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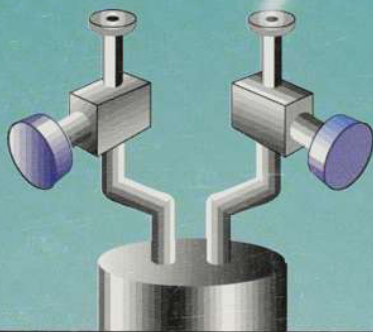
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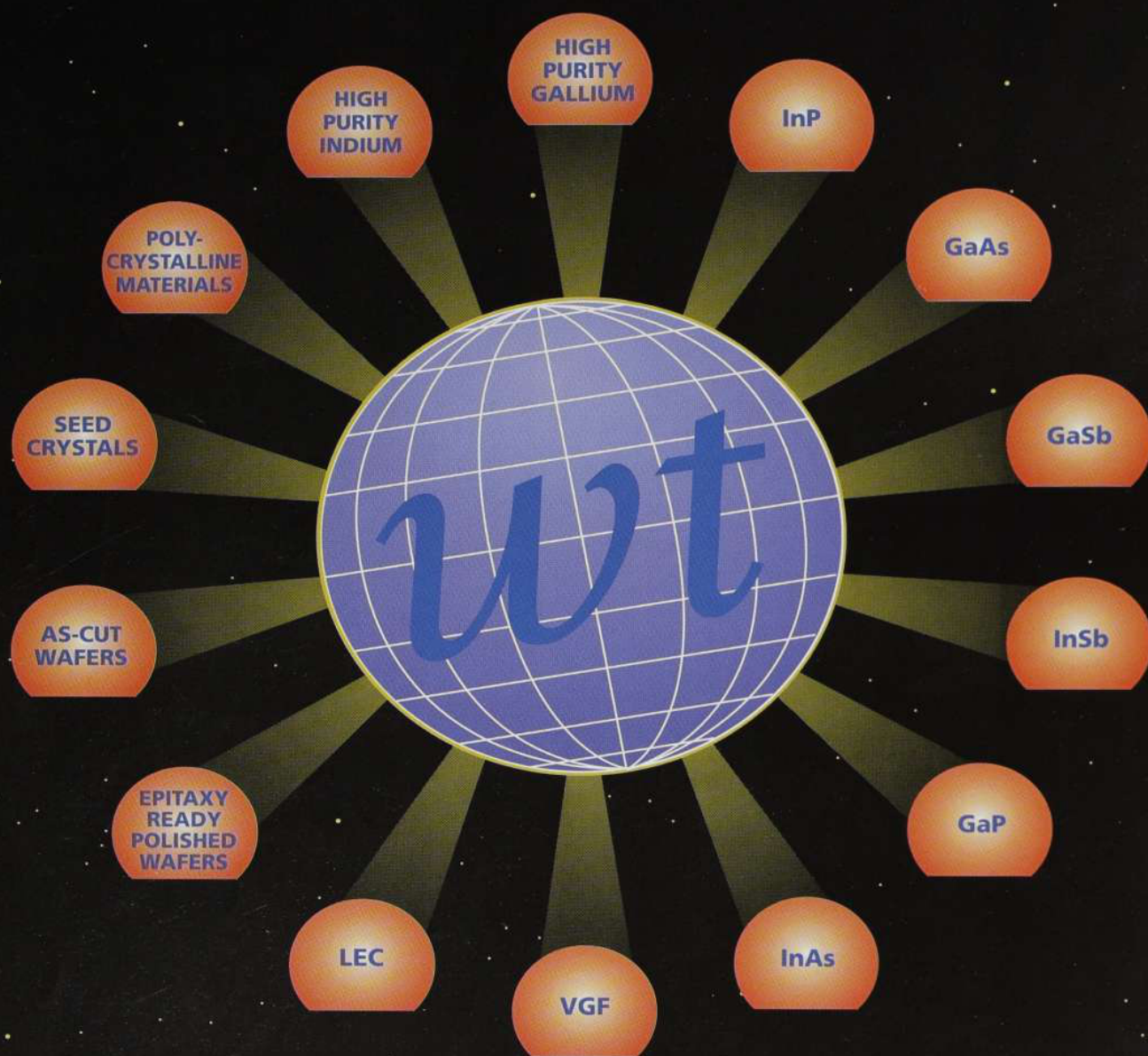
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- Does CBE Have A Future?
- Directory of Epiwafer Vendors

Also in this Issue:

- Anadigics Takes a Tumble
- Resonant Tunneling Diodes
- Optical Fiber Conference



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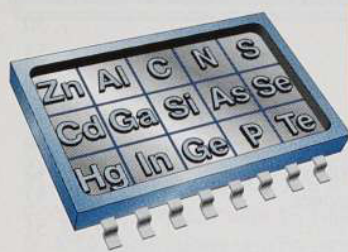
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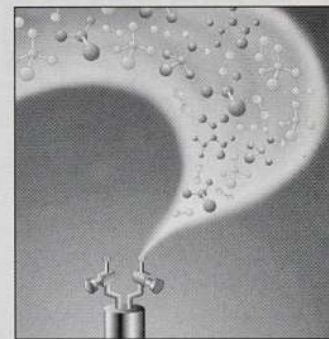
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The GaAs IC business loses some of its glamour as TriQuint & Anadigics struggle in the stock market.



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Anadigics, Celeritek, TriQuint launch 3V power amplifiers for cellular handsets...10W power amp module from Celeritek...Plus a report on new GaAs ICs for telecommunications, including new product introductions from the Multilink/TRW venture; a 10 Gbit/s PHEMT IC from Anadigics; and Rockwell enters SONET/SDH market with GaAs HBTs...Also: A review of the role of electronic components in optical networks.

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IBM Acquires Design Group to Boost SiGe Effort - page 7

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Disappointing Outlook for Power Amp Product Line Forces Anadigics to Cut Back

Loss of market share leads to layoffs and delayed opening of new fab; collapse in share price leads to lawsuits

For Anadigics, 1997 will be remembered as the best of times. Unfortunately, 1998 is, thus far, looking like the worst of times for this GaAs IC manufacturer.

The company passed two major milestones last year: it shipped its 100-millionth GaAs chip; and it surpassed \$100 million in annual sales. Anadigics' growth has been fueled largely by sales of power amplifiers and other analog ICs for wireless communications, which have recently made up more than half of their sales. See charts, below. In 1997 Anadigics claimed to supply 15% of the worldwide market for wireless handset power amps; all other GaAs suppliers combined are believed to have around 5% of the market.

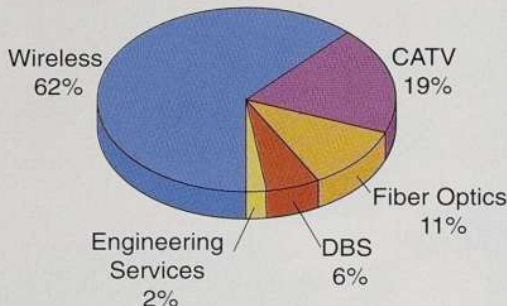
Anadigics reportedly told analysts last August that their goal was to capture up to 45% of the total power amp market. But now, in the face of more intense competition and loss of major orders, it looks like they will struggle for a 10% market share in 1998. According to Anadigics President and CEO Ron Rosenzweig, wireless sales for the first quarter of 1998 will be down by 50%. Any growth which may be expected from their other product lines, which include CATV and telecommunications, won't be enough to make up the difference, which means that Anadigics will likely show a decline in revenue and a loss for the quarter.

The company is reluctant to discuss the forecast for the rest of the year - but their recent actions speak volumes. The opening of their new fab, which would more than double their capacity, has been delayed until next year. And worse yet, on March 2 Anadigics announced it was laying off 100 of its 580 employees. In the face of shrinking orders, the extra capacity and the extra workers simply aren't needed.

What Went Wrong?

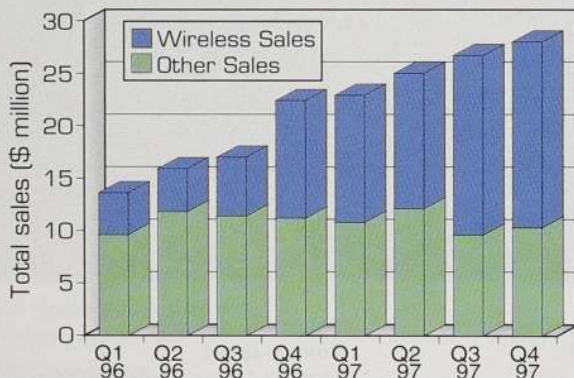
Anadigics appears to have been hit by a number of problems, all at once. The company has said that the Asian financial crisis, which may cause a slowdown in new phone sales, is partly responsible, as well as increased competition from other GaAs suppliers and Si MOSFETs (but not, as has been rumored, SiGe circuits). The company also experienced serious packaging-related production problems in the fourth quarter of 1997, which cost \$2 million to remedy and which apparently harmed some customer relationships. And, according to Rosenzweig, some of the major cell phone models that use Anadigics' power amps are being obsoleted more quickly than anticipated, while others are being produced in lower numbers than originally forecast. The company is beginning to sample its first 3V power amps. Other

Anadigics Q4 1997 Sales



Wireless ICs made up 62% of Anadigics' sales last quarter.

Anadigics Sales, 1996 - 1997



Wireless sales, as a percentage of total sales, have more than doubled in the past two years.

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GaAs fabs, such as RF Micro Devices and Alpha Industries, began volume production of 3V power amps last fall, but Anadigics is not expecting to go into production until the second half of this year at the earliest. Moreover, the major handset manufacturers have been very slow to roll out 4.8V dual band phones, which were supposed to be a big area for Anadigics.

As a result of all this bad news, Anadigics' share price has been hammered. See Chart, below. At least four shareholder class action lawsuits were filed in March, each alleging that the top management knew that their power amp business was heading for trouble, but they did nothing to alert shareholders to the problems. The most serious allegations revolve around the loss of orders from Nokia and Ericsson, who accounted for more than 25% of Anadigics' sales in 1996 (the last year for which figures are available). According to one of the class action complaints, Anadigics has known since September or earlier that Nokia was switching to GaAs HBT circuits from RF Micro Devices for the power amps for its new series of GSM handsets. The complaint also states that "throughout 1997, Anadigics repeatedly failed to meet Ericsson's contract deadlines for numerous products", and that "Anadigics was unable to satisfy Ericsson's output power and battery efficiency specifications for several of Ericsson's products, including Ericsson's latest series of dual band/dual mode phones". As a result, the complaint states, Ericsson switched to Si power amps manufactured by Hitachi.

What Does This Say About GaAs?

While Anadigics has been reluctant to discuss details about lost orders, they have made it clear that they are feeling more heat from Si manufacturers as well as other GaAs fabs. Who are the culprits? RF Micro Devices, obviously; selling Nokia on their HBT power amps (see CS 4(2), p. 7) was considered quite a coup. (Alpha is supplying most of their 3V chips to Motorola, which has not traditionally been one of Anadigics' big customers.) Rockwell has also recently suggested that they are cutting into Anadigics' market share.

There have also been rumors circulating about Anadigics evaluating samples of SiGe ICs from various sources, which was supposed to be indicative of a possible switch to a new technology. But Rosenzweig recently reiterated his company's enthusiasm for GaAs in a recent conference call with investment analysts. He predicts that GaAs will continue to increase its share of the power amp market "at a fairly good rate". He also said "We believe as we go forward towards 3 V technology that GaAs will get a substantially larger share of the total market, and we believe that Anadigics will be a beneficiary of that trend". He went on to say that in light of the major trends in the wireless handset market - the move to lower voltages and higher frequencies, coupled with the increased emphasis on higher efficiencies - he believes it is going to be "more and more difficult for silicon to compete".

The hope for the remaining employees and the investors who haven't already bailed out is that Anadigics does have the right technology to address the market, which would mean that the company's current problems are due to a combination of execution problems as well as some circumstances outside their control. This would mean that it is still possible for the company to fight its way back to the preminent position it held just a short time ago.

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Anadigics Share Price,
Past Six Months



Anadigics' shares have lost 2/3 of their value over the past six months. The heavy trading on January 28 was sparked by the company's announcement that orders for power amps were declining sharply.

Philips Establishes Independent Optoelectronics Company

Eindhoven, The Netherlands. On February 23 Philips Electronics announced that it has established its optoelectronics activity as a separate legal entity called Philips Optoelectronics B.V. This business area was formerly managed as a part of Philips Research. The new company, which is based in Eindhoven, the Netherlands, currently employs 300 people.

Products available from Philips Optoelectronics include laser diodes, photodiodes and amplifiers. For the telecommunication market, the company offers wavelength-selected lasers for WDM, Fabry-Perot and DFB lasers (some with integrated electro-absorption modulator), as well as 1480 nm pump lasers for use in EDFAs. For the CATV market, Philips Optoelectronics offers analog lasers, photodiodes, amplifiers, and 1550nm CW lasers for trunk lines.

IBM Acquires Design Group to Boost SiGe Effort

Armonk, NY. On February 12 IBM announced that it was acquiring CommQuest Technologies, Inc. via a merger agreement. CommQuest is a privately held company based in Encinitas, California employing around 200 people, specializing in semiconductor designs for wireless applications. The merger is intended to help IBM's SiGe technology gain entry into the communications semiconductor market, by porting CommQuest's designs for analog and DSP chips over to SiGe.

The companies predict the characteristics of low cost and low power along with the ability to operate at high frequencies and integrate thousands of transistors, will result in SiGe becoming the core chip technology enabling a wide variety of hand-held communications and computing devices connected to voice and data networks. They believe that chip industry revenues derived from these applications will grow more than 20 percent annually over the next four years.

