



COMPOUND

SEMICONDUCTOR

March 1999

Volume 5 Number 2

6" GaAs Gains Ground

**Silicon
Germanium
as a
Production
Technology**

Also in this Issue:

- High Power Laser Diodes
- Forecast for Compound Semiconductors
- Optical Data Storage
- MMICs for Automotive Radar

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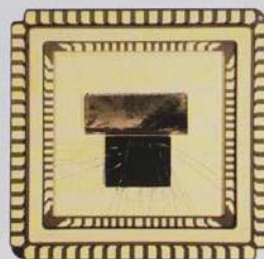


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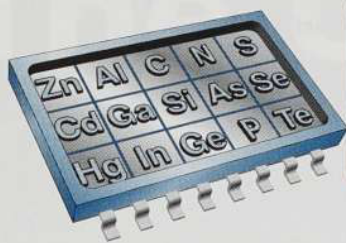


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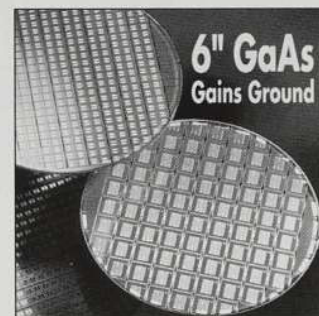


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COMPOUND SEMICONDUCTOR



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Raytheon has plans to join Vitesse, Anadigics and Siemens in building a 6" GaAs fab, and sees the move as inevitable for the leading players in the industry.

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Challenges and Opportunities for Compound Semiconductors: Stan Bruederle of Dataquest presents his view of the prospects for compound semiconductor devices in three main areas - wireless communications, fiber-optic communications and optoelectronics. This paper was the Keynote Address of the 1999 Gorham/Intertech Compound Semiconductor Outlook Conference.

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Special Feature: Micromachined passive devices in a standard GaAs HEMT technology.
Compound Semiconductor Materials: Deep UV Stimulated emission from AlGaIn...UV photoluminescence from In-doped GaN...Green light emission from GaInNAs.

Microelectronic Devices and Circuits: 100 W base station PAs...Single voltage operation of HFETs...MM-HEMTs with an AlGaAsSb buffer.

Optoelectronic Devices: OPFET with 200 A/W responsivity at 1.3 μm ...2.05 μm DFB laser with 10 mW power...GaAs/AlGaAs quantum cascade lasers.

Due to overwhelming demand, this issue features more "Things to Watch" for the coming year, including 6" GaAs, SiGe, high power laser diodes and optical data storage. Vitesse spearheaded the move to 6" GaAs, and now reports outstanding digital IC yields from its Colorado Springs facility. Coverage of how other companies plan to follow Vitesse begins on page 33. [Photo courtesy of Vitesse].

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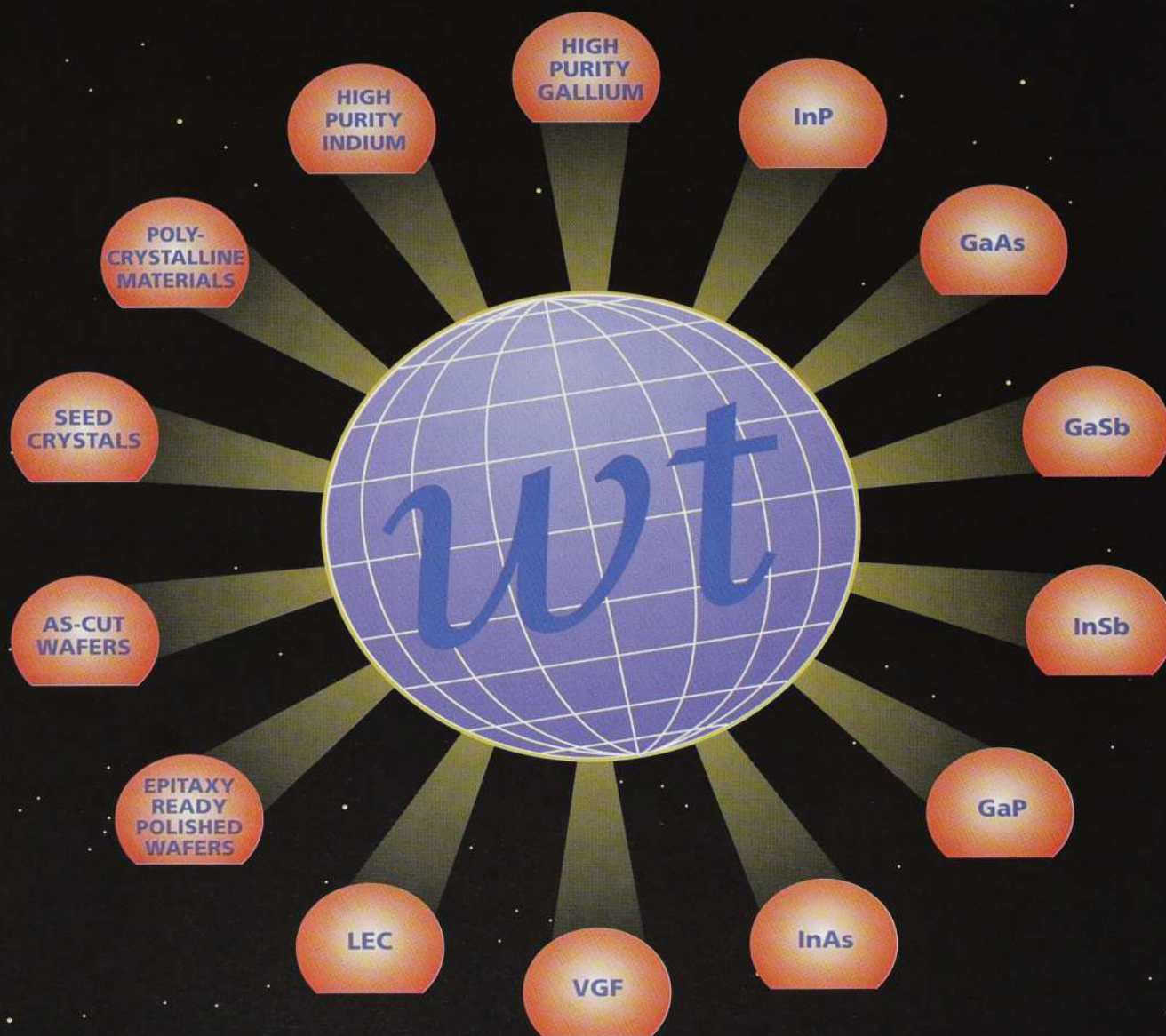
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Two More Companies to Produce Submarine 980nm Pumps

Following closely on the heels of Uniphase Laser Enterprise, SDL and Mitsubishi Chemical are the latest companies to reveal plans for supplying 980nm pump laser diodes for submarine applications. SDL has signed an agreement with Alcatel whereby the latter will produce undersea pump modules at their Optronics Division, using SDL's laser chips. Mitsubishi Chemical will be supplying 980nm pumps to KDD, which was also a partner in the development of the lasers.

As noted in our last issue (CS 5(1), p. 6), Uniphase recently announced the first deployment of 980nm laser diodes in under-sea fiber-optic links. Their installations will come via Lucent Technologies, which recently won a contract to supply EDFA modules to Tyco Submarine Systems. The submarine market has been tough to crack, because manufacturers of 980nm lasers had not accumulated enough field data to prove they could meet the ultra-stringent reliability requirements for undersea applications. So submarine cables have instead relied on the more mature 1480nm pump technology. But now that the reliability hurdle has been cleared, a rapid conversion to 980nm EDFAs is likely. This is due in large part to the fact that this new generation of pump modules has lower noise

characteristics, which effectively increases the available bandwidth and can also be used to increase the distance between amplifiers.

Alcatel and SDL have worked closely for more than a year to verify the performance and reliability of the submarine modules. The companies have also worked together for several years on terrestrial fiber optic networks. SDL has an exclusive four-year supply agreement with Alcatel, and is in the midst of ramping up to full production for the submarine lasers.

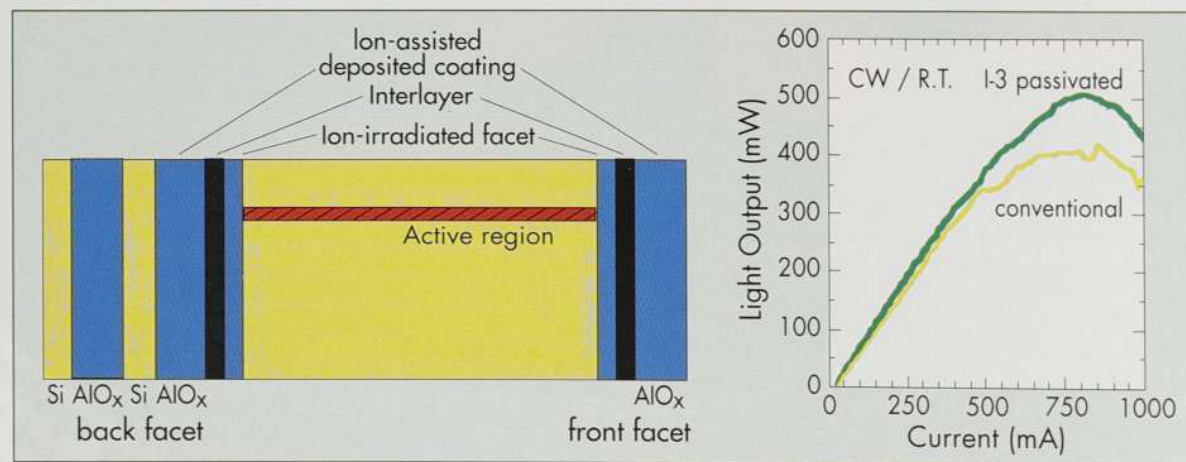
"Alcatel's extensive experience in the design and manufacture of submarine qualified components has been a powerful complement to SDL's world renowned high power laser chip technology," said Jean-Marie Vansteenkiste, chairman and chief executive officer of Alcatel's Optoelectronic activity. "In fact, we have exceeded some of our initial performance targets with enough margin to enable additional network performance benefits. We believe we can now offer the highest level of power and reliability available in the undersea market."

The Alcatel/SDL pump module design also features passive wavelength stabilization, which the companies say is a critical performance requirement for wide bandwidth DWDM optical ampli-

fiers. Variations in pump wavelength can cause changes in the amplification of the signal channels. To prevent this, SDL has designed the laser chip and grating to stabilize the laser wavelength. According to Donald R. Scifres, SDL's chairman and chief executive officer, "We are very encouraged that our high power grating stabilized laser appears to deliver the best combination of performance, reliability and manufacturability. The close cooperation between Alcatel and SDL for this program resulted in a combination of product performance and time to market that could not be achieved by either company alone. This partnership and contract is part of our ongoing strategy to capitalize on our technology by providing large telecommunications companies with leading edge products to boost throughput on their networks."

Mitsubishi Chemical developed their 980nm pump lasers working in conjunction with KDD Laboratory. Another KDD company, KDD Submarine Cable Systems, has a number of trans-Pacific and trans-Atlantic projects slated for service in 2000.

The companies have developed what they call the "I-3 process" for passivating and coating the facet. This is a critical manufacturing step, because facet degradation leading to sudden failure is the primary reliability problem for these types of lasers. The I-3 process involves, in sequence, (i) ion-irradiation, (ii) interlayer deposition, and (iii) ion assisted deposition of a dielectric material. The first stage consists of low energy ion irradiation followed by the second stage of continuous deposition of a thin interlayer. Finally, AlO_x is deposited onto the interlayer to realize a 2.5% anti-reflection coating by



Left: Cross-sectional view of a laser diode passivated using the "I-3" process. Right: IL characteristics of conventional and I-3 passivated devices.

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ion assisted deposition for the front facet. For the back facet, the same method is used except an $\text{AlO}_x/\text{a-Si}$ multi-layer is used instead of AlO_x to achieve 95% reflectivity.

Mitsubishi Chemical is taking a highly vertically integrated approach to the production of the devices, going so far as to produce their own VGF (vertical gradient freeze) GaAs substrates. The company is already manufacturing other types of laser diodes, including pick-ups for optical data storage, at its Kashima Works in Ibaraki Prefecture. The 980nm module is priced at about \$10,000. The company is aiming for annual sales of 10 billion yen (\$73.5 mil) two to three years from now.

Other 980nm News

On February 25 **Lasertron** introduced a new family of 980nm Bragg gratings stabilized ("BGS") pump lasers. The company says they are available in production volumes with optical kink-free powers of up to 190mW at wavelengths from 973 to 986nm. "The shift to higher channel counts requires amplifiers that need high power pumps with extremely stable dynamic performance. We are excited about these new BGS pump lasers because they enable our customers to provide these state-of-the-art amplifiers to end users of the latest DWDM systems," stated Dr. Robert Hannemann, President of Lasertron. He reports that company's pump lasers are deployed in major long distance networks and rings, saying that Lasertron has "more than 35,000 devices in the field and over 400 million cumulative operating hours".

Not everyone thinks the 980nm pump laser market is a good place to be. **Ortel** recently announced that it was discontinuing its 980nm product line. The company had entered the market in Fall 1997, and over the course of 15 months registered just \$1.4 million in sales. Ortel says this was far below their expectations, "due largely to rapid and continual price reductions in the marketplace". The company decided to exit the business rather than take on the large R&D commitments that would be necessary to differentiate Ortel's product from the competition's.

Nokia Officially Tops in Mobile Phone Sales

It's official: Nokia moved past Motorola to become the top supplier of mobile phones in 1998, according to much anticipated figures released on February 9 by Dataquest.

Worldwide shipments of handsets rose an amazing 51% to 162.9 million units, driven in large part by the increasing popularity of the new digital services. Digital mobile phone sales surpassed analog phones for the first time, racking up 84.6% of total mobile phone sales. A typical wireless phone has a wholesale price of slightly more than \$170, which means that the total market can be valued at \$27.7 billion for 1998.

Having a better digital strategy is what allowed Nokia to surpass Motorola, grabbing 22.9% of the market. Motorola held its No. 1 position in the analog segment, but Nokia posted the strongest growth in the total mobile telephone market, with shipments increasing 81.5%.

"Nokia has based its product strategy on a few product platforms that have been adapted to all digital standards," said Peter Richardson, principal analyst for Dataquest's Mobile Communications Worldwide program. "The company's product designs and feature sets were created from an intelligently conceived market segmentation plan that looked to consumer desire for inspiration, not simply engineering ability."

The third largest supplier was Ericsson, with 14.6% of the market. While Ericsson's shipments grew 49.7%, they were not able to gain an additional market share compared to 1997.

Rounding out the top five were Panasonic with 8.2% of the market and Alcatel with 4.3%. A large number of other manufacturers accounted for the remaining 30% of the market.

With 32.5% of mobile phone sales, Western Europe was the No. 1 region in the world. The United States was second with 17.1% of sales, followed by Japan with 16.5% of sales and the highest per capita level of sales for any country worldwide.



Nokia

Worldwide Mobile Telephone Terminal Sales Estimates for 1998
(Thousands of Units)

Company	1998 Unit Sales	1998 Market Share (%)	1997 Unit Sales	1997 Market Share (%)	Growth (%)
Nokia	37,374	22.9	20,593	19.1	81.5
Motorola	32,319	19.8	25,328	23.5	27.6
Ericsson	23,827	14.6	15,914	14.8	49.7
Panasonic	13,397	8.2	8,627	8.0	55.3
Alcatel	6,967	4.3	2,631	2.4	64.8
Others	48,972	30.0	34,725	32.2	41.0
Total Market	162,856	100.0	107,818	100.0	51.0

Note: Because of rounding, the total percentage in 1998 does not add to 100 percent.

Source: Dataquest (February 1999)

TriQuint's Millimeter Wave Operation, One Year Later

In January of 1998, TriQuint Semiconductor acquired the former Texas Instruments GaAs operation in Dallas, Texas. One year later, this enterprise, now known as TriQuint's Millimeter Wave operation, accounts for roughly one-third of TriQuint's business.

Steve Sharp, President and CEO of TriQuint, reports that orders and shipments for the Millimeter Wave operation are at record levels. "This product line has grown every quarter since the acquisition," he says. He also notes that millimeter wave revenues for the most recent quarter were 30% higher than they were at the time of the acquisition.

Half of TriQuint's recent design wins came from the Millimeter Wave operation. They included 13 for LMDS applications, 10 for satellite communications, 9 for telecommunications, and 6 for defense systems. TriQuint defines a design win as "major" if it is likely to generate at least \$100,000 per year in revenues "if and when it reaches production". Defense-related sales have dropped to around 40% of sales, and are expected to decline further to around 30% in the foreseeable future.

From TI to Raytheon to TriQuint

The TI GaAs operation started out as an R&D effort in 1965, largely to support TI's defense electronics business. In 1997 it was acquired by Raytheon as part of that company's \$3 billion acquisition of the entire TI defense systems business. However, the U.S. Justice Department forced a divestiture, due to concerns about the possibility that Raytheon might develop a monopolistic position in the supply of GaAs MMICs for radar transmit/receive.

TriQuint acquired the operation for just \$39 million, which was less than two times annual sales, which were variously estimated to be in the \$25 - 40 million range. It appears that some potential bidders were put-off by concerns about prof-

itability. However, TriQuint reports that the operation is profitable, and has been since the acquisition.

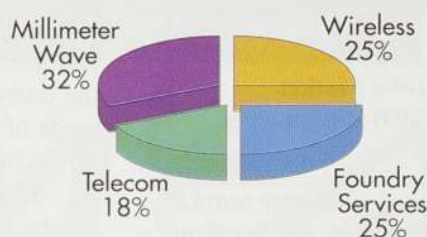
The business came with some built-in advantages, especially since it gave TriQuint access to high frequency technologies that it previously lacked. Five production processes are currently offered for foundry customers needing circuits operating at frequencies through 40 GHz.

- MESFET (0.5 μm): Two versions are offered; one for LNAs, mixers, and signal amplifiers; the other for moderate power and general-purpose amplifiers and switches; both options to 18 GHz.
- HFET (0.5 μm): High breakdown voltages, RF output power, and efficiency. For high voltage power amplifiers and switches; lower voltage, high power density linear circuits to 18 GHz.
- Power-pHEMT (0.25 μm): Both high power and low noise designs through 40 GHz frequencies.
- pHEMT (0.5 μm): High power density, gain, and efficiency; Low noise figures; for applications through 18 GHz.
- VPIN (Vertical PIN): High performance switches, limiters, and attenuators through 20 GHz.

TriQuint Texas also has high performance HBT technology.

All processes are run on a 4" production line. While the company says it is monitoring developments in the area of 6" GaAs carefully, it doesn't plan to scale up at either the Texas or Oregon facility until the current 4" capacity is fully utilized.

TriQuint's Product Portfolio



Compound Semiconductor Foundry Opens in California

A new compound semiconductor foundry, Global Communication Semiconductors (GCS), has been formed in Torrance, California. While III-V epiwafer vendors abound, and many GaAs IC vendors also offer foundry services, GCS founder and President Owen Wu believes that his company is the first to offer all of the post-epitaxial growth processing steps while at the same time remaining committed to remaining purely a foundry service.

"We will not produce end products that will compete with our customers. Customers can be assured that their intellectual property will remain confidential and we are dedicated to maintaining ethical business partnerships with no conflicts of interests," he said. GCS will specialize in AlGaAs and InGaP HBT and HFET foundry services for telecommunications, high speed networks.

Dr. Wu is a well-known figure in the compound semiconductor industry, having worked for several years at Hughes. He reports that many of the other key employees in the company have compound semiconductor experience gained at a variety of industrial companies.

GCS employs a modular processing concept in wafer fabrication, utilizing common processing steps among different device technologies to simplify the production process. The process modules offered at GCS include lithography (<0.3 μm); metalization (AuGe, Ni, Ti, Pt, Au and NiCr); dielectric film deposition, etching, and wet process; backside via hole processing; epitaxial growth and characterization of 2 - 6" wafers; on-wafer RF testing from DC to 40 GHz. Assembly and packaging services are also available through allied companies.

GCS reports that delivery of fully processed HBT wafers has already begun.

Challenges and Opportunities for Compound Semiconductors

STAN BRUEDERLE

Chief Analyst, Dataquest, Inc.

This paper was the
Keynote Presentation of the
Compound Semiconductor
Outlook '99 Conference

The overall market for compound semiconductor technology will continue to grow at a healthy rate over the next five years, particularly in the field of opto-electronics. For other high volume applications, including mobile phones and fiber-optic communications, GaAs faces encroachment from silicon-based technologies. This study analyzes market dynamics and technology trends in three key areas - wireless communications, fiber-optic communications and optoelectronics - and identifies opportunities for compound semiconductors in the face of the challenge from competing technologies.

Market Growth

Dataquest estimates that the total market for products manufactured with compound semiconductor technology was \$5.7 billion in 1997. The market was dominated by opto-electronics with \$4.2 billion in revenues (see Figure 1). The key application sectors were LEDs and displays, which generated \$1.9 billion in revenues, and laser diodes, worth \$1.5 billion. Revenues from analog microelectronics were \$1 billion, primarily in wireless communications applications, while digital microelectronics

accounted for \$500 million in data communications, instrumentation and computer systems.

By 2002 we are expecting the overall market for compound semiconductors to reach \$9 billion, representing a CAGR of roughly 10%. Opto-electronic applications are expected to reach \$6.7 billion, or 74 % of the total market. Most of the growth in this area will come from LEDs and displays in a variety of new applications, which are expected to reach a total market of \$3 billion, and the continuing growth in demand for laser diodes in a variety of communications, consumer, and computer-related applications. The market for laser diodes is predicted to reach \$2.5 billion by 2002.

Dataquest expects the growth of analog and digital micro-electronic applications to be moderated by competition from silicon-based products for selected functions, particularly in applications up to 3 GHz. Silicon germanium in particular is threatening to challenge GaAs in both wireless and high speed communications.

Gallium arsenide has enabled high performance low power solutions in many applications, particularly cellular phones and fiber-optic communications. However, silicon is now challenging GaAs in a number of high volume applications, particularly the two just mentioned, and analysis of these application areas serves to point out the moving boundary between silicon and GaAs.

Cellular Phones - Silicon Moves In, GaAs Retains PA Sockets

Dataquest tears down and analyzes cellular phones among other applications. An example using a tear-down analysis of the Nokia 6110, a currently popular GSM phone, demonstrates the silicon challenge. This phone has a total component count of more than 300, of which 36 are semiconductors. Three integrated circuits and a few discrete devices comprise the RF section of the transceiver. Of the three ICs the power amplifier is made of GaAs, the others of silicon. Dataquest believes this is indicative of a future trend.

Silicon currently represents about 95% of all semiconductor revenues (roughly \$140 of \$147 billion in revenues in 1997). Massive investments in silicon con-

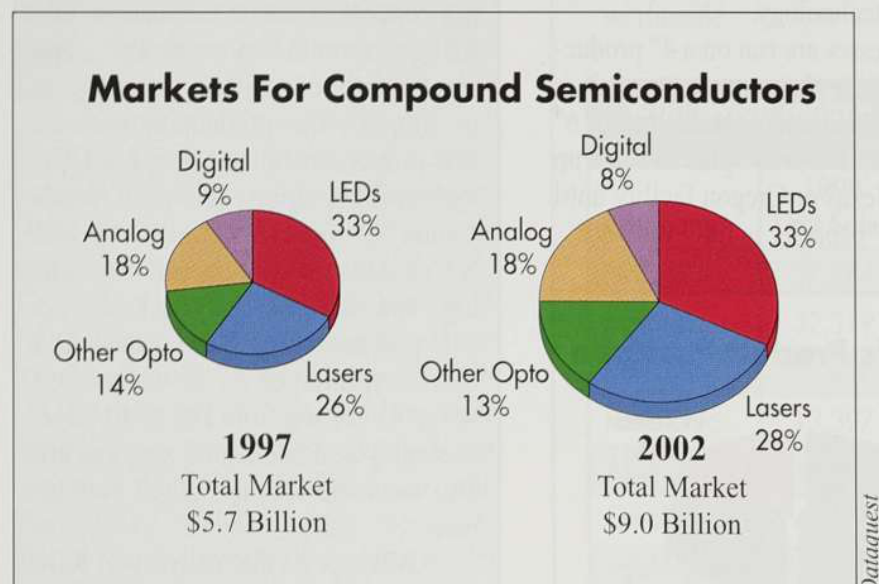


Figure 1. The total revenue from the compound semiconductor market will reach \$9.0 billion in 2002, with optoelectronic applications accounting for 74% of this amount.

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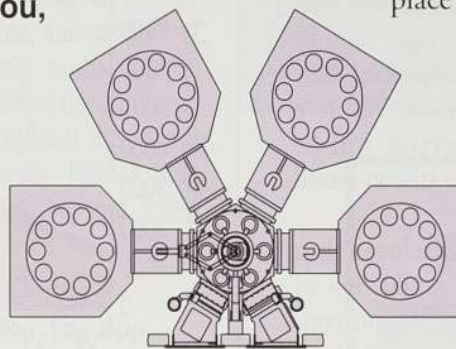
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continue to push the state-of-the-art. As a result, dimensions are approaching 0.15 μm and clock speeds 1 GHz. Silicon-On-Insulator (SOI) and Silicon-On-Sapphire (SOS) promise to make even further improvements in speed and power. And finally, SiGe makes it possible for BiCMOS to achieve performance levels comparable to GaAs with higher densities.

This continued improvement in performance of silicon-based technologies is creating a moving barrier between GaAs and silicon. As a result we have seen the continued encroachment of silicon into applications that are considered to be the domain of GaAs.

The good news is that we believe that GaAs will increase its share of the power amplifier sockets in cellular phones. It will also enable emerging market opportunities such as LMDS, millimeter-wave communications, and others.

As a result of these developments, Dataquest expects that by 2002, cellular phones will contain 14 semiconductors and five integrated circuits. The RF section of the transceiver will be made up of two ICs, a GaAs power amplifier and a silicon-based transceiver subsystem.

GaAs revenue growth in cellular phones will be lower than overall growth. By 2002 we are forecasting the production of 317.5 million cellular/PCS phones. They are expected to consume more than \$3.6 billion of RF semiconductors and about \$800 million of GaAs products. We predict that the share of GaAs will decrease from 24% in 1997 to 22% in 2002 (see Figure 2).

Fiber-Optics - CMOS and SiGe Challenge GaAs

Silicon is challenging GaAs in high-speed data communications as well. As the number of fiber-optic communication nodes continues to rise, driving demand for gigabit digital ICs, (see Figure 3), silicon solutions are being introduced for 2.5 Gbps applications and SiGe is being seriously analyzed for 10 Gbps applications. Most silicon-based suppliers of digital devices for fiber-optic communications have SiGe on their technology roadmaps. SOI and SOS promise to expand the capabilities of silicon while providing a high resistivity substrate for creating high quality passive components.

An examination of the demand for semiconductor devices shows that silicon technology improvements are appearing as the market demands higher performance. As a result, we expect to see the use of silicon to some extent in the highest performance segments of fiber-optic communications.

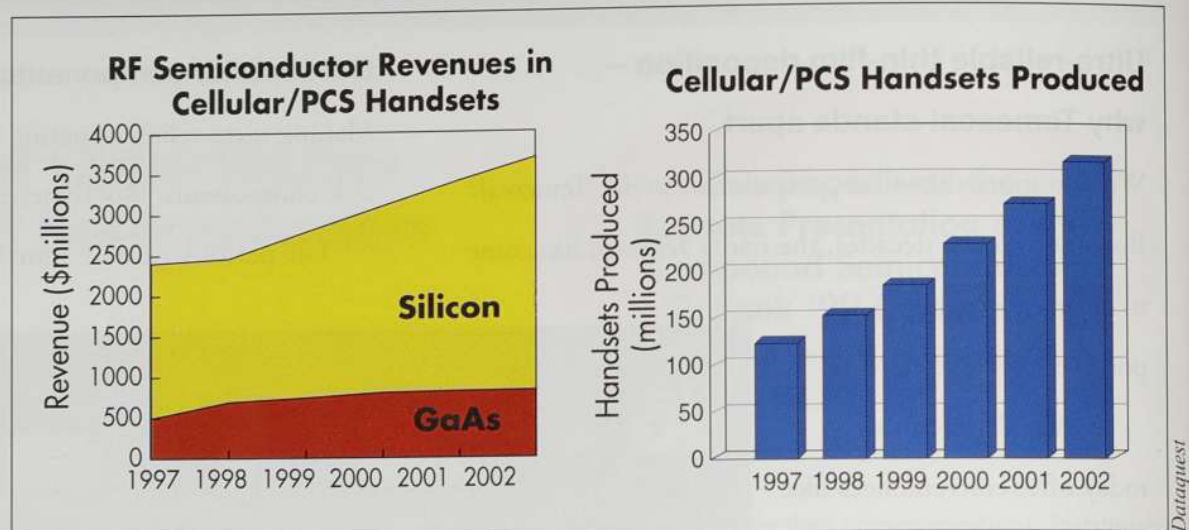


Figure 2. Dataquest forecasts the production of 317.5 million handsets in 2002, consuming \$3.6 billion of RF semiconductors, of which over \$800 million will be GaAs. While GaAs will increase its share of the power amplifier market, it will slowly be replaced by silicon for other handset functions.

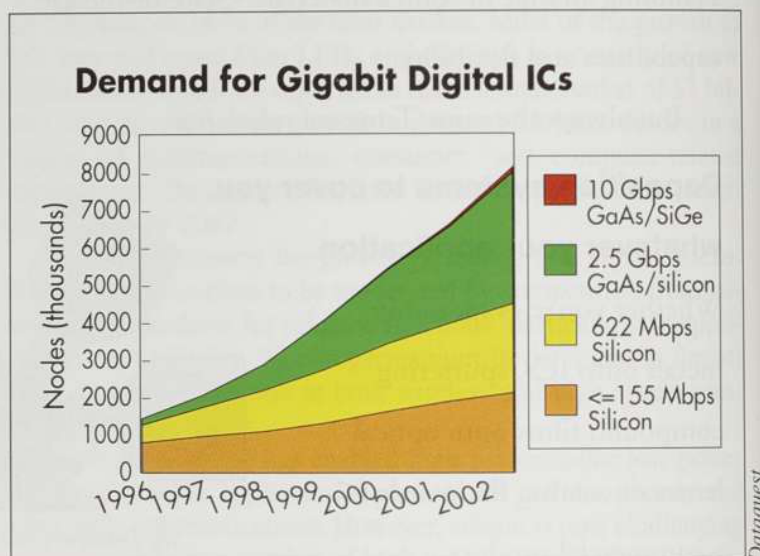


Figure 3. The number of fiber-optic communication nodes continues to rise sharply, driving the demand for gigabit digital ICs, but silicon is challenging GaAs even at 10 Gbps.

