabilities.

We asked Nakamura about the role that the blue LED plays in this new product. After all, shouldn't it be at least theoretically possible to produce white light by combining an orange or red LED with a different phosphor? He was quick to acknowledge that "the idea of making a different color by combining LEDs and phosphors is not new". However, he states that the Nichia blue LEDs are the key to the commercial practicality of the device. As he puts it, "To excite a phosphor, the blue LEDs must be required because the short wavelength LEDs have a higher energy, and the phosphors require a high energy to be excited in order to emit the different color." As an example, he points to fluorescent lamps, in which the phosphors are excited by UV light. Nichia's blue LEDs are capable of producing a luminous intensity of up to 2 cd at a forward current of 20 mA, with a dominant wavelength of 470 nm and a half width of just 30 nm.

There is an alternative way to generate white light using LEDs: combine the output of three different red, green and blue LEDs. This method is already used to produce white (and 16 million other colors) in LED-based full color displays. We asked Nakamura how Nichia's new product compares with this approach. He cited one possible disadvantage - the efficiency of the Nichia white LED will be inferior because the conversion efficiency of the phosphor is below 100%. But he points out that the new lamp is much better suited to applications where only white light is needed. It uses only one LED, and therefore requires only simple circuitry; in contrast, to produce white light using LEDs of different colors requires three chips and a special circuit to adjust the current to each chip to balance their output. Therefore, the 3 color approach will likely always be more expensive than the phosphor-based white lamp.

Nichia is currently offering the new technology in two packages. The first is a standard domed LED package as shown in Figure 1. They are sample-priced at ¥ 300 a piece in lots of 100. The other option is a flat panel, either 40mm x 136mm or 102mm x 126mm in area. These products are shown in Figure 3, and a schematic of their operation is shown in Figure 4. Nichia reports that their first target markets are car-mount panels, LED back lights and many other applications.

Other Nichia LED News

Nichia has also recently begun shipping blue and green LEDs in surface mount (SMT) packages, samples of which are shown in Figure 5. This new option is expected to be popular with manufacturers of color scanners, sensors and indicators, who can take advantage of the small footprint and easy assembly offered by SMT technology. The characteristics of the new devices are output power of 2.0 mW and luminous intensity of 45 mcd for blue, and 1.2 mW and 150 mcd for green, which is between 50-66% of the performance of the top-of-line domed models. SMT LEDs are expected to constitute the majority of the LED market within the next two years.

From our Nov/Dec 1996 issue

Figure 1

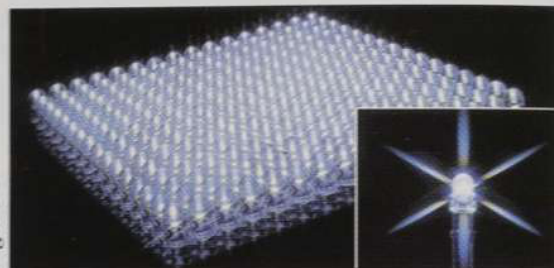


Figure 2

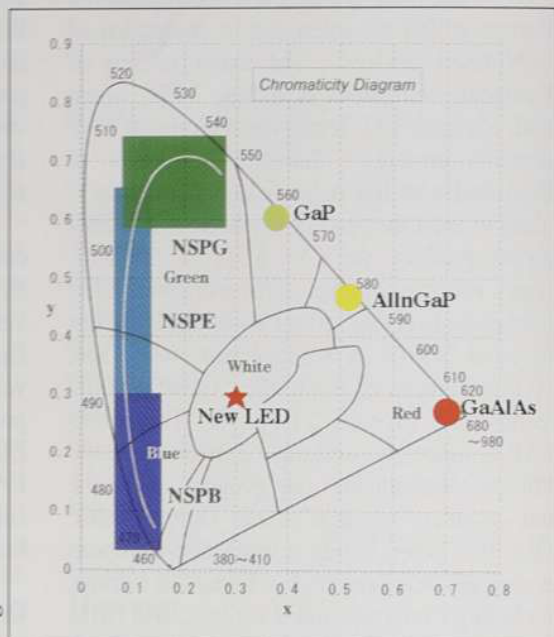


Figure 3

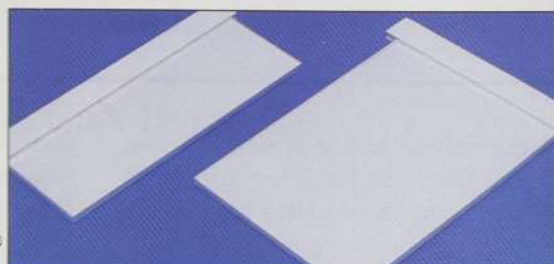


Figure 4

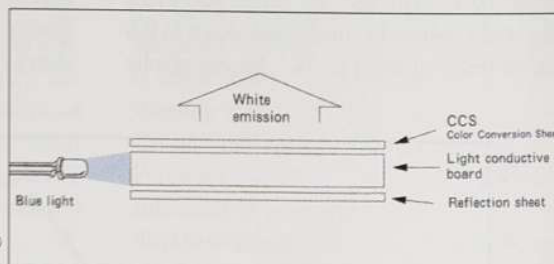
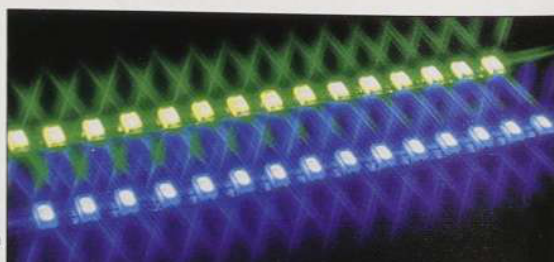


Figure 5



All figures courtesy Nichia Chemical

Ultraviolet Detectors

The same physical properties which make GaN and its related materials suitable as UV emitters also make them suitable for UV detectors

ROBERT A. METZGER

Detection of light in the ultraviolet (wavelength < 400 nm) has a wide range of applications, both commercial and military. Most require a "solar blind" detector - one which detects only in the UV, but does not sense longer wavelengths.

Traditionally, UV detection has been accomplished by two different devices - the photomultiplier tube (PMT) and the silicon PIN photodiode. But it is likely that the next generation of UV detectors will be made from bandgap semiconductors which can combine the best of both of these devices - the compactness, low voltage operation of the Si photodiode, with the solar blind capabilities of the PMT.

Why are wide bandgap semiconductors ($E_g > 3.0$ eV). Unlike Si which has a bandgap of 1.12 eV, and therefore allows the detection of visible and IR light along with UV, those materials with bandgaps > 3.0 eV can only detect light with wavelengths < 414 nm, thereby making them naturally solar blind. The bandgap of 3.0 eV represents a lower useable limit, while for many applications, especially the military ones, which require wavelengths of 200 - 300 nm, will require bandgaps which correspond to 6.1 - 4.1 eV. The two material systems which are being investigated for this application are those based on SiC ($E_g = 3.0 - 3.3$ eV depending on polytype) and $Al_xGa_{1-x}N$ ($E_g = 3.4 - 6.2$ eV for $0 < x < 1$).

SiC

Dale Brown and coworkers at Lockheed Martin [Schenectady, NY], Cree Research [Durham, NC], Rensselaer Polytechnic Institute [Troy, NY] and Optronics

Laboratories [Orlando, FL] have fabricated 6H-SiC epitaxial based p-n photodiodes for operation over the 200-400 nm range, which exhibit a responsivity of 175 mA/W at 270 nm. S. Sheppard, M. Melloch, and coworkers at Purdue University [West Lafayette, IN] have fabricated buried channel Charge-Coupled Device (CCDs) using 6H-SiC, taking advantage of the fact that SiC has a stable oxide which can be used in the CCD structure. Integrating a SiC photodiode with these CCDs would result in UV imaging system. In addition, Boston Electronics Corporation [Brookline, MA] now offers SiC photodiodes grown by Cree. These photodiodes can be used with and without filters, where the filters can block out a large amount of the light from the 300 - 400 nm region. Limitations of this device are due to the indirect bandgap of SiC (and therefore lowered quantum efficiency), and the fact that the 3.0 eV bandgap places it just on the wavelength edge of being useful as a solar-blind detector.

$Al_xGa_{1-x}N$

Anis Husain of DARPA, program manager for several key DARPA sponsored GaN emitter programs, is also initiating GaN-based UV detector programs. Husain says, "we have not exhaustively looked at SiC, but feel that AlGa_N is the superior choice for this application, since you can tailor the cutoff wavelength by varying the Al content." This is one of the key advantages that $Al_xGa_{1-x}N$ has over SiC - the ability to vary the cutoff wavelength from 360 to 197 nm by varying x (Al content) from 0 to 100%. When this is coupled with high quantum efficiencies due to the material's

direct bandgaps, capability to form heterojunctions, low surface recombination rates, and stability in harsh physical and chemical environments, DARPA finds AlGa_N the most promising materials system for UV detection.

M. Asif Khan and coworkers at APA Optics [Blaine, MN] have recently fabricated $Al_xGa_{1-x}N$ photoconductors where the Al content ranged from 5 to 61%. The 61% Al content device exhibited a cutoff wavelength of 240 nm, a record for the moment, but one that researchers are quickly improving upon. Photoresponsivities as high as 300 A/W were obtained for these devices. One of the critical issues that is being addressed is that of defects and the effect that they have on the bandwidth of the photoresponse. As compared to a commercially available silicon photodiode, which can operate at frequencies of 100 kHz, Khan and coworkers find that GaN-based devices can operate only up to 5 kHz, this speed limited by the charge which gets stored at defects in the AlGa_N material. Khan says "that even though the GaN shows twice the responsivity of the SiC photodiode, its speed is greatly reduced by defects - this is an issue which is currently under investigation." APA Optics which has been working on the fabrication of GaN-based HFET structures, has utilized the HFET (0.2 mm gate length GaN/AlGa_N structures which exhibit f_{max} of 70 GHz and f_t of 20 GHz) as a photodetector, which has exhibited responsivities as high as 3000 A/W for wavelengths from 200 to 365 nm. These large responsivities are caused by the photoinduced shift of the HFET's threshold voltage by the trapped light-generated holes. In terms of applications and markets for GaN-based photodetectors, Khan says "at the moment, 30-40

different customers are evaluating our photovoltaic and photoconductive detectors for a wide range of activities - we believe that detector applications will be a very good market for GaN-based devices."

Northwestern University

Like the APA Optics effort, researchers at Northwestern University's Center for Quantum Devices, lead by Manijeh Razeghi, are actively pursuing the development of AlGaIn for photoconductive and photovoltaic UV detectors. An interesting device under consideration is a self filtering detector which gives a very sharp spectral responsivity. See Figure 1 for the energy band diagram of this detector in which the n-GaN layer is 0.5 μm thick and the p-GaN layer is 2.0 μm thick. Utilizing backside illumination through the AlN buffer layer, all light with energy above 6.2 eV is absorbed by the AlN, while permitting lower energy light to pass through. Photons with energy between 3.4 eV (GaN bandgap) and 6.2 eV (AlN bandgap) get absorbed in the n-GaN layer. Because GaN has a very high absorption coefficient (10^5 cm^{-1}) the photons entering this region all get absorbed within the first 0.1 μm . The diffusion length of minority carriers in GaN is much less than the thickness of the n-GaN region, so the minority carriers recombine before reaching the p-n junction depletion region, and as a result produce no photocurrent. It is only for light which has an energy very close to that of the bandgap of GaN (3.4 eV - wavelength 360 nm) that can penetrate deeper into the device and reach the depletion region to form electron-hole pairs (light of lower energy than the GaN bandgap simply passes through the device) which in turn contribute to the photocurrent. Therefore, the responsivity of this detector is essentially tuned to the

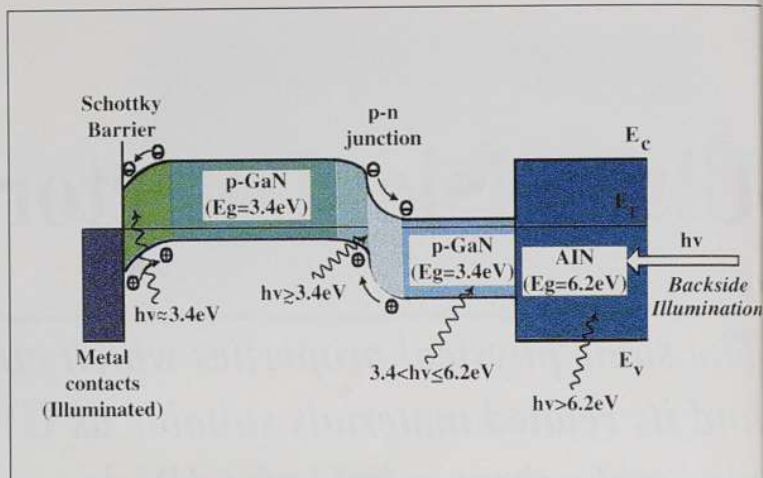


Figure 1. Band diagram of GaN-based self-filtering detector. Courtesy of Northwestern University.

bandgap of the GaN. By adding Al to the GaN in this detector, it should be possible to shift this self-filtering detector response to shorter wavelengths.

In the future, all these UV photodetectors (PMT, Si, SiC, AlGaIn) will be available, each exhibiting their own particular strengths and weaknesses. However, for applications requiring small volumes, low powers, and the ability to tune cutoff frequencies, AlGaIn based-detectors offer clear cut advantages, which may well make AlGaIn the material of choice for future UV detectors.

From our May/June 1996 issue

Thinking Blue?

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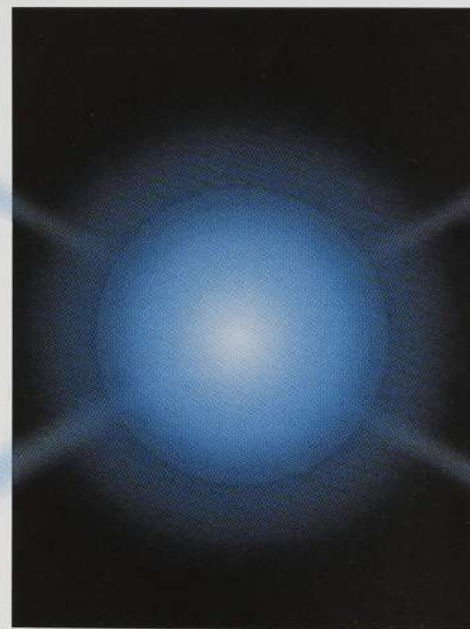
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Water	< 200	ppb

Applications: the Key to Continued Prosperity

The key to the future success of the compound semiconductor industry lies in exploiting applications with good growth potential. A statement such as this may seem almost too obvious to warrant printing, but the truth is that anyone who has worked in this field for very long can remember a time when most people worked on little more than basic research or low-volume military projects.

Some of the most popular articles from our first two volumes were reviews of new and existing applications for compound semiconductor devices and circuits. The following pages contain five of our favorites, ranging from cellar phones - everybody's current favorite - to LED-based displays, power processing, and more.