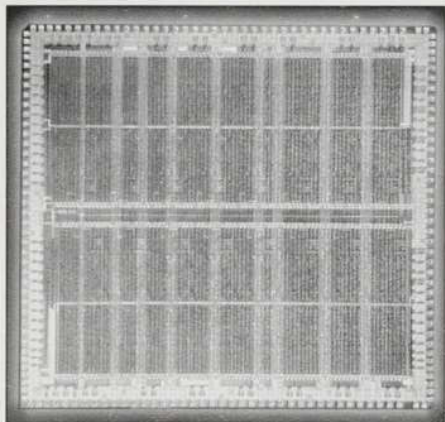
Product development will also include IBM's copper-interconnect technology. The new organization will become a unit of IBM's Microelectronics Division. The deal is valued at around \$180 million.

Motorola Affirms Plans for GaAs Logic In Satellite Network

Phoenix, AZ. Motorola recently confirmed that it is pursuing the development of complementary GaAs (CGaAs) logic for use in the Celestri satellite network. As reported previously (see CS 4(2), p. 13), GaAs fabs have failed to find mass-market opportunities for microprocessors, but they enjoy several advantages for space applications. Commenting on the CGaAs technology, Daniel Artusi, vice president and general manager of Motorola's Wireless Infrastructure Systems Division said "the superior performance of these devices translates in to lighter payloads and lower launch costs for space vehicles".

The standard CGaAs logic circuits operate on a 1.2 volt supply with 500 MHz clock rates, with integration levels of ~100k gates. Motorola claims that CGaAs has a 7:1 power advantage over rad-hard CMOS.

The Celestri System, which is still in the planning stages, will consist of 63 low earth orbit (LEO) and 9 geosynchronous earth (GEO) satellites. It is scheduled to be in service by 2002.



An example of a CGaAs chip for a Celestri satellite.

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PIE on the Menu for 1998 CLEO Conference

Semiconductor lasers will play an important part in what is billed as "the world's most important conference and exhibit on lasers and electro-optics"

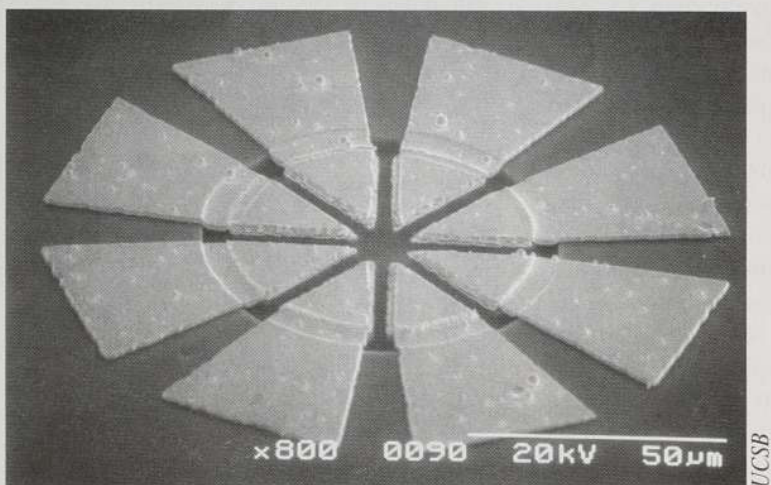
This year's CLEO (Conference on Lasers and Electro-Optics), sponsored by OSA and IEEE, will be held May 3-8, 1998 at the Moscone Center in San Francisco, CA. As always, there will be a substantial number of laser diode papers among the more than 1,000 presentations. The highlights include:

*** "High Performance Multiple-Wavelength Vertical-Cavity Photonic Integrated Emitter Arrays For Direct-Coupled Multimode Optical Links"**

For short-haul WDM applications, it is desirable to have individually-addressable multiple-wavelength emitter arrays that can deliver many channels of information directly into a fiber. With this in mind, a research team from UCSB, headed by Larry Coldren, have developed what they call a VCSEL PIE, an example of which is shown in the photo below.

"PIE" stands for "photonic-integrated-emitter". The device is an array of eight bottom-emitting VCSELs (fabricated from InGaAs quantum wells with AlGaAs mirrors), arranged within a 60 μm diameter area to match to the core of a multimode fiber. The basic VCSEL design used is for a 0.98 μm emitter, but actual emission wavelength for each VCSEL was tweaked by using an anodic oxidation process to alter the thickness of a phase-tuning layer which is located close to the central cavity of each device.

For the array shown in the photo, the eight lasing wavelengths ranged from ~970nm to just slightly less than 1000nm.



The UCSB "VCSEL PIE". The large triangles are probing pads, the eight pie-shaped VCSELs are directly underneath them, with their edges just barely visible in this photo. The apertures are formed by lateral oxidation which proceeds uniformly from all three sides. As a result, the emission pattern from the VCSEL is triangular.

The six shorter wavelength channels were evenly spaced, averaging ~3nm separation, with output powers of ~5 mW or higher. However, the overall quality of the two longer wavelength channels was not as good, due in large part to the low mirror reflectivity above 990 nm. These two lasers also demonstrated much wider wavelength spacing, due to nonlinearity in the mode tuning characteristics. But for practical applications, a device such as this would likely use the central part of the available free spectral range. Therefore, it will be easier to make all eight devices with uniform characteristics.

The presentation at CLEO will include the first results of actual data transmission using this device.

*** "High Temperature (210°C) Operation of Long Wavelength Strained Quantum Well Lasers on InGaAs Ternary Substrates"**

Many types of optical systems require 1.3 μm semiconductor lasers with excellent temperature characteristics. A research group from Fujitsu will report on the growth of the InAlGaAs separate confinement heterostructure lasers grown on InGaAs ternary substrates. This approach was adopted because it enables much deeper quantum well potentials than is possible in the InGaAs/InP system. The compositional wavelength of the InAlGaAs separate confinement heterostructure layers was set at 0.9 μm to give deep potential wells (the depths of the conduction and valence bands were 288 and 145 meV, respectively). Lasing in pulsed mode was obtained at temperatures up to 210°C.

*** "10.6 W CW Front-Facet Power from 100 μm Aperture 0.97 μm Emitting Al-free Diode Lasers"**

The research team from the University of Wisconsin and Sarnoff Corporation continues to set records for high power lasers. Their abstract reports 10.6W of output power from a 100 μm -stripe, 2 mm-long InGaAs/InP/GaAs diode under CW operation; however, Wisconsin's Dan Botez reports they will be announcing an even higher number at the conference. An interesting aspect of these Al-free devices is that their series resistances are 2-4 times lower than for comparable AlGaAs-clad devices. This leads to better wallplug efficiency (50% higher at 9W). Coupled with significantly lower Joule heating, this characteristic should allow Al-free devices to operate reliably at higher CW powers than their Al-containing counterparts.

This year's meeting will also feature tutorials on "Designing Interband and Intersubband Quantum Well Lasers", by Peter Zory of the University of Florida, and "Recent Advances in Vertical Cavity Surface Emitting Lasers and Their Applications", by Connie Chang-Hasnain, of UC Berkeley. Several laser-diode-related short courses will also be offered.

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Controversy Over Northwestern Blue Laser Paper

Aluminum-free theory is intriguing, but questions remain about proof of lasing

A controversy has arisen over whether a research group from Northwestern University has become the latest to successfully fabricate a blue laser diode. On January 14 Professor Manijeh Razeghi and colleagues from the Center for Quantum Devices at Northwestern University published a paper on GaInN/GaN multi-quantum well diodes in the MRS Internet Journal of Nitride Semiconductor Research (MIJ-NSR), an "internet-only" publication which is well known in the nitride community¹. The paper claimed that the lasing had been observed at a wavelength of 405 nm under pulsed operation at 79K. In a subsequent presentation at the SPIE Photonics West Conference in San Jose in late January, Razeghi reported 140 hours of CW room temperature operation.

But the Northwestern data has been criticized by several laser experts for failing to show proper proof that lasing action was observed. In the absence of that data, they suggest that the diodes should be considered LEDs, not lasers.

This debate is much more than academic in-fighting about who gets to claim membership in the "blue laser club". If the Northwestern results are valid, they constitute a major development in the GaN field. The material system they are working with is an "Al-free" system: the diodes are fabricated entirely from GaN

and InGaN. See figure, page 11. All other reports of GaN-based laser diodes have used AlGaIn in the cladding layers. AlGaIn has the advantage of having a higher bandgap and a lower refractive index than GaN and InGaN, which means that it improves the confinement of carriers and light in the active layer. However, AlGaIn is also a very difficult material to work with. Ideally, AlGaIn cladding layers would either be quite thick, or would have a high Al content, or perhaps both. But in practice, either of these conditions causes the layer to crack, due to lattice mismatch and the difference in thermal expansion coefficients between the clads and the adjacent layers. Shuji Nakamura of Nichia Chemical reported last fall that finding a better design for the cladding layer was one of the critical steps that enabled him to achieve a 10,000 hour blue laser. His solution was to use a modulation-doped AlGaIn/GaN strained-layer superlattice; but other groups will likely need to find another route if they want a patentable design.

The Al-Free Approach and Threshold Current Density

The Al-free approach would sweep away all of these problems and, theoretically, could lead to devices which are easier to manufacture, and which are conducive to higher quality ohmic contacts and which have lower series resistance.² And, perhaps more importantly, they would not be covered by the Nichia patents.

But reducing the Al-free approach to practice is a difficult task. An Al-free clad will be less effective in confining the laser's light to the waveguide core since the refractive index of the clad will not be

as low as it was with AlGaIn. To maintain a larger index in the waveguide core than in the clad, Northwestern has used a multi-quantum well InGaIn/GaN core rather than just InGaIn. This MQW stack is also their gain region. Their paper describes a 10 period MQW stack, which is more than twice the number reported in most other blue laser papers.

But whereas conventional wisdom says that the threshold current density (J_{th}) is expected to increase as the number of quantum wells increases, the MIJ-NSR paper claims $J_{th} = 1.4 \text{ kA/cm}^2$. In comparison, the best result reported by Nichia Chemical to date has been 1.5 kA/cm^2 for devices with two or three quantum wells. Most other groups have reported much higher numbers, especially in their initial announcements.

It now seems likely that the Northwestern diode was filamented, and therefore the J_{th} figure was not reliable. Razeghi explains: "In our subsequent paper [presented at Photonics West] we have discussed that these 100 μm broad area lasers usually exhibit formation of filaments due to a self-focusing effect of stimulated emission light, and thus actual threshold current density can be higher than the estimated value. In order to more accurately estimate J_{th} recently we have fabricated lasers with a narrower aperture width (10 μm width aperture). These lasers did not show filamentation in near-field measurement due to tight gain guiding in the lateral direction and the J_{th} could be estimated accurately, which turns out to be about 3.8 kA/cm^2 . This is 3-4 times higher than the 100 μm width broad-area lasers, presumably due to non-uniform current injection in the wider stripe lasers. This value is comparable to the result of Nichia. Such a low J_{th} is not surprising,

¹ <http://nsr.mij.mrs.org>

² The phrase "Al-free lasers" is most commonly associated with longer wavelength III-V lasers based on arsenide and phosphide systems, where their main advantage (still inconclusively demonstrated) is that they may enable longer lifetimes and higher powers because their facets are less susceptible to oxidation. Given the relative immaturity of GaN laser technology, this issue has not yet entered into the discussion.

despite the absence of AlGaN, considering that our Al-free GaN structure has fewer threading dislocations, which significantly increases the internal recombination efficiency of the device, compared to AlGaN-based diode structures."

Proof of Lasing

The confusion over threshold current density is just part of the controversy swirling around the Northwestern claims. The larger issue is whether or not sufficient proof of lasing action has been presented. We spoke with six laser experts: none of them believed that Northwestern has proven that their diodes are, in fact, lasers.

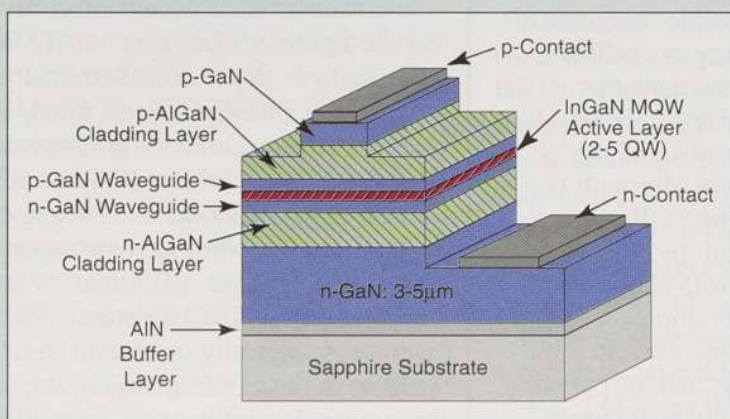
Nakamura, the unquestioned authority on GaN-based lasers, has publicly stated that the absence of narrowing in the electroluminescence (EL) spectra, and the low polarization ratio shown in the Northwestern MIJ-NSR paper makes the device seem more like an LED than a laser. Steve DenBaars of UCSB concurs. "The data presented by Northwestern is similar to that which we see for our InGaN LEDs" he said. "Their EL spectra has a 20nm FWHM, whereas GaN lasers typically have a FWHM less than 0.1nm." He reports that the high dislocation density in GaN-based structures can cause anomalous effects in LED structures that make them seem like lasers. One example is non-linear behavior in the L-I curve caused by saturation of non-radiative centers at the lower currents, wherein the power increases superlinearly as the current is increased, yielding "threshold-like" behavior in the LEDs.

Unfortunately, it appears that Northwestern is not currently equipped to properly characterize these types of devices, or at

least to generate the kind of data that skeptics would find convincing. As Razeghi explains "Because our equipment was not designed for short wavelength measurements, but for longer wavelengths ($>0.8\ \mu\text{m}$), the measurement was not performed in optimal conditions...[and] our emission spectrum showed a rather noisy background signal." She says that "appropriate equipment for blue laser measurements" has been ordered and is expected to arrive soon.