Dataquest developed a technology roadmap for fiber-optic communications a few years ago (see Figure 4). Each year we have had to incorporate silicon into higher performance segments of the roadmap. In our 1998 version of the roadmap we indicated higher levels of integration using higher performance CMOS. In addition, companies have adopted SiGe as a silicon-based solution for 2.5 and 10 Gbps systems. Specifically, we have found that transceiver functions at 155 and 622 Mbps are being integrated into a single IC. At 2.5 Gbps, bipolar devices have been introduced to compete with GaAs functions while companies have added SiGe to their roadmaps because it promises lower power than bipolar solutions. At 10 Gbps, transceivers are currently made with multichip GaAs designs with SiGe being considered as an alternative, particularly by silicon-based suppliers like AMCC.

Bright Future for Optoelectronics

Optoelectronics is an area with little competition from silicon, and an increasing array of emerging opportunities. The development of brighter and multicolor LED lamps and displays are enabling new applications. Greater efficiency and reliability make LEDs a natural replacement for incandescent lamps in selected applications. The insatiable demand for bandwidth is driving the need for laser-driven fiber-optic communications. And finally, laser-based discs (CD, DVD) continue to become the standard for recording and playing back music and video programming.

Cities are replacing the incandescent lamps in red stop lights with LEDs. The reductions in power consumption and higher reliability have a payback in about 18 months. They also have the benefit of doing a better job of catching your attention when they change to red. The faster response time of LEDs causes the light to almost jump out at you as you are approaching it. This could reduce the number of accidents that occur at intersections due to people not noticing the lights.

Similarly, LEDs are becoming more commonly used in autos, initially in the bezel in the rear window. Additional applications are being developed for the dash and other indicator light applications. LEDs have the advantage of using less power, being brighter, more reliable, and capable of being formed to fit different shapes. Lastly multi colored LEDs are beginning to appear in video monitors used in large arenas and for video displays in cities throughout the world. LEDs for these applications are substantially lighter than prior systems in addition to being more reliable and lower power. These applications alone are expected to generate \$1 billion in revenue by 2002.

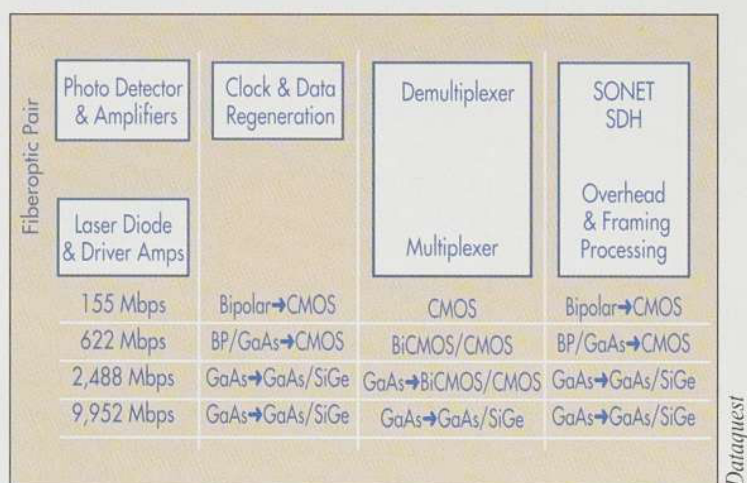


Figure 4. Dataquest's roadmap for fiber-optic communications, showing technologies used for the digital components that interface between the fiber-optic module and the system. Transceiver Functions at 155 Mbps and 622 Mbps are being integrated into a single IC using high performance CMOS. Bipolar silicon competes strongly with GaAs at 2.5 Gbps, while SiGe is being considered as an alternative solution to GaAs at 10 Gbps.

Challenges and Opportunities

After considering the prior analysis it is clear that markets for compound semiconductors will continue to grow, even though the technology is being challenged by silicon in a number of important applications.

Semiconductor markets are entering a period of increased competition between companies and between technologies. I believe that companies making analog and digital GaAs products can benefit by recognizing that silicon may have a place in their technology portfolio. With the availability of silicon contract manufacturing services, companies can realize higher growth and more effectively use their scarce design resources by applying them to the best technology for particular jobs.

For those companies that might be concerned about the possible erosion of their GaAs business, there are emerging opportunities for millimeter-wave communications products that are best satisfied by GaAs technology. Over the next five years we expect these to provide a growing revenue source for GaAs companies of more than \$500 million. And optoelectronics has opportunities that will continue to provide increased growth for this segment for the foreseeable future.

This paper was originally presented as the keynote address at the Gorham/InterTech "Compound Semiconductor Outlook" Conference, which was held in San Diego, CA on March 2-3. Additional papers from that conference will be published in upcoming issues.

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Matsushita Reports CW Blue Laser, Minimum Spot Size for Next-Generation DVD

Matsushita Electric Industrial Co. Ltd. recently announced two key developments on the road to a next-generation, high density DVD system. The first development is that Matsushita has joined Nichia, Cree, Sony and Fujitsu on the list of companies that have demonstrated room temperature CW operation of a GaN-based laser. Matsushita also demonstrated that the 400 nm laser could be focused to a spot with a diameter of 440 nm. Both these features are likely to prove crucial as Matsushita, along with other manufacturers of DVD players, seeks to increase the single-side capacity of DVD disks from 4.7 GB to 15 GB.

Spot Size and Data Capacity

For optical storage systems (e.g. CD, DVD), the disk capacity is determined to a large extent by the size of the laser spot after it has been focused through the objective lens [see "How It Works...Optical Data Storage"]. Put simply, a smaller laser spot can read and write features which are closer together, allowing more data marks to be put onto the disk. The diffraction-limited spot size is proportional to the laser wavelength, which is driving the move from IR lasers, used in CDs, to red lasers, used in DVDs, to blue lasers for the next generation of DVDs (see graph).

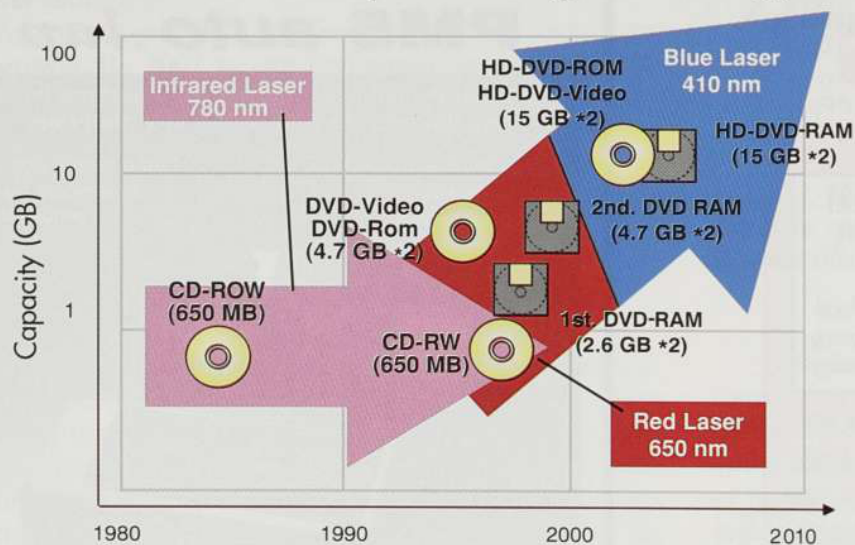


Matsushita's second harmonic generation (SHG) laser mounted onto an optical head to demonstrate the feasibility of high density recording and direct modulation.

At present, DVD-ROM has a storage capacity of 4.7 GB for a single-sided disk, compared to 650 MB for a CD-ROM. This increase in capacity is, for the most part, enabled by decreasing the size of the data marks on the disk and putting them closer together. The minimum feature size which can be read from or written onto CDs is 0.82 μm , while for DVDs it is 0.4 μm . In turn this is made possible by switching from 780 nm AlGaAs lasers, used in CD-ROMs, to 650 nm AlGaInP lasers, which are used in DVD-ROMs. The target storage capacity for the next generation of high density (HD) DVD is 15 GB. In order to achieve this, the minimum feature size will be reduced to 0.24 μm , requiring the use of short wavelength blue lasers.

According to Panasonic, a capacity of 15 GB will allow rewritable DVD to compete directly with (and perhaps eventually replace) standard analog VCR for home recording applications. Television-quality image data, such as is currently supplied through digital satellite broadcasts, uses an encoding speed of 4-6 Mbit/s. At 6 Mbit/s, a 15 GB DVD disk would be able to store almost 6 hours of data, which is the same as a standard 120 minute VCR tape running in extended

Evolution of Optical Storage Technology



The trend toward increasing optical data storage capacity is creating a demand for shorter wavelength lasers. CD technology using 780 nm AlGaAs lasers offers 650 MB capacity; fully rewritable (CD-RW) systems were introduced by Philips in 1997. Current DVD technology, using 650 nm AlGaInP lasers, offers a single-side capacity of 4.7 GB, with DVD-RAM drives providing 2.6 GB. Matsushita/Panasonic plans to introduce a 2nd generation DVD-RAM with 4.7 GB capacity at the end of 1999, using 650 nm laser technology. Blue lasers will enable high density (HD) DVD with a capacity of 15 GB per side, enough for 6 hours of TV programming or 2 hours of HDTV programming.

recording/playback mode (one third normal speed). However, the picture quality from DVD would be significantly better than the VCR recording. The 15 GB capacity should also allow recording of over 2 hours of high-definition television (HDTV) broadcasts.

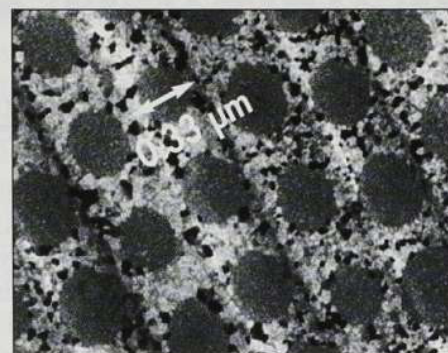
Blue Lasers - GaN v. SHG

The GaN-based laser reported by Matsushita was grown on a sapphire substrate and exhibited room temperature CW operation at a wavelength of 400 nm. The threshold current was 440 mA, the threshold voltage was 11.4 V, and the average output power was 5 mW. Although further development is required, Matsushita now has two types of violet laser to choose from; the newly developed GaN-based device, or the second harmonic generation (SHG) source which has been around for nearly two years [see CS 3(4), p. 18]. This laser combines a 100 mW, 850 nm tunable DBR laser diode with a MgO-doped LiNbO₃

waveguide, to deliver 15 mW output power at 425 nm. Marks corresponding to a capacity of 15 GB have been recorded on an optical disk using this laser (see photo).

The GaN-based device is more compact than the SHG laser, and is far more suited to mass production. According to Matsushita, it is much easier to make a tightly focused spot on the disk using an SHG laser, and this is also the lower noise solution, since reflected light is unable to re-enter the optical waveguide. Also, it should be readily straightforward to adapt the SHG design to allow it to output more than one wavelength, making playback of current DVD disks and CDs possible. However, the SHG device requires precise adjustment of the laser source and the waveguide. The challenge for both laser technologies is substantial. For a typical DVD player, the optical head is budgeted at 5-10% of the total cost, which means that the laser must come in at 1-2%.

Matsushita believes that GaN and SHG lasers will both be used for future



SEM photograph showing marks recorded on a phase-change optical disk containing land-and-groove tracks with a pitch of 0.33 μm. The demonstrated recording density corresponds to a capacity of 15 GB per side.

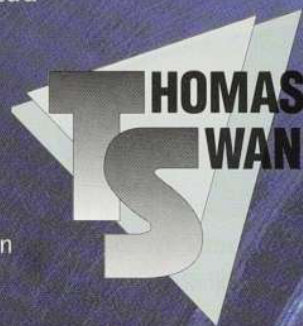
generation DVD, according to different models of DVD players. "For compact DVD players, GaN will be used, taking advantage of its compact size," said a spokesperson. "For high-end table-top DVD players, SHG will more likely be used for the purpose of achieving higher precision."

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Optical Data Storage

The optical storage market, which includes the many variants of CD and DVD technologies, consumed over 260 million lasers in 1998, making it by far the biggest laser diode market in terms of units shipped. This figure is expected to top 300 million in 1999. CDs use AlGaAs lasers at 780 nm, while DVD players use AlGaInP lasers at either 635 or 650 nm. The next generation of DVD players will use blue lasers at around 410 nm.

Read-only variants (CD audio, CD-ROM, DVD-ROM etc) use lasers with an output power of around 5 mW to detect pits which are permanently pressed into the spiral groove on the disk's surface during manufacture. Write-once and fully rewritable variants (CD-R, CD-RW, DVD-RAM etc) read data in the same way, but in these cases the laser is capable of higher output powers (30-50 mW) to write data marks onto the disk.

The generic optical head arrangement is shown below. The combination of collimator, polarizing beam-splitter and quarter-wave plate produces a parallel beam, which is circularly and linearly polarized. This is focused onto the surface of the disk by the objective lens. The diffraction-limited spot size of the laser beam on the disk is largely determined by the wavelength of the laser. The reflected beam is diverted by the beam-splitter to the photodiode.

"CD audio players and CD-ROM drives used over 240 million lasers in 1998, making this the largest market for semiconductor diode lasers"

Compact Discs

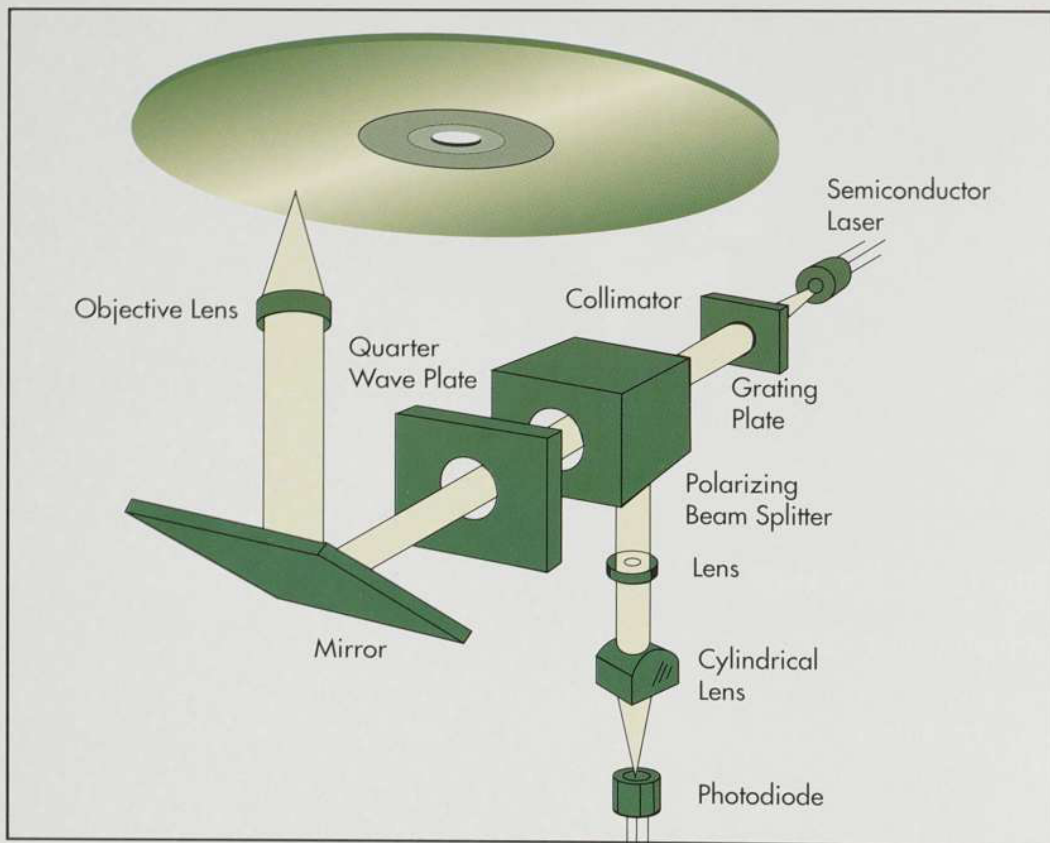
In **CD audio** and **CD-ROM** disks, the data is permanently pressed into a polycarbonate plastic substrate as a series of pits. The top surface is covered with a reflective aluminum layer, a protective acrylic layer and a label. When the laser shines on the underside of the disk, tracking along the spiral groove, it encounters pits which have a very low reflectivity, and the areas between them, which have a high reflectivity. The player registers the difference in reflectivity as a binary data sequence.

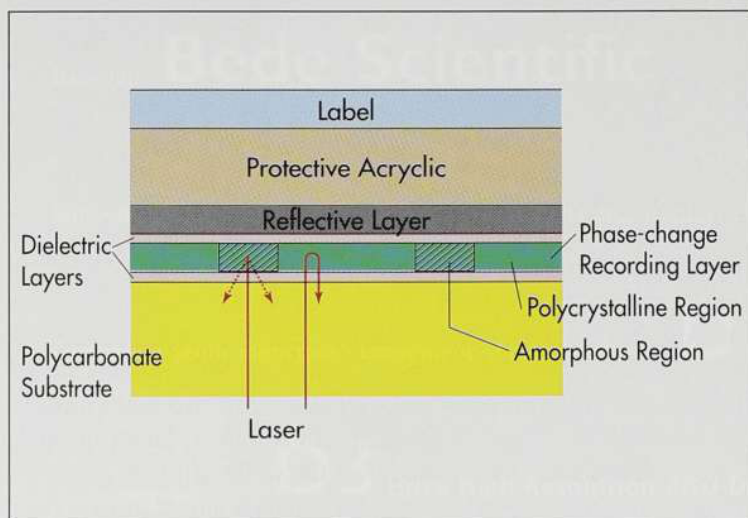
CD-R (CD-Recordable) disks are write-once CDs containing a dye layer which absorbs laser light during recording, permanently generating low reflectance pit-like marks on the surface. CD-R is gaining popularity for permanent archiving of official documents or medical data, or for generating high data-content, multimedia promotional material. Photo CD is a form of CD-R, used for recording digital photos.

CD-RW (CD-ReWritable) disks contain a layer of phase-change material, such as AgInSbTe. This is initially polycrystalline, but during the writing process the laser heats areas of the material to above its melting point (around 500-700°C). This requires a laser output power of 35-50 mW. Rapid cooling forms an amorphous region which has a much lower reflectance than the polycrystalline regions. During rewriting, the laser heats amorphous areas to around 200°C for sufficient time to allow the material to re-crystallize.

Read-only CD audio players and CD-ROM drives used over **240 million lasers in 1998**, making this the largest market for semiconductor diode lasers by an order of magnitude. (Second place was taken by visible lasers for laser pointers, which accounted for around 20 million units in 1998). The slow take-off of DVD, and confusion over standards, has opened a window for writable CD formats. Around **5 million CD-R and CD-RW drives** were shipped in 1998, and this figure is expected to double in 1999.

CD video is a CD-based technology for storing motion pictures, which is only used in China. Sony's Playstation games console has created a further large market for CD-ROM technology.



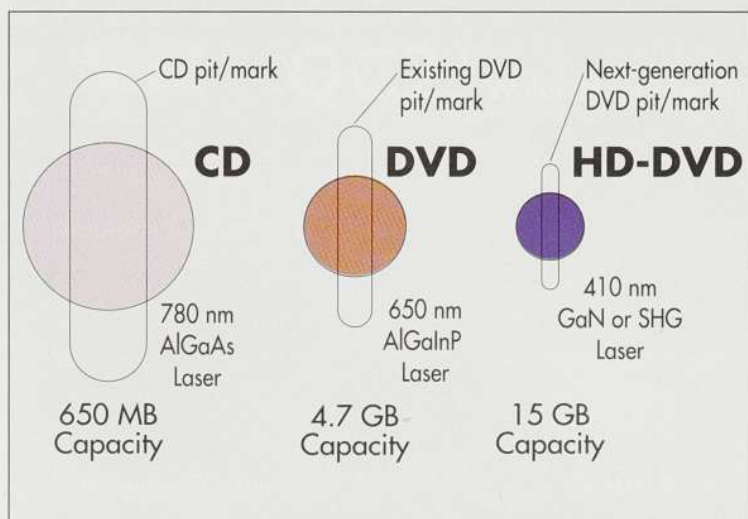


Cross-section through a rewritable CD (CD-RW) disk. The phase-change layer contains data marks in the form of highly reflective polycrystalline regions, and amorphous areas which have a very low reflectivity.

DVD

Depending on who you ask, DVD stands for Digital Video Disk, or Digital Versatile Disk, or nothing at all. DVD uses the same basic principles for data storage and retrieval as CD technology. **DVD video** and **DVD-ROM** are read-only formats, with the data permanently imprinted into the carrier, while **DVD-RAM** is a rewritable format that uses a phase-change material.

The most important difference between CD and DVD technologies is that DVD offers a **higher storage capacity**, mainly by virtue of using **635 or 650 nm** lasers instead of 780 nm lasers. The shorter wavelength results in a smaller spot size on the disk, allowing the features to be closer together. The pitch of the spiral track is reduced from 1.6 μm on a CD to 0.74 μm on a DVD disk, and the minimum feature size is 0.40 μm for DVD, compared to 0.822 μm for CDs. DVDs also have a faster rotational speed and use MPEG-2 digital data compression.



Schematic representation of the relative sizes of laser spots and pit marks in CDs, current DVDs and the next generation of high density DVDs.

Current DVD-ROMs have a capacity of **4.7 GB** for a single-sided, single layer disk. A DVD disk can be single or double-sided and can have one or two layers of data. CD-ROM, CD-R and CD-RW have a capacity of **650 MB**. The advent of blue lasers is expected to increase DVD capacity to **15 GB**, by reducing the minimum feature size to 0.24 μm (see accompanying article). Panasonic's technology for high density media includes recording both in the spiral groove and on the area between the grooves (lands).

A typical laser for DVD video and DVD-ROM, supplied by Rohm Corp., has the following specifications. The device is a 650 nm AlGaInP laser with a strained MQW active region, which has a maximum output of 7 mW and can operate at temperatures as high as 70°C. The device has a MTTF of 10,000 hours at 60°C and an optical output power of 5 mW.

DVD sales got off to a slower than expected start. Around **1 million DVD video players** were shipped in 1998, along with around **5 million DVD-ROM drives**. DVD-ROM drives are expected to replace CD-ROM drives on all new PCs in 3-4 year's time; Toshiba has stated that it will stop manufacturing CD-ROMs by the end of this period.

DVD-RAM

First generation DVD-RAM drives offer a capacity of **2.6 GB** for one-sided media. A typical DVD-RAM laser (from Toshiba) operates at 658 nm, with an output power of 35 mW CW and 50 mW pulsed. Panasonic is working towards a second generation of DVD-RAM with a capacity of **4.7 GB**, which should be launched by the end of 1999. The enhanced capacity will be achieved at the same diode wavelength by using improved media and disk writing techniques. However all the major DVD-RAM laser manufacturers, including Matsushita, Toshiba, Mitsubishi, Hitachi and NEC, continue to report improvements in AlGaInP laser technology, with a target specification of reliable operation at 50 mW and 70°C.

Panasonic's current DVD-RAM drive, the LF-D101, offers unprecedented compatibility with other optical storage media. The unit contains both 650 nm and 780 nm lasers and two objective lenses, allowing it to play all types of CDs, including CD-RW, as well as DVD-ROM, DVD-video and DVD-R.

Magneto-Optical Data Storage

Magneto-optical (MO) systems use a substantially different technology for storing data. Both a laser and a magnetic head are required to record onto the magnetic layer of an MO disk. The laser heats the magnetic layer to around 300°C and the magnetic head changes the magnetization (direction of magnetic spin) of this layer. During readout by the laser at low output powers, the spin direction affects the polarization of the reflected laser light.

Sony's MiniDisc system uses MO technology. The laser source is a 790 nm AlGaAs laser with an output power of 0.6 mW during reading, and 4.5 mW when writing data. High capacity MO storage systems use 685 nm lasers.

LEO Unmasked By Pendeco-Epitaxy

A new approach for lateral epitaxial overgrowth (LEO) results in nearly defect-free GaN material without the need to use a SiO₂ mask. The technique has been designated "pendeco-epitaxy" by its originators at North Carolina State University^[1]. Rather than growing GaN through windows in a SiO₂ mask, the material is grown laterally from {11 $\bar{2}$ 0} sidewalls of [0001]-oriented columns of GaN, and does not have contact with or support from an underlying substrate. The prefix "pendeco" means "hangs on" or "suspends from".

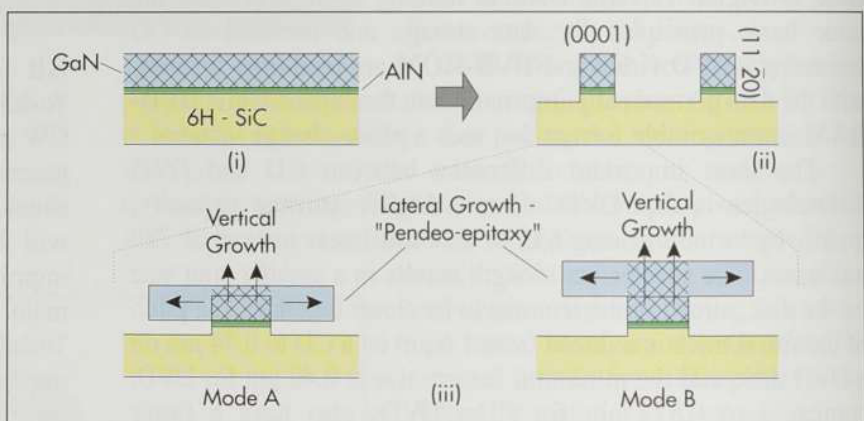
The conventional LEO technique involves growth of a GaN layer on a sapphire or SiC substrate with the appropriate buffer layers. The GaN layer has a high dislocation density, typically 10⁸-10⁹/cm². Next, a patterned SiO₂ mask is deposited, with the window regions exposing the underlying GaN layer. In subsequent epitaxial overgrowth, the GaN grows vertically through the window opening but also grows laterally above the SiO₂ mask regions. Dislocations from the underlying layer propagate in the vertical growth region above the window but do not extend laterally, resulting in low-defect, laterally grown material above the mask regions.

NCSU showed that, while vertical growth occurs on the (0001) GaN face, the crystallographic templates for lateral growth during LEO are either the vertical {11 $\bar{2}$ 0} side facets if the SiO₂ stripes are oriented along the <1 $\bar{1}$ 00> direction, or the 62°-inclined {1 $\bar{1}$ 01} facets if the SiO₂ stripes lie in the <11 $\bar{2}$ 0> direction. Hence, if these facets are present then lateral growth should occur even without a SiO₂ mask.

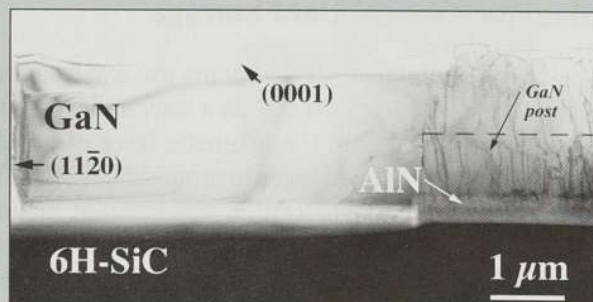
Removing the Mask

The pendeco-epitaxial growth and process sequence used by NCSU is as follows (see figure). Firstly, a GaN layer is deposited on a 6H-SiC substrate with an AlN buffer layer. Then, selective etching down to the substrate through a Ni mask forms GaN/AlN/SiC columns. Subsequent growth of GaN without the use of a mask material can occur in two main modes, depending on the MOVPE growth conditions. In Mode A, lateral growth occurs from the {11 $\bar{2}$ 0} sidewalls into and over the wells, while in Mode B, initial growth occurs from the (0001) planes followed by lateral growth over the wells.

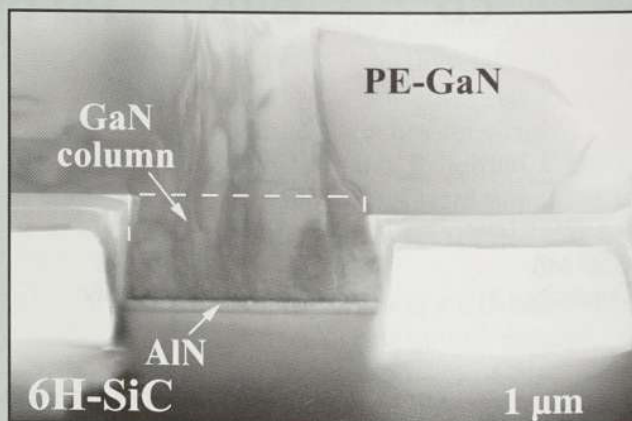
In both cases, TEM studies reveal that the laterally grown regions exhibit 4-5x lower dislocation densities compared to the regions within and vertically above the GaN column (see photos). The regions above the voids where the pendeco-epitaxial GaN structures coalesce are usually free of defects. SEM and TEM studies also indicate that the lateral growth rate of PE-GaN is 4-5x larger than the growth rate of conventional LEO GaN, for the same geometry.



Pendeco-epitaxy process sequence (i) growth of GaN (ii) etching to form columns in the <1100> direction, and (iii) lateral growth from the {11 $\bar{2}$ 0} sidewalls into and over the wells. In Mode B, growth initially occurs from the (0001) surface. Shaded areas denote high dislocation density GaN. As in conventional LEO, dislocations do not extend laterally.

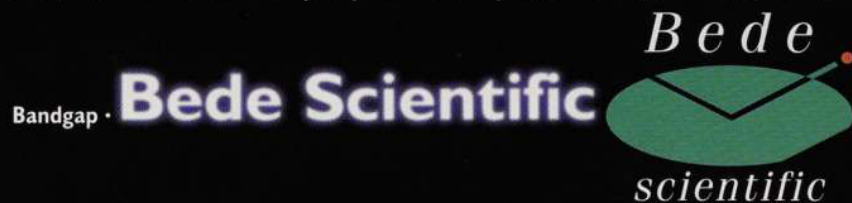


TEM micrographs of pendeco-epitaxial GaN, showing growth mode A (above) and B (right). In both cases, the areas of vertical growth above the GaN post or column show a high dislocation density, while the pendeco-epitaxial regions show defect-free growth.



[1] See T. Zheleva et al, MRS Internet J. Nitride Semiconductor Res., 1998, 4S1, G3.38

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American Xtal Technology to Build Facility in China; Expand into Ge & GaN Substrates

On January 28 AXT announced that it is building a new production facility in China. The company has obtained a business license for operations in Beijing, and has purchased a 30,000 square foot facility in a tax-free industrial park. The facility is expected to be operational during the second quarter of 1999. The new facility will concentrate on processing Ge substrates. The company's VGF crystal growth operations will continue to be housed in Fremont, Calif.