Also in this section:

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- ▶ **Hall Elements from Asahi Chemical - page 38**
- ▶ **III-V Solar Cells - page 40**
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Cutting the Cord

Wireless communications are freeing analog GaAs from reliance on low-volume military markets.

ROBERT A. METZGER

Since the creation of the first radar systems in the mid-1930's the microwave and millimeter wave fields have been dominated by military and large industrial needs. But now a massive RF market is taking shape which will be driven by the needs of consumers in search of wireless communications.

Evidence of the exploding market for wireless communications equipment is readily available in almost any urban area - just look at the number of people talking on cellular phones, or wearing pagers. There is also a plethora of other types of wireless equipment: cordless phones, direct broadcast satellite (DBS) TV, wireless local area networks (WLANs), global positioning systems (GPS), mobile computing, etc., to name just a few. How big is the market? One research firm, Electronic Trend Publications [San Jose, CA], estimates that almost 91 million units of wireless communications & computing devices were shipped in 1995, and that this figure will rise to more than 175 million units by the year 2000.

Some of the potentially very large wireless applications, such as WLANs and other two-way data transfer systems, will operate at high frequencies (2.4 GHz and above) that are well suited to GaAs's capabilities. But, the most interesting areas at present are cellular and cordless telephones, which operate at frequencies <2 GHz, where Si is more competitive. The huge demand for cellular services is quickly filling up the 800-900 MHz frequency range - so the companies that provide cellular services in the US recently spent over \$7 billion at the FCC Broadband Auctions for the right to use the PCS frequency band (1800-2000 MHz) for future cellular/data communications services.

Every one of the millions and millions of consumer-oriented handsets requires RF or microwave components. While there are many different types of wireless equipment, each with their own specifications for operating frequency, output power, etc., all share certain fundamental building blocks in the RF "front end" portion. It can generally be divided into four sections: 1) the receiver, which amplifies the incoming signal through a low noise amplifier (LNA); 2) the transmitter, which amplifies the outgoing signal through the power amplifier (PA); 3) the downconverter, which takes the incoming signal from the LNA, reducing it to the IF, and then passing it along to the non-RF portion of the phone, as well as the upconverter, which receives the IF from the non-RF portion of the phone, increases it back to the RF frequency, and then passes it into the PA; and 4) a transmit/receive switch to control incoming and outgoing signals.

The RF/IF components used in today's wireless phones range from GaAs and Si MMICs to GaAs and Si discretes. Device types used include Si-BJTs and Si-CMOS, while GaAs-based devices include MESFETs, HBTs and HEMTs. At the moment, Si-based discrete devices dominate the RF/IF market, but that fact does not help explain where the market is going. Depending on the type of wireless device, its capabilities, its niche in the market place (high-tier or low-tier), and the quantity of the product being produced, each device type offers unique advantages and disadvantages. One of the more interesting contests currently being waged is not between GaAs and Si, as one might expect, but between discretes and MMICs - and some of the more sophisticated manufacturers are trending toward discrete solutions.

Natural Place

"GaAs has its natural place and silicon has its natural place. GaAs must compete head-to-head with Si only where their capabilities overlap," says Joe Skovron, marketing manager of TriQuint Semiconductor (Beaverton, OR), a GaAs-based MMIC fabrication house. At the moment, there is not one best set of RF components for a cell phone, and there will not be one as long as the requirements and capabilities of the phones themselves are as varied as they are in the current marketplace. But by using the guideline of finding the "natural" place for a component - matching the phone's needs with a device's capabilities - a design approach can be established. For example, performance requirements will vary depending on the type of phone (high-tier or low-tier, analog or digital). The capabilities of the phone manufacturer are also important. Smaller companies may not be able to afford large numbers of designers to optimize a discrete solution, and will therefore often opt for the MMIC solution, whereas the larger and more sophisticated manufacturers with more design resources may prefer to wring every last drop of performance out of their phones by assembling more complex solutions based on discrete devices. Of course, the availability or lack thereof of in-house discrete or MMIC capability is also important.

Each electronic device also has its own unique set of capabilities, which may or may not make it compatible with a specific phone. For example: there is widespread agreement that GaAs is a natural choice for PAs. But what kind of GaAs? Depletion mode MESFETs and HEMTs provide the best power added efficiencies (PAEs) (approaching 80% at 3V operation), making them suitable in the PAs of many high-tier phones where long talk time is needed. However, these devices require a negative power supply which adds to the cost of the phone, and in the case of HEMTs, require sophisticated epitaxial growth capability. Enhancement mode MESFETs and HEMTs do not require a negative supply, and they provide excellent PAEs for PA applications, but there are limits to their maximum output power. HBTs require no negative supply, have very competitive PAEs, and exhibit excellent linearity, but they also require sophisticated epi. And there are silicon alter-

natives as well. Silicon bipolars require no negative power supply and are relatively low cost, but they have inferior RF integration capabilities due to the lossy silicon substrate and have poorly-competitive PAEs (40-50%), making them ill-suited for high-tier phone applications. RF MOSFETs require no negative supply and they suffer from the same inferior RF integration as silicon bipolars, but exhibit competitive PAEs (60-70%) and are very low cost. These different characteristics make all these devices applicable to some phone applications and inappropriate for others.

Discrete vs. MMIC

Major GaAs producers such as TriQuint and Anadigics (Warren, NJ), supply a full range of GaAs-based RF MMICs for cellular phone applications. According to Jerry

One of the more interesting contests currently being waged is not between GaAs and Si, as one might expect, but between discretes and MMICs - and some of the more sophisticated manufacturers are trending toward discrete solutions.

Miller, sales manager of Anadigics "we are currently shipping over 100,000 power amplifiers for 900 MHz applications (AWT0900-series - PAEs of 55%) a month. What we find is that our real competition is not from Si MMICs, but from both Si and GaAs discretes. Customers add up the price of the discretes and ask if can you meet the price - if not, then they'll go for the discrete solution."

While MESFETs are the mainstay of Anadigics and TriQuint, HEMTs are being commercially produced by other companies. Hewlett Packard Communication Components Division (Newark, CA) offers an integrated LNA/mixer, as well as the LNA and mixer alone, all based on MBE-grown PHEMTs. This part requires 8 mask layers, E-beam written gates, as well as a gate recess etch. Henrick Morkner of Hewlett Packard says, "because we have been running this part

in high volume for the last three years, we have established a very stable, manufacturable process - in which we are running small enough die so as to get 20,000 LNA per 3 inch wafer. Despite the complexity of the process, we can sell a PHEMT LNA in volume quantities for under \$1." Morkner has found that some customers actually prefer building blocks in which the LNA and mixer are sold separately, thereby giving them more design latitude.

Jack Di Bartolo of Pacific Monolithics (Sunnyvale, CA) also finds that the best marketing strategy is not to overly integrate their GaAs-based MMICs. "We don't want to be too applications specific," he says. "If we over-integrate a device so it meets one phone manufacturer's need, then we will not be able to sell that chip to another manufacturer who has slightly different needs."

GaAs houses are not the only MMIC producers to experience stiff competition from discretes. Harris Semiconductor offers a Si-BJT-based LNA/Mixer - the HFA-3600. Using a wafer bonded process so that the entire bipolar sits on SiO₂, this configuration cuts down on the high frequency parasitics which are normally present in Si-based MMICs. "Discretes are the chief competition and will probably dominate for years," says Wes Kilgore of Harris. "For the LNA/Mixer, we are competing against discretes which a good designer can put together for \$0.60-0.80. The advantage that we have is that we feel the MMIC approach is more manufacturable, since you don't have to worry about matching discretes which vary from lot to lot."

Once a part meets operational specifications, all that matters is cost. When it comes to cost, it is very difficult to beat a MOSFET. Hitachi (Brisband, CA) offers a wide spectrum of two and three stage MOSFET-based power modules. These devices operate at 4.8 V, and can deliver up to 1.2 W at 50% PAE. Because of these characteristics, Paul Patterson, Senior Product Marketing Engineer, says that "we have obtained a dominant position in GSM systems." However, Patterson says that he is the first to recognize that MOSFETs do not represent "the best solution to all the customers needs." But even though MOSFETs might not meet the needs of every customer, Patterson feels that Hitachi's product line as a whole can do the job.

Plenty for All

Companies like Hitachi, Siemens, M/A-COM, Motorola, Hewlett Packard, and Texas Instruments offer a range of technologies and device types, i.e. GaAs MMICs, Si-bipolar, or MOSFET modules. For these manufacturers, the device type or material used does not really matter. All that matters is that business is growing.

According to Andreas Nitschke of Siemens, "business is occurring at an unforeseen growth rate - it is booming!" And Siemens is not the only company turning in good results. RF MicroDevices (Greensboro, NC) has seen phenomenal growth over the last three years. The fabless facility, which sells only RF MMIC devices, has seen bookings climb from \$1.9 million in 1993 to \$9 million in 1994 to projected bookings of \$18-20 million in 1995. Jerry Neal, marketing manager of RF MicroDevices says, "growth is absolutely explosive. We're experiencing sales that are more than doubling every year and we will need to double our head count from the present 50 to 100 by the end of the year in order to keep up with demand." RF MicroDevices offers a wide range of MMIC technologies, including HBT-based circuits from TRW, MESFETs from TriQuint Semiconductor and ITT, and Si-based parts from IBM. Of the 5 million ICs they project selling in 1995, 60% of their sales will be due to GaAs-based MMICs with the remaining 40% due to Si-based MMICs.

Things are also looking good in the GaAs-only camp. Like Anadigics, TriQuint is having a very good year. They are currently running more than 10,000 4" wafers per year, and are predicting sales in 1995 of \$45 million, up by \$15 million from 1994. TriQuint's most popular RF part, the TQ9203, an LNA/Mixer for cellular phone operation in the 800-1000 MHz range, has recently surpassed the 3 million production level point. TriQuint believes that this growth is tightly coupled to their 1.0 mm, 13 mask layer E/D MESFET process, which they think is competitive in performance with the most aggressive bipolar process (which, with trench isolation, is typically a 21 mask layer process), and just as competitive in price.

GaAs Phone Home

Even though Si-discretes currently dominate the RF/IF market, this trend is beginning to give way to GaAs-based MMICs. The current predominance of both discretes and low levels of integration are a direct consequence of the literally hundreds of different models of cellular phones, and the more than a dozen different operating standards which currently exist. But when a given phone model can be produced in the hundreds of thousands of unit quantities, then it can make economic sense to spend the resources on designing and fabricating a specific chip set for that phone, where the volume of production will drive down costs, allowing the MMIC approach to not only compete, but to beat the discrete approach.

The GaAs industry has learned from hard experience that it should always mix some caution in with its optimism. Nevertheless, when one looks around the cellular, cordless, and general wireless fields, it is easy to believe that the days of reliance on low-volume applications are over for good.

From our Sept/Oct 1996 issue.

The Three Chip Phone

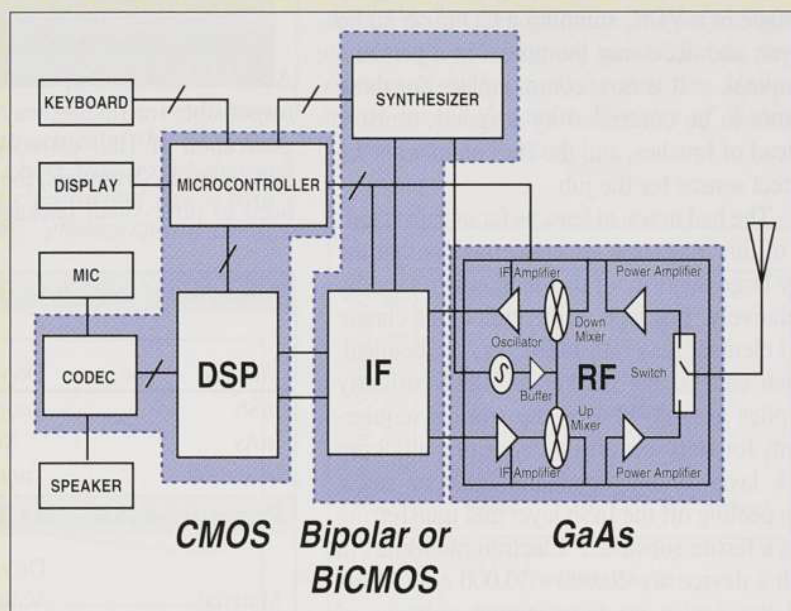
In the long, all analysts expect higher levels of integration in wireless handsets - especially as volumes for individual models increase.

TriQuint Semiconductor rounded out its offerings for the wireless market by launching a line of GaAs RF power amplifier ICs in late 1995, a move which is considered to have the potential to add up to \$20 million in sales per year to TriQuint's current total of around \$60 million. But perhaps more interesting in the long run is what it reveals about the company's vision for the future of handheld wireless products. TriQuint's President and CEO Steve Sharp says "whereas there are typically eight ICs or more in a next generation phone, we believe that the next breakthrough will be a three chip, three technology solution involving a single CMOS baseband chip, a bipolar or BiCMOS IF chip, and a single GaAs RF chip." TriQuint is openly critical of the often mentioned "single chip phone" concept, on the grounds that the variety of functions required in the handset can be implemented with the optimum price/performance ratio only by using different technologies. In fact, Sharp believes that even the silicon parts of the phone will not be integrated in the foreseeable future. "If a single silicon solution to combine the IF and baseband portions could be built, it would have to be BiCMOS, which would be more expensive than keeping them separate" he says.

As for the the RF portion, he envisions "a single GaAs chip that is a full function RF section which allows low cost and power consumption and high integration. This will provide the optimum architecture for low cost, minimal battery requirement phones." He concludes that his company's role in making this vision a reality is "to vigorously pursue a path of RF LSI to bring wireless equipment manufacturers the same benefits of integration in the RF section of the phone that is enjoyed in the rest of the system".

TriQuint believes that the overall worldwide cellular and PCS handset volume will exceed 30 million units per year by 1997.

From our Jan/Feb 1996 issue.



The "three chip phone": TriQuint's vision of the future of wireless handsets as a mixture of GaAs, CMOS and BiCMOS.

Hall Elements from Asahi Chemical

The company that claims >70% of the world market for Hall sensors shows us their next generation of products

The current status of the market for Hall elements, as portrayed by Asahi Chemical Industry Co. [Fuji-city, Shizuoka, Japan] could be classified as a "good news - bad news - good news" story. The first piece of good news is that the market for Hall elements, in terms of units required, is huge, approaching 1200 million units in 1995 (see Figure One). Furthermore, demand is likely to continue to grow, due to ever-increasing sales of audio, video and computer electronics. These types of equipment need high performance, finely controlled DC motors to perform functions like driving and taking up the tape in a VCR, spinning a CD in an audio player, and accessing the drives in a personal computer. It is now commonplace for these motors to be controlled by magnetic sensors instead of brushes, and the Hall element is the perfect sensor for the job.