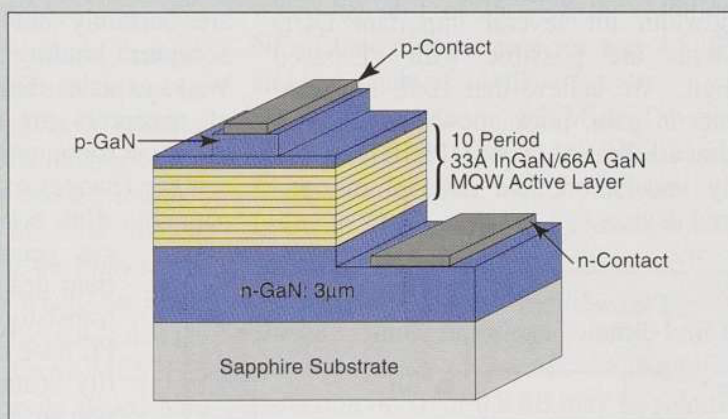
Until Northwestern can present better data, the rest of the nitride research community is likely to remain unconvinced. Professor Gary Wicks of the University of Rochester, who is also the Optoelectronics Editor for this publication, remarks "The current debate is somewhat like controversies in the field before the first Nichia laser. Back then there were preliminary reports of lasing action that often caused a lot of disagreement. Gradually, the consensus seemed to develop that lasing claims were inconclusive unless evidence of laser modes was presented, observable in two main ways: several equally spaced peaks in the spectrum, or multiple lobes in the far field pattern. Other characteristics, such as spectral narrowing, far-field narrowing, polarized emission, and threshold-like behavior in the output power vs. input current graph, are suggestive of lasing but could also be caused by superradiance." Since the Northwestern group has reported only these secondary characteristics, uncertainty about their lasing claims will still exist "until proof of lasing modes can be presented".

Thus it seems that the Northwestern group will need another, more detailed presentation before it can press its claim to having achieved a major breakthrough in blue lasers.



How do you make a blue laser? The most common approach is to use a structure similar to that shown on the left. The active layer is a 2 - 5 period $\text{In}_x\text{Ga}_{(1-x)}\text{N}$ MQW stack. AlGaN cladding layers are used to improve electrical and optical confinement.

In the Al-free approach which is being tried by Northwestern (shown on the right, above), the active region is an $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}/\text{GaN}$ MQW structure. The outermost GaN layers serve as the cladding layers, and the waveguide is the InGaN/GaN MQW stack, which is also the active layer. As Prof. Razeghi explains, the theory behind this structure is that because InN and GaN have a large refractive index



difference ($\Delta n \sim 0.8$), the difference of the effective refractive index between the MQW and GaN cladding layers should be ~ 0.03 . The optical confinement factor for the active region should be $\sim 7\%$, which is similar to other Al-free structures, such as $\text{InGaAsP}/\text{GaAs}$ structures with a wavelength of $\sim 808\ \text{nm}$. In addition, the energy gap difference between $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$ and GaN is $\sim 500\ \text{meV}$, which is comparable with most longer wavelength lasers (e.g., ΔE_g for $\text{AlGaAs}/\text{GaAs}$ lasers is typically $\sim 400\ \text{meV}$). Therefore, she concludes, "the Al-free structure should be enough for optical and electrical confinement as long as a sufficient number of QW's are used".

ONR to Fund Development of Power GaN Devices Based on Piezoelectric Effects

The U.S. Office of Naval Research (ONR) is planning to provide up to \$900,000 in research funds over three years for the development of microelectronics using GaN or other materials with high piezoelectric (PE) coefficients. The program, which is aimed at combined university/industry research collaborations, is being conducted under the U.S. Department of Defense's (DoD) Dual Use Applications Program (DUAP). ONR hopes that research in this field will lead more efficient microwave power components for DoD systems. If all goes well, it will be the first of a number of PE-related research programs from ONR, funded for up to \$6 million.

Colin Wood, Electronics Program Officer at ONR, will administer the program. He explains the motivation behind it: "All current electronics rely on dopant atoms for electrical conductivity. Such dopants scatter carriers, and thus reduce optimum conductivity. But the very strong PE coefficients of GaN-based semiconductors can be leveraged to develop largely dopant-free devices. Significant improvements in noise, power and bandwidth for several important DOD systems are possible with PE-based design. We believe that 10dB improvements in gain, noise, power, and bandwidth are feasible, once PE effects are fully understood, and adopted in optimized devices."

PE-based designs will likely be implemented by designing strained layer lattice structures into FETs, HEMTs, bipolar transistors, thyristors, lasers, detectors and modulators.

The piezoelectric constant of GaN in comparison to other compound semiconductors is shown in the figure, below. All compound semiconductors, because they lack inversion symmetry (as opposed to Si or Ge which crystallize in the diamond crystal structure) become electrically polarized when they are elastically strained. Conversely, the lattice constant of piezoelectric materials is modified by external electric fields. In GaN materials, strain induced polarization due to the lattice mismatch in pseudomorphic heterostructures can be used to induce the formation of an electron or hole gas at the interface. In fact, early workers in AlGaIn/GaN HFETs often reported higher electron sheet densities than expected by the intended doping level and the culprit was the piezo effect.

One area of particular interest to the ONR program is GaN HBTs. Nitride semiconductor based bipolar transistors are currently not possible because of acceptor binding energies $>200\text{meV}$. Wood explains that this means that $<1\%$ of acceptors are ionized (electrically active) at room temperature, and this percentage changes exponentially with temperature. But, according to Wood, hole gas generation by PE strain-field design will allow bipolar transistor development using PE base regions wherein impurity scattering and recombination are virtually non-existent.

Wood believes that the microwave power and low frequency switching functions for some of the DoD's future systems will depend entirely on GaN and SiC semiconductors, because of their high breakdown voltage and thermal conductivity.

The new program will include a major theoretical and modeling component, and it

should not require major capital investments.

Contract awards are expected to be announced May 18. Two contract awards may be made.

Latest Blue Laser Reports

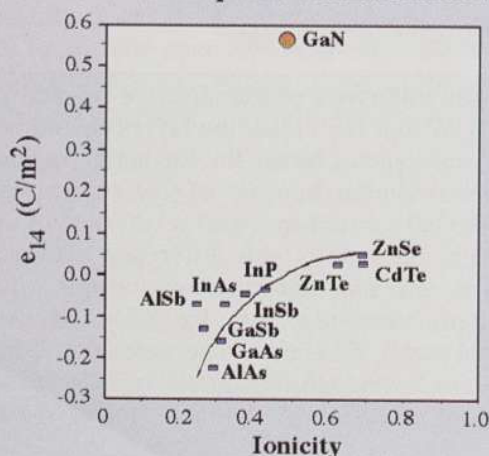
On February 13 SDL announced it has successfully fabricated GaN-based lasers operating in pulsed mode at wavelengths between 400 - 410 nm. The output powers were said to be in excess of 150 mW per facet.

According to Donald Scifres, President and CEO of SDL, these pulsed power levels are higher than any reported previously for GaN-based lasers. SDL's research is supported by matching funds from DARPA through the Blue Band II Consortium. The program teams SDL with HP, Xerox and five universities, with the intent of commercializing single spatial mode blue laser diodes in 1999.

A team from Boston University and the Epitronics Division of ATMI published a paper on "Optically Pumped InGaIn/GaN Double Heterostructure Lasers with Cleaved Facets" in the February 19 issue of *Electronics Letters* (Vol. 34, page 373). Like the Northwestern papers discussed on page 10, this work employs an "Al-free" structure. The diode was optically pumped (and therefore quite far from being ready for practical applications), but the authors believe that this is the first report of lasing from an InGaIn/GaN double heterostructure.

According to Prof. Fred Schubert, who heads up the BU contribution to this work, the team hopes to demonstrate that DH blue lasers can provide lower operating voltages than the MQW blue laser designs that are being pursued by the majority of GaN research efforts.

Piezoelectric Constant of GaN and Other Compound Semiconductors



Michael Shur, Rensselaer Polytechnic Inst.

Cree to Ship Conductive Buffer LED

On March 23 Cree Research announced that Siemens has authorized the company to begin deliveries of the next generation of its blue GaN-on-SiC LEDs. The new version, designated the CB290, is the first Cree LED to include a conductive buffer layer. It allows current to pass vertically through the device, whereas the buffer layer in the current product is insulating, requiring the fabrication of a shorting ring as part of the device to route current around the insulating layer. Therefore the CB290 is easier and less time-consuming to manufacture. This later factor should allow Cree to increase their output of LED chips without additional capital investment.

Cree plans to begin volume shipments of the CB290 chip to Siemens within the next quarter, and expects that the new chip will represent at least 80% of the quarter's LED production.

Neal Hunter, Cree's President and CEO, commented: "The approval by Siemens marks a final step in our design for low cost gallium nitride/silicon carbide LEDs. Our strategy has been to drive to lower LED prices to open new markets. The lower costs promised by this new chip are essential to executing that strategy...We believe that once CB290 production is ramped up we can maintain or expand our product margin even as we reduce LED prices."

Pricing for the CB290 product in large volumes (one million or more pieces) is said to be 23% less the current product. Pricing under the previously announced supply agreement with Siemens, which extends through the 1998 calendar year, was not disclosed. Siemens incorporates LEDs purchased under the supply agreement into a packaged product used in an automotive dashboard lighting application.

SILICON UPDATE

What Noise Figure Would You Like?

ROBERT A. METZGER



Both Si and GaAs can provide sufficiently high f_t and f_{max} values (> 20 GHz) to be able to operate in the 850-2400 Mhz range.

What then determines which technology is best for a given application? When raw speed is not the issue, what typically become the deciding factors are noise figure (NF), linearity, and PAE. For LNAs, NF is of critical importance, since even a 0.1 dB reduction in NF will enable a base station to operate at lower power, since the lower noise LNA is able to detect lower signal levels. In a recent review article on various RF technologies, Lawrence Larson of the University of California at San Diego [IEEE Journal of Solid State Circuits, Vol 33(3), March 1998, pg. 387] notes that LNA noise can be expressed as:

$$NF = 1 + k g_m r_{b/g} (f/f_t)^2$$

where g_m is the device transconductance, $r_{b/g}$ is the base or gate resistance, depending on whether the device is a bipolar transistor or FET, and k is a material dependent constant. When looking at this equation, it is apparent that an intrinsic advantage which GaAs has over Silicon, is that for a comparable f_t , the higher low-field mobility of GaAs results in lower resistances to device contacts, and that the metal gate structure of GaAs MESFETs and PHEMTs, or the heavily doped base regions of HBTs, reduces resistances as compared to that of a silicided MOSFET gate. Both of these effects produce an intrinsically lower NF. However, if a Si based MOS or Bipolar process is specifically designed for RF applications, utilizing metal gate cladding or large area emitter-base junctions, then the NF for Si devices can be reduced. But even not considering $r_{b/g}$ issues, a Silicon process can still produce excellent NF by utilizing

a high f_t process, of which Silicon is certainly capable of (f_t in excess of 50 GHz for Silicon bipolar has been reported in recent years). What needs to be realized is that the intrinsic material characteristics of GaAs do not guarantee a lower NF. Fabrication processes, device size and structure, and careful attention to improving f_t without degrading $r_{b/g}$, are all key elements to obtaining a device with low NF.

A recent example of a Si bipolar-based LNA is that fabricated in a joint Nortel/Carleton University effort [Jose A. Macedo et al, IEEE Journal of Solid-State Circuits, Vol 33(3), March 1998, pg. 378], which produced a 1.9 GHz monolithically integrated front end receiver consisting of an LNA, an image rejection filter using a notch filter centered at the image frequency, and a Gilbert cell mixer. Using the Nortel 0.5 μ m bipolar transistor process, which has an f_t of 25 GHz, the resulting NF of the complete receiver was 4.8 dB and had a gain of 24 dB.

As a comparison, RF Micro Devices offers the RF2411, a GaAs HBT-based front end receiver which includes an LNA, an RF amplifier and a mixer, which for 1800 MHz operation, exhibits a NF of 4.0 dB and a gain of 22 dB. The LNA alone at this frequency gives a NF of 2.6 dB and a gain of 10 dB. Although a reduction in NF of 0.8 dB may be significant for some applications, in others it may not be so critical. And for those of you who need the lowest NF you can possibly get, I should remind you that it was back in 1996, at the IEEE International Solid State Circuits Conference [J.R. Long et al, Technical Digest, pg. 82], that IBM reported on its SiGe HBT technology (50 GHz f_t devices), demonstrating a 2400 MHz LNA which exhibited a NF of 0.95 dB and a gain of 10.5 dB.

Sourcery

We take a look at the 'magic potions' used as starting materials in MOVPE.

MOVPE is now firmly established as a major production tool for certain categories of optoelectronic devices, particularly solar cells and high brightness InGaAlP and nitride LEDs. By 2000, MOVPE could have an estimated 25% share of all opto-devices grown, cutting into the lead of LPE and VPE. Also, an increasing proportion of electronic devices originate in MOVPE reactors, including the majority of HBTs produced today.

MOVPE typically uses group III metal-organic (MO) compounds in combination with group V hydrides - ammonia, phosphine and arsine. See pages 16-17 for a quick overview of some of these compounds. As MOVPE technology has matured over the years, growers have demanded higher performance starting materials to keep pace with the structures they want to produce. In the case of arsine, used as a dopant in the silicon industry, high purity is readily available. For other chemicals including group III metal-organic compounds, MOVPE has provided a niche opportunity for companies like Morton International, Epichem and Akzo Nobel to develop high purity product lines.

Growing Markets

In terms of substrate usage, solar cell manufacturing is the biggest application for MOVPE, and the largest consumer of alkyl compounds. With the numerous satellite constellations that are currently being built to serve commercial communications networks, this market is set to expand over the next few years. The other major growth market is in visible LEDs, an area traditionally dominated by LPE and VPE. The proportion of LEDs grown by MOVPE is rapidly increasing through the advent of high brightness InGaAlP diodes and shorter wavelength nitride-based devices.