"We are pleased to announce the new facility," said Morris Young, president and chief executive officer. "Our goal is to become the leader in manufacturing gallium arsenide, germanium and other compound semiconductor substrates...The new facility in China will allow us to further reduce our costs so that we can be even more competitive, particularly in price-sensitive markets," he said.

AXT also recently announced that it has entered into a one-year contract with Spectrolab, Inc., for Ge substrates for satellite solar cells. The new contract, scheduled to begin in mid-February, replaces a rolling three-month contract previously in place. The amount of the contract was not been disclosed.

"AXT has demonstrated its ability to provide the product excellence and reliability required to meet the rigorous standards of diverse manufacturing and market applications," said David Lillington, vice president of solid state products for Spectrolab. "This contract is a result of AXT's core competence," he said. Spectrolab accounted for more than 10% of AXT's total sales in 1998, and AXT has also recently been qualified at two other solar cell manufacturers.

While the company sees the Ge business as an excellent growth opportunity, they acknowledge that it is a very price-

competitive market, with lower gross margins than the company's III-V substrate products. The new facility in China is meant to be a major part of the company's efforts to reduce costs in their Ge manufacturing operation. Sales of Ge at AXT in 1998 totaled more than \$6 million, up from less than \$1 million in the previous year.

III-V Materials

In the fourth quarter of 1998 AXT made its first sample shipments of substrates for GaN growth. These products are based on HVPE (hydride vapor phase epitaxy) grown GaN-on-sapphire, a technology which was licensed from MIT Lincoln Labs. In the past AXT had also supported research work in Poland aimed at producing large diameter bulk GaN crystals. However, AXT says that it is no longer pursuing this technology.

AXT has grown rapidly in the past few years, increasing from just a few employees when the company was founded in the late 1980's to currently more than 300. AXT's capacity at its California facility is equivalent to annual substrate production of approximately 5 million square inches.

In addition to Ge, AXT currently sells semi-insulating and semi-conducting GaAs and InP, and is manufacturing GaP substrates for LEDs in test quantities.

For the quarter ended December 31, 1998, AXT reported revenues of \$11.4 million, up 51% from \$7.5 million reported in the fourth quarter of 1997. Net income was \$1.7 million. This compares with net income of \$1.0 million for the fourth quarter of 1997.

Epigress Success in SiC

Epigress AB recently announced that it has been selected as the preferred supplier of a new VP508 "Hot-Wall" Silicon Carbide CVD production system to CEA - LETI, Grenoble, France. Epigress specializes in equipment for epitaxy / crystal growth of selected compound semiconductors such as SiC and SiGe.

According to Thierry Billon, manager of the SiC group in the micro technologies department, "Epigress AB have offered the best technical and commercial package. LETI would like to be the French platform in the SiC field. We are currently working on every aspect of its development: bulk growth, epitaxy, device technology and wafer processing. This will be further reinforced in the near future. The Epigress SiC CVD system will be installed in our facilities in the autumn of 1999. Alternative SiC is a major new project involving universities, research labs and industrial partners. With the purchase of this new piece of equipment, the LETI becomes a major player in this project."

Dr Lea Di Cioccio, engineer in charge of SiC material growth in the microtechnology department said "We have looked at the different alternatives on the market in our hunt for the best technical and commercial agreement. Every potential supplier has been measured and evaluated against the most stringent and advanced standards for growing of high quality, thick and thin layers on 2-inch wafers as well as larger diameter substrates in the future. The Epigress VP508 system for the LETI will be configured and designed as a production unit. It will include two separate reactors. The Epigress VP508 performance is guaranteed and will be validated on site as part of a technology transfer agreement between Epigress AB and LETI."

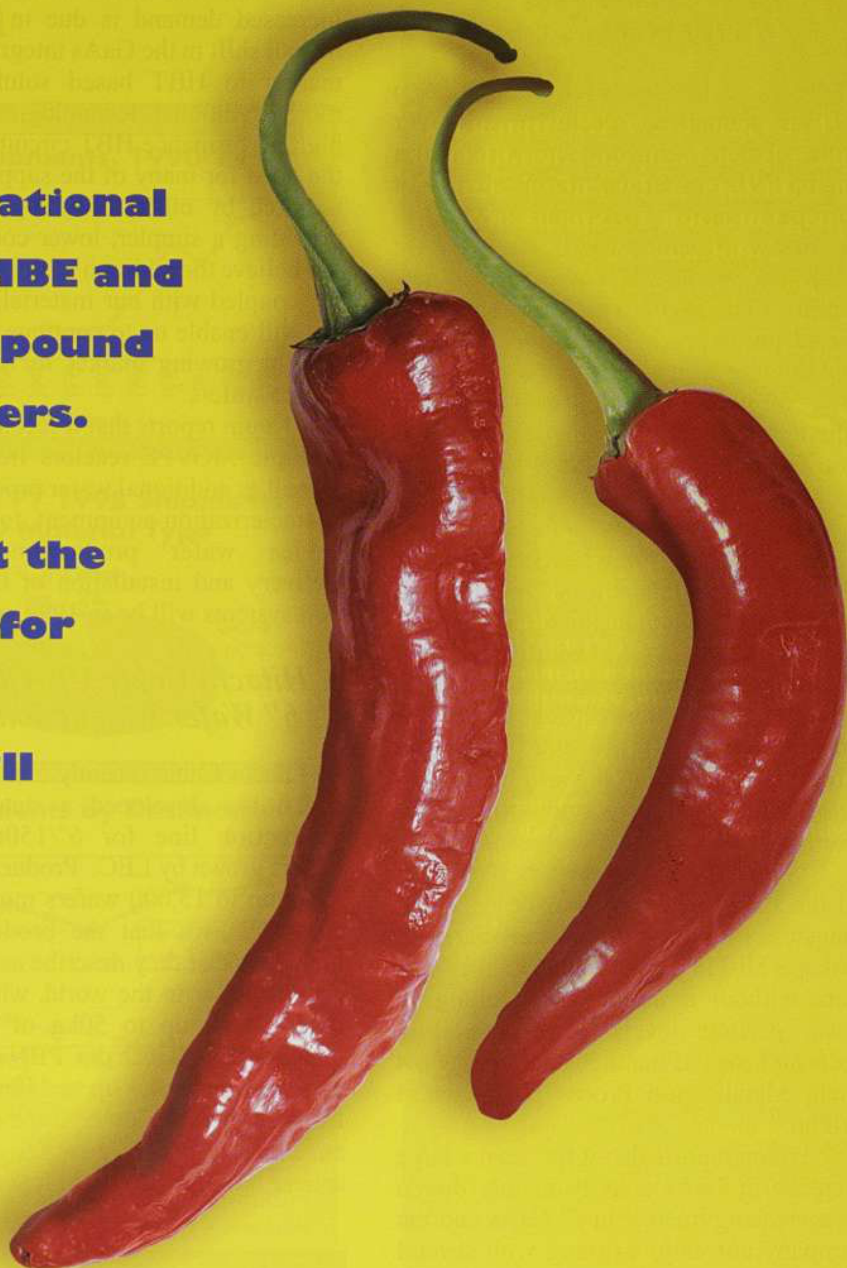
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Company Briefs

Siemens Orders Trikon PVD Cluster Tool for 6" GaAs Processing

Trikon Technologies (Newport, Wales) has announced receipt of an order from Siemens Semiconductor Group of a Sigma PVD cluster tool for installation at Europe's first 6" GaAs line in Munich, Germany. Siemens will manufacture MESFET and HEMT devices at the new facility. The Sigma system will be used for advanced processing of SiN, tungsten and tungsten silicide layers.

"We needed a high grade, low stress silicon nitride layer for capacitor formation and Trikon's pulsed DC PVD process produced results superior to all other low temperature processes compatible with GaAs," said Dr. Otto Berger, Manager GaAs Fab and Technology Development at Siemens Semiconductors. "GaAs processing presents a set of additional stress, handling and temperature constraints making them far more difficult to process than silicon...PVD processes have the advantage of offering higher quality processes at lower temperatures than CVD alternatives."

"Siemens Semiconductors also needed the PVD system to provide excellent tungsten silicide and tungsten barriers. Trikon's Hi-Fill provides high quality barriers without a collimator resulting in lower particle levels, lower operating costs and ease of maintenance," said Paul Rich, Metalization Process Manager at Trikon.

Trikon reports that it has seen a large increase in GaAs activity mainly driven by increasing interest in 6" GaAs and the company currently working with several potential customers on solutions for advanced metalization, CVD and etch.

Kopin Expands

Kopin Corporation is in the process of doubling its manufacturing capacity for its GaAs HBT epiwafers, its second major expansion in two years.

"Customer demand for our GaAs HBT device wafers continues to grow,"

said Dr. John C. C. Fan, Kopin's president and chief executive officer. "This increased demand is due in part to an overall shift in the GaAs integrated circuit market to HBT based solutions from more traditional technologies, as these high performance HBT circuits eliminate the need for many of the support circuits required by other technologies, thereby providing a simpler, lower cost solution. We believe the addition of this new capacity, coupled with our materials technology, will enable us to continue to lead the rapidly growing market for GaAs HBT device wafers."

Kopin reports that it recently ordered multiple MOVPE reactors from Aixtron as well as additional wafer processing and characterization equipment, to expand its device wafer production capacity. Delivery and installation of the production systems will be in 1999 and 2000.

Hitachi Cable Unveils New 6" Wafer Production Line

Hitachi Cable recently announced that it has developed a state-of-the-art production line for 6"/150mm GaAs wafers grown by LEC. Production capacity is up to 15,000 wafers monthly. The company says that the production line includes what they describe as the largest crystal puller in the world, which can be loaded with up to 50kg of GaAs raw material in a 16 inch dia. PBN crucible. It can produce boules up to 350mm long. A furnace system for a three-step boule annealing process under arsenic atmosphere has also been developed.



Hitachi Cable

Also included in the new production line are fully-automated wafer processing machines (saws, grinders, polishers, etc.) and a fully equipped inspection area.

According to the company, "150mm wafers produced by the new system have proven to be comparable to our commercial 100mm wafers in basic electrical properties, uniformity, and in surface quality."

QED Announces Two Promotions

Quantum Epitaxial Designs (QED) has promoted Dr. Keith Evans to Vice President of operations responsible for directing the Manufacturing and Engineering Departments. "Keith has done an exceptional job since joining QED", stated Thomas L. Hierl, QED President and CEO, "QED has leveraged Keith's talents and experiences to enter new markets and to develop new products towards supporting QED long-term growth and to enhance our current product offering."

QED also recently announced the promotion of Scott Massie to Chief Operating Officer (COO).

In other recent news, QED was named in Deloitte & Touche's prestigious "Fast 50" Program for Eastern Pennsylvania, a ranking of the 50 fastest growing technology companies in the region. Rankings are based on the percentage of growth in revenues for the five year period of 1993 through 1997.

Astex Acquires PlasmaQuest

Appplied Science and Technology, Inc. (Astex), has acquired PlasmaQuest, a privately-held manufacturer of ECR systems for R&D scale applications. PlasmaQuest revenues in 1998 were approximately \$3.7 million. The company reports that PlasmaQuest has developed a number of advanced processes for semiconductor manufacturing, and Astex has begun licensing discussions with several major OEMs for PlasmaQuest technology.

NEWS FROM JAPAN

Slight Drop in Compound Semiconductor Wafer Shipments in Japan

After posting excellent growth in fiscal year 1997, sales of compound semiconductor wafers dipped 3% in the first half of fiscal year 1998, according to statistics recently released by the Japan Manufacturers' Society of Compound Semiconductor Materials (JAMS-CS). For the six months ended August, 1998, shipments of GaAs, GaP, InP & other compound semiconductor wafers from JAMS-CS members totaled ¥22,929 million (US \$190.4 million), compared to ¥23,533 million (US \$195.4 million) for the previous six months.

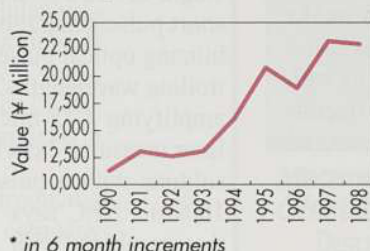
The decrease was due almost entirely to a 24% reduction in shipments of GaP wafers, which are used to manufacture LEDs. A JAMS-CS spokesperson said that demand was soft because of the continuing economic slump in Asia, which was hurting sales of consumer goods.

On the other hand, shipments of GaAs wafers were up 12% over the previous six months. This was attributed to continued strong demand for mobile phones, as well as IR and visible laser diodes and some types of LEDs. GaAs accounts for roughly 60% of the total shipments by JAMS-CS members.

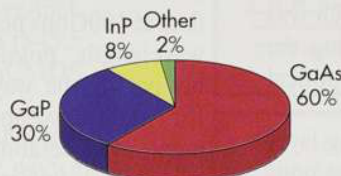
Shipments of InP wafers were unchanged from the previous period. 60% of the compound semiconductor wafers produced in Japan were consumed domestically, and the total value of domestic shipments rose 4%. But the value of export shipments dropped 12%. This is largely due to the fact that much of the GaP production is exported to LED manufacturers in Taiwan and other Asian countries outside of Japan.

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

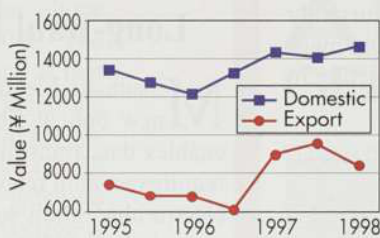
Total Shipments, 1990-1998*



1st Half FY 1998 Shipments by Material Type



Shipments by Destination



JAMS-CS statistics for the first six months of fiscal year 1998, ended March, 1998. Top: the total value of shipments of compound semiconductor wafers by the JAMS-CS members declined 3% for the period, following four consecutive periods of strong growth dating back to the first half of fiscal year 1996. Middle: GaAs (both semi-insulating and semi-conducting) wafers comprised the majority of shipments. Bottom: While domestic consumption remained steady, exports of compound semiconductor wafers fell, due largely to the fall off in GaP shipments to off-shore LED manufacturers.

JAMS-CS

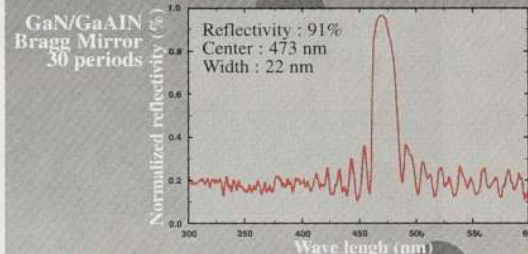
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Laser News

Matsushita Develops 100 mW Laser For High Speed CD Writing

Matsushita Electronics has developed a 100 mW laser which can be used to write data in optical and magneto-optical disk drives. For applications such as CD-R and CD-RW (CD-recordable and CD-rewritable; see page 14), a high laser output power is required to write data marks onto the recording layer. At present, CD-RW drives use a laser with a maximum output power of 50-60 mW; as with all CD-based technologies, these are AlGaAs lasers operating at around 780 nm. Higher output powers are desired because they enable faster recording speeds. However, commercially available lasers are limited to about 80 mW due to the problem of heat dissipation.

A two-dimensional simulator, developed in collaboration with Stanford University, takes into account the interaction between the carriers and the photons as well as their spatial expanse. This enabled a low power consumption design and solved the heat dissipation problem which was the largest hindrance to commercialization, achieving the industry's first 100 mW high performance laser for optical disk drives.

The device contains an AlGaAs current blocking layer instead of GaAs, which almost completely eliminates optical losses. The laser operates at a wavelength of 785nm and has a threshold current of 25mA. The mean time to failure (MTTF) of the device was over 10,000 hours for 100 mW pulses at a temperature of 65°C. Matsushita is currently sampling devices (priced at \$22 each), and will begin manufacture of tens of thousands of units per month starting in spring 1999.



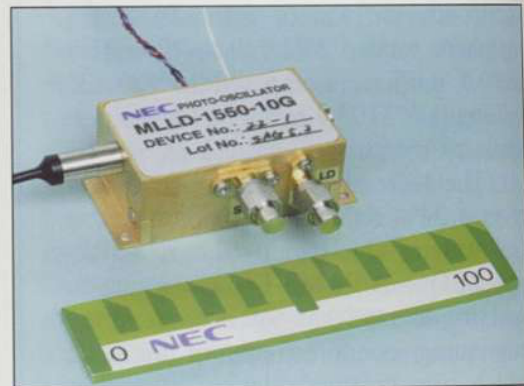
Panasonic

Matsushita Electric has become the latest member of the blue laser club. The company says its InGaN/GaN MQW device, shown here, operates at 400nm and can achieve a converging spot of 440nm which is regarded as the diffraction limit, a theoretical limit. For more information, see page 12.

Soliton Source Developed at NEC

Researchers at NEC have developed a semiconductor laser capable of generating ultra-short pulses of six picoseconds, known as optical solitons. It is of potential interest for use as a light source for high bandwidth optical communication systems. The laser accurately generates pulses at 10GHz, a synchronous digital hierarchy (SDH) frequency.

NEC says the laser is about 1/10 the size of conventional monolithic external resonance semiconductor lasers. It integrates into a single device a nonlinear saturable absorption area for enabling ultra-short pulse generation, an absorption optical modulation area for stabilizing optical pulses, a distributed feedback reflection area for controlling wavelengths, and a semiconductor quantum well gain area for amplifying 1.55-micron beams. A module with the semiconductor laser measures 2x5x1.5cm and can send signals at 10Gbps via optical solitons with a pulse width of six picoseconds over a distance of 100km. NEC says that, combined with optical time division multiplexing, the device will be able to transmit data at 100Gbps per wavelength, possibly paving the way for the development of a terabit-per-second optical communication system.



Photograph of NEC's soliton laser.

Long-Haul Laser from Mitsubishi Electric

Mitsubishi Electric recently announced sample shipments of a new optical fiber communications semiconductor laser which enables data transmission at 2.5Gbps over a distance of 700km. It requires an amp relay every 100km and integrates on a single chip an electro absorption semiconductor modulator, which uses changes in optical absorption rates for modulation, and a distributed feedback laser, which excels in single-wavelength operations. Capable of supporting WDM communications, the semiconductor laser is sample-priced at 200,000 yen (\$1,709). Mitsubishi will launch production at 1,000 units per month from April 1999.

Low Cost Module from NTT

NTT reports that it has developed a low-cost optical transmission circuit module, an essential device for substantially reducing the cost of optical network units (ONUs) for use in the fiber-to-the-home (FTTH) network that the company plans to deploy by 2010. The module can transmit light to a fiber without using a lens. Its Y-shaped optical waveguide guides light to transmission and receiving photo diodes. NTT claims that the new module helps slash production costs to about 1/4 those of producing conventional modules used for optical communications between telephone exchanges.

Microelectronics News

More GaAs from NEC, plus SiGe Development Effort

NEC says it plans to put more emphasis on GaAs ICs for wireless handsets. The company recently announced its intention to boost cellular phone compound semiconductor sales from an estimated 15 billion yen (\$128.2 mil) in 1998 to 25 billion yen (\$213.7 mil) in 2002. In order to make the plan a reality, the company, which currently makes Japan-standard PDC cellular systems, will develop GSM and next-generation wideband CDMA systems. NEC already manufactures GaAs switches for handsets, as well as discrete FETs for LNAs, especially in CDMA phones where dynamic range is a critical issue.

Under the new plan, the company will be introducing "heterojunction FET" or HEMT-based PAs. The company says it will produce 500,000 power amps and 200,000 switches per month from spring 1999.

NEC also recently announced that it has installed a silicon RF device pilot production line at its subsidiary NEC Yamagata. The line can process 10,000 five-inch wafers per month. Built at a cost of 5 billion yen (\$43.5 mil), the line will be used to develop bipolar, BiCMOS and SiGe RF devices.

The company says that it needs to have both compound semiconductors and SiGe products in its RF device lineup to respond to diversified user needs.

And in news from the R&D area, NEC reports that it has developed a high-output GaAs field plate field effect transistor (FP-FET) capable of boosting cellular phone base station output two- to threefold to 200-300W. The FP-FET structure enables the same level of voltage as that applied to the gate to be applied to a field plate electrode placed between the drain and the gate. When the FET is turned off, there is excess negative charges around the FP electrode, strengthening resistance between the gate and the drain. When the FET is turned on, positive voltage is applied to the FP electrode, allowing more current to flow. The company plans to commercialize the high-output FET later this year.

Anritsu to Produce MMICs

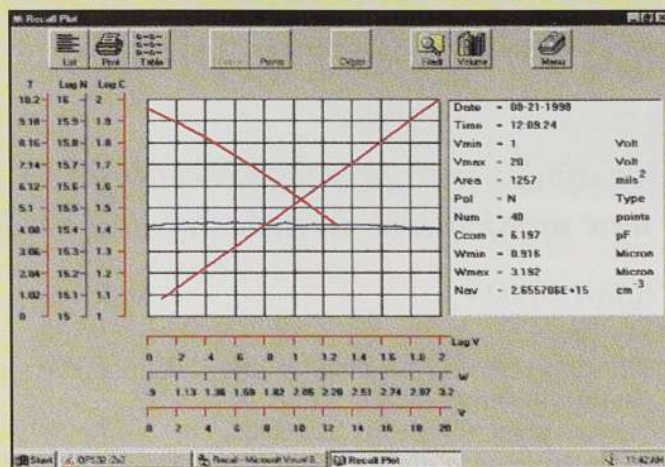
Anritsu Corporation says that it plans to launch its own MMIC product line. The company, which already offers discrete analog devices, plans to invest 1 billion yen (\$8.6 mil) to construct a dedicated MMIC production facility in fiscal 1999 and launch commercial production in summer 2000.

Anritsu says its primary focus will be millimeter wave MMICs for use in ITS (intelligent transportation system) transceivers. The company will also use the MMICs in its own measuring instruments.

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High Power Laser Diodes

Laser diodes with powers exceeding 1 W are opening up new applications in industry and medicine

RICHARD DIXON

The current market for diode lasers is worth around \$2.15 billion, a large section of which is accounted for by applications in optical storage and telecommunications. However, new opportunities and applications are continually emerging for laser diodes, especially those areas needing lasers with output powers in excess of about 1 Watt, according to Steve Eglash, VP of Sales and Marketing at SDL. "High power diode lasers are enabling new applications which are growing at the expense of other laser technologies," says Eglash. "Also, these opportunities are increasing as improvements in diode technology open up new markets."

High power lasers are now in demand for applications as seemingly diverse as printing, materials processing and medicine. In addition, solid state lasers, a fundamentally different type of laser which can also be used in some of the above applications, are dependent on optical pumping by diode lasers. The total market for high power lasers is currently in the region of \$130-150 million. Manufacturers include Coherent, High Power Devices, Mitsui Chemical, Opto Power, Polaroid, SDL, Siemens, SLI and Thomson-CSF.

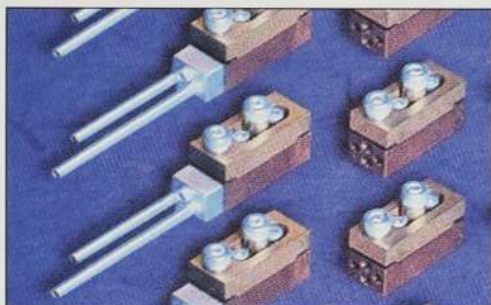


Figure 1. High power diode laser bars can be mounted onto a copper heat sink containing channels for active water cooling.

Laser Bars and Arrays

The simplest type of high power laser is a single broad area device with a stripe width in the order of 100 μm . As an example, Polaroid sells 808 nm AlGaAs lasers with 100 μm stripe widths, and an output power of 2 W. High power devices are multi-mode, because of the width of the stripe required to achieve reliable high power operation. Traditional narrow-stripe, single-mode lasers such as those used to pump erbium-doped fiber amplifiers at 980 nm, are limited in power to around 200-400 mW. This discussion does not cover EDFA pump lasers.

Several broad stripe lasers, with typical cavity lengths of 500 μm , can be fabricated side by side, separated by high index spacers. The resulting laser bar can be around 10 mm in length and contain up to 100 devices. By stacking these mono-

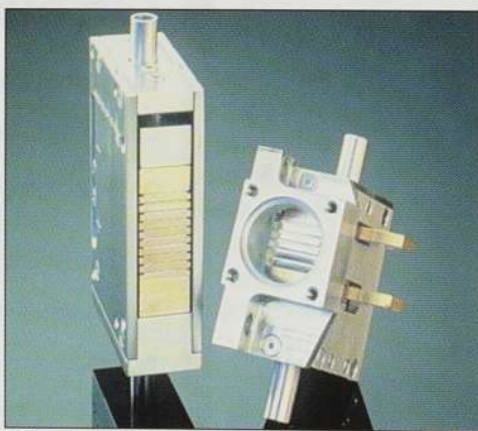


Figure 2. Laser diode bars can be stacked together with a variety of heat sink configurations to form extremely high power modules. Opto Power's Monsoon modules are water-cooled mini-channel platforms that can be stacked to obtain power densities in excess of 500 W/cm². These modules are available with power levels up to 3 kW over the wavelength range 790-980 nm.

lithic bars either vertically or horizontally, much higher powers are available, with commercial stacks delivering thousands of W in CW mode.

Siemens Microelectronics recently announced monolithic 10 mm bars made from MOCVD-grown quantum well structures based on strained layer InGaAlAs/GaAs materials. Laser product marketing manager Sal Algeri says, "We supply 808 nm and 940 nm diodes and can stack 40 W CW or 100 W quasi-CW diode bars to customer requirements. We have already demonstrated our actively cooled stacks producing 6 kW CW with bars operating at 50W."

Keeping Cool

Operating at these high output powers generates a lot of heat. For single stripe lasers with average outputs of up to a few watts, simple convection cooling by direct mounting on a copper block may suffice. Open heat sink packages that help dissipate heat from linear bar arrays are also a popular solution, or alternatively active cooling may be required (see Figure 1).

For larger arrays, Opto Power Corp is using two generic approaches for its stacked or multibar module arrays (Figure 2). In stacked arrays, the diode bars are bonded directly to a copper construction. This is several millimeters thick, and contains channels which carry the cooling water within tens of microns of the bar. These are then stacked into a manifold arrangement.

In the second approach, laser diodes are stacked with spacers that carry the heat away to a back plane. "In this set up you get higher packing densities, but lower average powers," says John Tracy,

Opto Power's CEO. "The first method allows very high output powers due to the aggressive water cooling."

Coupling the Power

For a more flexible delivery system, single emitters and linear arrays can be coupled to fibers. The lasers are sometimes sold as integrated units, with the laser manufacturers also offering the required power supplies, coolers and delivery optics (see figure 3).

If high power and diffraction-limited beam qualities are important, another option is the fiber laser. Typically, a high-reliability 808 nm or 920 nm diode is used to pump a rare earth-doped double clad fiber. This type of fiber can absorb high multimode power levels (unlike EDFAs, in which the pump has to be single-mode, limiting the power). The fiber acts as a single mode cavity resonator, allowing very high quality diffraction-limited output. Commercial fiber lasers currently operate up to 20W at a wavelength around 1 μm . (see figure 4).

APPLICATION AREAS

Pumps for Solid State Lasers

The major application for high power laser diodes is to provide optical pumping for the crystal inside a diode-pumped solid state laser (DPSSL). These devices operate in the 1-5 kW power output range in pulsed mode or provide hundreds of watts of CW, long-life output. The estimated market for diode pumps is around \$53 million at present. Depending on the required output power, DPSSLs can be pumped by single diodes, fiber-coupled arrays, or 2D arrays for large industrial machining lasers. The most common wavelengths for the diode pump are 808 nm for pumping Nd:YAG and 940 nm for pumping Yb:YAG.

The choice of DPSSLs or direct diode sources is determined by the application. According to John Tracy, diodes cannot deliver both high peak powers and very small spot sizes. "If you need a 2 μm spot, you can't do that with a diode laser operating in multimode and get much power out," he says. "If the high peak power and high brightness of a DPSSL

isn't important, you are better off using a diode. If you need either one of those two things then use a DPSSL."

Reprographics

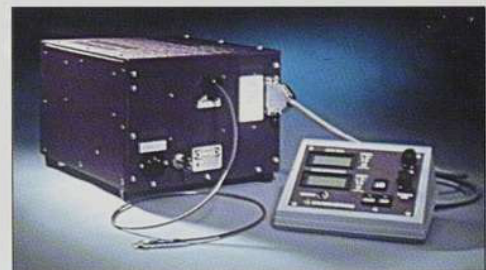
Another emerging market (currently valued at \$25 million) is the printing industry. "Printing processes which use conventional silver halide technology produce large amounts of waste and are not environmentally friendly," says SDL's Steve Eglash. "Increasingly, this technology is being replaced with low sensitivity, minimally-processed thermal film that requires lasers for its imaging."

For plate setting, polymer films are typically ablated with an array of 1 W IR lasers. The main drivers are price per Watt-hour, performance and reliability. Sophisticated optics or fiber coupling schemes are used to transmit the radiation to the plate. SDL supplies a system that couples 0.6 W CW power at 830 nm into a 100 μm diameter fiber (Figure 5). Eglash says the fiber enables small spots sizes and low divergence, facilitating long working distance and a greater depth of focus from a convenient source. This translates into higher image resolution across the entire field of view, and results in relaxed optical and mechanical system tolerances.

Materials Processing

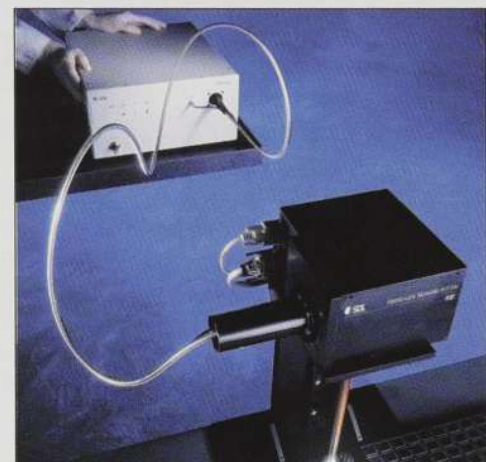
Currently, the materials processing market is dominated by CO₂ and excimer lasers, along with lamp-pumped solid state devices. However, the diode laser industry is reaching a point where prices are low enough to enable volume markets to compete in direct thermal applications. The expected market size in 1999 is around \$40 million. "The materials processing markets will eventually be the biggest markets for high power diodes," says John Tracy, "as well as being those requiring the lowest dollar per watt hour."