The bad news, at least as far as most readers of this magazine are concerned, is that the very large majority of this market is served by a relatively "low tech" utilization of the classic Hall element material, InSb. Asahi Chemical, which entered the market in 1980, currently supplies around 70% of the world's requirements for Hall sensors by depositing a 0.8 μm thick layer of polycrystalline InSb on mica, then peeling off the InSb layer and transferring it to a ferrite substrate. Electron mobilities in such a device are 20,000 - 30,000 cm^2/Vsec , and the device produces output voltages of 150 - 270 mV. See Table 1. While the development of these Hall elements is obviously a significant business achievement for Asahi - last year they sold 800 million such devices - persons with an interest in science

and technology would likely prefer to see more reliance on state-of-the-art compound semiconductor engineering.

The good news is that the next generations of Hall elements from Asahi are moving in exactly that direction, using different materials (InAs active layers, grown on GaAs substrates), different deposition methods (multi-wafer MBE growth) and different device structures (quantum wells) to produce Hall elements which offer improved characteristics over current production models.

The Next Generation

Ichiro Shibasaki and his colleagues at the Asahi Chemical Corporate R&D Facility are responsible for finding ways to make the next generation of Hall elements. Like the very successful InSb models, the new products will need to offer small packages, low costs, and

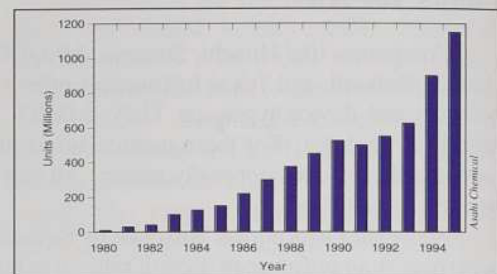


Figure 1: Asahi Chemical's estimate of the worldwide market for Hall elements as magnetic sensors.

compatibility with high volume production. The primary improvements that are sought are in the area of operating temperature range, because the one significant weakness of the established InSb product line is the large temperature dependence of the input resistance, caused by the narrow bandgap of InSb. This has the practical effect of restricting their use to near-room temperature conditions. A possible alternative is to use GaAs, which has a larger bandgap (1.43 eV, compared to 0.17 eV for InSb). However, the R&D team at Asahi concluded that the GaAs Hall elements did not offer sufficient sensitivity to magnetic fields, due to GaAs's lower electron mobility compared to InSb, and that they could not be used where high signal-to-noise ratios are required.

In the late 1980's, work began on another alternative: Si-doped InAs layers. The structures, with a typical thickness of 0.5 μm , are grown on 2" semi-insulating GaAs wafers, using one of the industry's first multiwafer (12 x 2") MBE systems. The variation in thickness uniformity among the wafers on the platen is + 3%, which is more than sufficient for this work. At 300 K and a doping level of $8 \times 10^{16} \text{ cm}^{-3}$, electron mobilities of 11,000 cm^2/Vs are obtained. A device fabricated from these layers is described in Figure 2. The

Properties of InSb, InAs thin film, and InAs QW structures.				
Material	Doping	Electron Mobility (cm^2/Vsec)	Electron Density ($\times 10^{16} \text{ cm}^{-3}$)	Thickness (μm)
InSb	none	20,000 ~ 30,000	2	0.8
InAs	Si	11,000	8	0.5
InAs QW	none	20,000 ~ 28,000	50	0.015
Properties of InSb, InAs thin film, and InAs QW Hall elements				
Material	Driving Voltage	Hall output voltage (mV) (B= 0.05T)	Offset Voltage (mV) (B=0T)	Resistance (Ω)
InSb	1	150 ~ 270	< + 7	240 ~ 550
InAs	6	100	< + 16	400
InAs QW	6	250 ~ 300	< + 16	700

Table 1. Selected properties of three different structures and Hall elements fabricated from them.

electrode structure allows highly reliable Au wire bonding using high volume equipment. Standard epoxy resin processes are used for packaging. Electron mobilities are $\sim 11,000 \text{ cm}^2/\text{Vsec}$, and typical output voltage is 100 mV. See Table 1. Although the sensitivity of these devices is reduced in comparison to the InSb models, they do offer much greater temperature independence - see Figure 3. This has helped them find a market niche, and, to date, Asahi has sold more than 5 million of these devices for use in brushless motors and as current sensors.

The State-of-the-Art

The challenge which is currently being addressed at Asahi is the development of low cost product that offers both the wide temperature range of the InAs Hall elements and the high output voltage of the InSb devices.

Higher sensitivity, and even lower temperature dependence, could be expected if it were possible to fabricate high quality ultra-thin films of InAs ($< 0.1 \mu\text{m}$). However, it is virtually impossible to do this, because of the lattice mismatch (7.0%) between InAs and GaAs. As an alternative, researchers at Asahi have turned to quantum well (QW) structures, using InAs sandwiched between insulating barrier layers which are lattice-matched to InAs. The InAs/AlGaAsSb material system was chosen because of the large conduction band offset of $\sim 1.3 \text{ eV}$. Experimental results show that the quality of the InAs layer is very high, yielding electron mobilities of $\sim 20,000 \text{ cm}^2/\text{Vs}$. Higher mobilities have been reported for InAs QW structures which use AlSb barriers and buffer layers, but this approach was considered to unsuitable for high volume manufacturing due to the potential for oxidation of the Al-containing layers.

The typical characteristics of the InAs QW Hall elements have been found to be exceptional. As shown in Table 1, electron mobilities comparable to InSb have been obtained, but even higher Hall output voltages are achieved. According to Shibasaki, the Hall output voltage for constant drive voltage is as large as 600 mV @ $V_{in} = 6 \text{ V}$ and $B = 1 \text{ kG}$, which is 2 to 2.5 times larger than that of the Si-doped InAs devices, and 4 or 5 times larger than that of conventional GaAs Hall elements. Under normalized conditions (the same Hall output voltage and the same magnetic field), the power dissipation of the InAs QW elements is 1/5 to 1/10 that of commercial GaAs Hall elements - an attractive feature for use in battery operated devices.

As shown in Figure 4, Hall output voltage

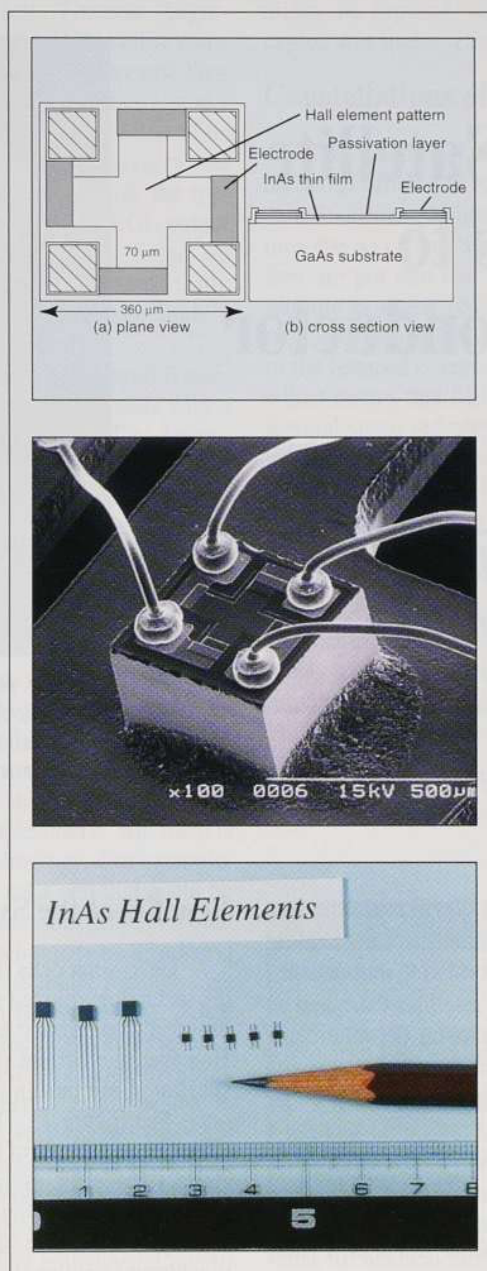


Figure 2: Top: structure of the InAs thin-film Hall element chip; Middle: photograph of an unpackaged chip (actual size = $0.36 \times 0.36 \text{ mm}^2$); Bottom: photograph of the finished product.

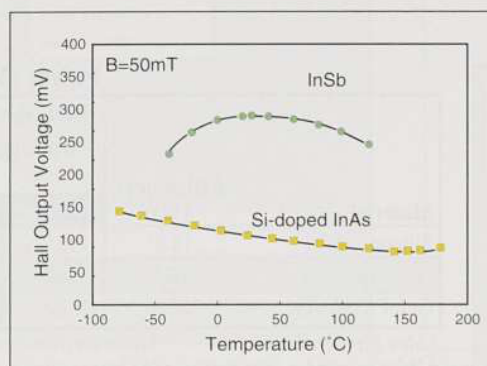


Figure 3: Temperature dependence of Hall output voltage for InSb and InAs thin-film Hall elements. The driving voltage for the InSb models is 1 V, and for the InAs models it is 6 V.

at constant driving voltage decreases monotonically as temperature increases, corresponding to the monotonic decrease in electron mobility. The temperature coefficient of Hall output voltage for voltage driven InAs QW Hall elements is $0.1\%/^{\circ}\text{deg.}$, which is the lowest figure for all reported Hall elements. Regarding sensitivity, the InSb devices characterized in Figure 4 may appear superior; however, Hall output voltage is proportional to the driving voltage and the maximum driving voltage for InSb Hall elements is limited up to 2 V due to burnout, and the breakdown voltage at room temperature is 4 or 5 V due to the negative temperature coefficient of resistance. On the other hand, a driving voltage of more than 12 V is possible for InAs QW Hall elements because of its positive temperature coefficient of input resistance. Therefore, InAs QW Hall elements are more than equivalent to InSb hall elements in their effective sensitivity.

The InAs QW structures are also suitable for mass production. They can be grown in the same MBE system which is used to produce the Si-doped InAs structures, and the growth time required is only one hour. Shibasaki and his colleagues believe that the InAs QW structures are the ultimate solution for industrial sensors, automotive sensors, and other new applications for the future. And, given the characteristics of the device, including its very high output voltage, low power dissipation, and small temperature dependence, the evidence suggest that they may be right.

Editor's Note: Ichiro Shibasaki was awarded the 1996 Commendation as "the person of scientific and technological merits" for the development of high sensitivity thin film Hall elements by the Japanese Ministry of State for Science and Technology.

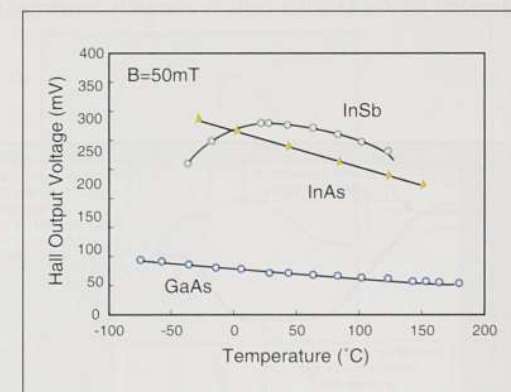


Figure 4: Temperature dependence of Hall output voltage for InSb and InAs QW Hall elements, with a commercially available GaAs Hall element shown for comparison. The driving voltage for the InSb models is 1 V, and for the InAs QW and GaAs models it is 6 V.

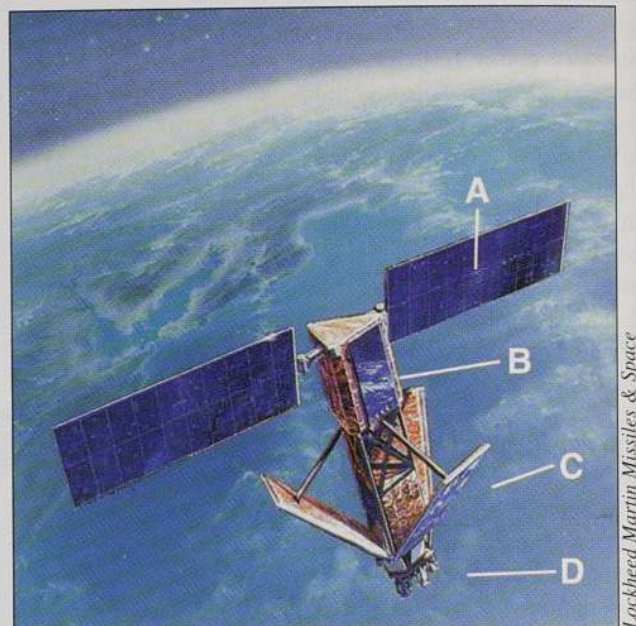
Flying High: The Commercial Satellite Industry Converts to Compound Semiconductor Solar Cells

They are still more expensive than silicon, but benefits gained at the system level make III-V devices competitive

MARIE MEYER and ROBERT A. METZGER

This winter, if all goes according to plan, Motorola will make the first space launch for its massive Iridium project, which is a 66-satellite network that is scheduled to begin providing worldwide mobile communications services in 1998. On board each of those satellites there will be 24 square meters of III-V material, in the form of GaAs-on-Ge solar cells. And Iridium is not the only GaAs-powered project in the works: experts estimate that between 50 - 70% of all of the commercial satellites now under construction will be equipped with III-V solar cells.

The switch to compound semiconductor solar cells is something of a revolution in the satellite industry. The traditional material of choice has been silicon, because it is lightweight, reasonably efficient, and inexpensive. But improvements in III-V solar cell design, coupled with demand for satellites with more on-board power, have changed the market dynamics in favor of compound semiconductor materials. The transition happened so fast that it may have caught the suppliers by surprise, because by all accounts the demand for GaAs solar cells is currently outstripping supply.



Lockheed Martin Missiles & Space

Artist's rendition of an Iridium satellite. Components include: A = solar panels; B = command module; C = main mission antenna; and D = crosslink antenna (for satellite-to-satellite communications).

Benefits at the System Level

GaAs solar cells first became a viable option around five years ago. As the technology moved into volume production the price of GaAs solar cells dropped from around ten times the price of Si cells to closer to five times. However, the current shortages, exacerbated by insufficient supplies of Ge substrates, are pushing the price ratio back up to around seven or eight to one. See Figure 1. This may be the upper limit for GaAs: according to Klaus Bogus, Head of the Solar Generators Section of the European Space Agency, once the ratio exceeds 8:1, GaAs ceases to be price competitive with Si. However, Bogus believes that GaAs has a promising future because corrections in the Ge substrate supply and increased epi capacity at the manufacturing facilities should improve price competitiveness.