These two markets present different challenges for the precursor suppliers. The efficiency of high brightness LEDs can be seriously affected by contamination in the precursor, particularly by oxygen-containing species, and extremely high purity sources are required. However, the quality of the starting material is not quite so critical for solar cell manufacturers, so a less expensive,

lower grade of precursor can be chosen. Equally important is that the starting material is of the same quality, from batch to batch. As Roy Blunt, Special Projects Manager at Epitaxial Products International (E.P.I.), points out, 'The aim all the way along must be to grow a good but reproducible product that satisfies the customer's expectations rather than get a world beating result one day and rubbish the next - we expect our suppliers to have the same attitude.'

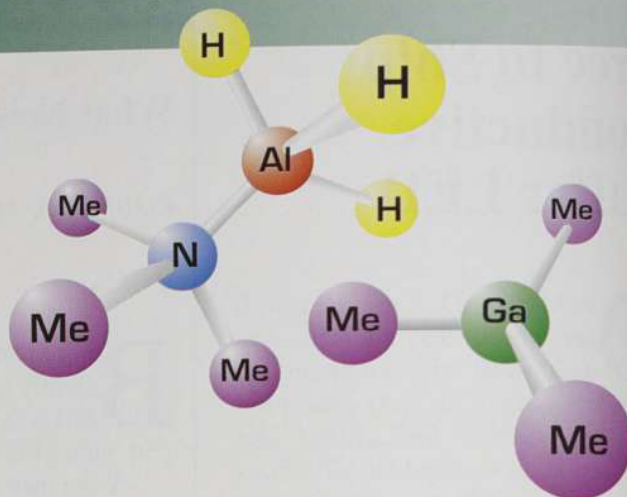
In terms of specific compounds, the largest product by volume supplied by Morton International's Metalorganics group is trimethyl gallium (TMGa), followed closely by trimethyl aluminum (TMAI) and trimethyl indium (TMIn). The volumes of alternative precursors shipped at present are fairly small in comparison.

A potential use for metalorganic compounds outside compound semiconductor growth is to deposit Al for interconnects in the silicon industry. According to Morton's Joe Reiser, Business Manager Metalorganics, the move to copper may have already made

this redundant. 'Aluminum precursors such as diethyl alane were evaluated', he says, 'However, the technology didn't really take off, probably because everyone was aware that copper interconnects were just around the corner. We have been looking at MO precursors for copper deposition.'

Making the Chemicals

TMGa, TMAI and TMIn are difficult compounds to synthesize, handle and purify, which largely accounts for their high cost. For example, TMAI is a clear, colorless liquid that is highly pyrophoric (ignites spontaneously in air) and reacts violently with water. The compounds are stable under an inert atmosphere, and the synthesis of relatively small quantities can be carried out in glass reaction vessels under a nitrogen overpressure. For volume production, the larger manufacturers are now applying chemical engineering principles and using purpose-designed stainless steel equipment and batch processing. As the markets continue to expand, the suppliers are investing in new plant having both higher capacity and improved quality of product.



TMGa, TMAI and TMIn are difficult compounds to synthesize, handle and purify, which largely accounts for their high cost.

Cost and Efficiency

In the chemical industry quality comes with a price tag. Different grades of precursor are available at prices reflecting the efforts made to eliminate all possible impurities. This can involve additional purification stages, which reduce the overall process yield, or may require a different reaction scheme. MOVPE precursors are high cost chemicals, and will likely remain so until the market grows significantly; the chemical industry lacks the price reduction history of semiconductors.

Efficient use of the high quality, expensive starting materials is a key consideration. MO compounds are supplied in stainless steel bubblers and transferred to the growth chamber by bubbling a carrier gas, usually hydrogen, through the precursor. If the compound in the bubbler is a solid, pick-up by the carrier gas is not so straightforward and can vary with the amount of material remaining. This presents technical difficulties such as run-to-run reproducibility, but is also a commercial problem since it prevents full use of the bubbler contents.

According to Doug Collins of Emcore, knowing the quantity of material remaining in a bubbler is a big problem. 'Besides losing runs because the bubbler ran out,' he says, 'the last few grams of a bubbler tend to be different than the initial material. As you run the bubbler you're distilling the contents: pulling out the high vapor pressure material more readily than the low vapor pressure material. As a result, if there is more than one species (and there always is), the material coming out of the bubbler changes.'

Collins notes that TMIn can be a troublesome source in terms of inconsistent quality, which can seriously affect device yield. The material is difficult to purify, and exists as a solid tetramer (four molecules joined together)- this physical state limits the reproducibility of the pick-up rate by the carrier gas. One option offered by Epichem is 'Solution TMIn', which is a saturated solution of TMIn in an involatile, organic amine solvent. This liquid-phase complex acts as a constant vapor pressure source of TMIn, and the output is more stable than the solid source in the bottom half of the bubbler.

Why Trimethyl Compounds?

TMGa, TMAI and TMIn are the standard group III precursors for MOVPE, and there seems to be no sign at present that these are about to be replaced. To do so would require extensive re-qualification of production growth processes. Compared to other alkyl compounds, trimethyls contain relatively strong metal-carbon bonds and during growth this can result in C being incorporated into the layers along with the group III element. Precursors with larger alkyl groups (ethyl, propyl or butyl) have progressively weaker metal-carbon bonds that result in lower carbon incorporation levels, and these have proved highly beneficial in CBE.

However, one reason to have a high V/III ratio during MOVPE growth is to provide lots of H radicals from the group V source (arsine, phosphine etc) which getter carbon-containing species such as methyl groups. Also, compounds with larger

A Range of Possibilities

Chemical formulas and materials shown around the images include: SiGe, MgO, YBCO, BaTiO₃, BST, ZnSe, Ni, PZT, Cu, AlAs, GaSb, InSb, CdTe, GaAs, InAs, AlSb, GaN.

Process labels: Silicon Germanium UHV-CVD, Oxide & Metal CVD, Silicon Carbide CVD and Bulk Growth, Molecular Beam Epitaxy.

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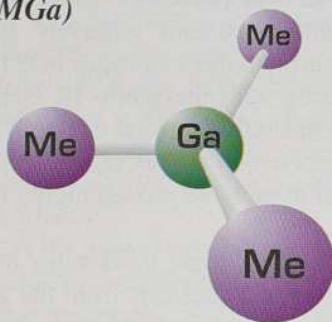
Chemistry of Metal-Organic and Hydride Precursors

1) Group III Metal Alkyls

The most common group III MO compounds are alkyls, with three alkyl groups surrounding the group III metal (Al, Ga, In) atom. Alkyl groups include;

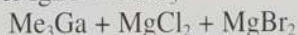
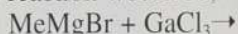
Methyl (Me)	-CH ₃
Ethyl (Et)	-CH ₂ CH ₃
Isopropyl (iPr)	-CH(CH ₃) ₂
Tertiarybutyl (tBu)	-C(CH ₃) ₃

Trimethyl gallium (TMGa)



In general, the larger the alkyl group, the weaker the metal-alkyl bond. This makes the compound decompose at lower temperatures, which is good for growth but not good for long term storage. The larger alkyl groups also have alternative, lower energy decomposition pathways that can result in lower carbon incorporation in the epilayer.

Metal alkyl compounds are commonly synthesized by reacting a Grignard reagent (eg RMgBr, where R is the alkyl group), with a metal chloride. For TMGa, this reaction would be;

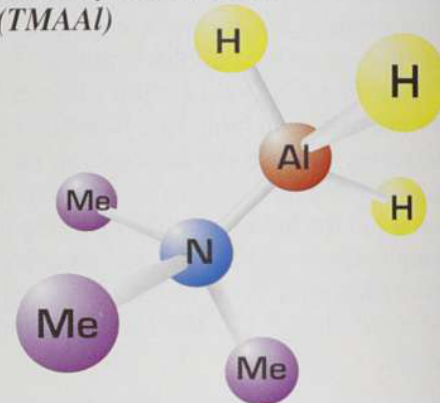


Subsequent purification stages are key to producing a high purity material. One approach used by Epichem is to add large ligand molecule, which forms a complex with the product. After distillation and other purification techniques have been applied to remove reaction by-products and solvents, the product is liberated from the complex.

2) Aluminum

Aluminum hydride (alane) is unstable unless complexed, for example with NMe₃ to form trimethylamine alane. The Al-N bond in this complex is much less strong than conventional covalent bonds, so the compound acts as a source of AlH₃. Substituted alanes such as diethyl alane (Et₂AlH) have also been evaluated as growth precursors.

Trimethylamine alane (TMAAl)



alkyl groups have lower vapor pressures and are more difficult to synthesize and purify, hence trimethyl precursors are pre-eminent. Alternative aluminum precursors such as alanes have no Al-C bonds, but gas-phase pre-reactions and low thermal stability make them inappropriate for MOVPE.

Oxygen Contamination

Any unintentional dopant in epilayers can affect the optical and electrical properties, but oxygen is a real killer. Due to the high affinity of Al for O, this is a particular problem in layers with a high Al content. There are many sources of oxygen in an MOVPE reactor, but precursors tend to get most of the blame. Oxygen in layers grown using TMAI arises in part from precursor contamination by Al-methoxide (Al-OCH₃). Removing these species is very difficult, due to the similarity between the vapor pressures of methoxide and TMAI.

AlGaAs is usually grown above 700°C to enhance methoxide desorption. Also, very high V/III ratios in MOVPE ensure a high group V partial pressure and limit the incorporation of O-containing contaminants. These process conditions have drawbacks, such as the expense of meeting environmental regulations for the safe disposal of huge quantities of reactor waste gases. High temperatures affect temperature-sensitive dopants e.g. Zn, Mg, Te and Se. 'You really have to pour them into the reactor to

get anything into the film,' says Collins. 'This magnifies memory effects in the upstream gas handling systems.'

According to Jeff Tsao of Sandia, oxygen contamination falls rapidly with decreasing Al content, and so does not pose a huge problem for layers such as the active regions of 850 nm VCSELs. 'For shorter wavelength emission or absorption requiring higher Al content, lower oxygen contamination is definitely desirable', says Tsao. 'For Al-based mirror stacks, incorporation of either C or O is not ideal, but does not prove to be a show-stopper.'

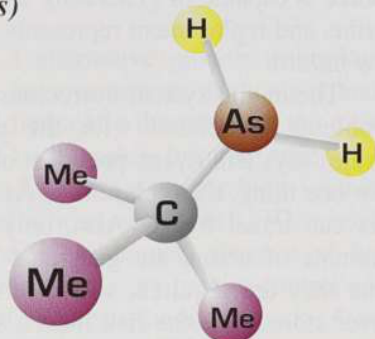
Similarly, in high brightness InGaAlP LEDs shorter wavelength emission requires a higher Al content in the active layers. Higher O incorporation with increasing Al is one of the factors significantly impacting the device efficiency in the yellow-green portion of the spectrum. Oxygen can also compensate p-type doping in the cladding layers. One 'trick' is to grow disordered material on misoriented substrates (up to 15° from [100] towards [110]). A monolayer scale GaP-InP (or AlP-InP) superlattice forms on the [111] crystal plane, resulting in an increased bandgap. Therefore, a smaller Al mole fraction is required to achieve a given wavelength.

'Oxygen contamination is a limiting factor in some high Al-containing structures', says Roy Blunt. 'However, it is possible to partially circumvent the problem by altering growth conditions, but this puts extra limitations on the procedure and produces other problems. Thus if lower oxygen content precursors were

3) Group V Sources

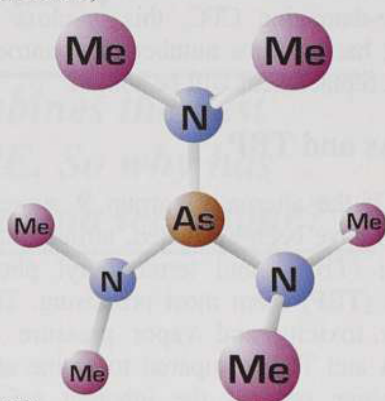
The simplest group V compounds are hydrides - the group V atom has three surrounding hydrogen atoms as in ammonia (NH_3), phosphine (PH_3) and arsine (AsH_3). One or more hydrogens can be replaced with alkyl groups, as in TBAs (tertiarybutyl arsine) and TBP (tertiarybutyl phosphine). The alkyl-group V bond is relatively weak, so the compound decomposes to release AsH_2 or PH_2 .

Tertiarybutyl arsine (TBAs)



Tris(dimethylamino) compounds have a central group V atom (P, As, Sb) surrounded by three $-\text{NMe}_2$ groups.

Tris(dimethylamino) arsenic (TDMAAs)



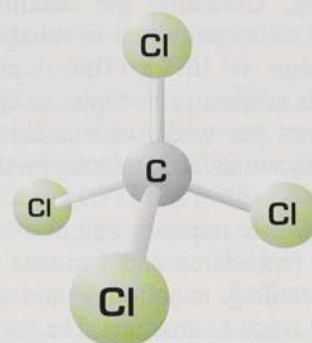
4) Nitrogen

Amines are derivatives of ammonia, with one or more hydrogens replaced by alkyls. Tertiarybutyl amine is the N analog of TBAs and TBP. Trimethylamine (NMe_3) is too stable to act as a source of N. Hydrazine (H_2NNH_2) can also be substituted with alkyl groups to form compounds such as phenyl hydrazine or unsymmetrical dimethyl hydrazine ($\text{Me}_2\text{N}-\text{NH}_2$). Azide compounds contain the $-\text{N}_3$ group and have shown good growth results but can be highly explosive.

5) Dopants

Dopants are usually fairly straightforward molecules, with the dopant atom surrounded by alkyls groups (dimethyl zinc, tetraethyl tin, diisopropyl telluride), hydrogen atoms (hydrogen sulphide, silane) or halides (boron trichloride, carbon tetrabromide). Bis-cyclopentadienyl magnesium (Cp_2Mg) has the Mg atom sandwiched between two flat, 5-membered C rings, and looks like Darth Vader's fighter.