In the range of a few watts to several hundred watts of CW power, direct diodes can replace traditional sources for micro-heat treating and micro-welding, and compete with more expensive Nd:YAG lasers. For example, butt-welding of 8 mm stock steel can be achieved using a laser diode with a 500 μm spot size, con-



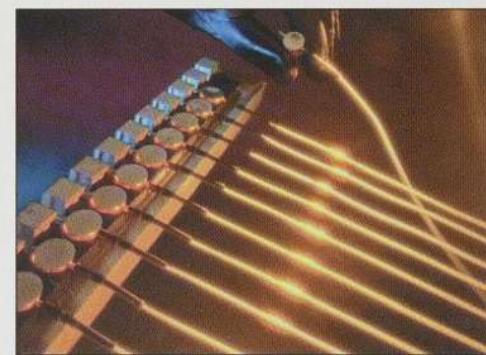
Opto Power Corporation

Figure 3. Opto Power's newest fiber-coupled diode laser has an output of 70 W at 915 nm when coupled into a single, 0.6 mm diameter, 0.22 NA fiber. The system is designed for direct thermal applications in materials processing (welding, soldering, heat treating etc) and medicine.



SDL

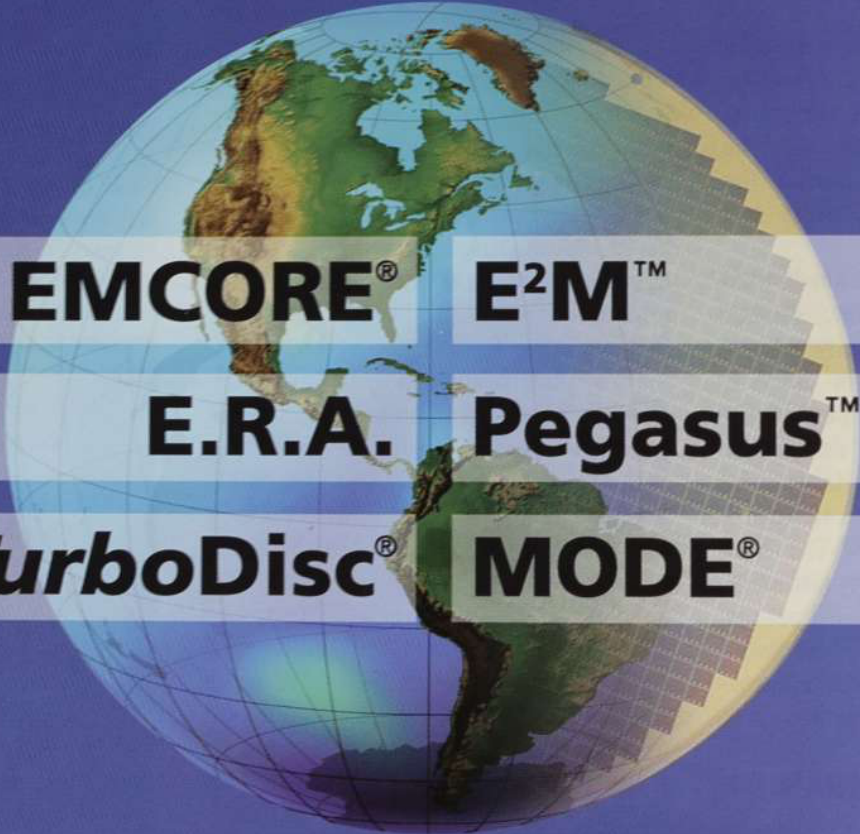
Figure 4. The FLM1 fiber laser marking system from SDL has a power output of 9 W at a wavelength of 1.1 μm . It can be used for non-intrusive marking of very thin packaging layers such as semiconductor molding compounds, as well as lead frames, wafers, and ceramic substrates and packages.



SDL

Figure 5. Fiber coupled laser diodes and newly developed plates allow printers to go directly from computer-to-plate or image plates directly on the press. The result is significant savings in time and the expense of converting digital files to film. The photo shows an array of fiber-coupled lasers (devices are circular) for digital printing applications

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siderably reducing material phase changes caused by heat affected zones.

Micro-machining, polymer bonding, cutting, micro-positioning and sintering all benefit from high power laser diodes. Metal/ceramic sintering with laser diodes enables rapid production of intricate, close tolerance parts as an alternative to current prototyping techniques that use wax and plastics.

For non-contact soldering applications that typically require outputs of around 15-20W, the ability to supply a very small spot of localized and controlled heat limits damage that occurs with hot air guns and other methods. Siemens, for example, uses its own fiber-coupled diode lasers to solder optoelectronic chips at its fabrication facility in Germany.

Similarly, epoxy curing can be performed with a few W concentrated onto a 5 mm-sized spot. The beam can be further line-shaped with microlenses and macro-

optics to accentuate its linear character. The resulting rectangular focal spot can be 1 mm in height and of variable width. Researchers at the Fraunhofer Institute in Michigan have used the technique to solder a line of leads for surface mounted devices in one pulse, considerably reducing soldering time (see figure 6).

For output powers in the kW range, DPSSLs enable heavy industrial welding. By harnessing these high peak powers and power densities, pulsed diodes lasers harden surfaces with beam shaping techniques. More than 10^5 W cm^{-2} can be focused for abrading and milling of surfaces.

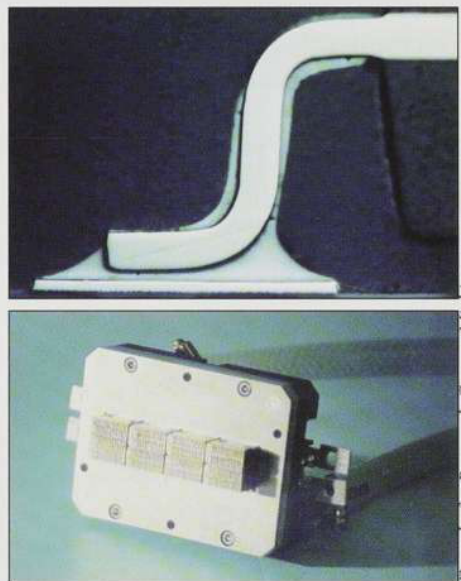
Medicine

In the medical area, examples of direct thermal devices are evolving in hair removal, (which typically requires 20 ms pulses of 5 W power) and for cutting and burning in laser surgery. In the field of ophthalmology, lasers can tap a potentially large market for the cure for glaucoma, the number one cause of blindness in the world today.

Endoscopic delivery is becoming more prevalent as brighter sources reach the market. For wavelength specific lasers, which take advantage of the narrow linewidth, photodynamic therapy (PDT) is another promising field for cancer treatment. A number of different chemicals can be photosensitized in the 630-770 nm wavelength range. For example, a photoreactive dye called luteinium texaphyrin accumulates in cancerous tissue. The dye can be selectively targeted with 730 nm radiation, releasing oxidizing agents that kill cancer cells and leave healthy tissue unharmed.

Meanwhile, diode lasers are also pumping energy into a new procedure for magnetic resonance imaging (MRI) which uses gas instead of water to form the MRI image. Developed by Princeton University and the State University of New York, gas MRI is throwing light on lung diseases that have been difficult or impossible to diagnose with conventional proton MRI (Figure 7).

Under normal circumstances, lungs are filled with air and not water, and therefore lack the quantity of hydrogen atoms to produce a resolute image using



Fraunhofer Research Center, Michigan

Figure 6. (Top) Cross-section view of an IC lead joined to a solder pad. The 10W fiber-coupled laser produced a spot size of 0.8mm to solder a homogeneous joint with no inclusions or cracks. (Bottom) Laser diode array used for surface hardening. Eight individual packages each employ 12 diode laser arrays to give a total output of 200W and power density of 160 W/cm^2 . Unacceptable variations in the intensity distribution due to 2mm gaps in the mounted stacks are compensated for by a beam guide that shifts the radiation optically together.

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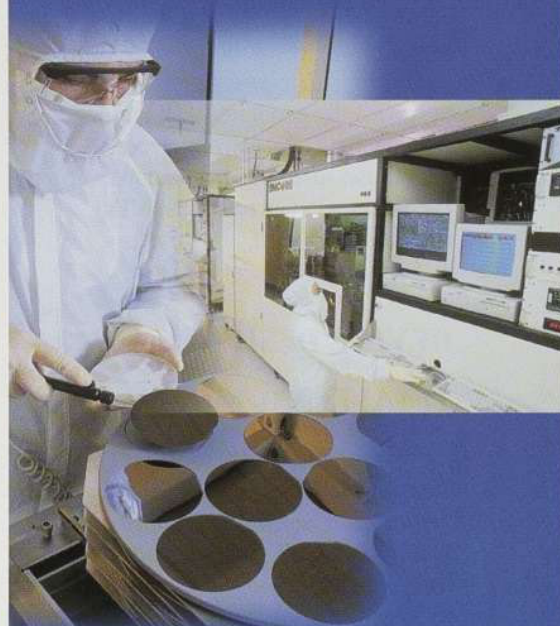
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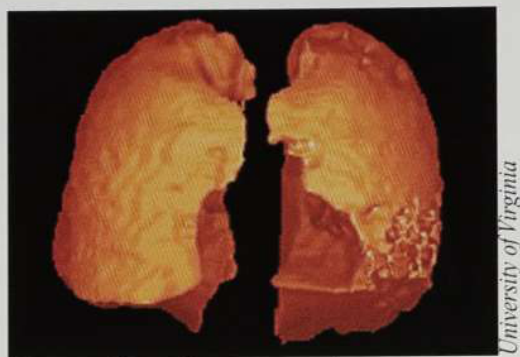


Figure 7. Gas magnetic resonance image of lungs obtained using compact, high efficiency 20 W laser diode sources.

conventional proton MRI, which looks at water in the body. Laser diodes operating at 795 nm are used to orient the spins of Nobel gases, usually ^{129}Xe or ^3He , which can then be inhaled and used as the source signal. "The exciting thing about the new technique is that you produce about 100,000 to a million times more signal per atom than you do with conventional MRI," says Princeton's Gordon Cates.

These signal gains far outweigh losses due to the lower density of molecules in the gas phase. "As a result, we've been able to make images of lungs with the highest ever resolution," says Cates. "In addition, sufficient signal for imaging purposes is generated when the gas is inhaled for less than ten seconds, which aids those suffering from acute respiratory diseases." Current gas MRI systems replace the older, far more expensive Ti:Sapphire lasers, says Cates.

DEVICE DESIGN

The Al-Free Debate

An ongoing debate in HPLD device design relates to the merits of Al-free devices. These are based on the InGaAsP/InGaP material system, rather than on more conventional AlGaAs/InGaAs materials.

Proponents of the Al-free approach claim that it enables higher reliability high power devices because it eliminates the problem of oxidization of Al-containing epitaxial layers (CS 3(2), p16). Uncoated Al-free devices are claimed to have a higher catastrophic optical mirror damage (COMD) limit, which is the usual limiting factor for maximum CW

operating power.

Some of the best results for single devices have been achieved with Al-free material. For example, the University of Wisconsin recently reported an 805 nm device with a CW output power of 8.8 W [see CS 4(6), p.41]. This device had an Al-free active region containing InGaAsP QWs and InGaP waveguides. However, in order to ensure sufficient bandgap discontinuity to prevent severe carrier leakage, Al is used in the cladding layer. The same approach is used by Coherent Semiconductor Group. "Coherent uses aluminum-free active areas for all our high power diodes," says Merrill Apter, Director of Sales and Marketing director at Coherent. "We call it our triple-A material. However, we are using a small amount of aluminum in the cladding layers." Coherent grows its laser device structures by MBE, unlike most other high power laser diode manufacturers, who use MOVPE-grown material.

Manufacturers of the Al-based structures believe the problem may be overstated, and addressable in the process and packaging stage. While uncoated Al-free devices have higher COMD limits and longer lifetimes than devices containing Al, commercial laser diodes all have facet coatings to protect the device and direct the optical power out of the front facet. Polaroid has aged twenty four 1 W, 100 μm aperture, AlGaAs/GaAs 808 nm laser diodes for over 5,000 hours without measurable degradation.

According to Siemens, one of the key features of achieving high reliability AlGa(In)As/GaAs devices is the minimization of oxygen incorporation during epitaxial growth (by using high quality MOVPE precursors) and also during the mirror coating process. At the 1999 Photonics West meeting, Siemens reported high reliability 40 W CW InGaAlAs/GaAs laser bars operating at 808nm. No sudden failures occurred, and no significant degradation was observed over 5,000 hours.

730 nm AlGaAs Lasers for PDT

Polaroid has developed an AlGaAs-based, 730 nm laser diode for photodynamic therapy (PDT) applications which demonstrates unprecedented reliability.

The device exhibits a room temperature lifetime of 1000 hours of CW operation at 1 W, and has a 500 μm cavity length and 100 μm emission aperture. The MOCVD-grown structure contains three 40Å AlGaAs quantum wells with 100Å barriers. Thick $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$ confining layers (3000 Å) are used and optical confinement is attained with 0.75 μm thick $\text{Al}_{0.75}\text{Ga}_{0.25}\text{As}$ layers to form a broadened waveguide.

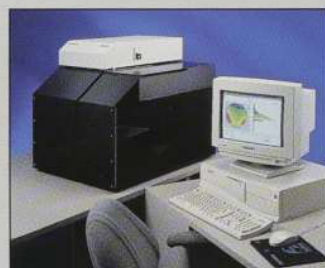
Dr. Edward Clausen, New Products Manager for Laser Diode Manufacturing at Polaroid, says the result is contrary to the belief that such performance could not be achieved with this material system. "What makes this possible are developments in epitaxial growth and a well controlled manufacturing process," says Clausen. The target reliability for PDT applications is 2000-5000 hours. "These systems are used only for short periods in CW mode, in the second to minute range, which would translate into years of field use."

Decoupled Confinement Heterostructures

Mitsui Chemical has developed a series of decoupled confinement heterostructure (DCH) lasers, designed to realize high power and high reliability with reduced Al composition. Injected carriers are confined by carrier blocking layers whose band gap is wide enough to stop carrier floods, and whose width is thin enough to influence the optical mode. In addition, the mode is controlled by the structure formed outside. As the carrier confinement and optical mode confinement are completely decoupled, Mitsui state that the ideal gaussian mode profile is achieved. At the same time, a reduction in the Al content and epitaxial thickness reduces the resistance and improves process stability up to 4,000 hours for devices operating at 1W at 50°C. A maximum CW output of 4.6 W was obtained from a 50 μm aperture 809 nm DCH laser diode.

Many new applications are being found for diode lasers as their power and reliability constantly improve, and the future market for this category of device could be very large indeed.

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Probing Compound Semiconductors

RICHARD DIXON

Scanning probe microscopy (SPM) has become a vital metrology tool for measuring fundamental material properties, for defect analysis and in process control in the semiconductor industry. The SPM measures surface features whose dimensions are in the range from interatomic spacing to a tenth of a millimeter. It gains information in 3D to fractions of Angstrom resolution with little or no sample preparation, is non-destructive in many cases, and can measure in ambient, liquids and vacuum.

The first SPM was the scanning tunneling microscope (STM), introduced in 1982. STMs rely on a sharpened conducting tip with a bias voltage applied between the tip and sample. When brought to within about 10 Å of the sample surface, electrons begin to tunnel through the 10 Å gap into the tip or vice versa, depending on the sign of the bias voltage. The resulting tunneling current varies with tip-to-sample spacing, and it is this signal that is used to create the STM image. For tunneling to occur, both

sample and tip must be either semiconducting or conducting, ruling out the analysis of insulating materials.

The Atomic Force Microscope (AFM) overcomes this. AFM uses a very sharp tip at the end of a long cantilever to maintain a constant force (known as 'contact' mode) and 'slide' across the surface at the resolution of the tip. The low spring constant (1N/m) is in the range of interatomic forces (10^{-9} N), hence "atomic force". There is now no requirement to draw current between the tip and the sample, considerably extending the range of materials that can be investigated.

In addition, a version of AFM called TappingMode (Figure 1) can overcome problems experienced in contact mode due to sticking and polishing of the surface by the tip. In this technique, the tip is oscillated at several hundred kHz and retains contact by intermittently 'tapping' the to surface, avoiding destructive frictional forces. Many other useful variations of SPM have since emerged that can measure magnetic, mechanical (hardness and wear), thermal and electrical properties.

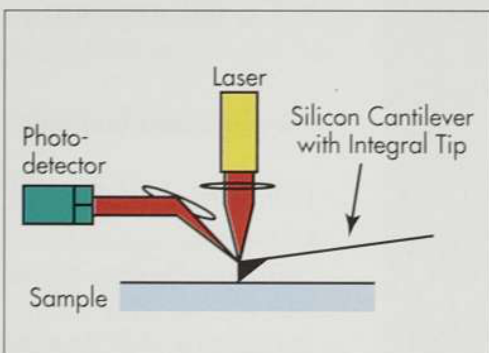
Scanning Capacitance Microscopy

The unique ability to measure carrier concentration profiles with the new Scanning Capacitance Microscopy (SCM) is very exciting. Techniques such as SIMS (Secondary Ion Mass Spectrometry), SRP (Spreading Resistance Profiling), and CV (Capacitance-Voltage) provide dopant or carrier concentration information with very high accuracy and resolution in only one dimension.

SCM can show carrier concentration profiles in two dimensions in real devices and - through its simultaneous acquisition of AFM images - the relationship of these profiles to critical device structures.

In SCM, a low frequency (5-100 kHz) ac field applied between the metallized tip and the semiconductor causes the free carriers to be alternately attracted and repelled by the tip. The resulting change in capacitance is measured by an ultra high frequency resonant capacitance sensor. Small changes in resonant frequency create enormous changes in the resonance sensor output signal.

The SCM image in Figure 2a shows an InP/GaInAsP buried heterostructure. The laser active region is in the center of the image. Figure 2b maps carrier distributions and concentrations obtained from the SCM results. AFM operating in contact mode is used to scan the tip across the surface without specimen preparation, says Digital Instruments' Dr. Robert



Digital Instruments

Figure 1. In the AFM TappingMode, developed by Digital Instruments VEECO Metrology Group, the cantilever and tip are oscillated near the resonant frequency. In the correct proximity to the sample surface it intermittently contacts or 'taps'. The resulting oscillation amplitude scales in direct proportion with sample to tip distance. A laser/photodetector maintains the average tip separation as it traverses the sample topography.

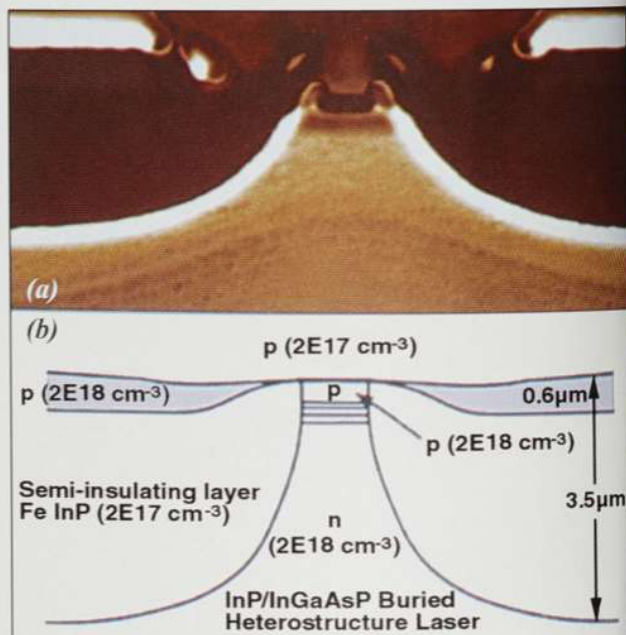


Figure 2. a) SCM image and b) carrier concentration map of InP/GaInAsP buried hetero-structure laser [Image courtesy Dr. R. Tench and Dr. A. Erickson, Digital Instruments VEECO Metrology Group].

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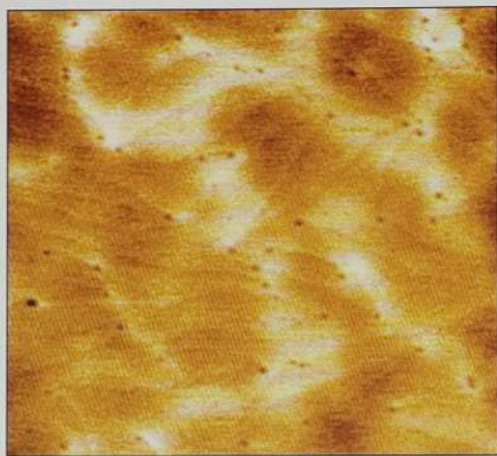


Figure 3. 2.5 μm x 2.5 μm image of GaN film on sapphire obtained with SCM and AFM images superimposed [From *Appl. Phys. Lett.*, 1998, 72(18), p.2247].

Tench. "For that image the sample preparation was the same as for producing the laser, which was by done by cleaving".

Having no free carriers, the semi-insulating iron-doped InP layer in Figure 2a produces no SCM signal (dark contrast). Where it contacts the n-doped layers, strong band bending from the large built-in field results in a strong contrast in the SCM signal (bright areas). In order to obtain similar details with a transmission electron microscope (TEM), says Tench, the sample preparation would take many hours and provide none of the electrical information.

Sometimes, though, additional preparation may be required. "Compound semiconductors are generally more difficult to work with because the oxide, or the surface condition, is a combination of

states that may not be appropriate for AFM imaging in contact mode," says Robert Tench. "What we try to do on all compound semiconductors is to coat them with a thin layer of oxide before imaging." The reason, he explains, lies in the junction between the tip and sample, which, like any capacitor, requires that a good insulator is present.

The polarity of compound semiconductors may also be a factor. "Particularly for GaAs materials, Ga metal can be on the cleaved face after preparation, which is conductive. In this case we don't have the capacitance junction we need to measure carriers." The oxides in these systems may also be soft, he adds. "In the contact mode used for SCM imaging, a thin oxide can be ploughed by the tip as it maps the surface, and this is why a harder oxide coating can really help [prevent artifacts]."

Nitride Materials

The III-nitride-based materials lend themselves well to the SCM technique, and Professor Jim Speck and co-workers from the University of California Santa Barbara have obtained images of GaN films grown on sapphire with minimal specimen preparation. "The big advantage is that GaN does not have a native oxide," says Speck. "Using the SCM technique in air we can see the half unit cell height steps at the surface, and where the steps end abruptly at a surface it has to end at a dislocation."

The topographic information acquired in AFM has been superimposed on the capacitance signal to form a correlation with electrical data (Figure 3). In the image, regions of light contrast represent areas that displayed a smaller change in measured capacitance with applied voltage relative to adjacent areas. These are correlated with the pits (dark spots) that are associated with termination of the dislocations at the surface.

Also, these reduced capacitance regions tended to lie along boundaries consisting of dislocations that have formed during coalescence of grain boundaries in island growth.

According to Jim Speck this direct correlation and 2D profile of the carrier concentration could not be obtained with

other techniques, including secondary ion mass spectrometry (SIMS). "With SIMS, you don't get the nanoscale electrical properties. And with other techniques such as TEM, you get chemical data and some information on the nanoscale, on bonding, for example, using a combination of imaging and EELS [electron energy loss spectroscopy]. It is one of the few measurements where we can obtain extraordinarily high resolution structural information concurrently with the electrical properties of materials."

Scanning Tunneling Microscopy

Finally, figure 4 shows the color-enhanced image of a multilayer system comprising alternating GaSb (12 monolayers) and InAs (14 monolayers) obtained by STM. "What the STM technique reveals are details of the chemical identity through the electronic structure, in this case from the difference in bandgaps," says Dr. Lloyd Whitman of the US Naval Research Laboratory (Washington, DC).

"The image describes the topography of the Sb (red) and As (blue) atoms." The atoms in the rows are just 4.3 Å apart and differ in height by only 0.5 Å in the two compounds. The STM probes the two elements that are exposed on the cleaved structure, he says. "The information is purely chemical." It is possible to see details of intermixing of the two elements in the growth, which takes place from top left to bottom right. "A similar structure image could have been obtained in high resolution TEM, but this method averages over many columns of atoms and the chemical information is lost," says Whitman.

Scanning probe microscopy clearly brings a level of information not found in other techniques. The ease of preparation in many cases, range of properties that can now be probed, and level of spatial resolution, including the third (or height) dimension, is unparalleled. The recent introduction of the scanning capacitance technique brings all-important electrical information to compound semiconductors, and will continue to be invaluable for probing and correlating defects at both the fundamental level and in the process laboratory.

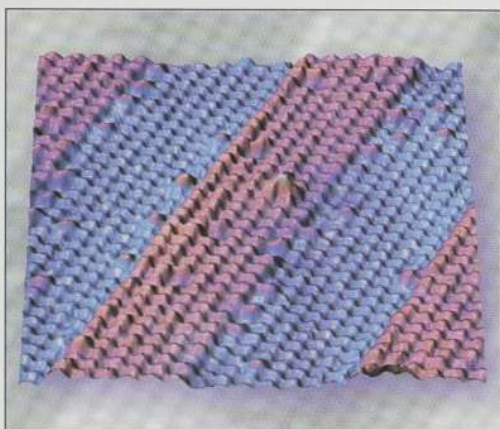
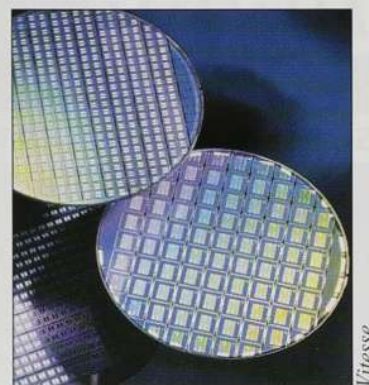


Figure 4. STM image of GaSb/InAs multilayer showing Sb (red) and As (blue). [Recorded by W. Barvosa-Carter, B. Bennett and L. Whitman].

6" GaAs Gains Ground

Raytheon joins Vitesse, Anadigics and Siemens by announcing plans for a 6" fab, says scaling up is key to being competitive in the next decade.

MARIE MEYER



Vitesse Semiconductor ushered in a new era in the history of the compound semiconductor industry a year ago when it began shipping devices from the first 6" GaAs fab in March, 1998. As we reported in our last issue, they will soon be joined by Anadigics and Siemens, who both have 6" GaAs fabs under construction. And on March 2, at the Compound Semiconductor Outlook Conference in San Diego, Raytheon announced they would also be building a 6" line, scheduled to be operational in the second half of 2000. Jim DiLorenzo, who heads Raytheon Microelectronics, told the audience "If you are going to be a player, we believe unequivocally that you've got to have a 6" fab."

Passing the First Test

Vitesse's experiences at their new fab in Colorado Springs, CO, will undoubtedly offer encouragement to anyone who is thinking about scaling up. "Things con-

tinue to go much better than we could have expected," says Bob Cutter, General Manager of the new facility. Though it has only been open for twelve months, and in full operation for less than six, the new fab is already settled down into "fully routine" operations, he reports. In fact, within six months the new fab was demonstrating better yields and better wafer-to-wafer and lot-to-lot uniformity than the company's 4" fab in Camarillo, CA.

Vitesse was the logical candidate to pioneer 6" processing – after all, they were also the first company to complete a full 3" to 4" conversion. They are the leading manufacturer of digital GaAs ICs, and have been enjoying phenomenal sales growth over the past four years. The company foresaw a capacity shortage in 1996, and began plans for their new fab.

At that point, "the 4" vs. 6" decision [for the new fab] came down to the economic factors" says Cutter, because the company had already determined that the infrastructure they needed would be in place. Most importantly, they were sure that they would be able to secure high quality 6" substrates. "We had many discussions and a lot of interactions with vendors," says Cutter, "and companies such as Airtron were able to show the uniformity and consistency in the 6" substrates that we needed." In fact, the supply is so good that Vitesse is able to use the 6" wafers "straight out of the box", with no inspection steps.

Also important to Vitesse

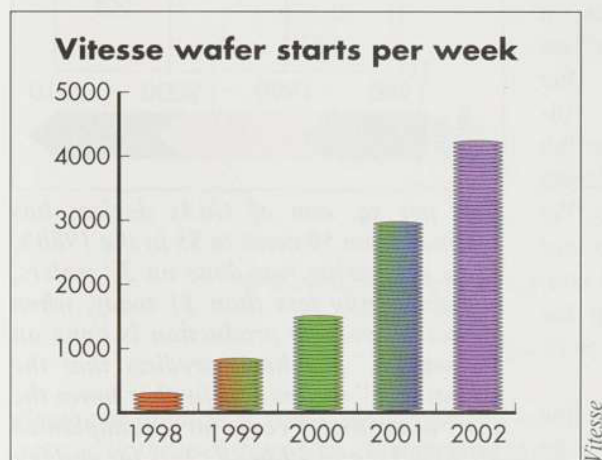
was the availability of state-of-the-art processing equipment. In the semiconductor industry as a whole, it is difficult to find a cutting-edge equipment manufacturer who will build 4" equipment without charging substantial NRE (non-recurring engineering) fees.

Depending upon the product, Vitesse reports that the per-wafer yields at the new fab are from two to five times higher than their old fab. Of course this is due in part to the larger surface area of the 6" wafer; but the company is also getting a higher percentage of good die on each wafer, which they attribute to the use of state-of-the-art equipment.

Anadigics and Siemens

Over the next 12 months, both Anadigics and Siemens will be bringing their 6" GaAs fabs on line. In Anadigics' case the decision to scale-up was based on the desire to reduce per-die costs. Their 4" fab is not currently used to full capacity. In Siemens' case, the motivation was capacity constraints, as their existing 4" line can no longer keep up with demand. Thus they are converting a 6" line which was originally intended for silicon products to GaAs. Both companies plan to shut down their 4" lines once the 6" lines are in full production.

These two fabs will be the first to run epitaxy-based processes: HEMTs in Anadigics' case; HEMTs and HBTs in Siemens' case. Both companies are outsourcing their epiwafer growth, and are in the process of qualifying epiwafer vendors.



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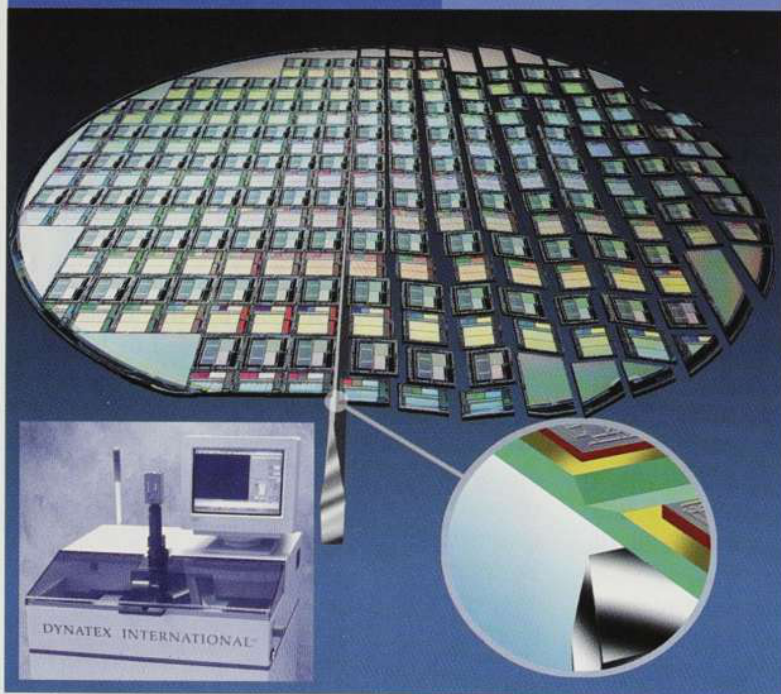
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COVER STORY

Raytheon's GaAs Model for the Future

Raytheon's decision to scale-up is the centerpiece of their strategic plan, as the company believes that there is a shake-out coming in the analog GaAs industry, and it is those companies who have 6" fabs that will survive and grow.