III-V solar cells will never be as cheap as Si on a per/meter sq. basis. However, price parity in terms of surface area is not the goal. Satellite manufacturers are willing to pay a premium for GaAs because of its higher efficiency. On a laboratory test bench one would likely measure a typical effi-

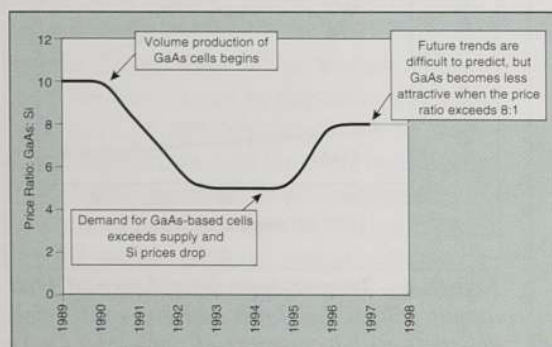


Figure One: Summary of price trends for GaAs and Si solar cells in this decade.

Power (Watts) Per One Square Meter of Solar Panel

Material	Efficiency ² (%)	BOL Power (W) Un-Irradiated		EOL Power (W) ¹ 1 MeV Electron Fluence			
				3x10 ¹⁴ e/cm ³		1 10 ¹⁵ e/cm ²	
		28°C	50°C	28°C	50°C	28°C	50°C
Silicon	14.8 ³	170.9	149.5	129.0	112.2	113.0	98.8
GaAs/Ge	18.5	218.1	208.2	188.1	179.6	166.8	159.3
GaInP/GaAs/Ge	21.5	253.5	242.8	223.0	211.9	192.7	183.0

¹ MeV Electron Fluence

² Minimum Average Cell Efficiency at 28°C.

³ Values given for silicon are for the best available commercial product. Less efficient models are also available.

Table One: Comparison of specifications for three types of solar cells offered by Tecstar [City of Industry, CA USA]. The power specifications are for output in Watts (W) for a one square meter solar panel.

ciency of ~19% for a GaAs cell and ~15% for a Si cell. Thus the "beginning of life" (BOL) difference between the two is ~25%. But satellite companies base their designs on "end of life" (EOL) specifications, because they need a system that functions properly right through to end of its mission - anywhere from 5 to 15 years for a communications satellite. Because of its wider bandgap, GaAs has superior radiation hardness characteristics and suffers reduced degradation in high temperature operation (in orbit, the typical ambient temperature for a solar panel is ~50°C). Thus its EOL output is 40-60% higher than silicon. And new III-V solar cells based on GaInP/GaAs compounds grown on Ge substrates are now commercially available, providing even better BOL and EOL performance. See Table 1 and Figure 2.

Most commercial satellites share a relatively similar structural framework which allows two wings, each holding up to four solar panels with a maximum dimension of ~2.5 x 3.5 meters for each panel. A satellite designer can take advantage of GaAs's greater efficiency in two ways. One is to make use of the full panel area allowed (~70 sq. meters) to provide the maximum amount of power to the system. Current technology can deliver up to 15 kW (EOL value) to the satellite using GaAs, compared to ~6 kW for a Si-powered unit. Among others, Hughes is using this approach to win commercial satellite contracts by offering superior payload power. The other option is to simply use fewer solar panels, which reduces the materials and assembly costs for the satellite, and also reduces its overall weight. Commercial launches currently cost around \$20,000 *per kilogram*, so the later factor is clearly important.

Practical considerations, not least of which is the need to mesh with existing commercial launch capabilities, mean that satellite developers will continue to adhere to this framework for the foreseeable future. But there is still need for additional development of solar cell technology. For example: the industry would welcome a high efficiency III-V solar cell that could be grown on substrate which is more readily available than Ge. Silicon would be the obvious candidate, but its use requires that techniques be developed to overcome the lattice mismatch. Also, there may be future requirements for satellites that can exceed the current maximum power supply. Since adding more solar panels is not an attractive option, the best way to achieve this goal is to further increase the efficiency of the cells. Technology which is not currently price competitive, such as InP-based cells, might be able to find a niche here. And, thirdly, the availability of a very rugged solar cell technology would facilitate the use of orbits that intersect the Van Allen belts. These orbits are attractive for commercial reasons, but are extremely challenging for the satellite designers because of particle radiation. Whereas the main body of the satellite can be shielded, the solar cells must, by defi-

nition, be exposed, so superior rad-hard characteristics will be needed to exploit this niche. (See page 26 for a more complete discussion.)

Constellations of Satellites

The traditional telecommunications satellite is intended for a geosynchronous orbit (GEO), where from one spot it can "see" around 1/3 of the earth's surface. Iridium, however, is part of a new class of commercial venture, the so-called "satellite network", wherein a chain of interlinked satellites are put into low earth orbits (LEOs)¹. The surface coverage of each satellite is much reduced, but the time required to transmit data is also reduced, making LEOs well suited for broadband communications. Because of the reduced coverage of the LEOs satellite, more spacecraft are needed - which means that LEO projects could be a huge boost for the entire commercial space industry. Two of the highest profile "big LEO" projects are listed in the table below. The Iridium projects is the furthest along, but there is an even bigger one in the developmental stage: Teledesic, a project which is being developed by Craig McCaw and Bill Gates, requiring a staggering 840 satellites. But even if Teledesic fails to get off the ground, the forecast for the satellite business looks rather good, with plans for several dozen units a year for the next several years. Whether III-V solar cells can hold the majority of the market remains to be seen. The typical power requirements for a LEO satellite are much lower than for a GEO satellite (1-2 kW, as opposed to ~6-8 kW), which may make it easier for silicon to recover lost market share. For now, though, the III-V solar cell business is flying high.

¹ There is also an intermediate range of orbits called "Medium Earth Orbits" or MEOs.

From our Nov/Dec 1996 issue.

System	Proponents	# Satellites	Orbit Altitude (km)
Spaceway	Hughes	8	35,000 (GEO)
Odyssey	TRW	12	10,350 (MEO)
Immarsat P	Immarsat	10	10,350 (MEO)
Globalstar	Loral/Qualcomm	48	1,390 (LEO)
Iridium	Motorola	66	740 (LEO)
Teledesic	McCaw Cellular	840	700 (LEO)

Table 2. Summary of some of the major satellite communications systems which are under construction or have been proposed.

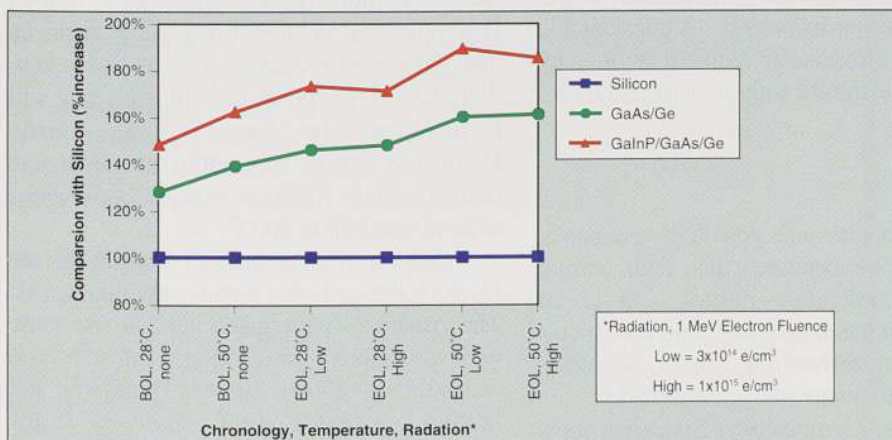


Figure Two: Comparison of the output power of three types of solar cells offered by Tecstar at different times (BOL or EOL), temperatures (28°C or 50°C) and for EOL measurements, radiation levels (low or high).

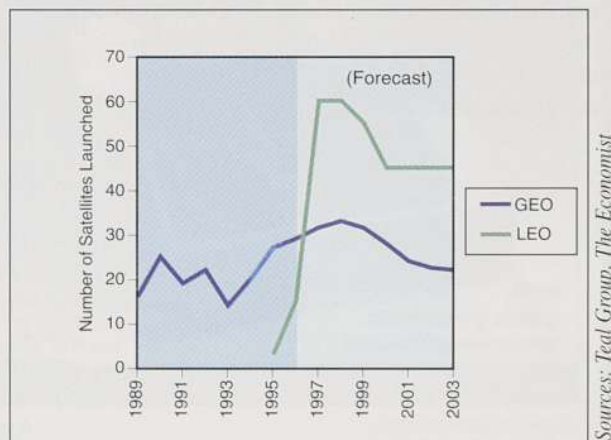


Figure Three: Estimate of the number of commercial telecommunications satellites launched to be launched for GEO and LEO orbits. The proposed Teledesic project, which would require more than 800 LEO satellites, is not included in the forecast.

High Temperature Semiconductors: Evolution, not Revolution

MARIE MEYER

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

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

High Temperature Electronic Devices and Technologies

The primary types of devices under consideration for high temperature applications are sensors and their controlling electronics. Five major semiconductor materials systems are being developed for this purpose. (See Table One on page 50 for a summary of some of their most important characteristics.)

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

Silicon

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

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

Summary

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

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

currents can be virtually eliminated by using silicon-on-insulator (SOI) technology, which is under development at many companies worldwide. SOI is especially attractive for small signal applications, but is less suited to power devices¹.

Gallium Arsenide

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

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

¹ For a review of SOI technology, page 54

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

Silicon Carbide

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

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

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

Group III-Nitrides

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

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

Diamond

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

Funding Policy and Developmental Paths

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

Probably not. High temperature semiconductors hold a great allure for materials scientists as an intellectual challenge, but the market forecast (see page 51) demonstrates that system designers have learned to live without them, and are likely to continue along those lines to the greatest extent possible. And in cases of absolute necessity, they can make-do with a Si solution. Undoubtedly there are many instances where system design can be improved by positioning electronic sensors or controls in extreme environments. A report issued last year by the U.S. National Academy of Sciences³ offers an interesting biological analogy: just as an animal is more agile, efficient and durable when its nervous system (sensor signal processing), skeleton (physical structure) and muscular system (actuator operation) are integrated, so there are many electromechanical systems that can benefit from such a "distributed control network". However, the NAS report acknowledges that "in all the processes of our economy there are currently few in which inser-

² For a complete review, see page 52.

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

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

System Circuits

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

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

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

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

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

Conclusion

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

For more
information about
high temperature
semiconductors and
their applications,
visit the
HITEN Web Site
at
<http://www.hiten.com>

High Temperature Semiconductor Materials					
	<u>Si/SOI</u>	<u>GaAs</u>	<u>SiC</u>	<u>III-N</u>	<u>Diamond</u>
Technical Considerations					
Bandgap (eV)	1.1	1.3	2.9	3.4-6.4	5.5
Intrinsic Temperature	400°C	650°C	>1000°C	600°C - 1000°C	>1000°C
Small Signal Devices (Tmax)	300°C	300°C	>600°C	>550°C	n/a
Power Devices (Tmax)	250°C	250°C	>600°C	>550°C	n/a
Processing Maturity	Si: Very High SOI: Medium	High	Low	Very Low	Very Low
Key Development Issues	Electro-migration	Ohmics, EM	Substrates, Ohmics	Substrates, Ohmics, EM	Substrates, Dopants
Commercial Considerations					
Development Costs	Low	Medium	High	Very High	Very High
Commercial Availability*	Now	Now	1997	2000	Sensors: 1997 Electronics: beyond 2000
Synergistic markets / R&D opportunities	Rad hard, high speed, low voltage operation	Power, rad hard, opto-electronics	Power, opto-electronics	Opto-electronics	Opto-electronics, sensors
*for high temperature applications			Source: HITEN News, May 1995, after Sandia National Labs Report SAN94-0850J, Dreike et al		

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

The Market for High Temperature Semiconductors

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

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

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

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

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

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

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

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

From our July/August 1996 issue.

**World Wide Market for
High Temperature Electronic Components**

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

*See text above for explanation of TAM.

Source: HITEN/Magus Research

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

Major Applications for High Temperature Electronics

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

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

Source: HITEN/Magus Research

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

Rectifiers: a New Application for GaAs

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

ROBERT A. METZGER and MARIE MEYER

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

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

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

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

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

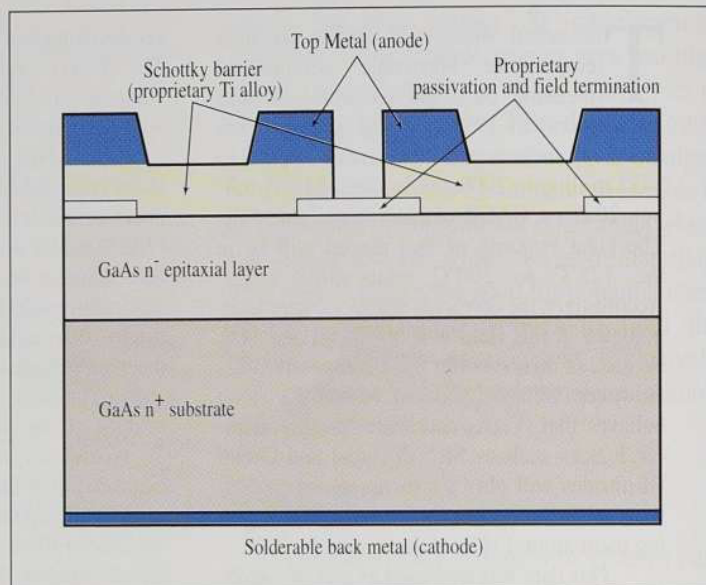


Figure One: Schematic diagram of Motorola's new GaAs Schottky diode rectifier, fabricated from n- GaAs epi grown by VPE on an n+ GaAs substrate.

Background: Power Diodes

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

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

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

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

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

The Advantages of GaAs

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

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

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

Benefits at the System Level

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

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

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

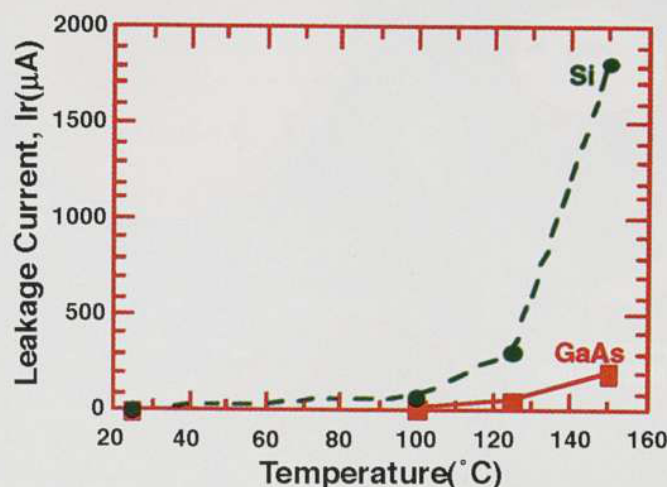
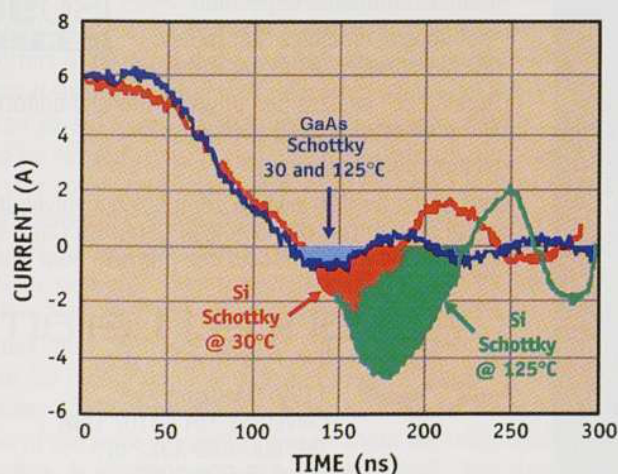


Figure Two and Three: Figure Two (left) shows the reverse recovery characteristics for a GaAs Schottky diode in comparison to a Si Schottky diode at room temperature and 125°C. Figure Three (right) shows the leakage current as a function of temperature for GaAs and Si diodes.