Carbon tetrachloride (CCl_4)



available it would make for more freedom in growth and probably allow further improved device structures to be grown.'

Characterizing the Product

The complete elimination of methoxide species and other sources of oxygen is the goal of the most sophisticated synthetic procedures, and the subject of competitive claims and counter-claims by the suppliers. However, it is very difficult to know exactly what's in a bubbler before the contents are used to grow epilayers. This requires the customers to grow standard test structures with each bubbler. 'This is absolutely essential not only from the point of view of incoming material quality but also as a check on kit integrity after changes', says Roy Blunt. 'We have seen, and still do see occasionally, some batch-to-batch variability and this provides valuable feedback for our suppliers.'

The problem comes down to the effectiveness of characterization tools. Fourier transform NMR spectroscopy identifies organic impurities such as alkoxides, but was originally designed as a tool for structural elucidation. Both Morton and Epichem have made great efforts to try to increase the sensitivity of FTNMR and in addition use ICP (inductively-coupled plasma) techniques to detect low levels of metallic impurities. However, since extremely low levels of contaminants can cause detrimental effects in epitaxial layers, further improvements in character-

ization are required before growers are able to bolt new bubblers straight onto their MOVPE systems and grow.

Growing Nitrides

Production nitride LEDs are invariably grown by MOVPE using ammonia as the N source. Ammonia is a stable molecule, and very high substrate temperatures are required for efficient cracking. High V/III ratios are also required to maintain a high surface partial pressure of N and reduce O incorporation, which arises in part from water in the ammonia source. Other, less stable sources of N have been investigated, especially for mixed group V-N alloys such as GaInNAs , containing $<1\%$ N. Due to the very low N composition required, alternative precursors are more suitable, avoiding the extreme growth conditions necessary when using ammonia. Unsymmetrical dimethyl hydrazine has been used successfully although issues relating to its purity and stability are unresolved, and both cost and toxicity are high; common complaints with any new precursor.

Dopants are also an issue with nitride growth; as Emcore's Doug Collins puts it, 'A better Mg source in terms of memory effects and purity would be valuable. Cp_2Mg tends to be dirty and pre-react.' Epichem are currently developing a solvent-free process to obtain a methylated derivative of Cp_2Mg , which is a liquid at room temperature.

Is It Safe?

Group III MO compounds are not nice chemicals, but the safety precautions necessary to use them are fairly insignificant when compared to arsine and phosphine, the common group V precursors. These materials are highly toxic gases, meaning that the failure of a high pressure cylinder could have catastrophic consequences. There are many regulations relating to the storage of these materials, particularly in areas of high population density or those at risk of earthquake damage, such as Japan or the US West Coast. At Siemens' production facilities in Regensburg, Germany, the maximum amount of arsine permitted in storage at any one time is 10 kg. This requires hydride gas sources to be replaced up to several times per week, with additional safety implications and reduced productivity.

Arsine use requires complex and expensive procedures and facilities for storage, handling, monitoring and safe disposal of reactor emissions. The cost of these can easily outweigh the expense of a new epitaxial reactor, and is a major consideration when establishing new MOVPE facilities. Transportation is also subject to strict regulations; for example, high pressure gas cylinders cannot be flown into Japan.



In-situ arsine generator manufactured by Electron Transfer Technologies.

Electron Transfer Technologies.

One other safety issue is the use of carbon tetrachloride for C-doping; as a ozone-damaging CFC, this is close to being banned in a number of countries, and a replacement will be sought.

TBAs and TBP

Of the alternative group V sources which have been evaluated, tertiarybutyl arsine (TBAs) and tertiarybutyl phosphine (TBP) seem most promising. The lower toxicity and vapor pressure of TBAs and TBP compared to arsine and phosphine reduces the inherent safety risk. TBAs and TBP also have a low cracking energy, due to facile cleavage of the As-C bond, allowing lower growth temperatures to be used. According to Epichem, the temperature required for 100% decomposition is 760°C for arsine, 850°C for phosphine, 475°C for TBAs and 550°C for TBP. Decomposition also yields hydride species, which are able to getter alkyl groups.

A major advantage of TBAs or TBP arising from their efficient decomposition is that the V/III ratio can be reduced significantly, improving material consumption and reducing the amount of toxic waste from the reactor which must be dealt with by scrubber units. In other areas, such as interface quality, the case for TBAs and TBP is not so clear-cut. The purity of these precursors, which is difficult to control, largely determines the purity of the epitaxial layers. All possible synthesis routes are tricky, and the one yielding the highest purity product uses arsine and phosphine as starting materials. The use of TBAs and TBP is limited; E.P.I. and Emcore concur that these precursors are too expensive and insufficiently pure at present to use in production.

In-situ Generation of Arsine

Many companies are considering the in-situ generation of hydrides as an alternative to using high pressure arsine or phosphine cylinders. The only arsine generator system currently on the market, sold by Electron Transfer Technologies (ETT) of Edison, NJ, comprises a com-

pact electrochemical cell, with a metallic As compressed bed as the cathode and KOH as the electrolyte. During electrolysis, arsine and hydrogen are generated at the cathode at a rate determined by the current, and at concentrations which can be varied up to 90% arsine. Water and other impurities are removed to levels of 10 ppb using molecular sieves and a resin drier; impurity levels of silane and germane are less than 2 ppb. After use the electrolysis process is switched off and the system is fully purged. The solid As source is capable of generating 2.4 kg of arsine, and replacement represents a very low hazard.

'The in-situ system overcomes many problems associated with the use of arsine', says Bill Ayers, president of ETT. 'For one thing, the replacement As canisters can travel by air. Also, only small amounts of arsine are generated at the time they are required, so that arsine is never stored, and the risk from a system failure or leak is greatly reduced. This has big implications for health hazards, associated claims for negligence, and plant shutdown times.' Ayers states that the material cost of As canisters for the system is competitive with arsine. The generators themselves are leased to the users, and a second system for generating phosphine is under test.

The Other Alternatives

There are two other alternatives for companies seeing to avoid the use of arsine and phosphine. One is outsourcing epiwafer growth to companies located where regulations are not quite so stringent, or who can afford a bigger investment in gas-handling and safety equipment. The other, more radical option is to choose solid source MBE, a technique currently used for laser production by both Coherent Tutcore (for InGaAsP-based IR lasers and InGaAlP-based visible lasers) and Uniphase LE (for Al(In)GaAs lasers). Also, QED recently announced the availability of carbon-doped HBTs grown by MBE. However, despite these successes, there is little danger of the precursor suppliers going out of business just yet.

Does CBE Have A Future?

Chemical Beam Epitaxy combines the best features of MBE and MOVPE. So why has it failed to mature as a production technique?

TIM WHITAKER

As alternative growth technologies, MBE and MOVPE have numerous advantages and disadvantages. CBE is frequently described as the technique that combines the best of both worlds, bringing together the gas-phase precursors used in MOVPE with the high vacuum environment of MBE. (For definitions, see Table 1). This implies availability of in-situ monitoring techniques, absence of boundary layers and gas-phase reactions, very precise control of flow rates, easy replacement of sources - the list goes on. A summary of the important features is shown in Table 2.

But skeptics often turn this description on its head, and say that CBE combines the worst aspects of the other techniques. This boils down to two main technological points; CBE uses sources chemicals which are either highly dangerous or have relatively low purity (or both), and CBE requires a high vacuum, thus involving all the difficulties inherent to such equipment. Many major research facilities have evaluated this technology, but to the best of our knowledge, CBE is not used for device production at the present time, raising questions about its future as a production technique.

Epitaxial Technique	Group III sources	Group V sources
MOVPE	Gas-phase MO compounds	Gaseous hydrides/MOs
CBE (Chemical Beam Epitaxy)	Gas-phase MO compounds	Gaseous hydrides/MOs
MOMBE (Metal-Organic MBE)	Gas-phase MO compounds	Solid elements
GSMBE (Gas-source MBE)	Solid elements	Gaseous hydrides/MOs
MBE	Solid elements	Solid elements

Table 1. Comparison of epitaxial growth techniques. CBE refers to epitaxial growth in a UHV chamber using gas phase sources only, such as group V hydrides (arsine, phosphine) in combination with metal-organic (MO) group III compounds. Typical reactor pressure is $\sim 10^{-4}$ Torr.

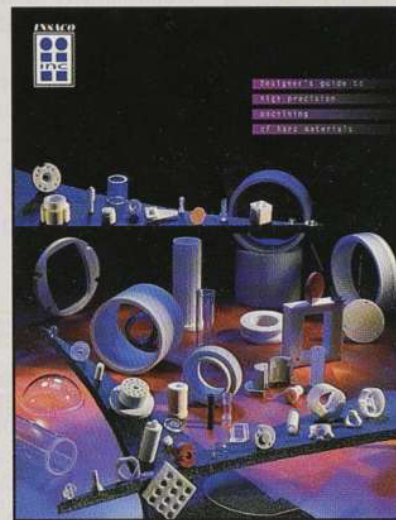
Certain Structures Need CBE

Some device types and heterostructures are particularly suited to the growth conditions found in CBE. For example, low growth temperatures can be exploited to increase the critical thickness in strained MQWs. In the InAsP system, at least three times the number of QWs can be grown by CBE at a growth temperature of 520°C, compared to MOVPE growth at 620°C. This increases the high temperature performance of 1.3 μm laser structures, and introducing even more strain (1.75%) allows the fabrication of strain-compensated 1.55 μm devices. Siemens

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Corporate Technology has reported the growth of graded index separate confinement heterostructure (GRINSCH) lasers in the InGaAsP system. The excellent flow control in CBE permits growth of lattice-matched layers with a continuously graded composition. Normally, these grades are achieved with a series of layers with discrete compositions, implying many heterointerfaces and high internal losses.

Selective area epitaxy appears to be another winner for CBE. Solid sources in MBE have near unity sticking coefficients on both semiconductor and mask surfaces, resulting in unwanted polycrystalline growth on the latter. In atmospheric MOVPE, decomposition of group III alkyls is significant in the gas-phase, which can mean little surface selectivity. Since precursor decomposition occurs entirely on the substrate surface in CBE, the growth parameters (temperature, V/III ratio etc) can be controlled to prevent deposition on masked areas while epitaxy proceeds on the exposed substrate.

Investigating Multiwafer Systems

One of the more advanced multi-wafer CBE systems was developed at Fujitsu's Compound Semiconductor Laboratory. Up until 1996, the research group led by Hideyasu Ando investigated growth of HBTs on a self-designed CBE system capable of handling up to three 4" wafers. Excellent uniformity and performance was obtained for InGaP/GaAs HBTs, suggesting a future breakthrough for CBE mass production. 'I thought (along with other researchers in the world) that CBE was a powerful tool for growing HBT epiwafers,' says Ando. 'However, because MOVPE and MBE had already established their status for the production of HEMT devices, the laboratory manager decided to use MOVPE for HBT device production also. CBE research activities in Fujitsu Labs have now finished.'

At Thomson-CSF's Central Research Lab (LCR) in France, Jean Charles Garcia's group have evaluated HEMTs and HBTs

Feature	For CBE	Against CBE
High vacuum process, with molecular flow	• In-situ monitoring (RHEED, ion gauge flux measurements) and mechanistic studies. • Avoids complex boundary layers and gas-phase pre-reactions found in MOVPE.	• Periodic vacuum breaks still required for routine maintenance (e.g. cleaning) or in case of component failure.
Precursors decompose on substrate	• Selective area epitaxy - control parameters to prevent deposition on mask, allow epitaxy on exposed substrate.	• Growth rate, doping can be very sensitive to substrate temperature, V/III ratio.
External gas sources, with pressure control and fast-response switching	• Precise and reproducible fluxes. Sharp hetero-interfaces. Continuously graded layers. • Accurate compositional control, particularly for mixed group V alloys. • Sources replenished without a vacuum break. • Reduced calibration compared to MBE	• Source purity is low compared to solid elemental sources. • Gas sources place high load on reactor pumping system • New P sources for MBE have improved compositional control
MO precursors used, without carrier gas	• Reduces pumping requirements on vacuum system. • Avoids carrier gas 'pick-up' problems.	• CBE growth conditions preclude use of methyl compounds. Optimum precursors are more difficult to purify, more expensive. • Transferring material effectively places constraints on source choice, reactor design.
Gas source dopants	• Avoids cross-contamination of solid sources. • Accurate doping ramps.	• Carbon tetrabromide now used successfully in MBE
Pre-cracked group V sources	• Efficient use of sources and much lower V/III ratios. Important environmental advantages. • Higher efficiency allows more expensive 'alternative' precursors to be considered. • High V/III ratios in MOVPE getter methyl groups.	• High V/III ratios in MOVPE getter methyl groups. • Cracking introduces hydrogen, difficult to pump. • Use of arsine or phosphine still needs expensive safety procedures and infrastructure.
Low growth temperatures	• Growth of otherwise inaccessible structures • Decreases unintentional dopant diffusion • Lower V/III ratios required	• High growth temperature in MOVPE reduces oxygen incorporation from alkoxides.
Scale-up for production	• Low material usage compared to MOVPE • Reactor design simplified compared to MBE • State-of-the-art device performance comparable to other technologies	• Technology is immature • Lack of production reactors • Lack of extensive data from multi-wafer systems

Table 2. Some of the advantages and disadvantages of Chemical Beam Epitaxy

grown on a semi-production CBE reactor handling three 2" wafers, in terms of the economical aspects as well as material quality [1]. In Garcia's view, the market for HEMTs and related devices is now dominated by MBE, and it is difficult for a new technology to supplant a well-established one. 'However, the HBT market is now growing considerably, opening new perspectives for CBE,' he says. 'In our experiments, the reproducibility of the process with constant growth parameters was better than 1% over a 2 year period, and the cost appears significantly reduced compared to other growth technologies. Personally, I am convinced that CBE can be the technology for GaAs HBTs.'