Raytheon's fab model shows a 30-45% cost advantage for 6" wafers over 4" wafers, assuming equal utilization of capacity. According to Jim DiLorenzo, Raytheon's research

Raytheon's decision was also motivated by capacity constraints and cost considerations. It is the centerpiece of their strategic plans, as the company believes that there is a shake-out coming in the GaAs industry, and it is those companies who have 6" fabs that will survive and grow.

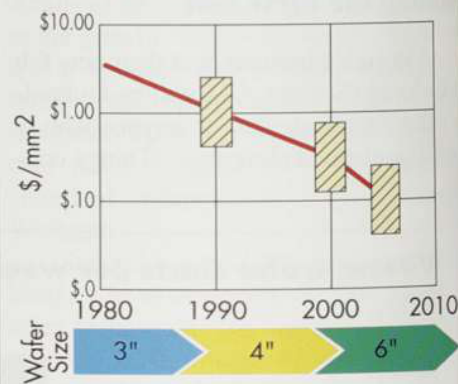
showed that the materials costs – photoresist, gases, metals, etc. – for the 6" line would not be much different from those used in a 4" line. Therefore the fab model assumes that material and labor costs, and some equipment depreciation costs, can be amortized over the area of a 6" wafer, which is 2.25x greater than that of a 4" wafer. If the company can actually use the extra capacity, the economic

benefits of scaling up become obvious. "It's not magic, silicon's been doing it for years," DiLorenzo notes. "When we look at what the customer needs in terms of price, and we translate that to cost, and we know we want to operate with a 50% or better gross margin, we are driven to the 6" wafer."

Raytheon's summary of cost trends for GaAs ICs is given in Figure 2. "In the 80's GaAs was processed exclusively on 3", and you saw costs per square millimeter anywhere from \$5 to 50 cents," says DiLorenzo. "In the 90's we saw 4" become prevalent and costs correspondingly decreased. That was a function of two factors: the increased volume in the fab and the larger wafer size. We expect to see that trend continue with the transition to 6" wafers."

At the low end, he believes that

Trends in GaAs Device Costs



Cost per sq. mm of GaAs devices has declined from 50 cents to \$5 in the 1980's, when processing was done on 3" wafers, to consistently less than \$1 today, when almost all volume production is done on 4" wafers. Raytheon predicts that the advent of 6" wafers can further lower the costs to around 5 cents for ion implanted MESFETs, and 10 to 30 cents for epitaxially based processes (HEMT and HBT).

MESFETs can cost as little as 5 cents per square millimeter, assuming that the process is extremely "lean". He points to Vitesse as a model, as they have a process which uses just 11 mask layers, aluminum metalization (much cheaper than gold, which is more commonly used), and self-aligned technology. More complex MESFET processes might cost up to twice as much on a per square millimeter basis.

For the epitaxially based processes (HEMT and HBT), DiLorenzo predicts costs in the 10 – 30 cents range. At the low end would be 0.5 micron ICs for the lower frequency wireless applications. These devices are an important part of Raytheon's roadmap. "Our opinion is that in wireless communications, especially in handsets and wireless computing, HBT technology will emerge as the clear winner," says DiLorenzo. "ED [enhanced depletion mode] PHEMT is also a good candidate, but it is more difficult to implement than HBT."

At the upper end of the cost range would be chips for millimeter wave applications. "Right now you need e-beam lithography to produce 0.1 micron gates for 77 GHz circuits, so you

have to put that kind of a cost structure in your fab." Raytheon has not yet decided whether these products will be integrated into the 6" fab, or whether some other provision might be made for high frequency products. "That's a big issue for us right now," says DiLorenzo. "If you want to run a very efficient 6" fab for high volumes, you may not want to add into it things like millimeter wave technology, because it can add variability that reduces efficiency and cycle time. We are in the process of evaluating how we can blend our desire to participate in the millimeter wave opportunities with our 6" fab strategy."

A Consolidation in Wireless On the Horizon?

Raytheon's decision to scale-up to 6" was based upon their forecast for the wireless handset business. "Maybe we are myopic," DiLorenzo says, "but right now we don't see another truly large volume application." Therefore they excluded consideration of all other applications from their forecast when attempting to justify the investment in the new fab.

In the Raytheon model, by 2003, wireless handsets will have on average 1.5 PAs and 1.5 switches, all done exclusively in GaAs, with some small additional GaAs content in transmit/receive integrated modules.

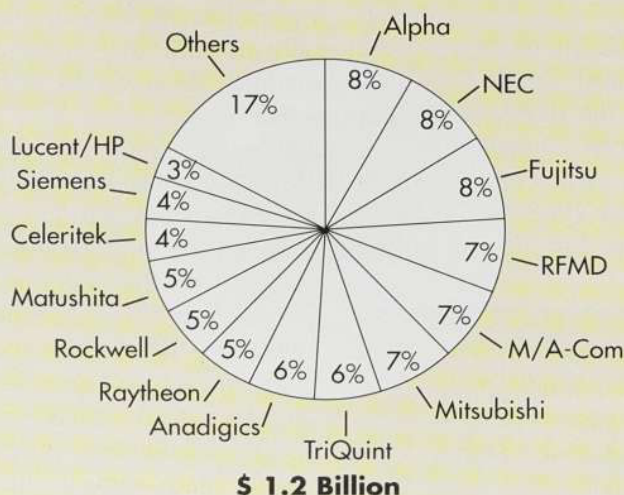
Assuming an overall market of slightly more than 350 million handsets, this adds up to the need for 820 million GaAs ICs in 2003, with a value of \$2.4 billion. Roughly 200,000 6" wafers would be required to supply this market.

Currently, the analog GaAs market is highly segmented. As Figure 3 shows, there are more than 15 players vying for a \$1.2 billion market. DiLorenzo believes this situation is not sustainable. He predicts that by 2003 there will be just 3 or 4 leading fabs which share 75% of the market.

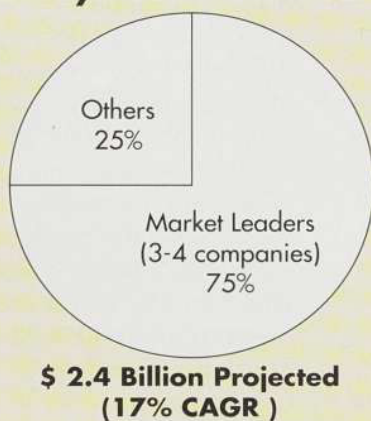
"Consolidation must occur," says DiLorenzo, "there will be winners and losers, and in our view, the winners will be the companies with 6" fabs that use them well."

Not everyone we spoke with agrees with this viewpoint. Several GaAs fab managers believe that it is more important to utilize their current 4" capacity more effectively, and some mentioned that other considerations, such as higher throughput 0.1 micron lithography, were more important priorities. Most companies we spoke with have 6" GaAs on their roadmap for the 2001-2003 timeframe. But these early-adapters of 6" GaAs have the potential to shake up the rest of the industry, and may even force their competitors to reassess their own strategies.

Wireless GaAs Today...



... and Raytheon's View for 2003



Source: Raytheon

Raytheon predicts a consolidation in the wireless GaAs business, with three or four fabs emerging as the dominant suppliers in this currently fragmented market.

In the Raytheon model, by 2003, wireless handsets will have on average 1.5 PAs and 1.5 switches, all done exclusively in GaAs...roughly 200,000 6" wafers would be required to supply this market, and there will be just 3 or 4 leading fabs which share 75% of the market.

Silicon Germanium as a Commercial Technology

ROBERT A. METZGER

It has taken about five years longer than anyone expected, but SiGe has, at last, arrived. You can pick up the phone, get a part number, and have a SiGe circuit delivered to your desk. Therefore the question is no longer if we will see SiGe devices and circuits in the commercial market, but rather it is what those devices and circuits are, and how they might impact manufacturers of GaAs devices.

I. Players and Products

IBM

In the last quarter of 1998, IBM made the all important transition from the promise of SiGe technology to the reality of commercial products. For the last decade, IBM has focused on the implementation of SiGe technology through a BiCMOS process, in which they hoped to merge both the high speed and RF compatible characteristics of SiGe HBTs with the low cost and large scale digital capabilities of CMOS. Their 8" SiGe BiCMOS line in Burlington Vermont supports high levels of integration in both the high speed SiGe portion (f_t and f_{max} of 50 and 70 GHz, respectively), and in the CMOS portion of the process (gate length a conservative 0.4 micron).

In the past, this line was sometimes touted as the pathway toward an entire phone on a chip, using the SiGe HBTs for the front-end RF portion, while the CMOS would handle IF and baseband/DSP applications. However, it has turned out that this type of revolutionary design is not what the market is looking for.

"Traditional cell phones are the market," says George Lauro, Director of Business Development of RF Communications and Storage Products at IBM. "There are a bewildering number of places to apply SiGe, but we wanted to focus on a few in order to make a success. We originally looked at 25 applications and reduced this down to two to focus on. The first was hand-held cellular, while the second application is GPS."

All of the standard SiGe products which IBM offers are intended for RF front-end applications, with the devices designed primarily for receiver components such as LNAs, VCOs, mixers and discrete HBTs. SiGe HBTs are attractive for this area because of their low base

All of the standard SiGe products which IBM offers are intended for RF front-end applications, with the devices designed primarily for receiver components such as LNAs, VCOs, mixers and discrete HBTs.

resistance, which result in low noise characteristics, a critical characteristic for these front-end receiver applications (see box, page 36). IBM's SiGe LNAs typically exhibit a low NF of 1.2 dB. These front-end devices and circuits are all configured to operate at 3 V, and over a frequency range of 800-1900 MHz, satisfying the operating requirements of many standards, including GSM, CDMA and PCS.

In the GPS area, IBM reports that they have demonstrated SiGe-based receivers which use direct conversion of the signal. "This allows us to remove a few stages and operate with $1/2$ to $1/3$ of the parts required in a conventional GPS

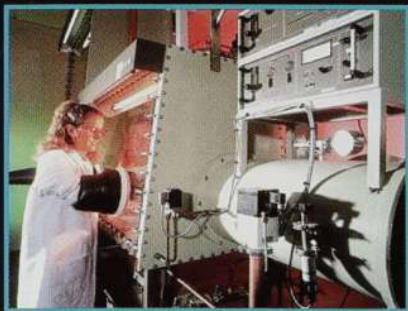


SiGe GPS chip on the head of a quilting pin, and a thimble full of the same chips.

system," says Lauro. Currently, 70% of GPS applications are in the automotive area, with potentially larger opportunities on the horizon. "The US government is considering mandating an E911 directive in which embedded GPS systems would be placed in cellular handsets so that in case of emergency calls to 911, the phone location would be automatically relayed," Lauro reports.

In addition to commercial components, IBM's SiGe strategy includes foundry services so that customers can implement their own SiGe designs. In order to further exploit this foundry capability, in February 1998, IBM acquired Commquest Technologies, a company with extensive RF design capabilities, which had already made inroads into the RF systems market. Using the SiGe capabilities at Burlington, Commquest has developed and is now offering front end RF components, including both a tri-band LNA and tri-band PA/VCO, designed to eliminate the need for multiple components in the 900, 1800 and 1900 bands.

Commquest continues to be interested in the elusive "single chip phone". However, they do not see this application in terms of hand held cellular. Says, Marilyn Jordan, Director of Communications for Commquest, "we see the single chip solution on a motherboard, to make portable devices such as your laptop also a wireless device." Plans such as these are being driven by the Bluetooth Special Interest Group (SIG).



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an association of nearly 400 companies, and founded by IBM, Ericsson, Intel, Nokia and Toshiba. It is the aim of this SIG to define the technologies and standards to implement the 2.45 GHz ISM band for wireless short range communications between portable electronic devices, an area in which IBM hopes to use its SiGe technology.

George Lauro is quick to point out that such wireless applications are key to IBM's long range strategy, not only for SiGe, but for the company as a whole. "The thing to remember is that IBM has a greater interest in SiGe than in the current applications. At the highest corporate levels, it has been determined that the implementation of SiGe technologies is strategic in our long term plans to implement what we see in the future of computing - the untethered network, with PDAs, Thinkpads, Internet access, large computing - all of it connected by a wireless network which will be implemented with SiGe."

In addition to IBM's commercial offerings through Burlington and Commquest, it has also entered into foundry agreements with such companies as Hughes, Applied Micro Circuits Corp (AMCC), Alcatel, Nortel, Harris, Qualcomm and National Semiconductor, all of which are using the foundry to develop their own SiGe devices.

Some companies are also evaluating SiGe for datacomm applications. Jim

Ebentier, Director of Technology and Partnerships at AMCC, characterizes their datacomm effort, saying, "right now we are in full production at OC-12 (625 Mb/s), with designs being implemented in OC-48 (2.4 Gb/s), and development work at OC-192 (10 Gb/s)." AMCC intends to use IBM's SiGe for 10 Gb/s Sonet applications. According to Ebentier, "we hope to have 10 Gb/s product out this year." But competition in this area is already mounting, with Alcatel having announced at the end of 1998, that with the aid of IBM's SiGe technology, that they have already developed a 10 Gb/s data module. Other contenders with access to IBM's technology which are targeting this application include Nortel.

According to Bernie Meyerson of IBM, Director of SiGe Development, "datacomm at 10 Gb/s shows the real potential of SiGe technology, driving this technology much harder than RF applications which only run up to 2.4 GHz and have smaller levels of integration. In addition, it's important to remember that Si has a thermal conductivity three times greater than GaAs, a very important consideration for high speed datacomm, where a lot of power is being dissipated." This high speed aspect of SiGe is also reflected in the work which Hughes is doing with IBM. Meyerson says, "we've built for them a large digital switch, which uses around 30,000 SiGe HBTs, in which the entire circuit clocks at 3500 MHz."

But for others, such as National, Harris, and Qualcomm, the rapidly growing RF market drives their desires to get involved with SiGe. Harris plans to use IBM's technology to boost its WLAN PRISM chipset capabilities. According to Ron Van Dell, Vice President and General Manager for Communication Business, "we will be moving beyond the current PRISM capability of 2 Mb/s to the newer, higher standard at 11 Mb/s, which we will implement in SiGe. The SiGe gives us higher levels of integration, which has allowed us to get down to 3-4 chips from the current 6-7. Eventually we'd like to use this technology to get down to 1-2 chips."

And lastly, Qualcomm has just announced its sixth generation CDMA chipset. In the receiver portion of the

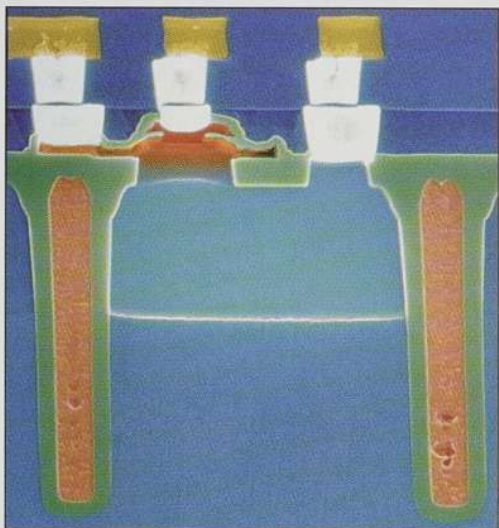
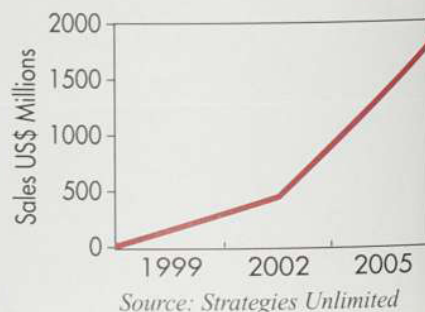
Market for SiGe Devices to Grow Quickly

According to Strategies Unlimited the worldwide market for SiGe wireless and digital semiconductor devices will reach \$1.8 billion in 2005, a 100 fold increase over current levels, capturing nearly 10% of an expected \$19 billion market for high speed devices at that time. Driven by strong global demand for communications, SiGe IC demand is projected to grow from \$15 million in 1998 to \$450 million in 2002, an annual growth rate of over 200 percent. Applications such as wireless and satellite-based voice and data services are expected to drive 79% of the demand in 2002, while high-speed computer networking applications will make up 16%, and consumer, industrial and military uses will account for the remaining 5% of world demand.

SiGe RF IC sales are forecast to reach \$200 million in 2002 and rise to nearly \$800 million in 2005. Mixed signal and digital IC applications, such as digital transceivers for wireless and optical communications are forecast to reach \$240 million in 2002, rising to \$1 billion in 2005.

More details can be obtained from the report, which is available from Strategies Unlimited (TEL (650) 941-3438; FAX (650) 941 5120; email info@strategies-u.com).

Worldwide Market for SiGe Devices



SiGe chip cross-section taken with a scanning electron microscope - color enhanced to show SiGe implant at top of photo, in orange.

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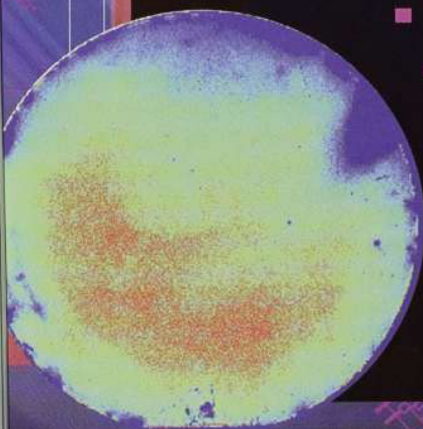


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chipset (RFR3100), this LNA/mixer chip is implemented in IBM's SiGe technology, meeting all CDMA standards for both the 800-900 cellular band, as well as the 1840-1990 PCS band.

Temic/Atmel

IBM continues to garner the bulk of the press and publicity with its recent announcement of commercially available SiGe products, but it is Germany's Temic which offered the first SiGe products more than 1 year ago. Unfortunately for Temic's SiGe effort, at the moment when commercial products were nearing the marketplace, the company itself went through both restructuring and sale.

Prior to restructuring, Temic was a conglomerate of two major units owned by Daimler-Benz - the automotive sector and the semiconductor sector. In an effort to streamline operations, Daimler-Benz retained the automotive sector, but sold the semiconductor division to Vishay, which in turn split the semiconductor operation into two segments, retaining for

themselves that part which dealt with discrete (diodes, transistors, LEDs and other opto elements), and sold the remaining semiconductor capabilities, which included the SiGe effort, to Atmel Corporation. That final restructuring took place in mid 1998.

"As of today," says Dominik Winau, Vice President of Communications ICs of Temic Semiconductor, "there are now three business centers within Temic Semiconductor, the Communications ICs which includes the SiGe effort, Automotive and Control Circuits, and lastly Microcontrollers, all of which represent one business unit within Atmel."

Currently, Temic Semiconductor runs a 6 inch SiGe HBT fab line at Heilbronn, Germany. The Temic SiGe process, which had started out as a MBE-based effort developed by researchers at the Daimler Benz Research Facility, and utilized an HBT structure similar to those found in GaAs products (see below) has evolved into a different process. According to Winau, "when it was done by MBE it was not reliable, very slow,

very expensive, and of no real use from a manufacturing perspective. We went to a lot of effort to use standard equipment that you can buy on the marketplace - just standard CVD equipment." With a manufacturable process, Temic has introduced SiGe LNA and power amplifiers. In the same manner that IBM and Commquest are introducing commercial product which address multiple standards and operating systems, Temic has developed dual-band power amplifiers (TST0911 and TST0913) which are applicable to both GSM and PCS over the range of 900 to 1900 MHz. In addition, they also offer standard LNA products.

As is the case of IBM, the facility at Heilbronn not only serves to generate commercial product, but also operates in a foundry mode. "We have one customer which has already implemented a full GSM transceiver on a single chip," says Winau, "and another which has built a transmission circuit operating at 40 Gb/s."

However, unlike the IBM effort, the line at Heilbronn is strictly an HBT line,

Technical Considerations

There have traditionally been two different approaches to the implementation of a SiGe-based HBT, with the difference dealing with the Ge profile within the base region. The original Temic approach as developed by Daimler-Benz would be considered a more "traditional" HBT structure. A narrow base region of 10-40 nm in width with a Ge content of 20-40% throughout the base was used. Arbitrarily high levels of Ge can not be tolerated in these structures due to the 4% lattice mismatch between Si and Ge - if too much Ge is added, the resultant strain will be relieved by the generation of dislocations which will quickly degrade device performance.

The narrow bandgap in the base acts to increase the current gain, β , of the device. In terms of this traditional HBT structure, β can be expressed as:

$$\beta = [N_e W_e D_p / N_b W_b D_n] \exp(\Delta E_g / kT)$$

where N and W are the doping level and

width of the emitter and base, and D_p and D_n are the minority carrier diffusion coefficients for holes (p) and electrons (n).

The enhanced gain of the HBT comes about through the bandgap difference between the emitter and base, ΔE_g , where in the case of SiGe, this can be as large as 250 meV (depending on the Ge content).

As can be seen from this equation, as the base doping N_b is increased, the gain drops. However, due to the insertion of the heterojunction, the gain is increased in an exponential fashion due to ΔE_g . As a result, while the impact of increasing the base doping level would be to decrease the gain, this effect can be compensated for due to the presence of the ΔE_g . This allows base doping levels in an HBT to be increased upwards of two orders of magnitude as compared to BJTs, and still exhibit acceptable gains. As a result, the RF performance of an

HBT is greatly enhanced over that of a BJT, in which the maximum frequency of oscillation, f_{max} can be greatly increased, where f_{max} is determined by:

$$f_{max} = (f_t / 8\pi R_b C_{cb})^{1/2}$$

where f_t is the cutoff frequency, R_b the base resistance, and C_{cb} the collector-base capacitance.

As a result of the higher base doping levels which can be utilized in an HBT, the f_{max} value is increased. In addition, because an epitaxial process is used to grow the HBT, very narrow base regions can be fabricated which reduces the electron transit time through the base, which in turn increases f_t and therefore increases f_{max} . As a result, the higher base doping levels give better higher frequency performance. But the benefits do not end there. In addition, the resulting lower base resistances improves the device noise figure, a critical parameter for RF performance, while

without any CMOS capability. However, it was this SiGe HBT capability which attracted Atmel. "We are in the process of transferring the SiGe know-how from Heilbronn into our Colorado Springs BiCMOS facility in order to make that a BiCMOS SiGe facility," says Jeff Katz, Vice President of Marketing for Atmel.

According to Tony Giraudo, of Atmel's Colorado Springs operation, "to give you a little bit of context, the Colorado Springs facility has been engaged in providing BiCMOS RF wireless products into the cellular, two way pager and two way radio markets for about 5 years now. So it was a logical evolution with the growth of that business that we make an investment in SiGe and that is why we acquired Temic's business, and more specifically, the intellectual property concerning SiGe. We believe that for those companies involved in the RF and wireless market, new technology is critical for going forward, especially when a lot of the communication protocols are going up in frequency. So that was our motivation. We are now taking

the next step which is to create the SiGe BiCMOS technology, a technology that our existing customers are asking for."

Unlike IBM, which is offering some commercial products, this is not currently in the plans for the Atmel Facility in Colorado Springs. "The customers that we tend to deal with are the big three in this business - Motorola, Nokia and Ericsson," says Giraudo, "and they essentially define their own products. They design their own products if we provide the capability for them to do that. We are not in the business to compete, in terms of the sockets that the big three try to create for themselves. So our market segment is defined as a customer-owned tooling relationship, allowing the people who know how to design radios to do that job."

Once the SiGe process transfer has been completed, and product shipments begin in the middle of the year, there are no plans to shutdown the Heilbronn SiGe facility. The fact that the company will have two sources of SiGe gives the company an internal backup if there is a problem with either line.

the presence of the heterojunction results in a much more linear device, a very important consideration for many RF applications.

At the time that Daimler-Benz was employing this conventional HBT structure, the IBM approach was to grade the Ge throughout the base, starting with only 2-3% at the emitter-base junction and increasing it to approximately 10% at the base-collector junction. In this case the resultant field generated by the graded region enhanced electron transit time, which in turn decreased f_t and increased f_{max} . And because there existed some level of Ge throughout the base, there was still a ΔE_g effect which permitted higher doping levels.

Over the last three years, as they've moved into production, both IBM and Temic have made changes. IBM has slightly increased their Ge content, running from 3 to 13% from base to emitter, while Temic has reduced their constant Ge content to 20% (higher levels resulted in generation of dislocations

upon thermal cycling). The typical Ge profile used by SiGe Microsystems runs between these two points, optimized for the specific application of the customer. As this technology has moved out of the lab and into production, a merging of the different approaches has taken place, driven by the requirements of the commercial market. In the *real world*, a good 50 GHz f_{max} device easily satisfies the commercial demands of 2.5 GHz and 10 Gb/s applications, and can be achieved without the heroic profiles and low yield processing which in the past were used to achieve record breaking figures of merit. In the past it seemed that there was a "figure of merit contest" in which f_t and f_{max} values were driven past the 100 GHz level by using extremely high Ge content, or very narrow bases and heavily doped collectors (which resulted in degraded breakdown voltages). But the trend now is toward more manufacturable, more conservative profiles that meet the needs of the current applications.

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Another interesting supplier is SiGe Microsystems of Ottawa Canada. Originally conceived as a service company offering SiGe epitaxial growth, using the same Leybold UHV CVD system as IBM utilizes in their SiGe deposition process, the direction of the company has recently been altered. "Our new business model is not one of providing a service," says Derek Houghton, president of SiGe Microsystems. "We provide a solution. We are transitioning into a fabless semiconductor company. We now have a potent team of RF SiGe designers, which allows us to engage a customer such as Ericsson or Nokia, which provides us with a spec, and then we can deliver a particular solution through our different foundry arrangements."

An example of such a foundry arrangement is the one which currently exists with Maxim Integrated Products through the utilization of its BiCMOS processing line. Maxim provides all processing, except for the critical SiGe deposition step, which is done at SiGe Microsystems.

This capability not only allows Maxim and SiGe Microsystems to go after customers which neither one of them might capture by themselves, but has also resulted in the production of commercial SiGe products. Like IBM, which is focusing on the low noise capabilities of SiGe for receiver applications, Maxim offers LNA and LNA/mixer ICs (MAX2640/41 and MAX 2680/81/82). These impressive LNA's exhibit a NF of only 0.9 dB at 900 MHz, and 1.3 dB at 1900 MHz.

According to Walter Lau, Business Manager for Maxim's Wireless Group, "we are bringing up our own in-house SiGe capability which is being transferred from SiGe Microsystems. The equipment is in house and we are currently qualifying the process. We have quite a few SiGe products in development. The main markets as we see them are cellular, GPS and WLAN at both 2.5 and 5.2 GHz."

And while Maxim establishes its own internal SiGe capabilities, SiGe Microsystems continues to evolve. "The fact that we have a SiGe capability makes us very attractive for foundries to interact

with us, giving them a greater capability. But beyond this, we also plan on introducing our own products that will begin to appear in the third quarter of this year, products whose capabilities will interleave with those which our customers are offering."

NEC

Details about SiGe activity in Japan are sketchy. However, it is known that NEC is planning to have commercial SiGe HBT products in the marketplace within the next two years. The company recently invested \$45 million to set up a SiGe line at NEC Yamagata to cover R&D through to mass production. Samples will be available in March. NEC says they will have capacity for 180 million SiGe devices per month.

The SiGe vs GaAs mindset, which over the last decade was often driven by who could produce the highest f_{max} and f_t , is finally over. Business strategies now are not centered around material systems or device types, but on coming up with solutions for a specific application.

II. The Future

Given that SiGe is being targeted toward wireless and datacomm, everyone in the compound semiconductor industry is surely wondering about its potential impact on demand for GaAs ICs. But making predictions about which technology will win and which will lose is difficult at best, and in all likelihood futile. The SiGe vs GaAs mindset, which over the last decade was often driven by who could produce the highest f_{max} and f_t , is finally over. Business strategies now are not centered around material systems or device types, but on coming up with solutions for a specific application. Nowhere is this approach more evident than at RF MicroDevices.

"We have never identified ourselves as a GaAs company," says Jerry Neal, vice president for marketing. "We've always had the view that is described by our slogan - optimum technology matching. We believe that you satisfy the application with the best price/performance and whatever technology satisfies that is whatever

technology it happens to be. Even though the majority of our business is GaAs, with our GaAs HBT accounting for 83%, the remaining 17% of our business is in silicon, and it is the fastest growing segment of our business."

Even though RFMD is currently expanding its GaAs HBT fab, it is also aggressively expanding Si-based RF business. This effort includes a recent agreement with IBM for SiGe foundry work. This agreement now gives RFMD four external sources of different materials and devices - GaAs HBTs from TRW, GaAs MESFETs from TriQuint, Si Bipolar from IBM, and now SiGe HBT from IBM Burlington.

With regard to SiGe, Neal says, "it has a role to play in low noise, such as in receivers. Many of these applications you can do with GaAs HBTs, however, the SiGe gives you an extra capability because it is a BiCMOS process, so you have a large wafer (8 inch in IBM's case), along with the CMOS which allows you to implement additional functions, which could be in the IF, baseband, or in control circuitry. But even beyond that, we are looking past MMICs and at modules. Prior to this year we only shipped MMICs, and now we are getting into modules, which allows us to mix technologies. This gives the possibilities of mixing technologies, of using both SiGe and HBTs in power amplifiers."

In all likelihood the future belongs neither to GaAs or SiGe. The future belongs to the applications which drive the market, and the winners of that race will be the companies with the flexibility and multiple technology capabilities to create solutions for those applications at the lowest cost, to recognize that each application will be best served by a combination of technologies.

"We expect to ship SiGe this calendar year," says Neal. "We will utilize both the SiGe and the BiCMOS in these first chips. We believe that the SiGe which is available now, will continue to advance in its capabilities, so we think the timing now is correct to get familiar with designing products with SiGe, so we will be positioned in the future as its capabilities increase."

Beyond the 2.5 Barrier

ROBERT A. METZGER



The number 2.5 marks an important boundary in the two most important commercial markets for GaAs devices. Wireless local area network (WLAN) bands, operating up to 2.5 GHz, represent the upper bound of the commercial RF sector. On the digital side the OC-48 standard, supporting data transmissions up to 2.5 Gb/s, drives the data communications market segment. Conventional wisdom says the realm beyond 2.5 belongs solely to GaAs, and this is a territory into which silicon simply can not encroach.