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

GaAs Niche

Motorola's new GaAs rectifiers are currently being used primarily in one niche - telecommunications networks. According to Delaney, "the initial early acceptance has been in the high performance end, with Lucent and Astec featuring the diode in some of their high end power supplies. Entry into the market via such a niche is to be expected, because of the premium that must be paid for the product." However, Delaney also reports that volume manufacturing has been launched¹, and this fact, coupled with increasing yields, is bringing prices down. He doubts whether GaAs diodes will be competitive with Si at much less than 200V, but he is optimistic that the lower price

points will bring broader market acceptance at the higher voltage ranges.

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

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

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

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

From our July/August 1996 issue.

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Full Color LED Displays

For manufacturers of red, green and blue LEDs, there are millions of reasons to love this application

MARIE MEYER

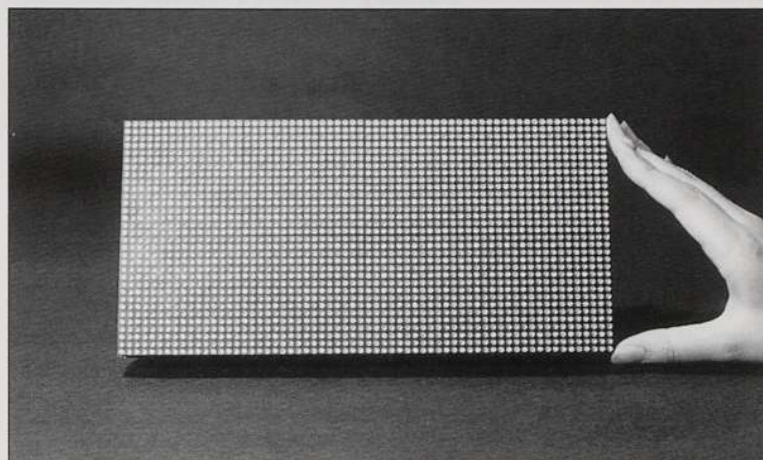
Full color LED-based displays are going to be big - both literally and figuratively. The market is immature, but any medium that can provide a more attention-grabbing method of delivering advertising and entertainment seems guaranteed to succeed. And a handful of recently-released products provide evidence for how the hundreds of millions of red, green and blue (RGB) LEDs that application requires will be packaged and sold.

Integration, of a Sort

There are basically two ways to construct the RGB pixels. The first is to use discrete LEDs. An example of that method, as executed by Toshiba, is shown in Figure One. The RGB pixel is formed using one red, one blue, and two green LEDs, each in its own conventional domed package. (Why use two green LEDs? More on that later...) The second way is to package the individual red, green and blue chips together as one integrated lamp. Sharp's implementation of that method is shown in Figure Two. (A third method, a "single-chip" RGB LED constructed using red AlGaAs and green and blue ZnSe emitters grown on a single GaAs substrate is sometimes discussed, but it is still restricted to the research-only realm for now.)

Both of the illustrated methods have their own strengths and weaknesses. The pixel made from discrete LEDs is best suited for outdoor applications, because it allows the use of a lens to focus the output. This has the effect of decreasing the viewing angle (to a cone $\sim 40^\circ$), but at the same time it sufficiently improves the intensity so that the display can be used even in sunlight. And given that outdoor displays are usually meant to be viewed from a relatively long distance, the loss of viewing angle is not considered a fatal flaw. On the other hand, the integrated lamp approach is more suited for indoor applications. Here the viewing angle is more important than intensity, since the display won't be competing with sunlight. Sharp specifies 60° for the example shown in Figure Two, and Siemens offers a surface mount RGB integrated lamp with a maximum viewing angle of 120° . Total resolution is also more important for indoor applications, and the smaller size of the integrated pixel allows $\sim 33\%$ more chips to be packed into the display.

One of the most interesting things about the integrated lamp is the fact that it is, in reality, not very integrated at all. For starters, there is the fact that the RGB chips are individually processed (using three different materials systems) and then bonded together. Moreover, each of the chips has quite different performance characteristics. For example,



Coming soon to a billboard near you: four of Toshiba's full color display modules, built using red, green and blue LEDs.

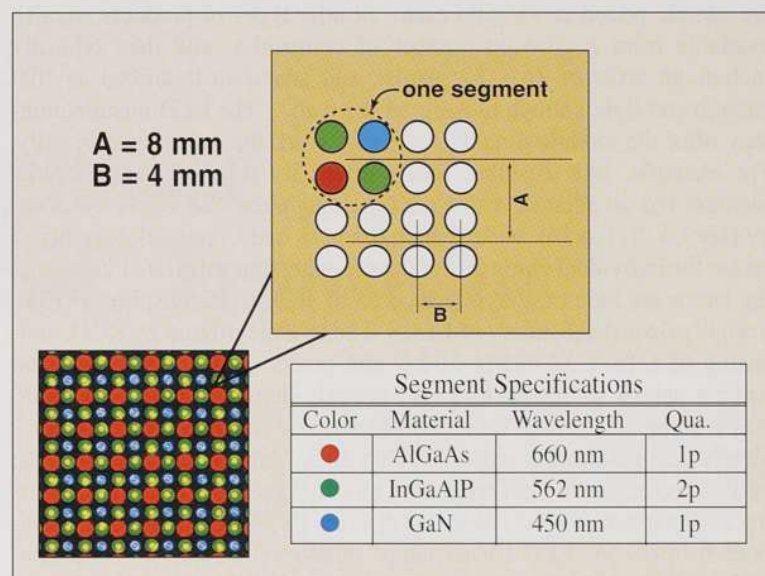


Figure One: Lower left: photo of Toshiba's full color display; upper right: schematic of LED placement.

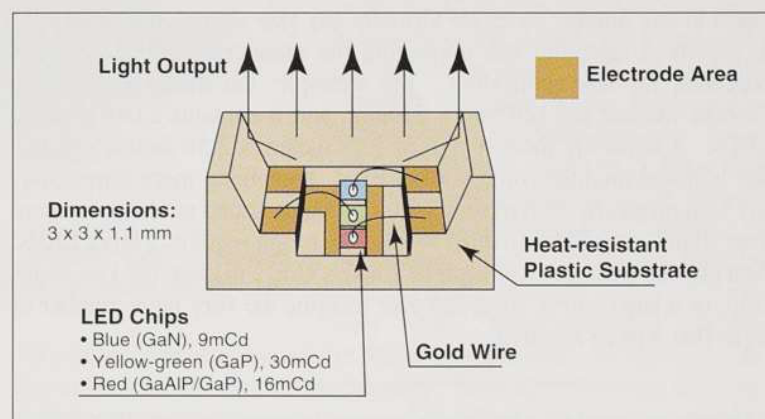


Figure Two: Schematic of Sharp Corporation's full-color LED integrated lamp which combines red, yellow-green and blue LED chips into a single package.

to produce white light in the Siemens integrated lamp, you must supply the red chip with 2 mA, the green chip with 10 mA, and the blue chip with 50 mA. It is therefore necessary to supply a separate drive circuit for each of the chips. For now, the superior resolution and viewing angle provided by the integrated lamp are enough to compensate for the more complex biasing requirements. But, according to Jonathan Wafer, Senior Product Marketing Engineer for Siemens in Cupertino, CA, the future will require RGB LEDs which provide more closely matched output as well as roughly similar forward voltages, to simplify circuitry.

From Chips to Pixels to Modules

LED pixels are brighter than CRT pixels, and they allow a greater range of colors to be created than is possible with a monitor or projection screen. LED manufacturers calculate that the size of the palette is 16.77 million colors. However, the electronics which are required to execute that range of options are not insignificant, especially when full motion video is involved. Although this application is still at an early stage of its development, it is already apparent that the preferred marketing strategy will be to package the discrete devices or the integrated lamps into a "module" that includes built-in drive circuitry. The photo at the top of the preceding page shows four of Toshiba's modules, which are sample priced at ~\$4,500 each. Similar types of products are also available from a growing number of companies, and they typically include an array of 16 x 32 pixels¹, and are often described as "flat enough and light enough to hang on the wall". The LED manufacturer may offer the module directly, or it may work through a strategic ally. For example, like Toshiba, Sharp offers its solution as a module. Siemens has an alliance with Cree regarding Cree's SiC/GaN technology (see CS 2(1), p.14), under which Siemens and Cree work together to create the individual chips that go into the Siemens integrated lamp, and the lamps are then offered in a module by Real Color Displays (RCD), a wholly owned subsidiary of Cree.² The module offered by RCD, consisting of a 16 x 32 matrix of 5.5 mm pixels, is just 1 cm thick and weighs only 8 oz/225g. RCD is currently demonstrating a 10 foot/3 meter (diagonal) "video wall" built from these modules which, in completely finished form, is only 3"/7.5 cm thick. And Nichia Chemical, the undisputed leader in high brightness blue and green LEDs, is also offering modularized products based on discrete LEDs. For outdoor applications it offers an "LED cluster lamp" measuring 22 mm per side, consisting of two blue, three green, and three red LEDs. For indoor applications it offers a 128 mm square module.

The typical customer for the modules is a company that specializes in marketing and manufacturing signs. The modules are used like building blocks, and they can be placed horizontally or vertically and combined in any number to create virtually any size sign. Once you begin to picture a sign you can appreciate the number of LEDs that will be needed for this application. For example: the dimensions of the Toshiba module are 128 mm x 256mm, and it contains 2,048 discrete LEDs. A relatively modest sign of 1.28 meters x 2.56 meters requires one hundred modules, or 204,800 LEDs. Something more impressive, say 12.8 meters by 25.6 meters, requires one thousand modules, or more than 20 million LEDs. In other words: each sign requires a lot of LEDs. And anyone who has ever been to Tokyo's Ginza district, the Las Vegas strip, or a large sports arena can also imagine the very large number of signs that will be required.

Across the "Green Gulf" to White Light?

Of course this entire application was enabled by the breakthroughs achieved by Cree Research and Nichia Chemical in manufacturing blue LEDs. Further developments in the blue regime will certainly be welcome. For example, Cree's first product was a simple SiC homojunction structure, and that is the chip that Siemens uses in the current version of its integrated lamp. However, Cree is now ramping up production of a higher brightness product made from GaN on SiC, and Siemens will be switching over as soon as is practicable.

However, the real need for improvement lies with the green LEDs. Steve Lester of Hewlett-Packard describes the current problem as "the green gulf": high brightness blue LEDs are now available on the short-wavelength end of the visible spectrum, and, on the opposite end, very high quality red LEDs have been available for sometime. But between the two lies the green region where direct bandgap emitters have not been available in mass-produced form. Thus in the Toshiba example described earlier it is necessary to use two green LEDs to provide enough output for outdoor use. According to Siemens' Jonathan Wafer, "green is the weakest link right now, and it needs to be improved by at least one order of magnitude brighter than the current best". It appears that help is on the way. Nichia has recently begun mass production of 6 Cd GaN green LEDs; Siemens hopes to be using GaN/SiC green LEDs from Cree by mid-1997. After that, according to Wafer, it may be possible, in 4-5 years, to begin introducing dedicated white light LEDs that are sufficiently bright and efficient to compete with incandescent bulbs. But for now, the display application should be sufficient to keep the LED production lines running at full capacity for quite some time.

From our May/June 1996 issue.



Sharp Goes Into Pachinko Parlors

Sharp has developed a full color LED display that it will start marketing in early 1997, promoting it to pachinko parlors and other entertainment outfits. Three models will be available, ranging in size from 9.2x7.6m to 4.8 x 3.6m to 1.9 x 1.4m. The later is shown above - it utilizes just over 49,000 individual LEDs. The price is 4-8 million yen (\$36,697-73,394) per square meter. Sharp intends to develop the LED display business around this product into a 10 billion yen (\$91.7 mil) business by 2000.

¹ Multiples of eight are preferred for maximum compatibility with MUX/DEMUX circuitry.

² Siemens also offers the lamps separately. The author was unable to determine if Toshiba and Sharp follow a similar policy.

Other Materials

At *Compound Semiconductor*, our focus is on III-V, II-VI, and related IV-IV materials. Therefore, we like to think of our magazine as the only semiconductor-related publication that classifies silicon under the heading "Other Materials".

But for this Special Edition, we've gathered up several non-III-V materials, including silicon carbide, silicon germanium, diamond and SOI for our review of the "Other Materials". Some of them may compete with GaAs, some of them may complement it - at this stage, it is too early to tell, but they all warrant watching.

Also in this section:

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- Silicon on Insulator - page 54
- SiGe - the New "Material of the Future"? - page 56
- GaAs vs. SiGe from a Market Perspective -page 60

Westinghouse Lauches First SiC Transistor

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

According to Paul DeGonia, Director of HDTV Development at Westinghouse, if all goes well, the next few years might be a heyday for transmitter production. Regulatory approval for digital TV broadcasting in the US is hoped for from the FCC as early as 1997.

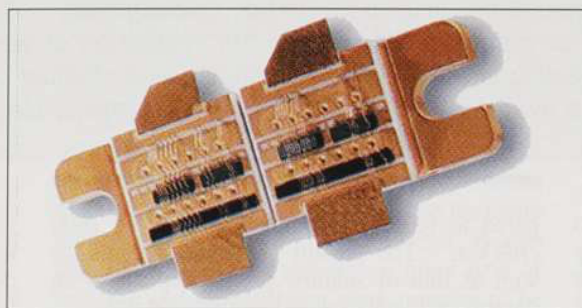
There are around 1500 television stations in the U.S., and many of them are relatively small enterprises. Therefore the cost of a new transmitter is an important consideration. Approximately two-thirds of the cost of a high power transmitter is in the power amplifiers, and a significant cost driver for the amplifiers is the power transistors. According to DeGonia, a conventional transmitter using vacuum tubes costs around \$400,000, but is not suited to advanced broad-

casting. A solid-state transmitter based on Si amplifiers costs around \$1 million - more than many stations can afford. But, DeGonia says, "by using the SiC amplifier technology we can reduce the cost of the solid-state transmitter to \$500,000 - 600,000". The keys, he reports, are SiC's high temperature characteristics, allowing it to withstand junction temperatures up to 300°C, and its much higher power-density capacity - up

to 500 W, compared to 124 - 140 W for standard Si products. As DeGonia puts it, "SiC transistors give us around four times more power than Si, which allows the use of far fewer devices, which in turn greatly simplifies the design of the transmitter and lowers its cost". SiC also provides excellent linearity. Some of the specifications for the Westinghouse power amplifier module are given in Table One.