Challenging MBE

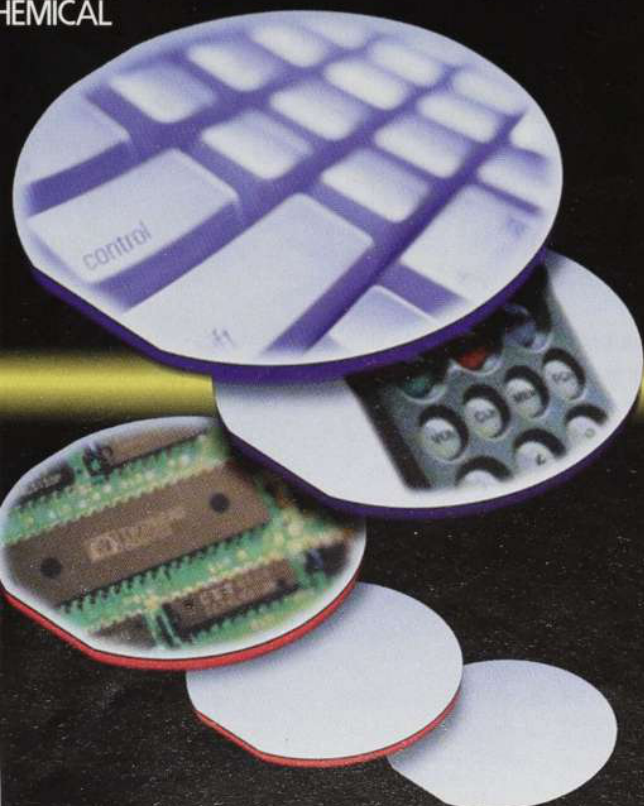
One of the big advantages of CBE over MBE comes from not having to open the UHV chamber to replenish the sources. The cost of MO compounds may be higher than the elemental sources used in MBE but this gives an incomplete picture, according to Garcia. 'The reloading cost is not just the cost of materials. You also have to add the cost of crucibles and other consumables and the cost related to the loss of production when the reactor is down (for reloading, cleaning, baking, calibration of new sources etc).' There is also the risk that the new sources will not result in device layers of the required performance, especially in the period immediately after the break. 'In contrast, the replacement of source for these CBE or MOVPE represents one day, including the purge and the stabilization of the flux', adds

Garcia. 'There is no real need to calibrate the growth rate, due to the inherent reproducibility of the process. In addition, the integrity of the growth chamber is maintained.'

However, with the use of larger effusion cells, multi-wafer MBE reactors now have to be opened far less frequently than in the past. Epiwafer vendor QED, which uses several multiwafer MBE systems, reports that they can run their systems for 12-14 weeks (24 hours a day, 7 days a week) between vacuum breaks to allow both reloading and scheduled maintenance, such as removing deposits from the reactor walls and floor. 'This type of work, and equipment failures, still have to be dealt with in CBE', points out Tom Hierl, QED President. 'Although external sources are an attractive feature of CBE, the main drawbacks of CBE are probably the purity of the precursors, especially compared to solid sources, and the safety aspects associated with using phosphine and arsine. Phosphine is a useful alternative to solid P sources for compositional control in quaternaries. However, new solid sources and types of cracker cell are being introduced, two of which we are evaluating at present. MBE technology is certainly not standing still.'

A traditional criticism of MBE is that it produces material with a poor surface morphology. But the 'oval defects problem' seems to have been largely eliminated from modern production reactors, due in part both to the increase in substrate-source distance, and to the use of hot-lipped Ga cells. 'Defects are down at the 10-20 per cm² level,' says Hierl. 'This represents a background caused by particulates that would be difficult to eliminate from any type of reactor.'

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Reactor Design

CBE reactors are available from the major equipment manufacturers, but not on the same scale as MBE reactors. 'We have supplied a number of 3 x 2" CBE systems and a smaller number of 3 x 4" platforms,' says Jim Thompson of VG Semicon. 'A number of our current customers have evaluated CBE technology for high volume production, and these systems been successful in specific areas. But, clearly, CBE has not achieved the level of acceptance as a reliable semiconductor process tool that solid source MBE currently enjoys, as a result of many years of process experience and cost optimization.'

There are a number of design issues specific to CBE reactors. Firstly, the use of gas sources greatly increases the load on the pumping system compared to MBE. For high throughput and high reliability, a large cold-trapped diffusion pump seems to be the best choice to pump hydrogen created by pre-cracking the group V sources. Pump designs are one of the limiting factors to reaching a high production throughput by increasing the total flow rate of the system.

Thompson notes that a relatively large proportion of the cost of a CBE system is in the sophisticated and ultra-clean gas line technology. 'Very high standards of purity, switching and control are required and this impacts the cost significantly,' he says. However, gas sources also provide advantages to system design. In MBE, throughput is increased by moving to much larger, multi-wafer reactors with large effusion cells. A large chamber is desired to ensure that the geometrical positioning of the sources and substrates maintains uniformity. Gas source inlets and injector cells can be designed with a much greater degree of freedom, allowing smaller reactors which are easier to maintain and bake. Group V sources can generally be pre-mixed inside a single cracker cell, and certain combinations of group III MOs and dopants can also use common injectors.

'The design of CBE machines can be significantly simplified and of reduced size, thanks to the gas sources,' says Garcia. 'This will give some improvements in terms of cost.' The limiting point at this time is the lack of a commercial production CBE machine, handling at least three 4" wafers. 'This increases the risk to start an HBT production line based on CBE material,' says Garcia. 'Qualification of a commercial production reactor is a long term process, and taking into account the stress in this field there are not many candidates to invest money (especially the machine manufacturer) and time to take up the challenge.'

Material	Consumption ratio CBE:MOVPE
Group III alkyls	0.5 - 1.0
Group V hydrides	< 0.1
Dopants	~ 1.0
Scrubbing material	0.01 -0.05

Table 3. Comparison of material consumption in CBE and MOVPE. From [2].

Siemens Evaluates CBE, MOVPE

In comparison to MOVPE, a major advantage of CBE is the reduced material consumption (Table 3), arising mainly from the pre-cracking of group V hydrides. This has important safety and environmental applications, and reduces not only the material costs but also the cost of disposing of toxic wastes. An extensive comparison of CBE and MOVPE for the growth of photonic devices has been carried out at Siemens Corporate Technology [2]. Eberhard Veuhoff, III-V Epitaxy Manager, thinks that CBE has many attributes including low material consumption, reproducibility and uniformity, and the versatility to perform selective area epitaxy, multi-step epitaxy and in-situ processing.

The R&D work carried out by Veuhoff's group has a strong orientation towards production, as a prerequisite for securing funding. 'At present, the MOVPE systems here in our R&D facility also grow wafers for sale to our production facility,' says Veuhoff. 'In the future, I could imagine a similar picture for our CBE technology, for small volume applications. Of course, our production facility has its own MOVPE equipment, but will not necessarily acquire a CBE reactor. The reason for adopting CBE would not be simply due to improved safety, but moreover the possibility to produce devices which are superior (not equal!) to MOVPE devices. Examples would be highly strained MQW lasers for high temperature operation, or monolithically integrated devices.' Veuhoff notes that very high volume LED and solar cell production will remain with MOVPE, and adds that the main epitaxial technique presently used at Siemens is LPE.

Veuhoff lists a number of reasons for the slow development of CBE. 'Production CBE needs substantial back-up in R&D, which many companies may not be able to provide,' says Veuhoff. Also, the number of people in the world with CBE expertise is still very small, consequently progress is relatively slow. 'Today, due to the difficult economic situation (in Europe at least), managers seem to be less patient than in the past. In addition, the necessity to replace LPE by MOVPE for certain applications has been more obvious in the past than the necessity to replace MOVPE by CBE for some applications today. Nevertheless, we at Siemens are still going ahead to explore the potential of CBE for industrial use.'

In conclusion, it seems that opportunities for CBE as a production technique lie in various niche applications, where the technology gives clear advantages for specific device types. Any move into more mainstream areas like HBT production will require extensive investment, both by equipment manufacturers and by R&D departments to support the effort.

See [1] 'Potential and prospects of CBE technology compared to MBE as a production tool for microwave devices', J.Ch. Garcia, Proc. 6th ICCBE 1997, to be published in J. Cryst. Growth [2] 'Potential of MOMBE/CBE for the production of photonic devices in comparison with MOVPE' E. Veuhoff, Proc. 6th ICCBE 1997, to be published in J. Cryst. Growth

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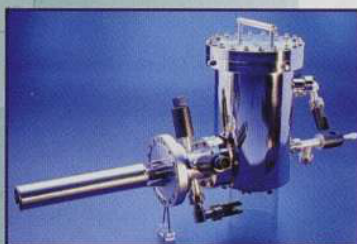
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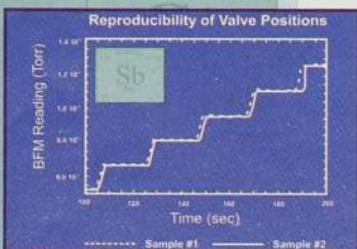
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DIRECTORY OF MERCHANT EPIWAFER VENDORS

If you are looking for an outside source for epiwafers, you have more choices than ever. There are 28 companies listed below - in comparison, for our first epiwafer vendor directory, (CS 2(1), p. 34), we were able to locate just 15 companies. Of those, only Mitsubishi Cable does not reappear in this listing. (They still offer epi material for LEDs, but their preference is to deliver it in die-form, not as epi wafers.)

Among the new entries is Emcore. At the time of our last survey, they did nothing but sell MOCVD reactors, with a sideline business in supplying MR material to General Motors. But now, just two years later, they claim to be the biggest merchant epiwafer vendor in the industry. Most of their business is said to come from LEDs, solar cells, HBTs and PHEMTs. Another big new entry is Sumitomo Chemical,

which recently announced that they are gearing up to produce 100,000 4" GaAs epiwafers/year by the first half of 1999.

This year's directory also includes three new entries from Taiwan: United Epitaxy (founded in 1994), Procomp Informatics (founded in 1996), and VPEC (also founded in 1996). And perhaps the most interesting development reflected in this year's directory is that five of the companies are offering nitride materials. This was a category which didn't even exist in our previous edition.

Among the established vendors, the common theme is expansion. In recent months Epitaxial Products International, QED, Picogiga, and several others have all announced plans to increase their production capacity. Of course, only time will tell whether the industry can simultaneously support both the emerging and the established suppliers.

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Cambridge, CB2 1HL, UK

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FAX: [44] 1223 354 701
jd@emf.co.uk

MOCVD	MBE	LPE/VPE	GaAs	InP	GaP	Antimonides	Nitrides	Other
•						•		
	•				•	•		
	•		•	•				
		•	•	•				
•	•						*	
•			•	•	•	•	**	
•	•		•	•				

Offers custom epitaxial GaN/AlGaIn layers; areas of special expertise include HFET devices and UV detectors.

A subsidiary of SVT Associates offering III-V epiwafers, including III-nitride wafers for HEMTs, photodetectors and emitters. Antimonide and other materials are available for development.

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**Oxides

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		MOCVD	MBE	LPE/VPE	GaAs	InP	GaP	Antimonides	Nitrides	Other	
Procomp Informatics 1F, No. 24-1, Industry E. Rd. IV Science-Based Ind'l Park Hsinchu, Taiwan	Contact: Clark C.K. Peng TEL: [886] 3 577 3727 FAX: [886] 3 577 3706	•			•						Offers GaAs MESFET, HEMT and HBT structures; laser and LED epiwafers will be available soon. Dedicated epiwafer foundry with multiwafer MBE systems and sound financial backing.
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Showa Denko Electronic Materials Division 13-9, Shiba Daimon 1-Chome Minato-ku, Tokyo 105 Japan	Contact: Hisao Mitsuishi TEL: [81] 3 5470 3590 FAX: [81] 3 3435 1034 hisao_mitsuishi@sdk.co.jp	•		•	•	•	•				Offers various kinds of epiwafers for LEDs, including UHB-LEDs by MOCVD; also InP epiwafers for photodiodes, and misc. other custom epiwafers by MOCVD.
Spire Corporation One Patriots Park Bedford, MA 01730 USA	Contact: Kurt Linden TEL: [1] 617 275 6000 FAX: [1] 617 275 7470 klinden@spirecorp.com	•			•	•	•	•	*		Offers 2", 3" & 4" epiwafers delivered with quality inspection reports confirming conformance to customer specifications. QW lasers, VCSELs, LEDs, and many other types of structures available.
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TLC Precision Wafer Technology 1411 West River Road North Minneapolis, MN, 55411 USA	Contact: Anju Sohal TEL: [1] 612 341 2795 FAX: [1] 612 341 2799 anju@tlcwafer@aol.com			•	•	•					Offers high performance epitaxial wafers, including MESFETs, HEMTs, HBTs and photonic structures. Specialties include high In and Al mole fractions, OEIC structures, varactor diodes, SEU-hard HFETs and dielectric insulated MISFETs.
United Epitaxy Company No. 14 R&D Road II Science-Based Ind'l Park Hsinchu, Taiwan	Contact: Jack Yeh TEL: [886] 3 567 800 FAX: [886] 3 567 8753 uecom@mail.ttn.com.tw	•			•		•				Offers GaAsP, GaP, AlGaAs and AlInGaP for optoelectronic applications, including UHB and IR LEDs. Also MOCVD custom epiwafers, and structures for visible laser diodes and MMICs.
Visual Photonics Epitaxy Co. 76 Kung-Erh Road Wu Lin Village Long-Tan, 325 Taoyuan, Taiwan	Contact: Kevin Phoon TEL: [886] 3 470 6568 FAX: [886] 3 470 6567 vpec@ms18.hinet.net	•			•						Offers AlGaAs and InGaP epiwafers for power and digital HBT applications, C-doped from 5E18/cm3 to 1E20/cm3. Also AlGaInP epiwafers for LEDs, including UHB-LEDs. Other structures such as solar cells and laser diodes also available.