Unfortunately, recent research has produced two prime examples of silicon-based RF and digital circuitry operating well beyond the 2.5 barriers.

Researchers at NEC Corporation in Kawasaki Japan, lead by Mohammad Madihian, have reported on a 5 GHz band multifunctional BiCMOS transceiver chip for GMSK (Gaussian minimum-shift keying) modulation wireless systems, specifically targeting the WLAN 5 GHz band. This transceiver chip incorporates a low-noise RF amplifier, a Gilbert down-mixer, and an IF amplifier in the down-converter path; and a Gilbert up-mixer, and a buffer amplifier in the up-converter path. In addition, to keep the phase noise and power consumption of the local oscillator (LO) low, rather than using a direct 4 GHz band PLL system for the LO signal, the chip uses a frequency doubler followed by an LO amplifier, thereby permitting use of a 2-GHz band PLL local signal. This circuit was implemented using NEC's 0.4 μm emitter-coupled logic/BiCMOS process, which utilizes a double polysilicon self-aligned emitter-base structure, and CMOS transistors which have a WSi/polysilicon gate lightly doped drain structure. The bipolar

transistors have an f_t and f_{max} of 22 GHz - certainly fast, but not faster than any other number of good commercial silicon bipolar processes. A two-metal system was used to fabricate on-chip inductors which exhibited a Q of around 3.5 at 5 GHz. The circuit uses a single 2.6 to 5.2 V bias voltage. For 5.2 GHz operation, the transceiver exhibits 15 dB of gain and a 5.5 dB NF on the receiver side, while in the transmit mode, delivers -6 dBm for an input IF power which ranges from -55 to -40 dBm. The noise performance of the receiver is dominated by the substrate leakage and inductor parasitic resistance, and if a lower NF is required for a given application, implementing this circuit in either an SOI or SOS substrate will certainly improve the NF.

On the digital side, researchers from Hitachi, led by Kenichi Ohhata, have fabricated a wide dynamic range, high transimpedance silicon bipolar preamplifier which is targeted for 10-Gb/s optical fiber links for short-haul systems. This circuit was implemented in Hitachi's 0.3 μm , 35 GHz f_t bipolar process which uses an SOI substrate and U-groove isolation to reduce the parasitic capacitance between the collector and the substrate. The preamplifier, when coupled with a limiting amplifier, exhibited a wide dynamic range from 16 mA peak-to-peak to 2.5 mA peak-to-peak, and a high transimpedance of 1 k Ω - giving this amplifier the highest reported transimpedance value of any bipolar preamplifier operating at 10 Gb/s.

Rather than looking over your shoulder, wondering if silicon is catching up to you, squeezing you against the 2.5 barrier, it might be wise to take a look in front as well, checking to see if silicon has leapt right over you.

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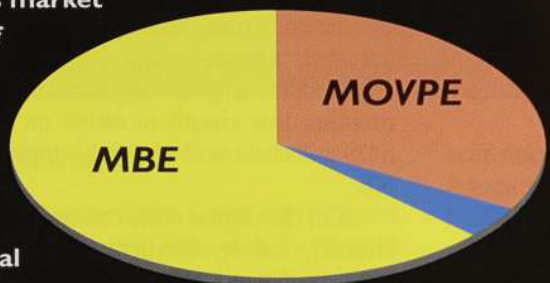
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HEMT-based Millimeter-wave Monolithic IC Technology for 76 GHz Automotive Radar^[1]

YUU WATANABE AND NAOFUMI OKUBO
Fujitsu Laboratories Ltd.

One of the most promising commercial applications for millimeter-wave systems is automotive radar to provide active safety for driving. Research on automotive radar started in early 1970s in the United States, and Fujitsu developed a 50 GHz radar sensor in 1981. Although these efforts did not meet the demands of the market in terms cost and size, more recent developments have stimulated commercial interest in millimeter-wave systems including automotive radar. These included several national research programs on millimeter-wave systems, and the strong growth of GaAs semiconductor manufacturing as a result of the rapid spread of wireless communications.

The Japanese Ministry of Posts and Telecommunications (MPT) assigned the 60 GHz band for low-power millimeter-wave radar systems in 1995. Following the allocation of 76 GHz band for radar in the US and Europe, MPT decided in 1997 to assign the same band to automotive radar systems in addition to the 60 GHz band. Although this action promoted a global standard for commercial use, it gave a rise a number of challenging technical issues.

To realize practical, reasonably-priced radar systems for passenger cars, the frequency performance of the devices must be improved and costs reduced. Monolithic integration is the usual approach to cost reduction, and much effort has recently been devoted to the development of MMICs. It has been shown that peripheral elements play a more important role in the millimeter-wave frequency region, and that die positioning and wiring in a

package can seriously affect the circuit performance and yield, resulting in higher costs. However, these difficulties can be overcome with flip-chip bonding. Chip positioning can be automated with greater accuracy, and the wafer process is simpler than for conventional microwave devices.

Here, we describe a MMIC technology for 76 GHz automotive radar that includes a 0.15 μm HEMT IC process, flip-chip bonding with pillar interconnection, and W-band face-down circuit design.

0.15 μm HEMTs - Device Technology and Performance

Heterojunction devices such as HEMTs have fundamental advantages over other types of transistors for challenging high frequency applications such as 76 GHz MMICs for automotive radar. Fujitsu has already developed a 0.25 μm gate length HEMT technology, which is commercially available for several millimeter-wave systems. However, even with 0.25 μm HEMTs, frequency performance is not sufficient for 76 GHz automotive radar system; high-performance transistors with f_{max} exceeding 150 GHz are required.

The reduction of gate capacitance and increase in transconductance

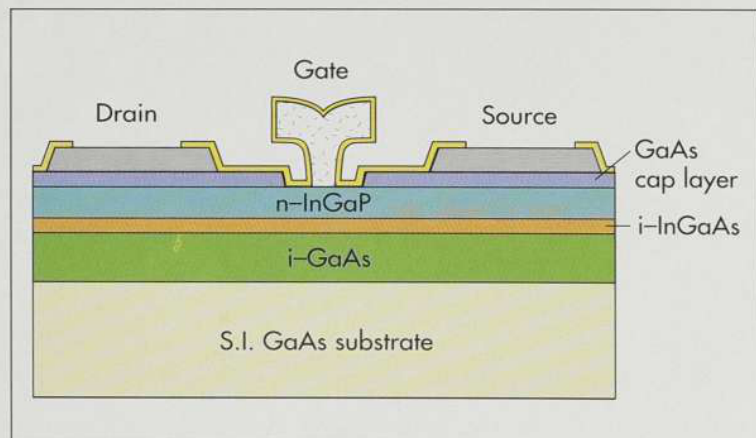


Figure 1. Cross-sectional structure of an InGaP/InGaAs HEMT.



Figure 2. SEM image of a MMIC prior to flip-chip bonding, showing HEMTs and 40 μm diameter pillar-shaped gold interconnections.

^[1] This article originally appeared in the *Fujitsu Scientific and Technical Journal*, 1998, 34(2), p. 153. It is reproduced here with permission from the authors and Fujitsu.

are important to improve the transistor characteristics. Scaling is the traditional approach for FET technology and is effective for improving performance even in the sub-micron region, but parasitic factors can not be neglected for high-performance devices. Such phenomena as the short channel effect, the increase of gate resistance and fringing capacitance degrade the transistor performance.

Figure 1 shows the new structure employed for 0.15 μm HEMT. The T-shaped gate was patterned by electron beam lithography. This separates the gate electrode from the sidewall, thus reducing the fringing capacitance. The i-GaAs/i-InGaAs/n-InGaP/n-GaAs epitaxial layers were grown by MOCVD, where n-InGaP is the electron supply layer instead of the AlGaAs layer used in conventional AlGaAs/GaAs HEMTs. Due to high doping in the InGaP layer, the distance between the channel and gate can be reduced compared with the conventional device. This structure suppresses the short channel effect for short gate lengths.

In the fabrication process, the recess region was etched after ohmic electrode formation. The Al gate electrode was aligned in the recess region with electron beam lithography, and lifted off. Using Al for the T-shaped gate electrode, the gate resistance is low even for a gate length of 0.15 μm . We optimized the structure, taking account of the high frequency and process stability.

The small-signal frequency characteristics of the 0.15 mm HEMT, measured under a bias condition of $V_{\text{ds}} = 3\text{V}$ and $V_{\text{gs}} = -0.4\text{V}$, indicated a cut-off frequency (f_T) of 90 GHz, a maximum

oscillation frequency (f_{max}) of 170 GHz, and a maximum stable gain of 9 dB at 76 GHz. The f_{max} value was determined from the maximum available gain curve instead of by the -6 dB extrapolation of unilateral power gain curve, showing that the new HEMT structure effectively reduces the parasitic effects.

MMIC Fabrication

Using the 0.15 μm gate HEMT, we developed a low cost MMIC process employing conventional passive elements including MIM capacitors, epitaxial resistors and air bridge wiring.

Conventional MMICs use microstrips as transmission lines, which need a ground plane on the backside of the chip and via holes to connect the backside ground plane to the face-side of the chip. The thickness of the chip must be precisely controlled to maintain the impedance of the transmission line, requiring wafer-thinning and wafer-penetrating fabrication processes. Controlling the wafer thickness and via size makes it very difficult to fabricate high frequency circuits with the micro-strip structure. A co-planar waveguide (CPW) is often used in millimeter-wave circuits and its structure is also convenient for flip-chip assembly, since all the electrodes in the circuit are placed on one side of the chip. No wafer thinning and via penetrating processes are needed for co-planar circuits. The chip can also be thick, thus retaining mechanical strength in the chip bonding process.



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Flip-Chip Bonding

The importance of assembly is much larger for high frequency applications than that for digital or low-frequency ones. The physical length of packages seriously affects on the performance of MMICs, because the wavelength is compatible with the dimensions of the package and leads. Flip-chip bonding of the MMIC to an alumina substrate was selected because the process causes little loss in performance, and its assembly precision enables low-cost fabrication.

Digital LSIs usually use bump technology based on transferred solder for the interconnections of flip-chips. Due to the short wavelength involved in W-band MMICs, these require more precise positioning and sizing of interconnection electrodes to avoid degradation due to impedance mismatching, compared to digital LSIs.

In order to obtain good positioning with a small diameter interconnection, we developed a pillar technique. After metallization to form the MMIC co-planar lines, 40 μm diameter pillar-shaped gold electrodes were formed on the wafer by electroplating (see Figure 2). This technique provides flexibility allowing the pillars to be placed anywhere on the chip and thus reduces the source inductance of each transistor by placing a grounded connection just beside the devices. Pillar formation, which replaces wafer thinning, backside alignment, via hole etching, and backside plating in conventional MMICs, greatly simplifies the fabrication process.

Despite the advantages of flip-chip bonding, two problems remain. Firstly, the transmission line on the chip to the substrate exerts a proximity effect on the high-frequency characteristics of the device. Secondly, the reliability of the lines may be compromised when subjected to thermal and mechanical stresses inherent in the inflexible structure of flip chip bonding.

The gold-tin eutectic reaction method was employed for flip chip bonding, in which the chip and substrate are heated after connecting the gold pillars on the chip to the tin of the substrate. This process potentially causes less damage to the fragile GaAs chips than conventional gold to gold thermocompression bonding because of its lower temperature and lower load. In addition, the gold-tin method avoids solder contamination of the gold

transmission line on the chip, which can be a problem in the solder-bump bonding method.

To evaluate the high frequency characteristics and reliability of the technique, a test piece was fabricated. This consisted of a 2 mm square GaAs chip with gold CPW lines and gold pillars on one surface, and a 10 mm square, 0.65 mm thick alumina substrate (see Figure 3). The alumina substrate had a patterned thin film surface metallization consisting of 100 nm Ti, 3,000 nm Cu and 500 nm Sn. The GaAs chip was mounted on the substrate with a pulse-heat tool at 350°C for 10 seconds under a 20 g/pillar load.

The insertion loss of the pillar was estimated to be -0.2 dB/pillar. Overall, flip-chip bonding was estimated to have both a lower insertion loss and a lower return loss than conventional wire bonding. The characteristic impedance of the transmission line on the chip was simulated as a function of the pillar height, and was $52 \pm 2 \Omega$ for a pillar height of $20 \pm 5 \mu\text{m}$. Below 15 μm , the characteristic impedance was very strongly dependent on pillar height.

A major problem in flip-chip bonding is the thermal expansion mismatch between the chip and substrate, because both are inflexible and thermal stress concentrates at the bonding portion. GaAs has a thermal expansion coefficient of 6.0 ppm/°C, which is similar to that of alumina (6.5 ppm/°C), resulting in a relatively small thermal expansion mismatch. The bonding reliability was estimated by thermal cycle test (-55 to 150°C; 1000 cycles), thermal shock tests (-0 to 100°C; 1000 cycles) and vibration tests (10 to 200Hz; 10 G; 6 hours). All samples passed these tests, indicating the high reliability of this bonding technology.

Face-Down Chip Design

Designing the W-band millimeter-wave circuit with face-down chips is another challenge. A precise model of the transmission line is one of the key issues for MMICs. In spite of much research on CPW design, there remain several difficulties in using CPW for flip-chip circuits, such as the proximity effect and signal transition to the chip. An actual flip-chip CPW line contains signal transition parts such as pillars or bumps to transmit a signal from the external feed line to the CPW line. When charac-

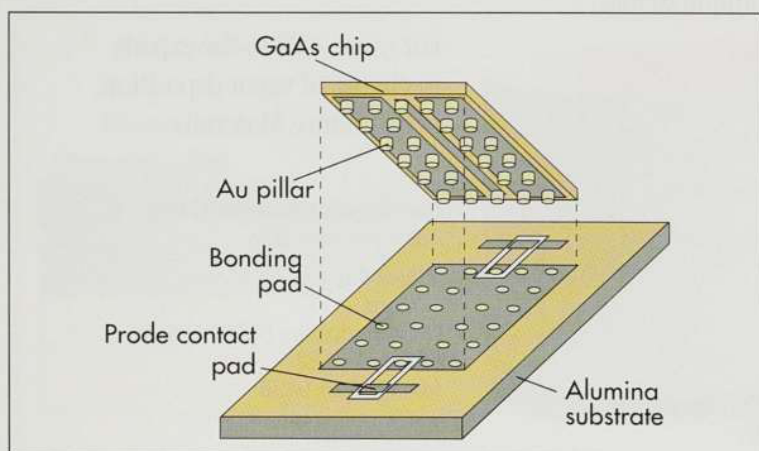


Figure 3. Schematic showing a GaAs MMIC with gold pillars about to be flip-chip bonded to an alumina substrate.

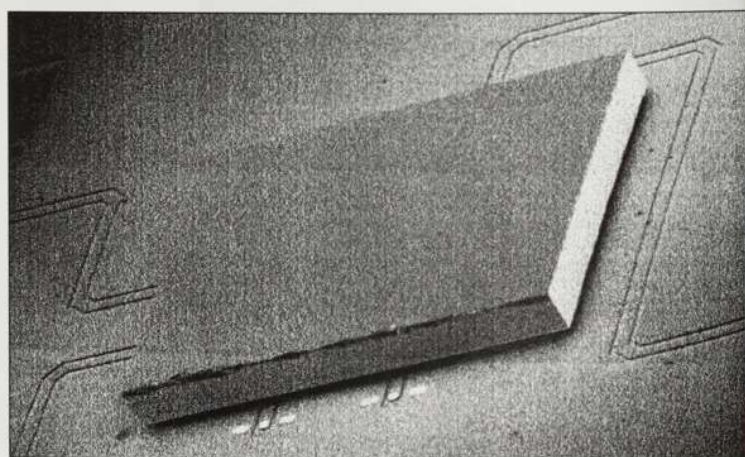


Figure 4. SEM photograph of an amplifier MMIC flip-chip bonded to an evaluation board.

terizing the actual CPW lines, however, the signal transition part hinders the de-embedding of the external feed lines since the transverse electromagnetic field expands toward each line.

When designing the circuits, the pillar transition and CPW lines must be characterized independently. Therefore, we propose an experimental technique to model the flip-chip CPW lines without signal transition pillars. This experiment is based on the reversed-structure flip-chip, which consist of a CPW line chip and lid ground. The CPW lines are measured with the lid ground attached to the pillar. By using this technique, the characteristics of the transmission lines can be evaluated without affecting signal transition through the pillars. We obtained $Z_0 = 49.0$ ohms, $E_{eff} = 5.41$ and $Attn = 0.300$ dB/mm from measured data for a line width of 20 μ m, a ground-to-ground spacing of 60 μ m and a pillar height of 20 μ m. We also obtained a $Z_0 = 55.9$ ohms, $E_{eff} = 6.33$ and $Attn = 0.241$ dB/mm with the same line widths and ground-to ground spacing for the line without the lid ground. As mentioned in the previous section, the CPW line and the ground on the substrate interact. These results are in close agreement with simulation results and indicate that W-band flip-chip MMICs with CPW line can be designed using the quasi-TEM mode approximation.

MMIC Chip Set For Automotive Radar

We developed a 76 GHz chip set for automotive radar, consisting of a 76 GHz amplifier, a 76 GHz mixer, 76 GHz SPDT switches, a 38/76 GHz frequency doubler, a 38 GHz voltage-controlled oscillator (VCO) and a 38 GHz buffer

amplifier. The two-stage amplifier had a small-signal gain of 10.6 dB at 76.5 GHz. The singly-balanced mixer had a conversion gain of -4 dB at 76 GHz LO frequency for an LO power of -1 dBm. The 76 GHz SPDT switch exhibited an insertion loss and isolation at 76.5 GHz of 3.4 dB and -17 dB, respectively. The 38/76 GHz frequency doubler IC had a conversion gain of -3.7 dB for a 38.25 GHz input signal power of 3 dBm. The 38 GHz VCO used a reverse channel HEMT configuration to generate sufficient negative resistance and reduce the size of the source feedback circuit. The 38 GHz buffer amplifier had an output power of -0.7 dBm at 39.6 GHz. Figure 4 shows an SEM photo of the flip-chip MMIC, indicating the amplifier chip on the evaluation board.

In conclusion, we have successfully developed a HEMT MMIC technology for 76GHz automotive radar. The wafer process is based on 0.15 μ m InGaP/InGaAs HEMTs, with a maximum stable gain of 9 dB at 76 GHz, and interconnecting pillars for flip-chip bonding. The flip-chip technology uses gold micro pillars and tin metallization on an alumina substrate. Results of reliability tests indicate that the flip-chip bonding is very resistant to thermal and mechanical stresses, and thus is suitable for practical use. For designing flip-chip mounted MMICs for the W-band, we proposed an experimental method to model face-down CPW transmission lines. By using this model, the chip set was designed and fabricated, and achieved sufficient performance for 76 GHz automotive radar systems. The results indicated that our MMIC technology is promising for achieving low-cost 76GHz automotive radar systems.

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Sterling was established in 1996 on the basis of a unique SiC crystal growth technology that was developed in Russia by two of the co-founders of Sterling.

In 1998, the company gained substantial additional capacity, technology, expertise, and an ISO-certified wafer production process, with its acquisition of the silicon carbide wafer production assets of Epitronics, a division of ATMI, Inc., in Danbury, CT [NASDAQ: ATMI]. Today, Sterling is shipping substrates to customers in North America, and to Japan and Europe through its local representatives.

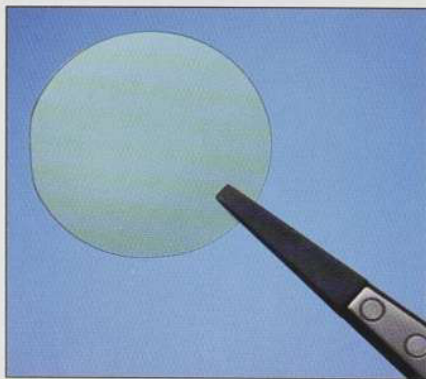
Silicon carbide is a third generation semiconductor material, and due to the novel properties of SiC, this remarkable material is capable of extending semiconductor electronics beyond the limits of silicon and gallium arsenide.

Sterling foresees four main application areas for SiC as a substrate for SiC and GaN epitaxy:

- blue opto-electronics
- high temperature electronics
- wireless communications
- high power electronics

New Products

Sterling introduced its 2-inch (51-mm) 4H and 6H SiC wafers produced in Danbury, CT, in February 1999, and already has these wafers under qualification with key customers worldwide. In the near future, Sterling will introduce SiC epitaxial services. In the longer term, the company plans to offer



*Sterling Produces
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application-engineering services for SiC-based devices.

Sterling aims to provide customers with a full portfolio of SiC substrates and related services. In doing so, Sterling will provide a means for its customers to quickly develop and test SiC devices.

ISO 9002 Certified Production Process

Sterling's Danbury, CT facility, which is co-located with ATMI, is ISO 9002 certified. SiC crystal growth is performed in highly automated equipment with precise process control. This ensures that customers have a reliable, consistent supply of substrates from a world-class facility. Sterling is committed to on-time deliveries of substrate products that meet customer expectations. In addition, Sterling has the capacity today to ship thousands of wafers annually - and can bring additional capacity on line with relatively short notice.

Sterling's SuperPolish

In addition to SiC crystal quality, surface finish is also critical in determining the quality of epitaxy and device yields. A proprietary process employed by Sterling has achieved RMS surface roughness of <10 Angstroms. Because the company



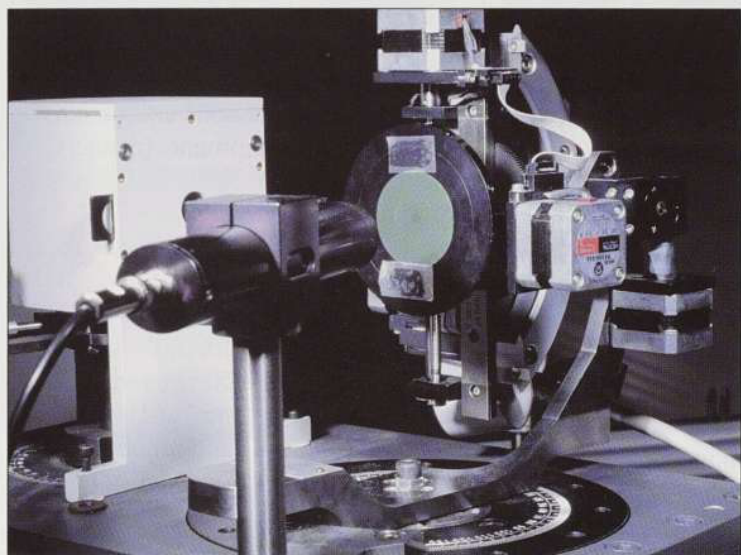
AFM Analysis of Wafer Surface

produces its own epi, Sterling knows what it means to have a truly epitaxy-ready surface, without the need for extensive, pre-epi cleaning or other surface prep, and with little sub-surface damage.

Quality Assurance

Sterling uses a full array of state-of-the-art characterization equipment to assure customers of a quality substrate product. In particular, Sterling is capable of providing the following measurements on its substrate products:

- X-Ray Rocking Curve Analysis to measure crystal quality
- Atomic Force Microscope (AFM) Analysis to measure surface quality
- Automated Micro-pipe Counting and Mapping to measure defects
- X-Polarizer Imaging, an easy way to measure crystal quality
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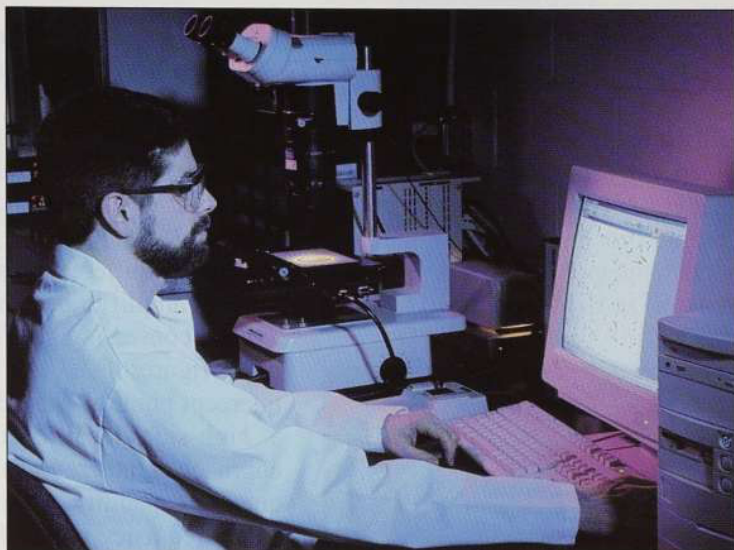
X-Ray Rocking Curve Analysis

A Commitment to R&D

The rapid success of Sterling is made possible by a long-term commitment to R&D. In combination with U.S. government support and its own funds, Sterling is pursuing a multi-million dollar R&D program in partnership with ATMI. The results are already apparent: 2-inch wafers and a *SuperPolished* surface have already been realized. The current R&D program aims for 3- and 4-inch wafers, with large micro-pipe free areas.

The Sterling Silicon Carbide Team

In combination with ATMI, Sterling has a world-class, international team of scientists and engineers. These experts, who have decades of combined experience in silicon carbide



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development for semiconductor applications, are dedicated to improving Sterling's technology. The company's managerial team and Board of Directors have many years of experience in bringing new technologies to market successfully - accomplishments they intend to repeat with SiC and Sterling Semiconductor.

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Cellular LNA/mixer IC from TriQuint

Hillsboro, OR. TriQuint's TQ5121 LNA/mixer IC is a 3 V, RF receiver designed specifically for cellular band TDMA applications, which meets digital IS-136 and analog AMPS standards, and can also be used for receiving functions in products designed for the 900 MHz Industrial/Scientific/Medicine (ISM) band. The component integrates a GaAs MESFET RF LNA, a buffered local oscillator (LO) input, a GaAs MESFET mixer, and an IF output amplifier in a single, small RFIC.



TriQuint's TQ5121 is a 3V LNA and mixer IC.

Typical conversion gain is 17.5 dB, with a noise figure of 2.7 dB. Input third order intercept point is -8.5 dBm minimum and a high-side local oscillator frequency approach is utilized enabling low IF frequency capability within the IF 70-140 MHz frequency range. The device uses a single operating voltage of +2.8-3.6 V and 10 mA of current, and the operating temperature range is -40 to +85°C. Pricing is \$2.69 each at quantities of 1,000.

Switches and Attenuators With Integral ASIC Drivers from M/A-COM

Lowell, MA. M/A-COM has announced two new families of multi-chip modules (MCMs) containing FET-based GaAs MMICs integrated with silicon CMOS ASIC drivers. The products provide high performance, single plastic package solutions that reduce board space, component count and time-to-market.



M/A-COM recently announced a family of digital attenuators with integral ASIC drivers, in surface mount multi-chip modules.

"Most of the plastic products in the wireless industry are packaged utilizing one or two components," said Don Carrick, Product Manager, M/A-COM. "We offer MCMs integrating up to six components."

The SW65 product family is a series of DC-3 GHz GaAs FET MMIC switches with integral ASIC drivers, for use in wireless infrastructure applications. The AT65 product family is a series of DC-2 GHz GaAs FET MMIC digital attenuators, also with integral ASIC drivers, that are well suited for both transmit and receive applications in wireless communications systems.

MODE Introduces 1x12 VCSEL Array

Albuquerque, NM. MODE, a division of Emcore, has introduced the Gigarray, a 1x12 array of 850 nm VCSELs designed for the gigabit data communication market. The new array is designed to enable parallel optical links with aggregate throughputs of up to 15 Gbps in high performance computer centers, workstation clusters and telecom cross-connect switches. The Gigarray product will be supplied to major OEMs such as AMP, which already markets parallel fiber-optic data links under the trade name "Lightray MPX". [see CS 4(3), p. 34].

HP Introduces High Brightness LEDs with Integrated Lenses

Palo Alto, CA. HP has launched a series of surface-mount, chip-type LEDs equipped with integrated lenses which concentrate the emitted light into a typical 70 degree viewing angle. The on-axis light intensity is double that produced by non-lensed surface mount chip LEDs using the same active die. This makes the new LEDs particularly suitable for illuminating buttons and switches on panels, and for transferring the maximum amount of light to optical pipes used to illuminate panel legends. They are an ideal choice for backlighting legends on radios and other dash-mounted devices in automotive interiors, and are also suitable as status indicators on computer panels, data communications equipment, office-automation equipment (printers, fax machines, copiers etc) and many types of industrial equipment.

The luminous intensity of all the units is specified at 20 mA, for a 70° viewing angle, and prices are quoted in 10k-50k quantities. AlInGaP LEDs, priced \$0.24, are available in red (626 nm) and red-orange (615 nm) at 100 mcd, and in orange (605 nm) and amber (590 nm) at 130 mcd. AlGaAs red LEDs at 639 nm have a luminous intensity of 32 mcd and are priced at \$0.17. GaP LEDs, priced at \$0.15, are available in orange (604 nm) and yellow (586 nm) at 10 mcd, and in green (57 nm) at 18 mcd.



HP's new surface-mount LEDs with integrated lenses are ideally suited for applications in automotive interiors, such as backlighting legends on radios.

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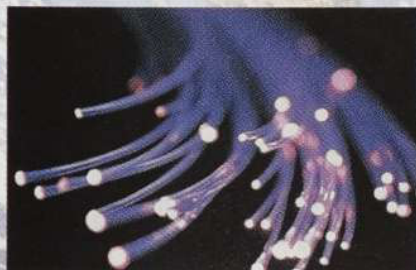
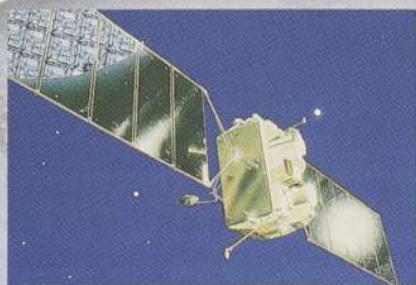
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20 W Ku-band GaAs FET from Toshiba

Irvine, CA. The TIM1414-20 is described by Toshiba America Electronic Components, Inc. (TAEC) as the industry's first 20 W internally matched GaAs FET operating within the Ku-band. The product operates in the

14.0-14.5 GHz range and offers superior power, gain and efficiency compared to travelling wave tube (TWT) products, for applications in satellite base station communications transmitters and very small aperture terminals. Typical P1dB is 43.0 dB, with a power added efficiency of 26.0%. The device, in a hermetically sealed package, costs \$1,100 in 1,000 quantities.



Toshiba

GaAs HBT Amplifiers from RFMD

Greensboro, NC. RFMD has introduced several new GaAs HBT amplifiers for digital communications systems.

The RF2119 is designed for use as the final RF amplifier in handheld digital cellular equipment, spread spectrum systems and other applications in the 800-960 MHz band. Operating from a single 2.0-5.0 V power supply, the device offers 30 dBm output power at 2.5V, 30 dB small signal gain and performs at more than 50% efficiency.