Westinghouse's SiC device technology was developed at its Science & Technology Center [Pittsburgh, PA] and was originally intended for military radar. Last year, Westinghouse's Defense

Electronics business was sold to Northrup-Grumman, and the two companies now jointly own this technology. Westinghouse plans to pursue further commercial opportunities, and Northrup will take responsibility for military applications.



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

From our July/August 1996 issue.

Progress and Challenges in the Diamond Semiconductor Field

ROBERT A. METZGER

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

Characteristics

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

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

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

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

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

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

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

Material Applications

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

A great deal of the interest currently being generated in diamond work is due to its NEA capabilities. ATMI [Danbury, CT] and SI Diamond Technology [Austin, TX], are actively working in this area, where diamond's NEA characteristics can be utilized for low power field emitters used either in flat panel displays, or as discrete emitters. In typical operation, the diamond is used as the cathode material of an emitter, in which the electrons can be extracted from the diamond's surface through a field applied by an anode placed several microns above it, and the electrons then used to strike a phosphor which excite it, and in turn cause it to emit a photon.

The work in field emitters can be characterized as being in the experimental/early development stage, with NEA characteristics being evaluated and modified as a function of the diamond field emitter shape, dopant within the field emitter, as well as altering the surface emission properties by coating the diamond surface with such materials as H_2 , Ti, Ni, Co and Cu. One of the challenges for this application is the need to inject electrons back into NEA devices so that high current density emission can be maintained. This has been attempted by introducing both phosphorus and nitro-

gen into diamond emitters. As recently reported in *Nature* (Vol 381, 9 May 1996, pg. 140), by Ken Okano, a group from Tokai University [Kanagawa, Japan], the Japanese National Institute for Research in Inorganic Materials [Ibaraki, Japan], University of Surrey [Surrey, UK] and the University of Liverpool [Liverpool, UK] used a saturated solution of urea $((\text{NH}_2)_2\text{CO})$ to obtain N concentrations in diamond films of 3.5×10^{20} as determined by Rutherford Backscattering (the degree of electrical activation of the N was not reported). Field emitters fabricated from these heavily nitrogen doped diamond films exhibited a threshold voltage as low as $0.5 \text{ V}/\mu\text{m}$ - a value significantly lower than that previously reported for either boron or phosphorous doped polycrystalline diamond films. If this material were used in the cathode of an emitter, driven by a commercial battery of 1.5 V, and utilizing a gap between the anode and gate of $3 \mu\text{m}$, it would provide a current density of more than $10^{-6} \text{ A}/\text{cm}^2$, a value suitable for use with existing phosphors.

Device Applications

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

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

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

Other device efforts include those of AEA Technology [Oxfordshire, UK] which has fabricated diamond-based thermistors which show a temperature coefficient of resistance of $70 \text{ kohm}/\text{K}$ over a range of $20\text{-}300^\circ\text{C}$, as well as using an insulated diamond gate structure in the fabrication of a MISFET similar in concept to those fabricated by Kobe Steel. Taking advantage of diamond's large bandgap, and the high breakdown voltages associated with it, Sandia [Albuquerque NM] and Alameda Applied Sciences [San Leandro, CA] have demonstrated diamond switches which can operate at 1 kV and 18 A, with future goals for operation of up to 10 kV and at currents of up to 100 amp. In addition, diamond has been utilized in the fabrication of surface acoustic wave (SAW) filters, taking advantage of its fast phase velocities (10 km/s as compared to the 4.5 km/s in LiNbO_3 and LiTaO_3 which are typically used in SAW devices) with researchers at Sumitomo Electric [Yokohama, Japan] having fabricated ZnO/Diamond SAW devices with $0.75 \mu\text{m}$ interdigitated transducers operating at frequencies of 3.5 GHz, which if having been made on the more conventional LiNbO_3 or LiTaO_3 substrates, would have required $0.25 \mu\text{m}$ IDTs to operate at 3.5 GHz.

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

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

From our July/August 1996 issue.

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Silicon on Insulators

Do Silicon-on-Insulator based devices have the Low Power and RF characteristics to compete with GaAs devices? Yes!

ROBERT A. METZGER

It is well recognized that one of the intrinsic advantages that GaAs-based devices have over Si-based devices is the availability of high resistivity (10^6 ohm-cm) substrates. These high resistivity substrates allow devices to be placed directly on a highly isolating layer, which can lead to higher packing densities, and does not require the sophisticated and area hungry implant schemes required to avoid latch-up, improve isolation and lessen device leakage, all of which can be problems in CMOS and BiCMOS devices. The high resistivity substrate also improves RF performance, by not only reducing parasitic capacitance, but by greatly reducing RF coupling to the substrate which can degrade RF signal propagation. For both high speed and RF applications, the performance of Si-based devices and circuits could be greatly enhanced, and the technology would be much more competitive with GaAs-based devices, if an equivalent high resistivity Si-based substrate were available. In fact, such a substrate is now commercially available through silicon-on-insulator (SOI) technology.

SOI substrates

There are two basic methods to fabricate SOI substrates. The first method to form SOI substrates is by Separation by Implanted Oxygen (SIMOX). In this approach, a high current, high energy O^+ implantation (100 mA at 200 keV, for a total dose of 1.8×10^{18} cm^{-2}) is performed into a silicon wafer to produce a buried layer of oxygen below the silicon surface. This implant is typically followed by 6 hours of annealing at $1320^\circ C$ which regenerates the crystalline quality of the silicon layer remaining over the oxide and drives the formation of a buried stoichiometric oxide layer

(SiO_2). This typically creates a 400 nm buried oxide (BOX) beneath a 200-400 nm single crystal silicon layer and the process is referred to as standard dose SIMOX. A lower dose SIMOX process is also used which utilizes a total dose of only 4×10^{17} O^+/cm^2 which produces a thinner 80 nm thick BOX. Crystalline defects such as threading dislocations and small stacking fault pyramids on the order of $3-15 \times 10^5$ cm^{-2} are typically obtained in the top silicon layer utilizing this technique. SIMOX wafers are now commercially available from such companies as Ibis [Danvers, MA] and SOITECH [Grenoble, France].

The second method is that of Bond and Etch Back SOI (BESOI). In this approach, two silicon wafers, both with thermally grown oxide layers, are bonded together using Van der Waals forces, in which the combined oxide layer formed by the two bonded SiO_2 layers will become the BOX. Subsequent annealing increases the mechanical strength of the bonded oxide interface. After wafer bonding, one of the substrates is thinned down, such that the remaining silicon on the thinned wafer is now situated above the BOX. This thinning process can be performed by mechanical means (polishing or grinding), or by wet etch means in which epitaxial etch stops are placed in the original wafer prior to oxidation. Final silicon thicknesses can range from 50 nm to 50 microns, depending on the amount of silicon etched away, and the BOX can range from 50 nm to several μm s in thickness, depending only on the thickness of the oxide on the original wafers. This process requires two starting wafers, adding to the expense of the process as compared to the one wafer required for SIMOX fabrication, but offers much greater latitude in both the final silicon thickness and

BOX thickness. BESOI wafers are now commercially available from such companies as SiBond [Hopewell Junction, NY] and Hughes Optical Systems [Danbury, CT].

Variations of these typical approaches include the use of H^+ implantation through the oxidized layer, such that after wafer bonding, the stresses generated by the H^+ implantation cause the H^+ wafer to shear, leaving behind a silicon layer on top of the BOX. This BESOI technique, referred to as Smart Cut Technology, is offered by SOITECH, and needs only 1 wafer for fabrication, since the sheared wafer can be reused, unlike the case of conventional BESOI, in which the second wafer is etched back to produce the silicon layer atop the BOX.

Business

It is estimated by Rose Associates [Los Altos, CA] that the current SOI market is at \$40 million per year and growing at a CAGR of 40-50%, with an estimated market by the end of the decade of \$400 million. Al Alioto, Vice President of Sales and Marketing of Ibis estimates that the current market is 45% SIMOX-based and 55% BESOI-based. Of all the SOI approaches, at the moment, the low energy SIMOX approach is probably the least expensive, although this approach can only produce relatively thin Si and BOX layers - suitable to some applications, but not for all. Alioto says that "our goal is for SIMOX to cost roughly 3 times that of bulk silicon, and we are able to do that for large orders". Typical wafer sizes used in SOI production are the same as used in conventional silicon production - 150 mm and 200 mm. In the case of SIMOX, Ibis offers 200 mm SIMOX for \$450 (substrate cost \$120). When using BESOI techniques, this cost can often be twice as high. Ibis is not only using oxygen implantation to produce SIMOX wafers, but is also manufacturing a commercial oxygen implanter, the Ibis 1000. One of these systems has recently been funded by Motorola [Mesa, AZ], in which the machine will be built and installed at Ibis, but Motorola will receive its dedicated capacity for the next five years. Other oxygen implanter systems are being offered by Hitachi, which have sold two to date, to Komatsu and Nippon Steel in Japan.

SOITECH, which had originally been a SIMOX driven company, actually using the same type of implanter as Ibis originally did (NV-200 produced by Eaton), is beginning to shift its production away from SIMOX to BESOI using their Smart Cut process. Although currently in the start up phase, they

have produced 2000-3000 wafers with their Smart Cut process, and plan by the end of 1996 to be at the 20,000 wafer/year level, with a capacity by the end of 1997 of 200,000 wafers. As explained by Andrew Wittkower, president of SOITECH USA, "we feel that the total capacity of SIMOX wafers for each O⁺ implanter is limited to about 15,000 per year, due to the long implant times, and limited number of wafers which can be run in each with each implantation batch (maximum 25). However, using just standard fabrication equipment, we believe that each Smart Cut processing line can produce 100,000 wafers per year. This is the direction that we plan to move in."

Subramanian Iyer, Vice President and Chief Technical Officer of SiBond, explains that the flexibility of using BESOI, allows them to produce a wide range of SOI types, offering varying thickness of both silicon and BOX which simply can not be produced by SIMOX. However, he does agree that if an application can be satisfied with SIMOX wafers (thin Si and thin oxides), that it is very difficult for a BESOI approach to compete with SIMOX on a cost basis. SiBond finds that the bulk of its market is for silicon thicknesses greater than 500 nm, a market which the SIMOX approach can not produce material for.

Applications

Even though the SOI manufacturers all utilize different approaches in the fabrication of SOI substrates, they all seem to agree on what the key applications are. At the moment, the driving application is that for low power electronics - those applications which include such things as wireless handsets, pagers, and any electronic equipment dependent on batteries - the very markets that GaAs is currently penetrating. The governing equation of power consumption (P) for an IC is:

$$P = CV^2f + VI_{leak}$$

where C is the total capacitance, V is the supply voltage, f the operating frequency, and I_{leak} is the standby current required when the device is turned off. As is apparent from this equation, large reductions in power consumption can be made by lowering operating voltages. The reduction of power supplies from 5 V to 1 V reduces power consumption by a factor of 25. It is generally felt that conventional CMOS on bulk or epi wafers will be able to operate at turn-on voltages as low as 1.5 V, but levels lower than this will be difficult to achieve. Using SOI substrates, the subthreshold slope for turning PMOS and NMOS

devices on and off is much steeper than that for devices on conventional Si substrates, thereby permitting lower turn-on voltages, while at the same time ensuring that I_{leak} is sufficiently small when the device is turned off. It is believed that CMOS/SOI will be able to operate with supply voltages of 1 V. These lower voltages become especially critical as the operating frequency increases (this increases power consumption), which is the current trend for many wireless devices, especially cellular phones and WLAN devices which are moving from the 800-900 MHz regime and into the 1.8-2.4 GHz range. Due to the buried oxide layer, both the capacitance, C and the I_{leak} are reduced, which further reduces the power consumption. I_{leak} can also be significantly reduced since the junction area of the device can now be reduced since it sits directly on an insulating layer (and no longer requires implants for isolation). In the case of GaAs, the semi-insulating substrate serves the same function to reduce both C and I_{leak} . DARPA is very interested in low power electronics for future military needs, and has established a low power electronics (LPE) program, with the objective of reducing power consumption by a factor of 100 as compared to current systems. The principal substrate technology that this program is investigating and investing in is SOI.

Other applications include using CMOS/SOI for radiation hardened ICs, as well as using thicker Si layers which can be used to form mechanical structures, such as sensors, actuators and accelerometers, all of which have potentially large markets in automotive applications. A potentially very large application is that of memory devices and very large circuits such as microprocessors. Reduction of leakage currents and the ability to design smaller devices on the insulating oxide are very attractive characteristics for these devices. Significant savings in capital investments may occur if the use of smaller devices can forestall the shift from 200 mm to 300 mm silicon wafers. DRAM and microprocessor manufacturers are currently investigating the use of SOI, but most SOI manufacturers believe that this application is at least several years away.

With major manufacturers such as Motorola, Analog Devices, AMD, DEC, Fujitsu, Honeywell, IBM, Intel, Mitsubishi, National Semiconductor, NEC, Philips, Samsung, Sharp, TI and Toshiba actively investigating the use of SOI substrates, it would appear that the commercialization of SOI-based devices is near and that GaAs will be facing competition from this new technology.

From our May/June 1996 issue.

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Is Silicon Germanium the New "Material of the Future"?

R&D groups are fabricating some very impressive HBTs from SiGe. However, eight years after the first reports in this field, there is not a single SiGe device in production. Is this about to change?

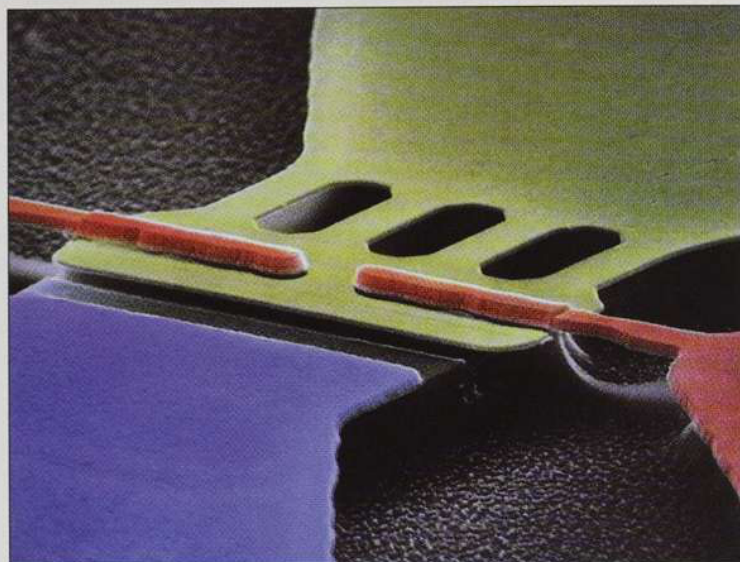
ROBERT A. METZGER

Since the first report of SiGe HBTs in 1987 there have been numerous demonstrations of its impressive potential: for example, f_i and f_{max} values in excess of 100 GHz. SiGe has often been touted as the natural complement to silicon for high frequency applications, and many believe that it can combine the "low cost" nature of silicon with the "high performance" nature of heterostructures, thereby eliminating the need for GaAs. The symbolic embodiment of this line of thinking was IBM's decision to disband its GaAs program in favor of SiGe. Other large companies, most notably Daimler-Benz and NEC, have also established SiGe development programs. Their results demonstrate quite clearly that SiGe can out perform conventional Si. However, as many in the GaAs digital community have learned, performance alone does not guarantee marketplace success.