*CdTe

Compound Semiconductors at the Optical Fiber Conference

III-V optoelectronic and microelectronic devices featured strongly at the world's largest telecommunications conference

February 23-27, 1998

San Jose, CA.

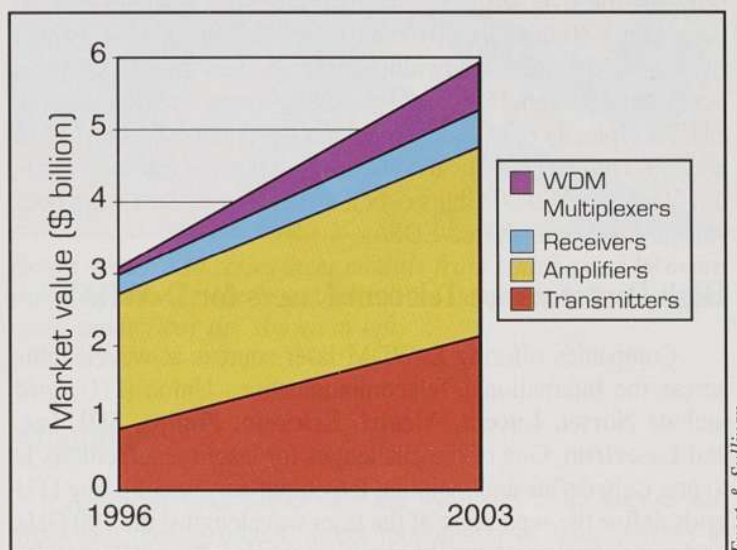
TIM WHITAKER

According to a recent Frost and Sullivan report¹, the current market for the major semiconductor components used in fiber-optic telecommunications systems is \$3.1 billion. It is expected to reach \$6 billion by 2003, which represents a CAGR of 12.5% (see figure).

These figures help to explain the level of activity at the recent Optical Fiber Conference, attended by over 9000 people. Compound semiconductor devices were well represented, and featured strongly in the new product announcements at the conference, particularly in the area of high speed microelectronics. Major interest centered on the expansion of D-WDM into the metropolitan and access markets, the rise of cable TV (CATV) and the proliferation of high performance components to support these systems.

WDM Systems & Terabit Transmission

Predictably, WDM featured strongly at OFC '98. Whereas the high bandwidth, long-haul market seems to have settled on multiple channel systems at the SONET OC-48 and OC-192 levels (2.5 Gbit/s and 10 Gbit/s respectively), the situation is far less clear for medium- and short-haul networks. System suppliers talk about metropolitan rings, which link offices within a city, for example, and access rings bringing fiber to the level of the individual user. Whereas long haul networks are essentially trunk routes with point to point service and a small number of points to add or drop bundles of wavelengths, metro and access rings require much greater flexibility. Large numbers of subscribers each require high bandwidth, but not necessarily as high as 10 Gbit/s, together with the ability to switch and route signals, and to add further capacity as required. Another requisite, besides low cost, is rapid installation.



Total worldwide revenues for the fiber-optic telecommunications equipment market.¹

The big system providers, such as **Alcatel**, **Ciena**, **Lucent**, **Nortel** and **Pirelli** are focussing on these aspects. Pirelli offers a system compatible with OC-3 through OC-48 standards, which can be installed at a low initial cost as a 2 channel platform and upgraded incrementally to 32 channels as demand for bandwidth dictates. The upgrades typically take 2 days and the system also features up to 4 add/drop channels.

Several new long-haul offerings were also being promoted at OFC '98. **Pirelli** were also offering their WaveMux system, carrying up to 64 channels at OC-48 over 600km spans using 4 optical amplifiers. **Lucent's** WaveStar system, due to be commercially available in Q4 of 1998, will carry up to 80 channels at

¹ "World Fiber-Optic Telecommunications Equipment Markets", report5270-60, \$2,950. Contact Frost & Sullivan, 2525 Charleston Road, Mountain View, CA 94043, USA; TEL [1] 650 961 9000 FAX [1] 650 961 5042; Web site www.frost.com

New Product Announcements at OFC

Alcatel Optonics - 25 mW laser modules for D-WDM
Altitud AB - Laser module tunable over full ITU grid
Amp, Siemens - Parallel optical arrays featuring VCSEL transmitters
Anadigics - GaAs PHEMT 10 Gbit/s amplifiers
Ericsson - Volume production of WDM lasers using e-beam lithography
Furukawa Electric - Pump laser modules at 1480 nm
Multilink - GaAs-based HEMT and HBT fiber-optic products
Mitel - Additions to range of VCSEL-based datacom products
Rockwell - GaAs HBT products for fiber-optic networks
SDL Inc - 400 mW pump laser module combining several 980 nm sources
Uniphase - 500 mW broad area pump lasers for dual-core fiber amplifiers

OC-48, or 40 channels at OC-192, the latter representing a capacity of 400 Gbit/s.

Two post-deadline papers both claimed the first Terabit/s transmission over distances in excess 150km. Lucent's experiment sent 100 channels at 10 Gbit/s over 400km and was enabled by their ultra-wide bandwidth amplifier, announced last year, operating between 1536 and 1601 nm. Commercially available EDFAs typically operate in a much narrower band between 1530 and 1560 nm. NTT Optical Network Systems were able to transmit 50 channels at 20 Gbit/s over a distance of 600km using both standard and gain-shifted EDFAs.

High Performance Telecom Lasers for D-WDM

Companies offering D-WDM laser sources at wavelengths across the International Telecommunications Union (ITU) grid include **Nortel**, **Lucent**, **Alcatel**, **Ericsson**, **Philips**, **SDL Inc.** and **Lasertron**. One of the challenges for laser manufacturers is to precisely define and maintain the output wavelength. The ITU grids define the separation of the laser wavelengths; the 100 GHz grid translates to a channel separation ranging from 0.78 to 0.81 nm. In a DFB laser, the wavelength is defined in part by the period of the laser's grating (typically around 0.2 μm and the operating temperature, which is why high performance D-WDM laser modules incorporate thermoelectric coolers to precisely control the temperature. Many also incorporate diodes to monitor the laser output through the back facet. **Ericsson** announced their use of e-beam lithography to define cavity gratings, which they believe to be unique in volume production of DFB lasers. This allows greater accuracy, better batch to batch consistency and greater flexibility to fabricate lasers with customized wavelengths from a single wafer.

As system capacity and number of channels continues to increase, higher power sources reduce the frequency with which signal amplification is required. **Alcatel Optonics** announced their high output power 1905 LMI laser module, designed for external modulation in 2.5 and 10 Gbit/s D-WDM applications. The modules have either 20 or 25 mW output power and are available across the ITU-T allocation grid from 1528 to 1563 nm

with 50 GHz spacing. The modules contain a thermoelectric cooler, precision thermistor, double stage optical isolator and polarization-maintaining fiber pigtail for use with an external LiNbO_3 modulator. A second range of directly modulated laser modules provides 15 or 20 mW power.

Other companies are also beginning to offer higher power lasers for use in D-WDM, for example **SDL** now has 30 mW output power lasers between 1545-1565 nm. **Lucent** is planning to offer 50 mW CW lasers for applications requiring narrow linewidth eg CATV head-end transmission and undersea telecommunication systems.

Tunable Laser Sources

Tunable sources are of interest principally to provide back-up for D-WDM systems in the case of component failure, or to service changes in demand for individual wavelengths, for example when these are assigned to specific subscribers. **Altitud AB**, a new company based in Kista, Sweden, has launched the Anywave 40 laser which is tunable to all ITU channels between 1528.7 and 1560.61 nm. The product features a monolithic InGaAsP-InP laser chip with a three-section distributed Bragg reflector and an additional integrated vertical cavity filter. Each of the laser modes can be selected and tuned in a range of around ± 2 nm, before moving on to the next mode. 'The end result is like having 10 or more DBR lasers in a single chip, all overlapping in tuning range', says Robert Plastow, director of marketing and sales. Altitud sells the device in a butterfly package with an optical isolator and polarisation-maintaining fiber, mounted on a board with microprocessor and all other electronics. The channel selection, optional fine tuning and optical power are conveniently controlled using the supplied software. The cost of the system is \$18,500 in small volumes.



Altitud AB's tunable laser module mounted with controlling hardware.

Pump Lasers for EDFAs

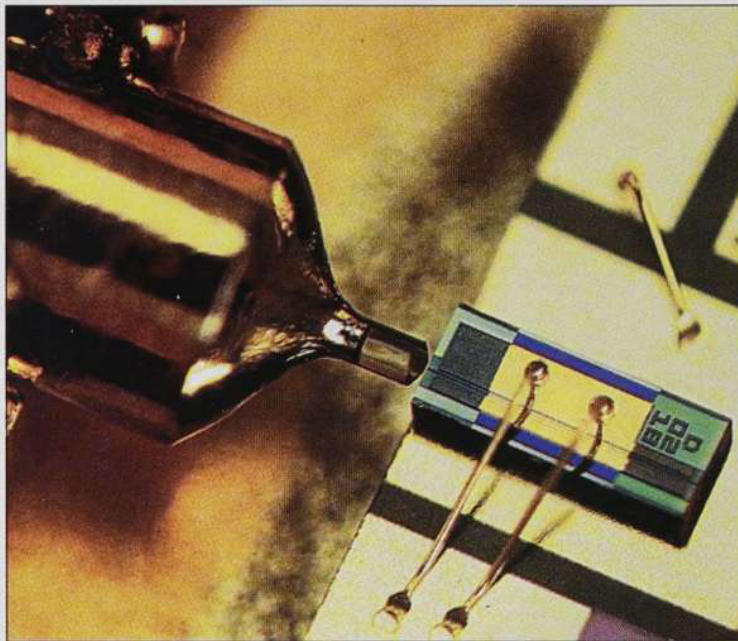
Optical amplification using EDFAs is one of the key enabling technologies for fiber-optic communications. In an EDFA, Er^{3+} ions doped into a section of fiber core are excited by a pump laser, usually at 980 nm, and the resulting lasing transition amplifies the 1550 nm transmission signal within the fiber. Long haul systems must use single mode fiber, otherwise the signal beam loses all of its optimal low dispersion and becomes rapidly unreadable. Current EDFAs are limited in gain by the amount of 980 nm pump power which can be coupled into single mode fiber, and this becomes an increasing problem as the number of WDM channels are increased. Current pump modules use two single mode 980 nm pump lasers coupled with around 75% efficiency, but from opposite sides of the EDFA, to get around 300 mW of 980 nm pump power into the fiber. This gives a gain of more than 20 dB in most designs.

Uniphase Laser Enterprise (ULE) currently offers a 980nm pump laser chip operating at up to 210 mW. The 150 mW version of this device is extremely reliable, with a proven failure rate of 500 FIT (failure in 10^9 hours) under operating conditions at 25°C. Pump lasers can be combined to produce high power pump modules. **SDL Inc.** launched a 400 mW EDFA pump, which combines the outputs of 4 separate modules. A WDM approach is used to multiplex the four laser wavelengths spaced at 5 nm across the 970-985 nm EDFA pump band.

Although only one laser output can couple into a single mode fiber at 980 nm, the Er^{3+} ions can also be pumped at 1480 nm. At this wavelength more than one 1480 nm laser can be coupled into fiber. Although more power is available, the noise levels are also increased due to the proximity of the 1550 nm transmission band. At OFC '98, **Furukawa Electric** was promoting 1480 nm InGaAsP lasers, with output powers of up to 180 mW. To meet the growing demand for this type of product, the company announced a new fabrication facility, opening in April 1998, which will have a capacity of 30k pump laser modules per year. Preliminary data sheets described higher power modules. Pump lasers combined using polarization and wavelength multiplexing to achieve a maximum output power of 800 mW (using 6 lasers), and two-stage pumping schemes capable of introducing 1.5 W are also proposed.

A relatively new idea is to use a dual-clad fiber, in which the cladding is Yb-doped and the single mode core is Er-doped. By pumping at 965 nm, the Yb is excited, and eventually transfers the excitation to the Er in the core, which amplifies the signal at 1550 nm. Since the Yb is in the cladding, it can be pumped by a multimode laser. At OFC '98, **Uniphase LE** launched its 965L-BA30 product series of broad output area lasers, using 30 μm stripe widths, a dimension corresponding to one of the standard cladding sizes for dual core fiber. Higher powers are available from broad area devices, and multiple lasers can be coupled into a single multi-mode fiber. The 965L-BA30 offers up to 500 mW of output power at 965 nm, although this wavelength is not the

only one available. Uniphase's Toby Strite says 'We can make this device anywhere from 900-1000 nm with equivalent reliability. Our initial customer wants 965 nm for their application, so that's the wavelength we qualified. Shifting the wavelength merely involves tweaking the In content in the QW during the growth'. Accelerated life-testing results for the 965L-BA30 product predict a minimum mean-time-to-failure in excess of 100,000 hours under operating conditions.



Uniphase Laser Enterprise

Broad area BA30 series laser module from Uniphase. The beam shape of this device is optimized for coupling into a wedged multi-mode fiber tip, shown at left.

Modulators

Although laser driver ICs are available from Vitesse and Rockwell among others, direct modulation of laser sources at high speed can lead to frequency chirping, which limits the transmission distance. Many companies now sell external modulators, either separately or combined with laser modules. These are either electro-absorption (EA) modulators, in which the applied field changes the absorption properties of the material, or those based on the electro-optic effect (material refractive index changes in response to an applied electric field). Single output electro-optic modulators, also known as Mach-Zehnder devices, can be based on GaAs or InGaAsP. A research paper by **Nortel** at OFC '98 described their efforts to monolithically integrate InGaAsP M-Z modulators with DFB lasers. The alternative to III-V materials is lithium niobate, which is a major product line for companies such as **Uniphase** and **Lucent**. A number of companies including **Ericsson**, **Hitachi**, **NEC** and **Phillips** were selling modules containing DFB lasers monolithically integrated with EA modulators for operation at 2.5Gbit/s, with 10Gbit/s devices either available for sampling or under development.