The RF2302 broadband linear variable gain amplifier is designed for digital communications systems that require linear amplification over a wide gain control range. The device operates in the 100-2000 MHz range, and is tuned to a specific frequency band with an output bias feed inductor and blocking capacitor. Operating from a single 3.0-6.0V power supply, this part features a 25 dB linear gain control range. At 836 MHz, the RF2302 delivers a maximum gain of 14 dB with an output 1dB gain compression of +14 dBm; at 1900 MHz, the maximum gain is 10 dB with an output 1 dB gain compression of +10 dBm.

Two new 3V GaAs HBT PAs are designed for use in digital subscriber PCS and cellular units where low transmit noise is a concern. The RF2324 is a low-noise CDMA/TDMA PA with a very high dynamic range, designed for PCS applications at 1880 MHz. The RF2347 offers low noise and a high intercept point for cellular applications at 830 MHz, and operates from a 2.5-6.0 V power supply. Both RFICs have an operating range of 150-2500 MHz, and feature an on-board power-down feature that can be used to turn off the device completely.

High Power IREDs from Dora Texas

Houston, TX. Dora Texas Corp. announced the availability of a new type of high power IR-emitting diodes, capable of producing 5W/sr at 880 nm when pulsed with 2 A. The device provides an on-axis intensity of up to 500 mW/sr from a single double-double heterostructure AlGaAs die measuring 15 mil². The company also offers LEDs operating at 660 nm, 730-760 nm, 800-880 nm and 900-4000 nm using AlGaAs, GaAsP and GaInAsSb die, and plans to offer epiwafers in the near future.

IR Data Transceivers from Siemens

Cupertino, CA. The Optoelectronics division of Siemens Microelectronics, Inc. has announced a new family of infrared data transceivers which combine low power consumption, variable data rates up to 4 Mbps, and very small size. They are designed for use in hand-held battery powered equipment such as cellular telephones, laptop computers, and personal digital assistants (PDAs), and provide wireless data links to other devices, such as printers or desktop computers. The IR data transceivers consume very little power in receive standby mode, typically 90 μ A at 2.4V, and 0.01 μ A in shutdown mode. In addition, the new parts are housed in a Slimline™ package, measuring only 4.0 mm x 4.8 mm x 9.8 mm, which enables low-profile designs. The devices incorporate a mode selection pin that toggles the transceiver between high data transfer rates (4 Mbps) and low data transfer rates (1.152 Mbps to 9.6 kbps).

"These IR data transceivers are just one part of the new generation of optical components from Siemens Microelectronics designed for the latest trends in wireless data transfer design," says Bob Lewis, Business Unit Manager for Siemens' custom optoelectronics products. "By combining

Siemens' [optoelectronics] expertise with state-of-the-art BiCMOS circuitry, the new parts bring together higher data transfer rates and low power consumption in a low-profile transceiver package that is ideally suited for small form factors where power consumption is an issue." Pricing is less than \$3.00 in volume.

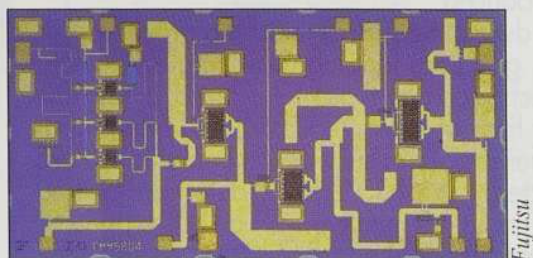


Siemens

Siemens' new IR data transceiver combines high data transfer rates and low power consumption in a package measuring 4.0 mm x 4.8 mm x 9.8 mm.

Fujitsu Announces Millimeter-wave Power Amplifier MMICs...

San Jose, CA. Fujitsu Compound Semiconductor, Inc. (FCSI) has announced two new GaAs MMIC PAs for base stations and customer premises equipment in Local Multipoint Distribution Service (LMDS) systems. The devices are manufactured on a 0.25 μm gold gate GaAs MESFET process. The FMM5802X is a 2-stage, LMDS band (26 - 32GHz) MMIC with 9dB gain and 27- 28 dBm (>0.5 W) P1dB output power. The FMM5804X is a 4-stage, wide band (15 - 32 GHz) MMIC offering 20 dB gain and a P1dB output power of 25-27 dBm (>0.3 W). This part can be used over the full range of two-way radio links in the 15-32 GHz spectrum. "The FMM5802X and FMM5804X have been specially designed with improved power supply efficiency and reduced power drain for remote rooftop and tower applications," says Gene Brannock, VP of Marketing and Engineering for



Fujitsu's FMM5804X is a 4-stage 15-32 GHz GaAs MMIC for two-way radio link applications including LMDS. Chip size is 2.65 mm x 1.45 mm.

Fujitsu

FCSI. "These devices are being offered to ease design efforts with the migration of radio link systems from lower frequencies (3-10GHz) up to the over-20GHz radio bands."

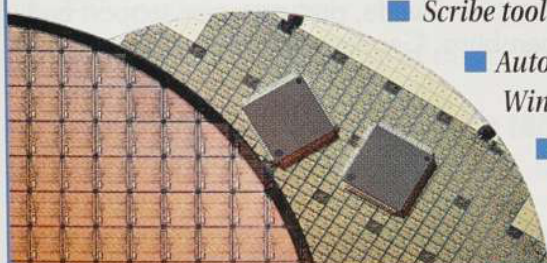
...and a Family of GaAs Power FETs for 3-15 GHz Radio Links

FCSI also recently announced a broad new product line of 50 ohm internally matched GaAs power FETs. Over forty new FLM-F series part numbers are available in the 3-15 GHz range. The FLM-F series devices are manufactured using a highly reliable, space certified process originally qualified in 1993 and verified by over five years of satellite production, resulting in improved device ruggedness and reliability. The use of gold for gate and capacitor metallization also enhances the gain and P1dB power output characteristics, resulting in higher efficiency and lower distortion over a wider bandwidth. As an example, the FLM1415-12F delivers over 40dBm (10 W) at 14.5-15.3 GHz. 3, 6 and 8 W versions are also available. For most frequencies, P1dB power options range from 4-35 W in 2dB increments. Gain ranges from 9.0 dB for frequencies under 6 GHz to 5 dB at 15GHz.

FCSI's products for the North American market are manufactured by Fujitsu Quantum Devices at the world's largest compound semiconductor operation, located in the prefecture of Yamanashi, Japan.

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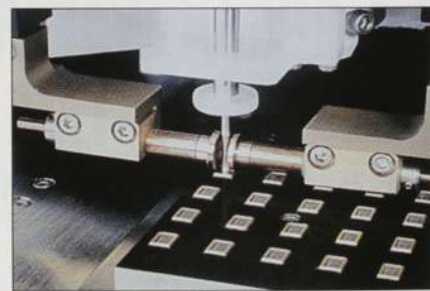
New High Speed Parallel Seam Sealer From Solid State Handles Parts In Matrix Tooling

Horsham, PA-A new high speed sealing system from Solid State Equipment Corporation implements the parallel seam sealing process for weld sealing of parts in matrix tooling. The Model 2200e Matrix Sealer has features throughout that offer high yields, lowest device temperature, and accurate, contamination-free lid placement. Tool-less lid alignment supports sealing of lower cost flat lids.

The parallel seam sealing process is superior because it seals the package effectively while the actual device temperature remains low. The process also allows dynamic control of digital sealing power and speed, so that difficult package shapes can be sealed as readily as simple shapes.

Automatic features of the Model 2200e Matrix Sealer include a vision system for accurate lid placement that examines both the entire lid and the entire seal ring. Extremely precise mechanics driven by brushless servo motors ensure rapid, accurate operation. Automatic package and height detection eliminate arcing, while feedback-controlled electrode force ensures uniform sealing. Electrodes are inexpensive, and are easily changed when package requirements change.

Solid State Equipment Corporation manufactures a full line of hermetic package sealers and spindle cleaners/processors at its headquarters in suburban Philadelphia. SSEC maintains sales and service offices worldwide, and customer support and process development centers in Horsham, Pennsylvania, Fremont, California, Regensburg, Germany and Tokyo, Japan.



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Cadmium	Cd	< 10	< 10
Calcium	Ca	< 10	< 50
Chromium	Cr	< 10	< 50
Cobalt	Co	< 10	< 10
Copper	Cu	< 10	< 50
Gallium	Ga	< 1	< 10
Germanium	Ge	< 10	< 10
Iron	Fe	< 50	< 100
Lead	Pb	< 10	< 10
Lithium	Li	< 1	< 1
Magnesium	Mg	< 10	< 50
Manganese	Mn	< 10	< 50
Molybdenum	Mo	< 10	< 10
Nickel	Ni	< 10	< 100
Potassium	K	< 1	< 1
Silicon	Si	< 10	< 50
Sodium	Na	< 10	< 10
Tin	Sn	< 10	< 100
Zinc	Zn	< 10	< 50

*all values in ppb

Specifications

Argon	< 20 ppb	Oxygen	< 100 ppb
Carbon Dioxide	< 100 ppb	THC (as Methane)	< 50 ppb
Carbon Monoxide	< 50 ppb	Water	< 200 ppb
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Micromachined Passive Devices in a Standard GaAs HEMT Technology

Although transistors are readily available with sufficiently high f_T for many RF applications, MMIC performance is often limited by the passive components in the circuit. Transmission lines, inductors and transformers all suffer low performance at high frequencies due to substrate losses and parasitic capacitances. One option for reducing these losses is to suspend the components, using either free-standing or membrane-supported structures, creating an air-gap between the suspended, shielded wires and the substrate.

The work described here is a collaboration between several French groups from the TIMA and LEMO Laboratories in Grenoble and the LEAME Laboratory of the Ecole Centrale de Lyon. Various papers* describe the use of front-side, bulk micromachining to create free-standing, passive components such as spiral transformers and inductors. These structures are fabricated by a maskless, wet etching process, which is compatible with the 0.2 μm GaAs HEMT technology used to fabricate the active components in the MMIC. The micromachining process is carried out after IC fabrication; the passivated electronic components are unaffected by the etching process.

Depositing spiral metal transmission lines on top of dielectric spirals forms spiral inductors or transformers. The areas inside the spiral are left open to expose the GaAs substrate. After passivation, except where the substrate is exposed, the die is dipped into the etching solution, and the bulk substrate under the spiral is etched away [see figure 1]. In large structures, such as the 7 turn spiral transformer shown in figure 2, dielectric arms at the corners of the structure provide mechanical support. The metal transmission lines marked "underpass" provide electrical connections to the center of the spiral.

The suspended structure with mechanical supports is very robust, and the free-standing spiral has an etch time approximately 10x less than the membrane-supported alternative, reducing the possibility of damage to the rest of the IC during etching. The required etch depth is small, since the effective permittivity decreases exponentially with etch depth. The capacitance between the wires and the backside ground plane can be reduced by a factor of two by removing only 5% of the substrate material beneath the metal line. One important factor to be incorporated into the design is the temperature rise which occurs when current flows in the spiral, since the substrate is no longer able to act as a heat sink.

Even with non-optimized transformer geometries, parasitic capacitances were reduced significantly using the micromachined structures, allowing a higher maximum operating frequency. The quality factor (Q) of free-standing inductors and the self-resonant frequency both increased by 60%. The technology is likely to prove advantageous in many RF circuits such as filters [see figure 3], matching networks and low noise amplifiers.

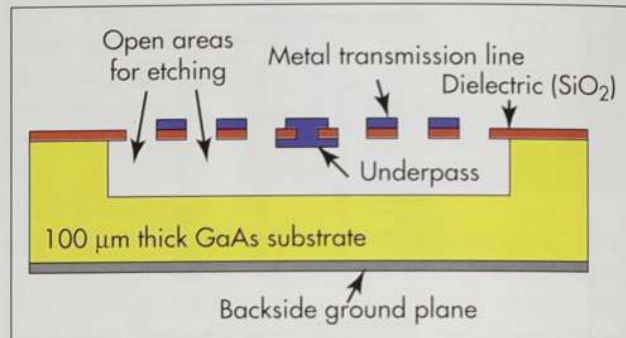


Figure 1. Cross-section of a suspended planar spiral inductor. Metal transmission lines are deposited on a spiral of dielectric material, and the underlying GaAs substrate is etched away through open areas to leave a free-standing structure. The underpass provides an electrical connection to the center of the spiral.

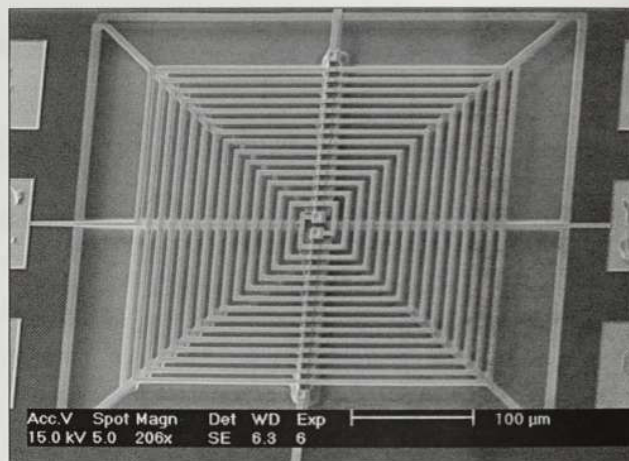


Figure 2. A micromachined, 7 turn planar spiral transformer. Dielectric "arms" at the corners of the suspended structure provide mechanical support.

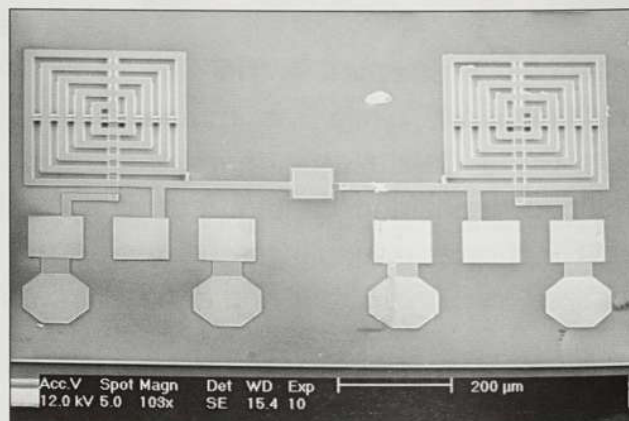


Figure 3. A filter incorporating 2 suspended inductors.

*See R. P. Ribas et al., *Mat Sci. Eng. B*, 1998, 51(1-3), p. 267; R. P. Ribas et al, *IEEE Electron. Dev. Lett.*, 1998, 19, p. 285; R. P. Ribas et al, *Proc. IEEE GaAs IC Symp.* 1998, 255; J. Lescot et al, *Proc. 10th Microcoll Conf.*, 1999



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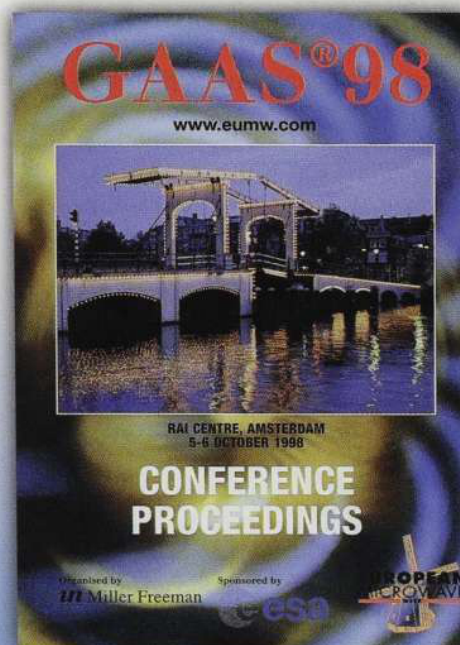
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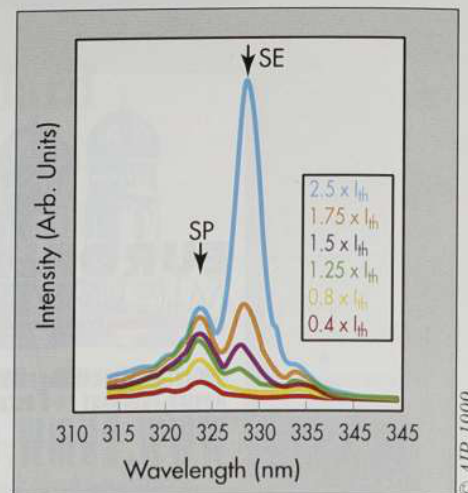
- Emission Studies of Nitride-based Materials

Deep Ultraviolet Stimulated Emission from $\text{Al}_x\text{Ga}_{1-x}\text{N}$

T.J. Schmidt et al, Appl. Phys. Lett. 1999, 74(2), p. 245

For the UV (190-350 nm) region the group III nitrides, in particular laser diodes and photodetectors based on $\text{Al}_x\text{Ga}_{1-x}\text{N}$, are interesting candidates for satellite communications, the remote sensing of contaminants, and for medical applications. Also, UV-emitting diodes are required as the light source for the next generation of white LEDs [see CS 5(1), p. 32]. Although there are many reports of AlGaIn-based UV photodetectors, there has been very little research into UV diode lasers using this material.

This paper, from Oklahoma State University and Honeywell Technology Center, reports room temperature stimulated emission from $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$ at 328 nm - this is the shortest such emission wavelength ever reported for a semiconductor. The 0.8 μm thick $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$ active region was grown at 1050°C by MOCVD on sapphire using an initial 625°C 50 Å thick AlN buffer layer. The device was optically pumped at 310 nm by a Nd^{3+} :YAG laser focused onto the edge of the specimen. The resulting stimulated emission is red-shifted from the spontaneous emission peak and centered on a wavelength of 328 nm (see figure). The results illustrate the suitability of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ based heterostructures for extending the range of semiconductor laser diodes deep into the UV region.



Room temperature emission spectra for $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$ at values above and below the threshold current, showing stimulated (SE) and spontaneous (SP) emission. The SE peak is centered at 328nm, deep in the UV - this is the lowest wavelength for room temperature SE ever reported for a semiconductor.

Intense UV Photoluminescence from In-doped GaN

X-Q. Shen & Y. Aoyagi, Jpn. J. Appl. Phys., 1999, Part 2 (1A/B), p. L14

This paper, from the Japanese research organization RIKEN, reports an alternative approach to achieving UV emission from GaN-based materials. The method involves doping a GaN layer with In at high growth temperatures, which results in a 35x increase in room temperature PL compared to undoped GaN. GaN films were grown on sapphire by GSMBE. The growth temperature was varied in the 690-800°C range, which is much higher than normal InGaIn growth temperatures, resulting in a very low level of In incorporation. Only the GaN peak was observed by X-ray diffraction of the In-doped GaN film, with no evidence for the formation of InGaIn alloy. The PL intensity of each film was highly sensitive to the growth temperature and the temperature of the In K-cell. The peak position of the GaN:In film (centered at 365 nm) and the FWHM linewidth were very similar to the undoped GaN films, however the PL intensity was much greater for GaN:In. The brightest sample showed a 35x increase in PL intensity relative to GaN. The authors suggest that the compensation of non-radiative centers by In doping may have a role in enhancing the PL intensity.

Green Light Emission from GaInNAs

S. Sakai & J. Wang, Jpn. J. Appl. Phys., 1998, Part 2 (12B), p. L1508

Fabrication of green InGaIn-based laser diodes has so far proved to be unsuccessful. Green emission requires a high In composition in the InGaIn active region, resulting in a large lattice mismatch between these layers and the AlGaIn/GaN cladding layers. Another approach is to use the quaternary alloy GaInNAs with a small amount of As, which has a bandgap corresponding to the 400-600 nm wavelength region. Obtaining sufficiently high material quality in this system is problematic due to thermodynamic phase separation between the arsenide and nitride alloys. At the other end of the compositional range, GaAs-based 1.3 μm lasers with a $\text{Ga}_{0.7}\text{As}_{0.3}\text{In}_{0.01}\text{As}_{0.99}$ active region have been demonstrated.

This paper, from the University of Tokushima, Japan, reports the first instance of room temperature green light emission from a GaInNAs/GaN superlattice, in which the active region has an estimated As composition of 10%. The samples were grown by atmospheric pressure MOCVD on a sapphire substrate, and consisted of 2.5 μm GaN, a 10 period MQW of GaN/InGaIn/GaInNAs/InGaIn, and 0.1 μm GaN. All layers were undoped and the MQW layer thicknesses were estimated as 0.7 nm, 0.23 nm, 0.23 nm and 0.23 nm respectively. Comparing room temperature photoluminescence spectra, the InGaIn/GaN MQW had a single peak at 401.2 nm while the sample containing the GaInNAs layers had several PL peaks in the 500-600 nm range, with an intensity 5-6x higher than the InGaIn/GaN MQW. The precise origin of these peaks is unclear at present, but they are clearly associated with the inclusion of GaInNAs in the structure.

Microelectronic Devices and Circuits

Base Station HFET Amplifiers with >100W Power

S. Goto et al, Proc. IEEE GaAs IC Symp., 1998, p. 77;

I. Takenaka et al, *ibid*, p. 81

Next generation personal digital communication systems in the 1.8-2.2 GHz range require linear base station transmitter amplifiers with output powers in excess of 100 W. Both these papers report the use of GaAs/AlGaAs heterostructure FETs, which offer improved maximum drain current and gate-to-drain breakdown voltage compared to MESFETs, as well as precise recess etch depth control. In both cases, 4 HFET chips were combined in a push-pull configuration with internal matching circuits to achieve 100 W output power.

Takenaka et al from NEC reported a push-pull amplifier with an output power of 140 W at 2.2 GHz, with 11.5 dB linear gain and 42% PAE. Under two-tone test conditions (2.2 GHz, 2.201 GHz), the amplifier exhibited low intermodulation distortion characteristics of less than -30 dBc at two-tone total output power of 46 dBm.

Goto et al from Mitsubishi Electric reported a 100 W FET chip with -35 dBc IMD3 and 24% PAE at 42 dBm output power. In order to reduce the component size and cost, the chip and package were miniaturized by lengthening the gate finger within the limits imposed by the gate resistance. The chip size ($1.41 \times 2.6 \text{ mm}^2$) and the package size ($17.4 \times 24.0 \text{ mm}^2$) are the smallest ever reported for this class of FET.

Single Voltage Operation of HFETs with >70% Efficiency

N. Hara et al, Proc. IEEE GaAs IC Symp., 1998, p. 198

This paper, from Fujitsu, reports a new type of enhancement mode HFET which provides single voltage operation of PAs in mobile phone handsets. To achieve single voltage operation and a low drain leakage current in the off state, it is necessary to use enhancement-mode FETs with a high current density and a high gate turn-on voltage V_f . It is difficult to obtain V_f in excess of 1 V using HEMTs and MESFETs, while FETs with ion-implanted n^+ -ohmic regions and high Al-content barrier layers make it possible to achieve V_f over 1.5 V.

In a conventional FET, there are two main leakage paths between the gate electrode and the n^+ -ohmic regions; one path is via the barrier and channel layers (path 1), and the other is directly through the cap layer (path 2). Leakage current along path 2 is inversely proportional to the distance from the gate to the n^+ -region (L_s), and increases when L_s is shortened in an attempt to increase the maximum drain current I_{ds} .

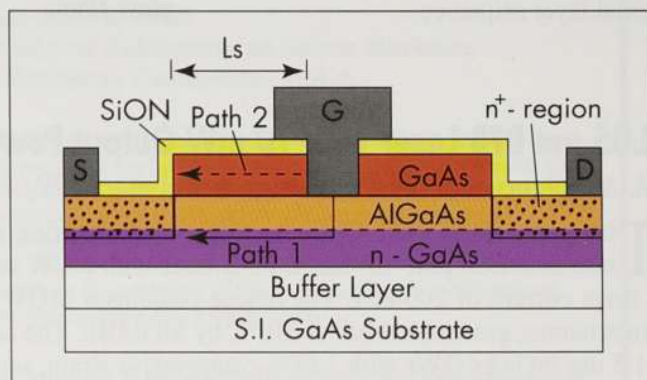
In the new device structure (see figure), the n^+ -region in the GaAs cap is removed, eliminating this leakage path. It becomes possible to increase I_{ds} by lowering L_s , without reducing V_f . The leakage current along path 1 is independent of L_s and can be reduced by including a high Al content barrier layer.

The maximum value of I_{ds} in the new FET (290 mA/mm) was 50% higher than in the conventional device, due to a reduction in L_s from 1.0 μm to 0.5 μm . However, the value of V_f remained unchanged at 1.4 V. In completely E-mode FETs ($V_{th} > 0.3 \text{ V}$), a power added efficiency as high as 70.6% was achieved for an output power of 33 dBm at a V_{ds} of 3.5 V and a frequency of 850 MHz.

Metamorphic HEMTs Grown on GaAs With an AlGaAsSb Buffer

M. Behet et al, Appl. Phys. Lett., 1998, 73(19), p. 2760

For high frequency applications, InGaAs/InAlAs HEMTs lattice-matched to InP substrates have demonstrated superior gain and noise performance over pseudomorphic AlGaAs/InGaAs HEMTs on GaAs. However, for reasons of cost, robustness, and crystalline quality, GaAs substrates are preferred over InP. Several groups have explored metamorphic (MM) InGaAs/InAlAs HEMTs on GaAs. This paper, from IMEC, Belgium and RWTH Aachen, Germany, reports growth of MM-HEMTs on GaAs, using a strain-relaxed $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}_{0.55}\text{Sb}_{0.45}$ buffer layer to accommodate the 3.8% lattice mismatch between the substrate and the $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{In}_{0.5}\text{Al}_{0.5}\text{As}$ quantum well. The 2 μm quaternary buffer was grown by MBE on a GaAs substrate with AlAs and AlSb nucleation layers. A 50 nm $\text{In}_{0.5}\text{Al}_{0.5}\text{As}$ layer was followed by the 20 nm $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ channel, a 5 nm $\text{In}_{0.5}\text{Al}_{0.5}\text{As}$ spacer and Si delta doping at $3.5 \times 10^{12}/\text{cm}^2$. The channel layer showed a carrier mobility of $8500 \text{ cm}^2/\text{Vs}$. Transistors with $0.25 \times 100 \mu\text{m}^2$ gates demonstrated transconductance values as high as 800 mS/mm, and S-parameter measurements revealed a cutoff frequency f_T of 87 GHz and a maximum oscillation frequency f_{max} of 140 GHz.



In conventional FETs of this type, leakage current can flow from the gate through the GaAs cap to the n^+ -region (path 2). In this structure, the n^+ -region in the cap is removed, eliminating path 2. The leakage current along path 1 is independent of L_s .

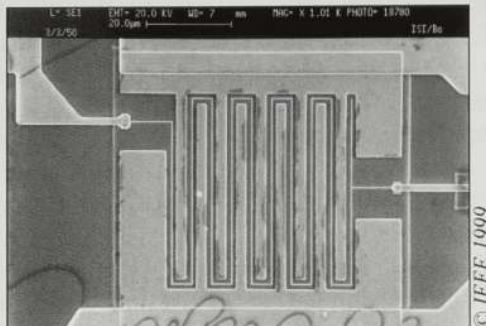
Optoelectronic Devices

OPFET with 200 A/W Responsivity at 1.3 μm

M. Marso et al, IEEE Photonics Tech. Lett., 1999, 11(1), p. 117

GaAs-based MESFETs and HEMTs have been reported to act as photodetectors in the 0.6-0.8 μm wavelength range. These devices, optimized for optical rather than electronic properties, are known as optically controlled FETs, or OPFETs, and offer the possibility of integration into optoelectronic circuits.

This paper, from Forschungszentrum Jülich, reports an optically-controlled, InGaAs/InAlAs/InP HEMT which is sensitive to a wavelength of 1.3 μm . The epitaxial layers were grown by MBE on a semiconductor-insulating InP substrate, and consisted of a 200 nm InAlAs buffer, a 200 nm lattice-matched InGaAs absorption layer, an 8 nm strained In_{0.75}Ga_{0.25}As channel, an 8 nm InAlAs spacer, $3 \times 10^{12}/\text{cm}^2$ Si δ -doping, a 40 nm InAlAs barrier and a 10 nm n⁺-InGaAs contact layer. The 0.3 μm gate length device (see photo) has a meander-shaped gate, avoiding the need for air bridges or via hole connections. Due to the InGaAs absorption layer beneath the channel, the device has a very high responsivity at 1.3 μm of up to 235 A/W with 11 μW incident backside illumination. The OPFET had a higher responsivity than an MSM photodetector with the same absorption layer thickness up to about 10 GHz. The OPFET concept should allow integration of high responsivity photodetectors and electrically-optimized HEMTs using the same epitaxial layer sequence.



SEM photo of the OPFET meander-shaped and interlocking finger-shaped source and drain contacts. The active area is square (50 x 50 μm^2) to optimize optical coupling with the light spot from a glass fiber.

2.05 μm DFB Laser with 10 mW Output Power

M. Mitsuhashi et al, IEEE Photonics Tech. Lett., 1999, 11(1), p. 33

This paper, from NTT Opto-electronics Laboratories, reports single mode operation of a 2.05 μm , InP-based DFB laser with a CW output power of 10.5 mW at a drive current of 200 mA. The device contains a MQW separate confinement heterostructure, grown on n-InP at 510°C by MOMBE. The active region consists of four 11.5 nm InGaAs QWs with 1.65% compressive strain, separated by 18.5 nm InGaAs barriers with 0.04% tensile strain. This region is surrounded by 50 nm lower and 100 nm upper InGaAsP SCH layers with a bandgap wavelength of 1.3 μm . To fabricate the DFB laser, first-order corrugations were formed on the upper InGaAsP SCH layer using electron beam lithography and wet etching. This was followed by a 3-step MOVPE regrowth process; firstly, a p-InP cladding layer was grown on the corrugated surface, then p-n blocking layers were grown around the 1.5 μm wide active region, and finally a p-InP cladding layer and p⁺-InGaAs contact layer were grown. The wafer was cleaved into 900 μm long bars, and the facets were coated with SiN. The tuning range of the wavelength was between 2.051-2.056 μm with a temperature tuning rate of +0.125 nm/°C. The CW output power at 200 mA was 10.5 mW at 25°C, and was over 4 mW at 55°C. The authors suggest that this laser is a suitable candidate for trace gas sensing at wavelengths beyond 2 μm .

GaAs/Al_xGa_{1-x}As Quantum Cascade Lasers

C. Sirtori et al, Appl. Phys. Lett., 1998, 73(24), p.3486

Quantum cascade (QC) lasers are the only semiconductor lasers operating at and above room temperature in the 5-12 μm range, and major developments have concentrated on the Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/InP material system. The output from a QC device results from intersubband transitions and is thus independent of the material system. This paper from Thomson-CSF, the University of Neuchâtel and the Ecole Polytechnique de Lausanne, demonstrates the general validity of QC laser principles by reporting a GaAs-based unipolar injection QC laser emitting at 9.4 μm . Although the general principles of population inversion are the same as for InP-based QC lasers, significant modifications were required to the active region design, the waveguide and the fabrication approach.