As of this writing there are no SiGe devices or circuits on the commercial market, and it may be another 1-2 years before they emerge. What direction will these initial SiGe offerings take, and what type of competition will they find from both Si and GaAs? We've all heard it said at least a hundred times: "GaAs is the material of the future - and it always will be!" But GaAs is, at last, finding high volume markets - especially in wireless communications. Can SiGe make the same transition? Or is it destined to become the new "material of the future"?

IBM

To many people, SiGe has become synonymous with IBM and Bernard Meyerson. During the mid 1980s, Meyerson pioneered a UHV/CVD SiGe growth technology at the T.J. Watson Research Center [Yorktown Heights, NY], which has now been transferred to IBM's 200 mm BiCMOS line at East Fishkill, NY. Meyerson says that "the SiGe



Daimler-Benz Research Center

SEM of Daimler-Benz Double Mesa SiGe HBT.

HBT effort has been spun into its own business unit within the Microelectronics Division at East Fishkill - we are in essence our own company". And as with any other company, in order to survive and grow, it must establish a product and find the customers. At the moment, that product is not in the form of a specific device or circuit, but in the form of a technology.

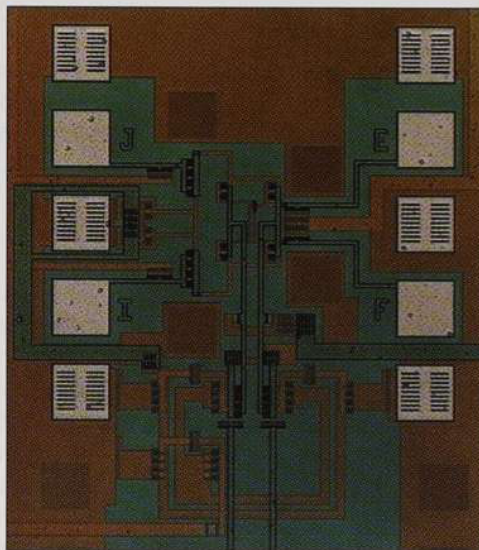
The IBM SiGe HBT approach typically uses a graded Ge profile in the base, in which a 1-2% Ge content is used at the emitter-base junction, and increased to 8-10% at the base-collector junction. All aspects of the SiGe HBT fabrication sequence are compatible with the CMOS portion of the BiCMOS process. The SiGe growth step is inserted into the BiCMOS process flow after the growth of a 7 nm gate oxide for the CMOS structure and a conventional CVD deposition of a thin polysilicon layer which protects the gate oxide. This polysilicon layer is then patterned and removed over the n-p-n active area (where the SiGe HBT will be fabricated) by a highly selective (polysilicon to oxide) RIE etch. Exposed polysilicon and silicon surfaces are then hydrogen passivated and the SiGe epitaxial base is grown by the UHV/CVD process. The polySiGe which is deposited over the field oxide as the epitaxial SiGe base is being grown is later utilized as extrinsic base electrodes. The remaining processing consists of a conventional dual poly BiCMOS processes. IBM believes that the future of SiGe technology lies in this merged process - combining high frequency SiGe HBTs for RF applications, with Si CMOS for digital applications, in which both analog

and digital functions are capable of high levels of integration. As an example of this technology, IBM has recently demonstrated 0.25 μm electrical channel length nFET and pFET CMOS devices fabricated on the same wafers with SiGe HBTs which exhibit f_{max} and f_t values of 49 GHz and 39 GHz, respectively, measured at a V_{CE} of 1V. CMOS circuits including ring oscillators (stage delay of 49 ps) and 64 K SRAMs were fabricated alongside SiGe HBT analog circuits which included ECL Ring oscillators (stage delay 25 ps) and voltage controlled oscillators. This kind of capability is in essence the product which IBM is offering.

In an effort to develop a customer base for its technology, IBM has been working with outside companies in the development and investigation of SiGe-based HBT circuits. Jack Glenn and coworkers at Delco Electronics [Kokomo, IN] and the Hughes Research Laboratories [Malibu, CA] in collaboration with IBM, reported at the 1995 BCTM on a 12 GHz Gilbert Mixer, using both a Si only epitaxial base, as well as a SiGe epitaxial base. They found that the Si-only base Mixer exhibited a f_{max} and f_t of 50 and 39 GHz, respectively, resulting in a gain-bandwidth product of 18.5 GHz, while the SiGe base mixer exhibited a f_{max} and f_t of 60 and 47 GHz, respectively, giving a gain-bandwidth product of 22.5 GHz. These results demonstrate that the SiGe-base structure improved RF performance by some 10-20%. However, they also clearly show that IBM's Si-only bipolar process, when using an epitaxial-grown base, is extremely fast. Meyerson comments on this by saying that "our bipolar process is outstanding, with the SiGe just one factor among many which makes it extremely fast. What the SiGe does is give the Si-only process an added kick".⁽¹⁾

Analog Devices

The most prominent among IBM's collaborators is Analog Devices Incorporated [Norwood, MA]. In 1993 they announced results on a SiGe-based 1 GHz, 12 bit, current output, D/A convertor with an ECL interface. The converter contained 2854 SiGe HBTs,



Delco Electronics

A 12 GHz SiGe-based HBT Gilbert Mixer, jointly fabricated by Delco Electronics, Hughes Research Laboratories and IBM, exhibiting a voltage-gain bandwidth product in excess of 22 GHz.

1465 poly-silicon resistors, a patterned p+ ground plane to speed signal settling, and three levels of metal for interconnections. This is still the highest level of integration attained to date for any SiGe technology. However, that product did not make it to the market, and since then Analog Devices has not published any other SiGe-based device results. Charles Fadel, marketing manager at Analog Devices, says that "delays occurred after the initial work on the 12 bit DAC as the SiGe technology was being transferred from IBM Yorktown to Fishkill, but a run of devices has just been completed which includes LNAs, mixers and prescalers, intended for 1.8 GHz operation. We will soon be evaluating their performance." In the meantime Analog Devices' conventional Si-bipolar processes have continued to improve, resulting in what marketing manager Rupert Baines, characterizes as "a good 25 GHz [f_t] process". He goes on to say that, "we thought we would need SiGe for 1.8 GHz applications, but now we don't need it there - conventional Si can handle it." For frequencies above the

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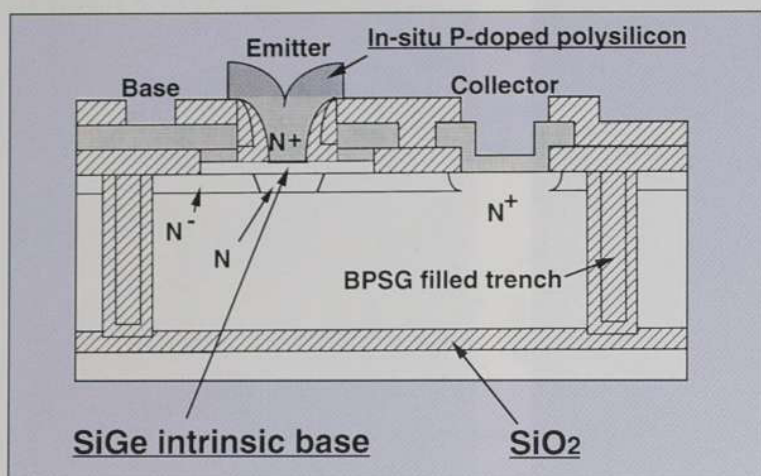
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⁽¹⁾ Other recent collaborative work has been performed with a team consisting of Carleton University and Northern Telecom [Ottawa Canada]. Weinan Gao and coworkers at Carleton University and Northern Telecom have fabricated an HBT Comparator which can operate up to sampling rates of 5 GHz using SiGe HBTs with f_{max} and f_t of 50 and 40 GHz, respectively, while dissipating 89 mW from a 3-V supply. Also reporting at the 1995 BCTM were Mike Case and coworkers at Hughes Research Laboratories on a 23 GHz static 1/128 Frequency Divider using SiGe HBTs. In order to obtain such high frequency results on a lossy silicon substrate, it was found necessary to fabricate microwave elements above a 13 nm thick layer of benzocyclobuten (where the BCB was used for wave propagation).



NEC Corporation

A cross sectional view of NEC's super self-aligned selectively grown SiGe-base (SSSB) HBT fabricated on Silicon on Insulator (SOI).

2.0 GHz level Baines says, "it is not clear if we will need SiGe at that point, but it is not a decision that we have to make now. We feel that, at the moment, the WLAN market at 2.4 GHz is small and undefined, and we have the time to make our decision as to which technology to choose - SiGe or Si." Baines' sentiments are echoed by Jerald Fishman, president and CEO of Analog Devices who has said that he feels that bipolar in standard silicon is now capable of operating at up to 2 GHz, while there may still be some opportunity for SiGe in very high-speed communications.

NEC

The NEC [Kanagawa, Japan] approach relies on the formation of a selectively grown SiGe base region. Initial work in the early 1990's relied on Gas Source MBE to perform the selective work, but this has now been transferred to a cold wall UHV/CVD system, an approach which is very similar to IBM's. NEC utilizes a self aligned structure in which a polysilicon overhang is placed above the region where the SiGe base will be grown. As the selective SiGe epitaxial base grows upward, polySiGe is also selectively being grown downward from the exposed polysilicon overhang. As growth continues, the single crystal SiGe from the base and the polySiGe from the extrinsic base contact meet during selective growth to form the extrinsic base contact. This process is referred to as the Super Self-aligned Selectively grown SiGe base (SSSB) bipolar transistor. NEC uses base thicknesses which vary from 45 to 60 nm, using both a graded Ge profile similar to IBM's, as well as a trapezoidal-like structure (a combination of the graded and flat Ge profile), where for both cases, a maximum Ge content ranging from 10-15% at the collector-base junction is used. Boron base doping is typically $7 \times 10^{18} \text{ cm}^{-3}$, a value similar to that used by IBM. In order to improve RF performance, a bonded silicon on insulator (SOI) substrate with BPSG-filled trench isolation is used to reduce collector-substrate capacitance. Using the SSSB approach, f_{max} and f_t values of 50 and 50 GHz, respectively, for V_{CB} of 1 V, are obtained.

Sato and coworkers at NEC have applied this technology in the development of the ICs required to implement a 20 Gbit/s optical communications system, as reported at the 1995 BCTM. These circuits include a SiGe-based HBT preamplifier IC which employs a dual feedback loop circuit, and exhibits a 19 GHz bandwidth with a 38 dB-ohm

transimpedance gain, and a decision IC which consists of a gain controllable amplifier, and a D-flip-flop which operates at 20 Gbit/s with 200 mV_{p-p} input sensitivity. In addition, this technology has been applied in the fabrication of 0.6 μm design rule SiGe HBTs in used in ECL circuits, producing 19 psec gate delays.

Daimler-Benz

The SiGe effort at the Daimler-Benz Research Center [Ulm, Germany] is based an MBE-grown, mesa-structure HBT. Using 1000 ohm-cm Si substrates, where the high resistivity substrate is used to enhance RF performance, the typical Daimler-Benz MBE grown HBT utilizes the flat SiGe base profile, which consist of a 25 nm boron doped $1 \times 10^{20} \text{ cm}^{-3}$ SiGe layer, with a 30-40% Ge content. The remainder of the HBT consists of a 50 nm Si emitter, Sb doped to $2 \times 10^{18} \text{ cm}^{-3}$, and a Si collector which may vary in thickness from 130 to 400 nm with doping ranging from 2×10^{16} to $5 \times 10^{17} \text{ cm}^{-3}$, where this range is used to trade f_t off against f_{max} , an example of which can be seen in Table 1.

Daimler-Benz utilizes three different SiGe HBT processes, all based on MBE growth of the SiGe epi. The first is a non-passivated double mesa technology, using dry etching and self aligned liftoff to define the emitter, base and collector; the second is a passivated double mesa technology, in which self-aligned oxide/nitride sidewall spacers are used for passivation; and the third is a differential HBT process used to reduce parasitic collector-base capacitances, where the collector is grown by CVD, and the base and emitter layers are grown by MBE, while a recessed LOCOS (Local Oxidation of Silicon) technology is used to define the active HBT area.

Daimler-Benz plans to announce at the 1995 International Electron Device Meeting (IEDM) that the double mesa SiGe HBT structure has achieved a record-breaking f_{max} of 160 GHz (with a corresponding f_t of 30 GHz) at a V_{CE} of 8 V. However, this high operating voltage makes this device inappropriate for many wireless applications. A more applicable structure for wireless applications will also be reported which utilizes a higher collector doping (increasing from

TABLE 1
DEVICE PARAMETERS

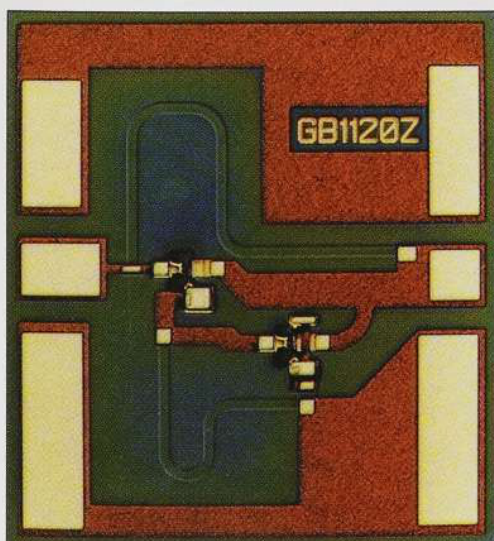
MBE sample	w_c [nm]	N_c [cm ⁻³]	β	R_{bi} [$\Omega/\square$]	f_T [GHz]	f_{max} [GHz]
B2845[8]	130	$5 \cdot 10^{17}$	22	950	46	49
B 2982	180	$2 \cdot 10^{17}$	32	450	17	55
B2984	250	$8 \cdot 10^{16}$	60	360	30	78
B2991	250	$5 \cdot 10^{16}$	60	360	33	2
B2992	300	$5 \cdot 10^{16}$	55	340	30	72
B2994	300	$5 \cdot 10^{16}$	55	380	34	100
B2993	400	$2 \cdot 10^{16}$	55	400	32	120

Daimler-Benz Research Center, and IEDM

Table 1. Device parameters for Daimler-Benz SiGe HBT, illustrating the relationship between f_t , f_{max} and collector structure. For w_c - collector width, N_c - collector doping, β - dc current gain, and R_{bi} - base resistance.