The QC laser was grown by MBE on a Si GaAs substrate, and began with a 0.6 μm Al_{0.90}Ga_{0.10}As cladding layer and a low-doped ($4 \times 10^{16} \text{ cm}^{-3}$), 1.4 μm GaAs layer. This design, which provides "double plasmon-enhanced confinement", compensates for the fact that the GaAs substrate has a lower refractive index than the active region and cannot act as a lower cladding layer for the waveguide. The subsequent 1.4 μm active area design contains a 30 period sequence of injectors/active regions made from Al_{0.33}Ga_{0.67}As barriers and GaAs wells. The upper waveguide was a 1.55 μm GaAs layer, which was followed by a 1.0 μm n-type Al_{0.90}Ga_{0.10}As cladding layer and a 0.7 μm n-type GaAs contact layer.

Lasing was achieved in pulsed mode from a QC active region 2.5 mm long and 24 μm wide with uncoated facets. A peak output power of 70 mW polarized normal to the layer (TM mode) was measured at 77K, and the device operated at a current density of 7.2 kA/cm² with a threshold voltage of 11.4 V. The maximum operating temperature was 140 K.

May

195th Meeting of the Electrochemical Society

May 2-7
Seattle, Washington
Contact: ECS
TEL: [1] 609 737 1902
FAX: [1] 609 737 2743
ecs@electrochem.org
<http://www.electrochem.org/meetings/195/symp.html>

11th International Conference on InP & Related Materials (IPRM '99)

May 16-20
Davos, Switzerland
Abstract Deadline: December 5, 1998
Contact: Hans Melchior
Swiss Federal Institute of Technology
TEL: [41] 1 633 2101
FAX: [41] 1 633 1109
h.melchior@iqe.phys.ethz.ch
<http://www.iqe.ethz.ch/iprm99/>

1999 IEEE Custom Integrated Circuits Conference (21st CICC)

May 16-19

San Diego, California
Contact: Melissa Widerkehr, CICC
TEL: [1] 301 527 0902
FAX: [1] 301 527 0994
cicc@his.com

9th Biennial Workshop on Organometallic Vapor Phase Epitaxy

May 23-29
Ponte Verda Beach, FL
Contact: Marlene Karl, TMS
TEL: [1] 724 776 9000 x234
FAX: [1] 724 776 3770
karl@tms.org
<http://www.tms.org/Meetings/Specialty/OMVPE99/OMVPE99.html>

1999 Conference on Lasers and Electro-Optics (CLEO '99) Quantum Electronics and Laser Science 1999 (QELS '99)

May 23-28
Baltimore, Maryland
Contact: OSA Conference Services
TEL: [1] 202 416 1980
FAX: [1] 202 416 6100
infor@osa.org
<http://www.osa.org>

1999 International Symposium on Power Semiconductor Devices & ICs (ISPSD)

May 25-28
Toronto, Ontario, Canada
Contact: Mr. Dan Kinzer, International Rectifier
TEL: [1] 310 726-8561
FAX: [1] 310 252-7167
dkinzer1@inf.com
<http://www.utoronto.ca/ispsd99>

Workshop on Compound Semiconductor Devices and Integrated Circuits (WOCSDICE) 1999

May 25-27
Paris, France
Contact: Joachim Würfl
Ferdinand-Braun-Institut
FAX: [49] 30 6392 2685
wocsdice@fbh-berlin.de

3rd International Workshop on MBE Growth Physics and Technology (MBE-GPT'99)

May 23-28
Warsaw, Poland
Contact: Prof. Marian Herman

TEL: [48] 22 83 15154
FAX: [48] 22 83 12160
itp@warman.com.pl
<http://www.warman.com.pl/~itp/MBE-GPT99>

June

1999 MTT-S International Microwave Symposium (IMS) and RFIC '99

June 13-18
Anaheim, California
Contact: Steve Maas
Nonlinear Technologies, Inc.
TEL: [1] 562 426 1639
FAX: [1] 562 426 1639
smaas@nonlinter.com
<http://www.mtt.org/ims1999>

57th Device Research Conference (DRC)

June 28-30
University of California, Santa Barbara
Contact: Bart Van Zeghbroeck
University of Colorado
TEL: [1] 303 492 2809
FAX: [1] 303 492 2758
bart.vanzeghbroeck@colorado.edu
<http://ece-www.colorado.edu/~drc/>

ABSTRACTS ARE BEING ACCEPTED ON THE FOLLOWING TOPICS:

Issues for Wide Bandgap Materials	Non-Destructive Testing in "In-Situ" Monitoring/Control
Issues for Reduced Dimensional Structures and Their Characterization	Novel and Artificially Structured Thermoelectric Materials
Issues for Ferroelectric and High Permittivity Materials	Thermoelectrics: Materials and Devices
Molecular Electronics	Infrared Materials and Devices
Organic Optoelectronics and Transistors	Si-Based Heterojunction Growth and Characterization
Epitaxy (MBE/MOVPE/CBE/MOMBE)	Compound Semiconductor Oxides: Processing and Properties
Epitaxy for Devices	Device Processing
Composite Materials and Applications	Defects, Defect Engineering, and Device Reliability
Ordering in Semiconductor Alloys	
Materials Integration	

The 41st Electronic Materials Conference

June 30–July 2, 1999
University of California at Santa Barbara
Santa Barbara, California, U.S.A.

The 1999 Electronic Materials Conference (EMC) will be the 41st in a series of conferences intended to provide a forum for topics of current interest and significance in the area of preparation and characterization of electronic materials. Sponsored by the Electronic Materials Committee of The Minerals, Metals & Materials Society (TMS), the conference will be held on the campus of the University of California at Santa Barbara, June 30–July 2, 1999.

The EMC is again being coordinated with the Device Research Conference of the Institute of Electrical and Electronics Engineers (IEEE), which will be held at the same location, June 28–30, 1999. This coordination is made in recognition of the strong interaction between electronic materials and device research and should provide for a maximum exchange of information between attendees of both conferences.

An exhibit of electronic materials technology and services is also planned. For information on how your organization can participate as an exhibitor, please contact: Cindy A. Wilson at telephone: (724) 776-9000, ext. 231; fax: (724) 776-3770; or e-mail: wilson@tms.org.

For general information, please contact: TMS Customer Service Department, 420 Commonwealth Drive, Warrendale, PA 15086-7514; telephone: (724) 776-9000, ext. 270; fax: (724) 776-3770; e-mail: csc@tms.org.

Information on this and all TMS-sponsored and cosponsored meetings is available via TMS Online at the following address: <http://www.tms.org/Meetings/Meetings.html>.

July

41st Electronic Materials Conference (EMC)

June 30-July 2
University of California,
Santa Barbara

Contact: TMS
TEL: [1] 724 776 9000
FAX: [1] 724 776 3770
csc@tms.org

3rd Int'l Conf. on Nitride Semiconductors (ICNS-3)

July 5-9
Montpellier, France
Contact: Pierre Lefebvre
Université de Montpellier
TEL: [33] 4 67 14 37 60
FAX: [33] 4 67 14 37 56
icns3@ges.univ-montp2.fr
http://bilbot.ges.univ-montp2.fr/icns3.htm

6th Int'l Workshop on Femtosecond Technology (FST '99)

July 13-15
Chiba, Japan
Abstract Deadline: April 16
Contact: FST'99 Secretariat
Femtosecond Tech. Research Assoc.
TEL: [81] 298 47 5181
FAX: [81] 298 47 4417
fst@festa.or.jp
http://www.festa.or.jp/meeting/fst99-e.html

1999 Integrated Photonics Research Topical Meeting (IPR '99)

July 19-21
Santa Barbara, CA
Abstract Deadline: March 17
Contact: OSA
TEL: [1] 202 416 1985
FAX: [1] 202 416 6100
info@osa.org
http://www.osa.org

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

July 27-30
Tsukuba, Japan
Contact: Dr. Makoto Konagai
Tokyo Institute of Technology
TEL: [81] 3 5734 2554
FAX: [81] 3 5734 2897
konagai@pe.titech.ac.jp
http://solid.pe.titech.ac.jp/cbe-7

August

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

August 1-6
Tucson, Arizona

Contact: Tony Gentile
ACCGE-11 Secretariat
TEL: [1] 805 492 7047
FAX: [1] 805 492 4062
aacg@lafn.org
http://www.aml.arizona.edu/aacg

1999 International Microwave and Optoelectronics Conference (IMOC '99)

August 9-12
Rio de Janeiro, Brazil
Contact: Ms Denis Consonni
LME-EPUSP, Brasil
TEL: [55] 11 8185255
FAX: [55] 11 8185585
imoc99@dmo.fee.unicamp.br
http://www.mc21.fee.unicamp.br/imoc99/

1999 International Symposium on Compound Semiconductors (ISCS '99)

August 22-26
Berlin, Germany
Abstract Deadline: April 12
Contact: ISCS'99 Secretary
Paul-Drude-Institute
TEL: [49] 30-20377-352
FAX: [49] 30-20377-201
ISCS99@pdi-berlin.de

September

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

September 6-7
Aachen, Germany
Abstract Deadline: July 2
Contact: Klaus Heime
TEL [49] 241 807745
FAX [49] 241 8888 199
mailbox@iht.rwth-aachen.de
http://www.iht.rwth-aachen.de/miomd.html

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

September 13-17
Miyagi, Japan
Abstract Deadline: April 30
Contact: Prof S. Zaima
Nagoya University
TEL: [81] 52 789 2762
FAX: [81] 52 789 3818
zaima@alice.xtal.nagoya-u.ac.jp

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

September 26-28
Minneapolis, Minnesota
Contact: Janice Jopke
CCS Associates
TEL: [1] 612 934 5082
FAX: [1] 612 934 6741
jjopke@aol.com

October

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

October
Las Vegas, Nevada
Contact: Jay Morreale
Palisades Institute
TEL: [1] 212 460 9700
FAX: [1] 212 460 5460
jmorreal@newyork.palisades.org

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

October 4-8,
Munich, Germany
Abstract deadline: March 19
Contact: Hans Hartnagel
Technische Hochschule Darmstadt
TEL: [49] 6151 162 162
FAX: [49] 6151 164 367
hfmwe001@hrz2.hrztu-darmstadt.de
http://www.eumw.com

18th North American MBE Conference (NAMBE-18)

October 10-13
Banff, Canada
Abstract Deadline: June 1999
Contact: Dr Z Waleilewski
National Research Council
TEL: [1] 613 990 4557
FAX: [1] 613 941 4667
zbig.wasilewski@nrc.ca

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

October 10-15
Research Triangle Park, NC
Abstract Deadline: May 15
http://www.icscrm99.ncsu.edu/

21st Annual GaAs IC Symposium

October 17-20
Monterey, CA
Abstract Deadline: April 30
http://www.gaasic.org

196th Meeting of the Electrochemical Society

October 17-22
Honolulu, Hawaii
Abstract Deadline: May 14
Contact: ECS
TEL: [1] 609 737 1902
FAX: [1] 609 737 2743
ecs@electrochem.org
http://www.electrochem.org

46th National American Vacuum Society (AVS) Symposium

October 25-29
Seattle, Washington
Contact: Marion Churchill, AVS
TEL: [1] 212 248 0200
FAX: [1] 212 248 0245
Marion@vacuum.org
http://www.vacuum.org

November

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

November 1-5
Kyoto, Japan
Abstract Deadline: May 20
Contact: Prof. Shizuo Fujita
Kyoto University
Tel: [81] 75 753 5364
Fax: [81] 75 753 5898
fujitasz@kuee.kyoto-u.ac.jp
http://fujita.kuee.kyoto-u.ac.jp/26kyoto/

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

November
London, UK
Contact: Ali Rezazadeh
Kings College London
TEL & FAX: [44] 171 873 2879
ali.rezazadeh@kcl.ac.uk
http://www.ieee.org

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

November 8-11
San Francisco, California
Contact: IEEE/LEOS
TEL: [1] 732 562 3989
FAX: [1] 732 562 8434
m.estrin@ieee.org
http://www.ieee.org/society/leos/

1999 Fall MRS Meeting

November 29-December 3
Boston, MA
Abstract Deadline: June 21
Contact: MRS
TEL: [1] 724 779 3003
FAX: [1] 724 779 8313
info@mrs.org
http://www.mrs.org

December

1999 IEEE International Electron Devices Meeting (IEDM)

December 5-8
Washington, DC
Contact: Ms Phyllis Mahoney
Widerkehr & Associates
TEL: [1] 301 527 0900
FAX: [1] 301 527 0994
pwmahoney@aol.com

Plan to Attend

IPRM'99

Eleventh International Conference on INDIUM PHOSPHIDE and RELATED MATERIALS

16 - 20 May 1999
Davos, Switzerland

IPRM'99 is the major conference worldwide on Indium Phosphide and Related Materials. It covers all aspects of Indium Phosphide and Related Materials, from bulk crystal growth and characterization, epitaxy, processing, electronic and optoelectronic devices, new materials and nanostructures. Since its inception in 1989, the conference is growing steadily, both in the number of high-quality submitted papers and in the number of attendees. It brings together basic scientists, technologists and device developers as well as manufacturers and exhibitors of Indium Phosphide related equipment, devices and characterization techniques.

Scope of the Conference
Bulk Crystal Technology and Characterization
Epitaxy
Processing
Electron Devices
Optoelectronics
New Materials and Nanostructures

For more information visit the conference WWW site at <http://www.iqe.ethz.ch/iprm99>
or send your inquiries by email to iprm99@iqe.phys.ethz.ch

ICCBE-7

7th International Conference on Chemical Beam Epitaxy and Related Growth Techniques

The 7th International Conference on Chemical Beam Epitaxy and Related Growth Techniques (ICCBE-7) will be held in Tsukuba, Japan on July 27-30, 1999.

Topics to be emphasized are:

- Advances in CBE, MOMBE, GSMBE, MBE, MOVPE and related growth techniques
- Growth mechanisms, selective and non-planar growth, novel precursors
- In situ monitoring and novel tools
- Characterization of grown films and interfaces
- Physics and device aspects of films and heterostructures
- Quantum-nanostructures, Nitrides, Oxides
- New/Novel materials: new semiconductors, organic films, metal alloys

IMPORTANT DATES

Late News Deadline	June 5, 1999
Manuscript Deadline	June 30, 1999
Conference	July 27-30, 1999

WWW HOME PAGE

More detailed information is available from the following web site: <http://solid.pe.titech.ac.jp/cbe-7>



July 27-30, 1999

Tsukuba, Japan

HP Reorganizes

On March 2, as this issue went to press, Hewlett-Packard announced plans to split into two independent companies. "We are taking this action to sharpen the strategic focus of our businesses, improve their agility and increase their responsiveness to customers and partners," said Hewlett-Packard President and CEO Lewis E. Platt.

A new company, focused on HP's measurement businesses, will be spun-out of the existing company. This new company, which has not yet been named, will be comprised of HP's test-and-measurement, chemical-analysis and medical businesses. It will also include HP's extensive compound semiconductor activities. These businesses represented \$7.6 billion of HP's total revenue of \$47.1 billion in fiscal 1998. An initial public offering (IPO) of 15% of the measurement company's outstanding shares is planned by year-end. This offering would be the largest technology IPO in Silicon Valley history.

The second company, focusing on computing and imaging, will continue to operate under the Hewlett-Packard name and will include all of HP's computing systems, software and services, personal computer, and printing businesses.

Industry observers speculate that the split results from lower pricing of personal computers, which has contributed to a two-year stretch of lagging stock price growth for HP. The test and measurement businesses, many of which are focused on fiber optic, wireless and optoelectronics components, have been comparatively more profitable than the computer businesses.

According to Strategies Unlimited, HP is the world's largest producer of compound semiconductor devices, with sales of more than \$800 million in 1997, the last year for which figures are available.

1998 Earnings Round-Up

Plus a review of recent news and financial results for the December quarter

MARIE MEYER

With the latest round of quarterly earnings reports now nearly finished, it is possible to assess the profitability of the Portfolio companies for 1998. As was the case last year, Vitesse leads all of the companies in profitability, earning \$57.8 million on \$200 million in revenues. Those figures are up 55% and 70% respectively in comparison to last year.

In terms of revenue growth, RF Micro Devices turned in the most impressive performance, generating \$108.9 mil-

lion in sales, up 160% over last year. Another GaAs IC manufacturer, Alpha Industries, reported the biggest improvement in profitability, raising income 1200% to \$16.6 million. Also showing an impressive improvement was SDL, which record income of \$12.7 million. In 1997 the company incurred a loss of \$25 million, most of which was due to one-time charges relating to a lawsuit.

Over all, ten of the portfolio companies reported a profit for 1998, and 11 reported a loss – see tables, next page.

Company	Symbol	Exchange	Description	Closing Price March 4	52 Week Low	52 Week High	Market Cap (\$M)	Daily Volume ('000s)	P/E Ratio
Alpha Ind.	AHAA	NASDAQ	GaAs ICs	18.25	5.75	27.88	291.3	273	17.66
Anadigics	ANAD	NASDAQ	GaAs ICs	13.69	4.63	21.38	201.7	202	-
APA Optics	APAT	NASDAQ	Optoelectronics	6.13	4.00	7.5	52.1	3,818	-
ATMI	ATMI	NASDAQ	Mtls & Equip	17.13	10.88	33.75	379.1	172	-
AXT	AXTI	NASDAQ	Mtls & Equip	15.31	5.25	19.88	246.1	186	36.01
Celeritek	CLTK	NASDAQ	GaAs ICs	4.63	2.50	15.00	33.6	44	-
Coherent	COHR	NASDAQ	Optoelectronics	14.13	7.50	24.75	337.4	120	22.12
Conexant	CNXT	NASDAQ	GaAs ICs	17.38	13.00	22.00	1,649	1,370	-
Cree	CREE	NASDAQ	Optoelectronics	33.00	10.50	53.25	429.1	290	48.39
Emcore	EMKR	NASDAQ	Mtls & Equip	19.13	6.00	28.75	180.3	59	-
Kopin	KOPN	NASDAQ	Mtls & Equip	16.31	11.38	24.88	199.3	82	-
Ortel	ORTL	NASDAQ	Optoelectronics	7.63	6.50	20.25	90.6	72	-
PlasmaTherm	PTIS	NASDAQ	Mtls & Equip	3.44	2.38	9.00	38.6	38	26.56
RFMD	RFMD	NASDAQ	GaAs ICs	84.75	10.50	84.44	1,661	424	+
SDL	SDLI	NASDAQ	Optoelectronics	59.63	8.13	60.25	841.4	204	65.37
SLI	SLIC	NASDAQ	Optoelectronics	0.38	0.31	2.06	3.8	40	-
Spire	SPIR	NASDAQ	Mtls & Equip	4.03	2.38	18.00	13.1	8	-
TriQuint	TQNT	NASDAQ	GaAs ICs	17.44	11.00	26.75	165.1	104	-
Uniphase	UNPH	NASDAQ	Optoelectronics	89.75	31.25	96.69	3,565	739	-
Uniroyal Tech.	UTCI	NASDAQ	Optoelectronics	8.38	6.75	10.88	101.2	32	18.47
Vitesse	VTSS	NASDAQ	GaAs ICs	46.63	17.13	52.94	3,467	1,133	61.47
European Companies (Currency data in Euros)									
Aixtron	AIX	Neur Mkt.	Mtls & Equip	190	88.3	218	950	17	+
Picogiga	n.a.	N. Marche	Mtls & Equip	13.01	11.60	44.52	20.5	5	20

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

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- GaN microwave power HEMTs – Gerry Sullivan (Rockwell)
- SiC epitaxial growth – Roland Rupp (Siemens)
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GaAs IC Briefs

For the December quarter **Alpha Industries** reported relatively flat sales of \$32.5 million, but a 50% increase in net income, which rose to \$4.8 million. The company's Wireless Semiconductor sector had sales of \$17.9 million while the Application Specific Products (ASP) sector had sales of \$7.7 million. Deliveries to Motorola represented approximately 27% of total sales.

Anadigics reported revenue of \$22.6 million for the December quarter, down

19% from the year ago period due to a significant decline in sales to the wireless industry. However, in comparison to the September quarter, net sales for wireless and CATV applications actually increased, but they were partially offset by a decline in fiber optic sales. CATV sales increased 48%, with strong growth from the cable modem and set-top box markets.

For the quarter, the company reported a net loss of \$3.9 million, as compared to net income of \$4.6 million in the year ago period. These results reflect special charges totaling \$7.3 million, primarily

associated with the planned closing of the existing wafer fabrication facility as the company switches over to a new 6" fab.

RF Micro Devices reported revenue of \$41.5 million for the December quarter, an increase of 212% over the corresponding quarter of fiscal 1998 and an increase of 32% over the previous quarter's revenue of \$31.4 million. Three-volt GaAs HBT power amplifiers continued to dominate shipments. Much of the sequential sales increase this quarter was attributed to output from the company's GaAs HBT fabrication facility, which

1998 Losses

Company	'98 Results (in '000's)	Comparison with 1997
Anadigics		
Revenue	\$86,060	Down 16%
Income	(\$9,558)	Down from profit of \$15.3 mil
APA Optics		
Revenue	\$1,047	Down 61%
Income	(\$2,183)	Down from loss of \$440K
Celeritek		
Revenue	\$46,810	Down 10%
Income	(\$4,764)	Down from profit of \$4.2 mil
Emcore		
Revenue	\$41,482	Down 20%
Income	(\$20,209)	Up from loss of \$31.2 mil
Kopin		
Revenue	\$26,904	Up 64%
Income	(\$2,968)	Up from loss of \$4.3 mil
Ortel		
Revenue	\$71,767	Down 15%
Income	(\$6,569)	Down from profit of \$23.9 mil
Semiconductor Laser Int'l ^[1]		
Revenue	\$1,974	Up 316%
Income	(\$4,322)	No change
Spire ^[1]		
Revenue	\$15,328	Down 34%
Income	(\$2,428)	Down from profit of \$2.3 mil
TriQuint Semiconductor		
Revenue	\$111,555	Up 56%
Income	(\$3,885) ^[2]	Down from profit of \$6.8 mil
Uniphase		
Revenue	\$212,394	Up 47%
Income	(\$74,447)	Down from loss of \$18.7 mil ^[3]

Notes

^[1] Based on estimated results for the December quarter.

^[2] Includes one-time charges relating to acquisition of the Raytheon/TI GaAs operation, settlement of a shareholder lawsuit, and the transition to a new fab.

^[3] '98 results include \$ 113.6 Million in one-time changes and '97 results include \$38.8 Million in one-time changes, both relating to acquisitions.

1998 Profits

Company	'98 Results (in '000's)	Comparison with 1997
Alpha Industries		
Revenue	\$123,909	Up 15%
Income	\$16,656	Up 1200%
Aixtron ^[1]		
Revenue	\$57,610	Up 33%
Income	\$6,160	Up 76%
ATMI		
Revenue	\$97,800	Down 15%
Income	\$6,500 ^[2]	Up 26%
American Xtal Tech.		
Revenue	\$43,290	Up 71%
Income	\$6,326	Up 96%
Coherent		
Revenue	\$414,711	Up 4%
Income	\$15,622	Down 63%
Cree		
Revenue	\$48,536	Up 36%
Income	\$8,851	Up 126%
Plasma-Therm		
Revenue	\$49,089	Up 10%
Income	\$1,418 ^[3]	Down 70%
RF Micro Devices		
Revenue	\$108,992	Up 160%
Income	\$5,991	Up 51%
SDL		
Revenue	\$106,167	Up 16%
Income	\$12,678	Up from loss of \$25M
Uniroyal Technology		
Revenue	\$218,538	Up 2%
Income	\$1,046	Down 62%
Vitesse		
Revenue	\$200,620	Up 70%
Income	\$57,883	Up 55%

Notes

^[1] Based on estimated results for the December quarter.

^[2] Includes one-time acquisition and restructuring charges of \$2.1M.

^[3] Reflects one-time charges of \$3.5 Million for restructuring and inventory write-down.

rose 161% from \$4.4 million in the second quarter to \$11.5 million in the third quarter. 89.8% of the company's revenues was derived from the sale of GaAs HBT products.

TriQuint Semiconductor announced that revenues for the December quarter were a record \$30.9 million, a 68% increase over the \$18.5 million in the comparable period of 1997. Net income was also a record at \$3.5 million, a 129% improvement over the \$1.5 million reported for the year ago period. December quarter revenue included \$495,000 in non-operational income.

TriQuint also recently announced that Nokia and Raytheon became its two largest customers in 1998. Sales to Nokia, which accounted for 12% of TriQuint's revenue, consisted of GaAs ICs for the receiver portion of "most of" Nokia's TDMA cell phones. Raytheon purchases a variety of GaAs ICs from TriQuint Texas, relating to the sale of that facility (the former Texas Instruments GaAs operation) by Raytheon to TriQuint in 1998. Raytheon accounted for just over 10% of TriQuint's sales.



Vitesse reported revenues of \$60.2 million in the December quarter, an increase of 73% over the year-ago period and an increase of 11% over the \$54.1 million reported in the previous quarter. Net income was \$15.4 million, compared to net income of \$10.4 million for the year-ago period and net income of \$16.5 million for the previous quarter. This was the result of an increase in the income tax rate from 20% to 33%.

Optoelectronics Briefs

Cree Research reported that its revenue increased 39% to \$14.0 million in the December quarter, attributable to an 128% increase in LED sales. This was

due in part to the introduction of new high brightness LEDs, but was mostly the result of strong demand for the company's older, "standard brightness" product. This despite the fact that Cree has recently seen a 35% decline in the average sales price for this product. Sales of SiC wafers were up 48%. The company says this was due to quality improvements, along with the availability of the larger 2" wafers during fiscal 1999.

Cree's gross profit margins rose Gross to 47% during the December quarter, as compared to 35% during the year-ago period. This is attributed to the introduction of the "conductive buffer" high brightness LED chip, which has a vertical structure that allows use of top and bottom contacts, thereby simplifying processing. Cree also began to use the larger 2" dia. SiC wafers; however, the company says it is still in the early stages and has not yet achieved production efficiency.

Consistent with their earlier pre-announcement, **Ortel** reported revenues for the December quarter of \$16.9 million, a 14% decrease from the \$19.8 million reported for the immediately preceding and 9% decrease from \$18.6 million recorded a year ago. The net loss totaled \$1.1 million, compared with net income of \$605,000, a year ago. Revenues from the sale of broadband products totaled \$12.0 million, down 8%. Sales of satellite and other communications products totaled \$4.9 million, down 26%. The company indicated that results would continue to be disappointing in the current quarter.

SDL announced record revenues and earnings for the December quarter. Revenues were \$29.4 million, compared to \$24.8 million in the year-ago quarter. Net income more than doubled, rising 125% to \$4.1 million.

Commenting on the quarter, Donald R. Scifres, Chairman and CEO, said, "We are very pleased by the growth of our communications product lines. Driven by demand in the long haul terrestrial sector, our communications products represented 66% of our total fourth quarter revenue

versus 47% in the same quarter last year." He indicated that demand for SLI's 980 nm pump modules has grown over 100% over the past 12 months.

On February 10, 1999, **Semiconductor Laser International** announced that secured between \$2 - \$2.75 million in equity financing from bmp Mobility AG Venture Capital, a German investment company. BMP will receive approximately 16% of the shares of SLI.

BMP describes itself as "a venture capital company with 25 investments in the areas of information, communication, medical, biotech, and laser technology." The company says it intends to continue to expand its investments in companies in laser and laser related businesses, and that one of its affiliated companies will distribute SLI's products in Western Europe. This appears to be BMP's first foray into the laser diode field. Representatives of the company were not available for further comment.

This transaction may be a reprieve of sorts for SLI - as reported earlier, the company was in immediate danger of running out of cash. However, given that SLI had operating losses of over \$3 million in the past nine months, it is unclear whether BMP's investment will be enough to keep the company afloat in the long term, if SLI cannot achieve positive cash flow. Currently, SLI's cost of sales exceeds the value of sales - i.e., it is selling its products for less than it costs to make them.

Compounding SLI's cash flow problems is the fact that most of its suppliers have, in the company's words, "either stopped delivery or conditioned delivery on payment of past due bills or COD [cash on delivery]". The company also recently disclosed that it has fallen behind on its tax and insurance obligations.

Moreover, SLI is engaged in a dispute with its largest customer, Rocky Mountain Instruments (RMI), leading to cancellation of \$1.5 million in orders. RMI claims that products it received were defective. SLI has indicated that RMI, which accounted for 39% of SLI's net sales in 1998, has now ceased making purchases from SLI.

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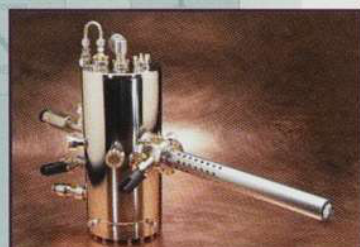
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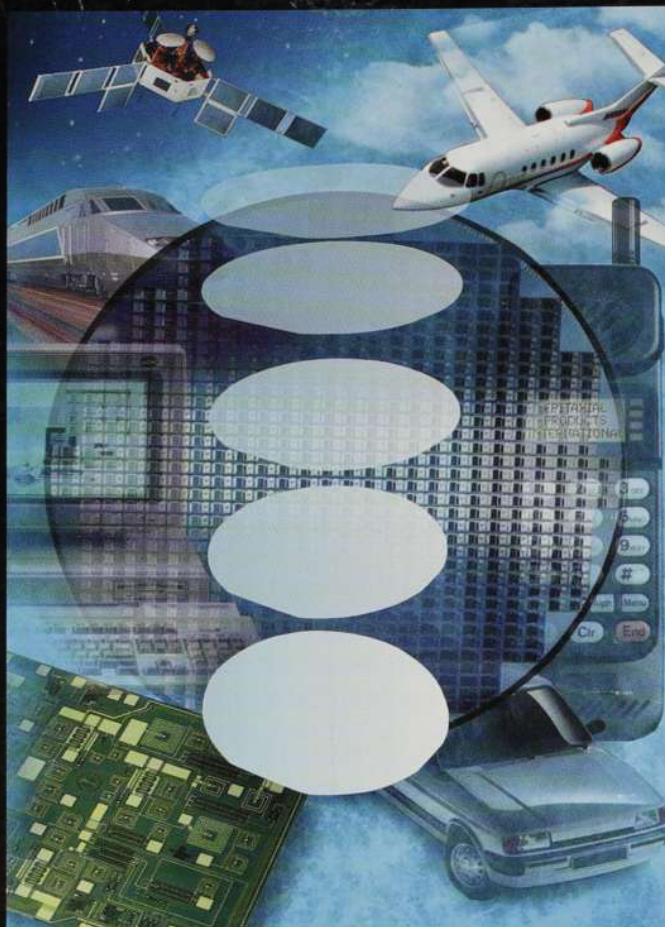
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