1.5×10^{16} to 2×10^{17}) where at a VCE of 3 V, gives an $f_{\max}$ of 90 GHz, with a f_t of 65 GHz. Some of the other highlights of Daimler-Benz's SiGe HBT technology include: a DC-18 GHz wideband amplifier exhibiting 9.5 dB of gain while drawing only 50 mW from a 3 V supply; a 26 and 40 GHz VCO which exhibits a tuning range of more than 3 GHz, with the output power behind the on-chip 10 dB attenuator reaching -13 dBm; a Ka band MMIC amplifier producing 4 dB of gain at 26 GHz; and a C-band (4-8 GHz) power amplifier producing 20 dBm of power at a 30% PAE.

Daimler-Benz has begun transferring its technology to its subsidiary, TEMIC Telefunken [Heilbronn, Germany], to begin commercialization of both discrete- and circuit-based SiGe components. TEMIC currently produces bipolar Si devices with f_t up to 15 GHz for wireless applications. It plans to implement Daimler-Benz's technology to create a UHFSiGe process (f_t up to 50 GHz). TEMIC is currently using the differential HBT process (MBE/CVD), with CVD defined collectors for the UHFSiGe process, but plans in the future to go to complete CVD structures - a critical step which may prove challenging when considering how MBE-dominated the Daimler-Benz effort has been up until this point. TEMIC is specifically targeting wireless applications. They hope to begin with production of discrete devices in the first half of 1996, and to start production of circuits by the end of next year.



A DC-18 GHz SiGe-based HBT Wideband Amplifier, fabricated by Daimler-Benz and University of Ulm. Providing 9.5 dB of gain from DC through 18 GHz, this 3 V supplied amplifier consumes 50 mW.

Competition

SiGe, Si and GaAs device technologies compete among each other in two fundamental categories: performance and cost. Success in the market place occurs for those who offer a device at the minimum cost which can just meet a performance specification. No one is willing to pay extra for performance that they do not need. Using these two criteria, how well does SiGe compete against both Si and GaAs?

IBM, NEC and Daimler-Benz have clearly demonstrated that SiGe can produce a high performance HBT technology. SiGe-based HBTs exhibit f_t and $f_{\max}$ values above 100 GHz (values which are 50% higher than the best Si-BJT, but some 2-6 times lower than the best GaAs devices). IBM has reported power added efficiencies at 1 GHz of 66%, which is slightly better than the best Si BJT, but somewhat less than those obtainable in GaAs. Though somewhat inferior in noise characteristics over the 1-2 GHz range as compared to GaAs, SiGe-based HBTs offer superior corner frequencies, f_c , with values down to 100 Hz as compared to GaAs which generally exceeds 2 KHz. Furthermore, IBM has demonstrated the capability of integrating CMOS with SiGe HBTs, where the resultant SiGe HBTs operated comparably to state of the art BJT performance levels. These characteristics show that the performance of SiGe-based HBTs is for the most part superior to conventional Si BJTs, while in some areas are becoming competitive with GaAs based devices, and in the case of f_c , even superior.

The most important "real-world" considerations are the characteristics required for a specific application. IBM and TEMIC both hope to pursue the RF segment of the wireless market, which currently requires discretes and MMICs which can operate over the frequency range of 900-1900 MHz, with some small growth starting to occur at 2400 MHz for WLAN applications. SiGe can readily meet the RF requirements for most wireless applications in this frequency range - but so can Si and GaAs. In reality, competition in this area is not so much determined by performance, but by cost. As a result, both Si and GaAs-based MMICs currently face stiff competition from discretes. MMICs currently occupy around 25% of the market, and they will be able to increase their share only if they can compete on a cost level with discrete solutions, or offer a needed performance enhancement. IBM reported at the 1995 BCTM that they believe that an important application for

their SiGe BiCMOS technology will be "single chip solutions" for wireless - a single SiGe BiCMOS chip which would handle both RF and digital functions. But this vision is contrary to that shared by the vast majority of the wireless community, where a "mix-and-match" approach is utilized to tailor both digital baseband circuitry and RF components for specific phones and applications. It is not clear at all that the wireless market is looking for large levels of RF integration, let alone integration of RF with digital baseband functions. If IBM is correct, then they are far ahead of current practice.

The first SiGe-based HBT MMICs will likely be targeted toward a cost/performance point somewhere between that of Si and GaAs MMICs. Unfortunately, this region is getting smaller. Silicon's performance is improving. It is already suitable for applications below 2 GHz, and at least one "all-Si" chipset for 2.4 GHz operation has been announced (see page 14). At the same time, GaAs-based devices and MMICs continue to get cheaper. TRW's GaAs HBT Darlington amplifiers are now being sold through RF MicroDevices for less than \$1 each. Hewlett Packard can sell PHEMT based LNAs, which are both MBE-grown and whose gates are E-beam defined, for less than \$1. And TriQuint sells a wide range of MESFET-based LNAs, as well as up and down converters for less than \$2 each. Industry wide GaAs MMIC production levels are already approaching 10 million per month, and will see continuing rapid growth with the introduction of TDMA and CDMA digital cellular services, as well as expansion of cellular services into the PCS band (1800 MHz) within the next two years. This increase in production will only further decrease GaAs-based MMIC costs.

Despite having demonstrated a high performance technology, neither IBM, NEC or Daimler-Benz have yet entered into the phase where they are producing any MMICs for insertion into commercial devices. All three are still in the investigational/demonstration mode, with Daimler-Benz looking like it will be the first to enter the market. Those SiGe parts will enter into a very competitive arena, especially if they take another 1-2 years to arrive. During that time both Si- and GaAs-based MMICs will continue to improve in performance, increase production, and drop in cost. SiGe is undoubtedly capable of producing a high speed bipolar technology, but it remains to be seen whether this technology can make the leap from the laboratory to the production line.

SiGe HBT and GaAs MESFET Technologies - A Market Perspective

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SiGe HBT technology has garnered a lot of press during the last year or so. While it has been touted to be manufacturable and ready for high volume production, it has not yet been used for generally available commercial products. The technical aspects, or the "hows," of the transistors have been reported adequately enough, however the marketing reasons, or the "whys," have often been glossed over. Usually the marketing reasons read something like, "if it's silicon on big wafers, it must be cheap" and "we could see 'radio on a chip' integration soon, because the integration potential of silicon is well known." Unfortunately, there are several assumptions built into these arguments that don't stand up to closer inspection. Let's examine them:

Assumption #1: SiGe HBT offers enabling performance improvements over other high performance bipolar processes. The main advantage of SiGe is that it allows for higher base doping than is practical in conventional bipolar transistors. This allows for thinner bases and lower R_{base} values. These allow for higher cutoff frequencies. The more Ge in the base the better. Unfortunately, there is a practical upper limit on the Ge concentration in order to get low defect epitaxy. Therefore, the performance advantages in practical SiGe devices are relatively small compared the best high performance bipolar. To many bipolar users, there is a real question whether it is worth investing in a new technology for relatively minor benefits.

Assumption #2: Transistor performance is the main barrier for integrated silicon to penetrate wireless RF front-ends. While transistor performance is an issue, RF isolation and system costs are much bigger barriers. Since silicon substrates are conductive, it is not practical to build high quality passive elements on-chip. However, much of the cost in current RF systems using discretes comes from the

passive elements. GaAs IC's are penetrating RF system designs based on system cost, not just performance. Integrated GaAs with on-board passive elements provide much greater consistency compared to discretes. This often results in higher radio yields and lower overall RF system cost.

Assumption #3: All silicon processing is inherently cheap. Not all silicon process technologies are equal on a cost basis. High performance bipolar and BiCMOS processes are more complicated and usually produced in lower volumes than CMOS memories and gate arrays. Simple GaAs MESFET processes are currently cost competitive with high performance bipolar and less expensive than BiCMOS for RF functions. For the same function, a typical GaAs MESFET process takes only 13 photolithographic layers compared to 21 layers for high performance bipolar with the same function. BiCMOS processes usually have 26 or so layers by comparison. As the infrastructure for GaAs grows, these differences will become more and more clear.

Assumption #4: It is always desirable to maximize the level of integration in RF systems. Some reporters mistakenly apply the pervasive digital integration paradigm that has dominated the computer industry to RF systems with the notion that "radio on a chip" is around the corner. Even if "radio on a chip" integration becomes technically possible, it would not be cost effective. It doesn't make sense to use real estate shared with very high performance RF transistors for baseband and signal processing functions. Likewise, it doesn't make much sense to force-fit high density CMOS with RF transistors. It is best to choose the appropriate technology for each function for both performance and cost reasons. Where integration is occurring, chip set makers and mobile terminal designers are slowly developing a consensus toward inte-

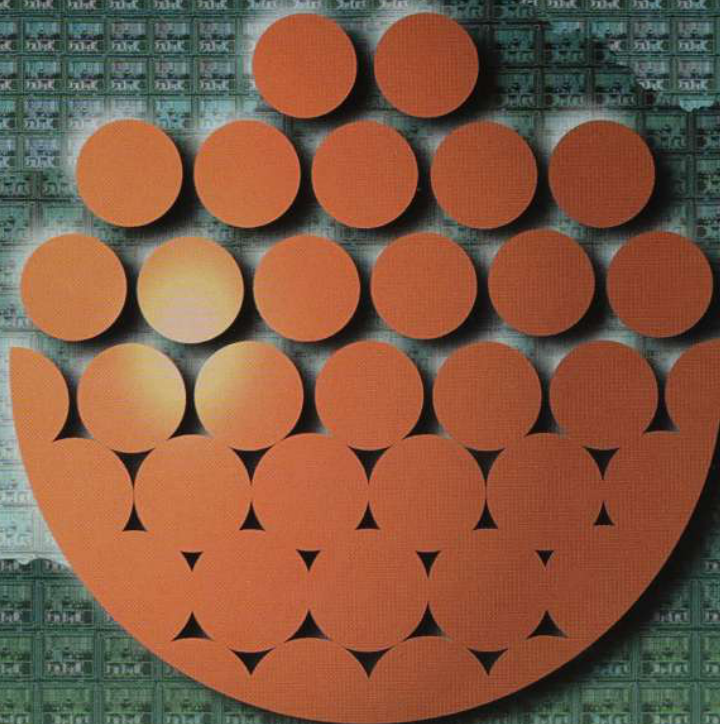
grated GaAs MESFETs for RF front-ends, Bipolar or BiCMOS for IF/Baseband functions and CMOS for signal processing and logic. Since the characteristics of each function are so different, each of these technologies has its natural place.

SiGe will not replace GaAs in circuit applications where it has been demonstrated that GaAs has clear performance and cost advantages over integrated silicon bipolar. This is particularly true in RF power amplifiers for mobile communications. GaAs MESFET power amps provide greater power efficiency than bipolar power amps. Also, GaAs MESFET technology offers the linearity required for today's emerging digital systems. On the other hand, SiGe provides no such advantage over silicon bipolar for power amps.

Since TriQuint produces GaAs devices exclusively, we are sometimes asked whether we are concerned about the emergence of SiGe HBT technology. While we are interested in the developments of this technology, we do not consider it to be a threat. SiGe HBT is essentially a performance enhancement of existing bipolar technology with all of its attendant strengths and weaknesses.

From our Nov/Dec 1995 issue.

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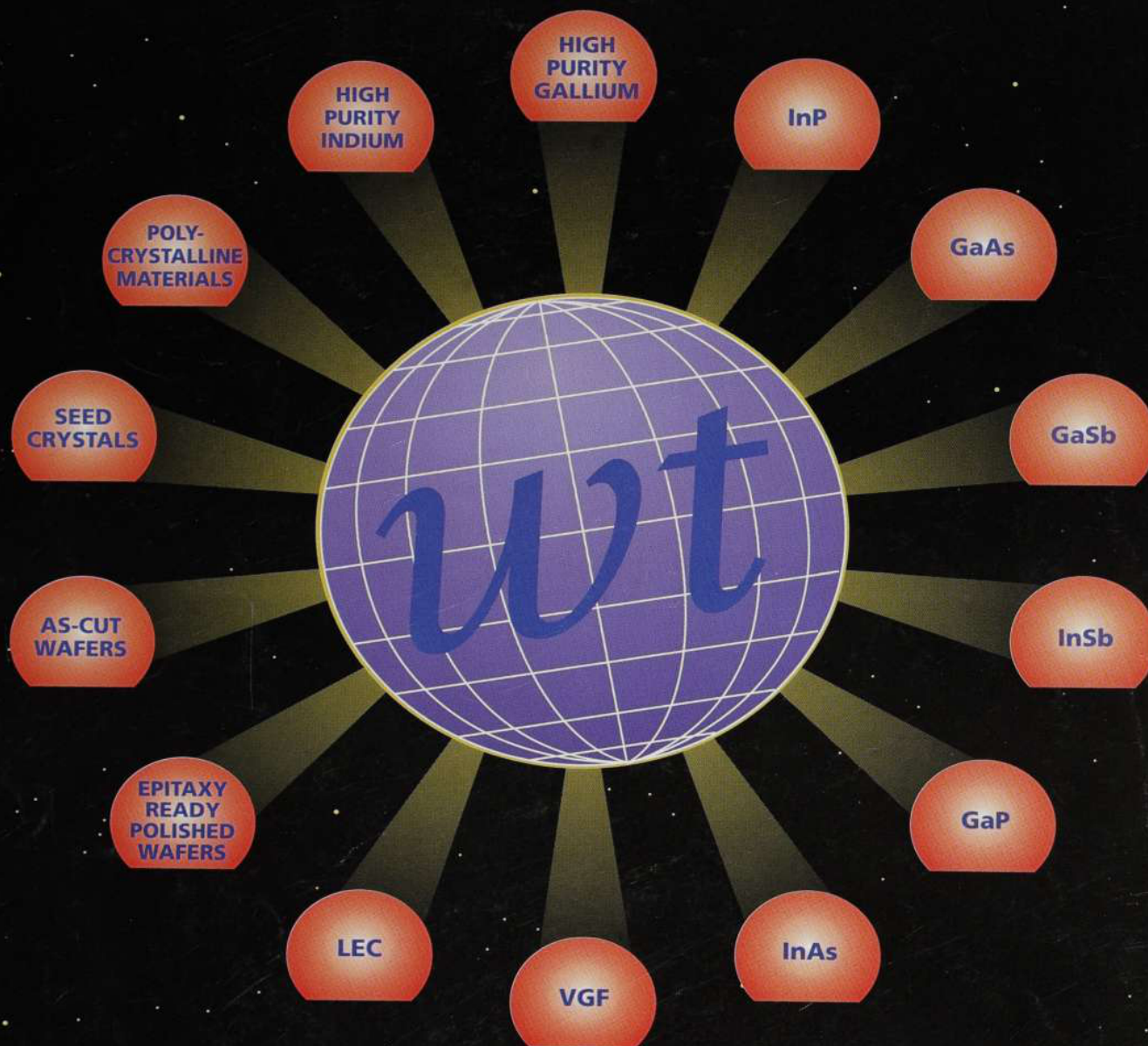
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