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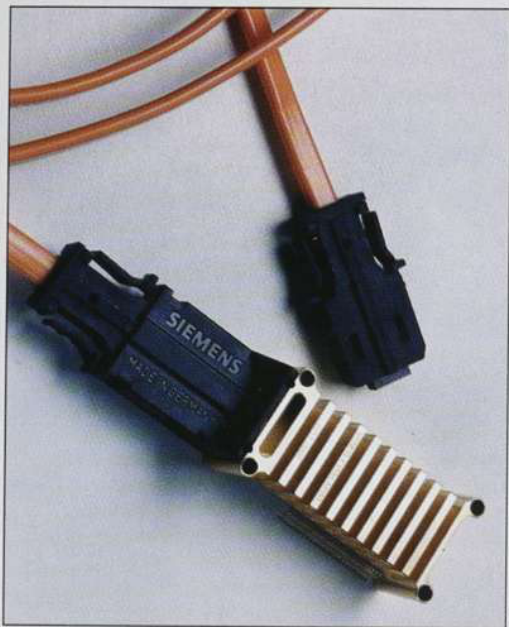
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VCSELs and Parallel Optical Links

VCSEL products are rapidly becoming an accepted part of the data communications component family. **Mitel** announced several extensions to its VCSEL portfolio, including VCSELs co-packaged with photodiodes to monitor the laser performance. 850nm VCSELs will shortly be available with 10 mW output power for industrial and sensing applications, compared to the 1.3 mW model on sale for general datacom use. Mitel is also addressing the parallel datacom market with a preliminary announcement of 4x1 arrays of VCSELs and photodiodes.

AMP and **Siemens** announced a multi-source agreement for supplying interchangeable parallel fiber-optic data links, incorporating VCSEL arrays in the transmitters. The products are marketed as 'Lightray MPX' by AMP and as 'Paroli' by Siemens. The parallel optical link consists of transmitter and receiver modules, containing 12 VCSELs or detectors respectively (see photo). The modules are linked through simplex MC connectors and 12-channel fiber-optic cable to the switch or switches serviced by the link. The operating speed ranges from 125 Mbit/s to 1.25 Gbit/s.



Transmitter module of Siemens 'Paroli' parallel optical data link, showing both an unplugged MT connector with 12-channel fiber optic cable in a protective jacket (top), and the complete module with gold-plated heat sink.

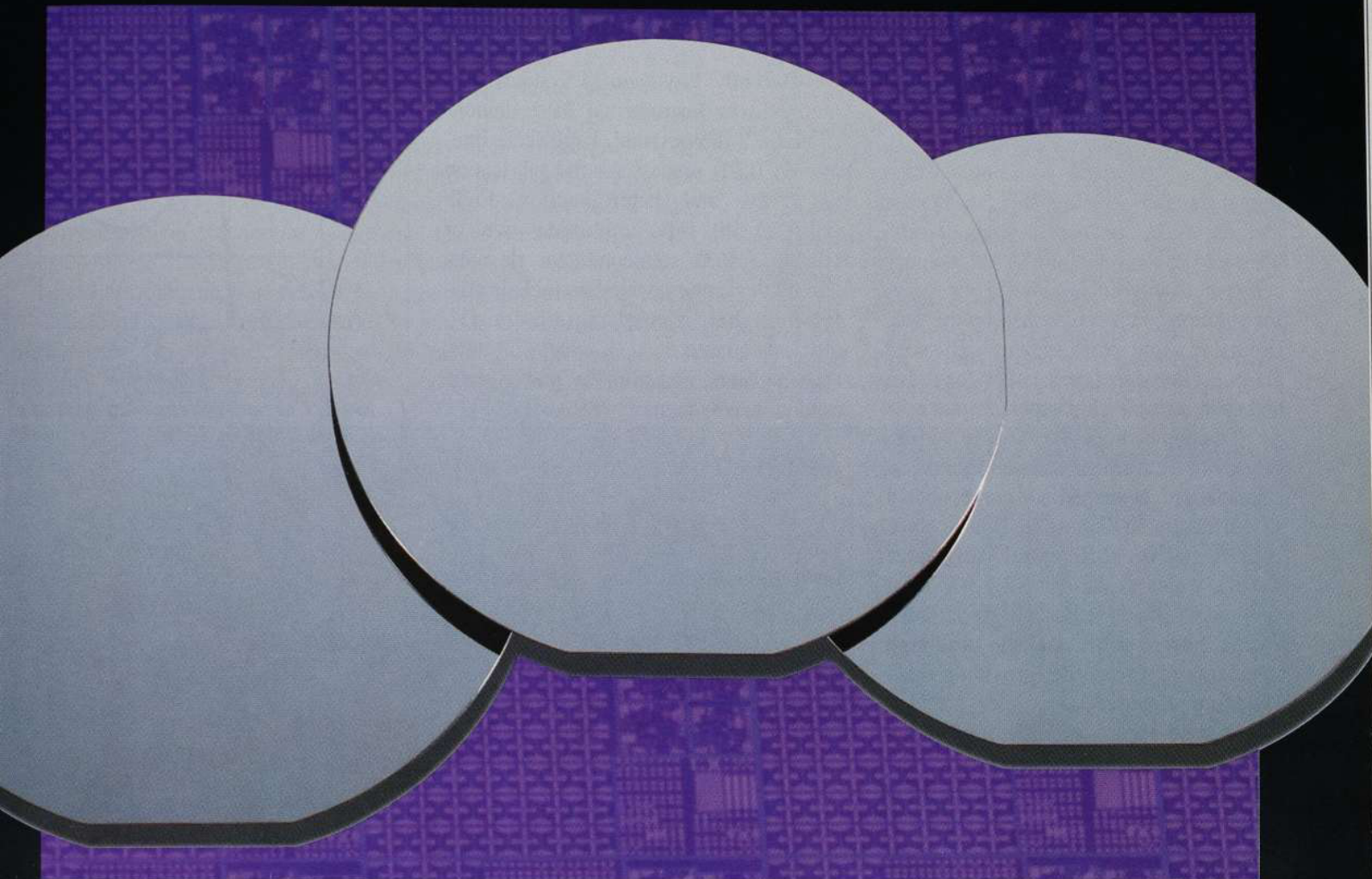
GaAs Microelectronics at OFC '98

Several companies including **Rockwell**, **Multilink** and **Anadigics** chose OFC '98 as the occasion to launch their new electronic products for fiber-optic networks, introducing a range of HBT and PHEMT devices. There is now healthy competition between GaAs-based products fabricated using different technologies (see Table) to access the high data rates required for optical systems. Some companies, for example **NEL**, continue to increase the maximum data rate available with their new family of products at 20 Gbit/s, while **Vitesse** is content to expand their portfolio at lower data rates to address the expansion of metro and access networks. (For more on microelectronics in fiber-optics, see page 50)

Company	Device Type	Product Examples
Anadigics	MESFET	• TIAs, limiting amplifiers and E-O modulator drivers up to 2.5 Gbit/s
	PHEMT	• 10 Gbit/s TIA, limiting amp
Fujitsu	0.5 μ m gate MESFET	• 2.5 Gbit/s laser driver and 16:1 multiplexer IC
Lucent	0.9 μ m gate MESFET	• Portfolio including modulator drivers, mux and demux ICs and TIAs for 10 Gbit/s, and range of 2.5 Gbit/s products
Multilink (TRW)	HBT	• 16-bit mux/demux chipset at 10 Gbit/s; Receiver MMIC integrating photodiode, TIA and limiting amp, operating at 1.25 Gbit/s
	0.15 μ m gate HEMT	• 2.5-10 Gbit/s TIAs, 30 KHz-10 GHz variable gain amp, 2-15 GHz power amp
NEL	0.15 μ m gate MESFET or 0.5 μ m gate MESFET	• Logic ICs - large family of 10 Gbit/s LSI products (eg OR/NOR gates, D-flip-flops) with advance information on 20 Gbit/s ICs.
	0.3 μ m gate MESFET	• Analog ICs - various types of amplifier operating up to 9.5 GHz.
Rockwell	HBT	• 2.5 Gbit/s products; 16-bit mux, laser driver, TIA, clock and data recovery with limiting amp, 16-bit demux. Available as die or chips.
Toshiba	HEMT	• 10 Gbit/s pre-amp co-packaged with InGaAs PIN photodetector
Vitesse	MESFET	• Portfolio includes; TIAs at 155 and 622 Mbit/s; 1:16 mux/demux chipset for 10 Gbit/s; Laser drivers at 2.5 Gbit/s; Gigabit Ethernet receiver with monolithically integrated GaAs TIA and MSM photodetector.

A selection of GaAs electronic products for fiber-optic networks on show at OFC '98

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Tunnel Diodes Break Through At Last

TIM WHITAKER *

After 40 years, tunnel diodes are finally moving towards high speed systems applications in computing, wireless communications, digital signal processing, and data storage and retrieval. The use of high density, ultra-low power tunneling-based memory cells will enable single-chip GaAs processor solutions, and could open up the possibility of applications such as high speed GaAs digital signal processors for radar, and even a single-chip supercomputer.

The tunnel diode has extremely interesting device properties based around its characteristic N-shaped I-V curve, shown schematically in Figure 1. This features both negative differential resistance (NDR), which is the decrease in current with increasing drive bias observed above a peak current value, and the ultra-high speed transient response, providing rapid switching properties.

Despite these properties, 40 years have passed since the discovery of the tunnel diode (by Esaki), and commercial applications are extremely limited. Only a few thousand discrete Ge and Si Esaki diodes are currently utilised per year, in picosecond pulse generators and microwave detectors in the 0.5-18GHz band. In the years after the discovery of these devices, the very broad potential of tunnel diode technology failed to be realised, largely because their development was overrun by the boom in transistor technology. However, due to the increased speed, density and design flexibility provided by Resonant Tunneling Diodes (RTDs - see Box A), this technology is now emerging as a strong contender for future generations of high performance, low-power microwave digital, mixed signal and optoelectronic systems.

* Additional material supplied by Alan Seabaugh of Raytheon TI Systems.

Recently, Raytheon TI Systems (formerly Texas Instruments) have demonstrated a 3-dimensional, large-scale integration (LSI) process for the fabrication of RTDs and heterojunction FETs (HFETs) on InP, combining two of today's fastest semiconductor devices. Circuit device demonstrators include analog-to-digital converters (ADCs) [1], clocked quantizers [2], clock circuits, shift registers, and ultralow power static random access memory (SRAM) [3-5].

Memory

Fast single-chip digital processors in GaAs require large amounts of fast, low-power, on-chip memory. This remains a significant bottleneck, even though 1M transistor circuits can now be fabricated in III-V technology [6]. Access times as low as 0.5ns [7] have been realised for a 4kbit HFET-only static RAM (SRAM - see Box B) but the array size has been limited to 64kbit, with 5W total power dissipation and 1.2ns access time [8]. Using standard designs, the n-channel GaAs 6-transistor (6T) cell cannot compete with the complementary Si 6T cell, which consumes less than 1pW. However, HFETs have intrinsic advantages for very high speed, low power addressing because of the high cut-off frequency at low drain current, and good short channel behaviour. A low power compound semiconductor memory could enable on-chip data processing for ultra-high speed chips.

For the realisation of low power, tunneling-based static RAM (TSRAM), Raytheon has concentrated on the development of ultra-low current density RTDs grown on InP, featuring InGaAs emitters,

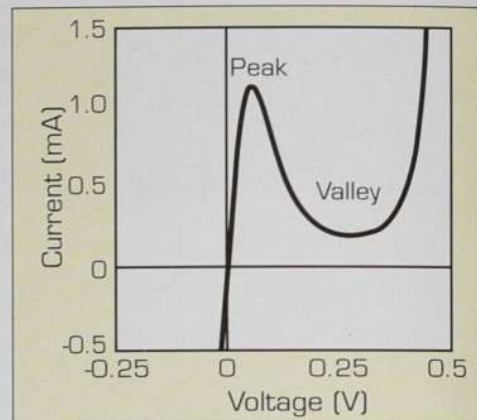


Figure 1. Current-voltage characteristics of a commercial Ge Esaki tunnel diode.

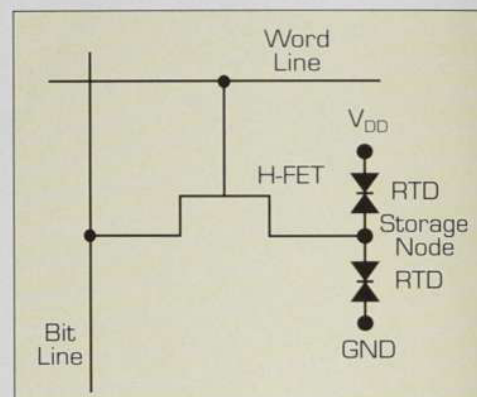


Figure 2. Single transistor tunneling-based SRAM cell with two RTDs. A single bit is stored at the storage node which is also the source of the HFET.

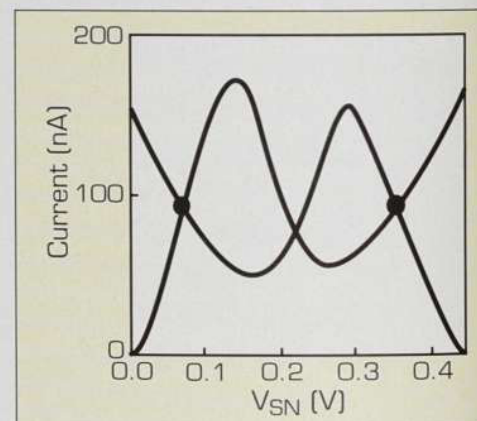


Figure 3. Measured load line for the TSRAM cell shown in Figure 2, under 0.45V bias. Dots show the stable latch states.

20Å AlAs barriers and an 18Å InAs well. An InAlAs prebarrier reduces the peak current density. In the TSRAM cell (Figure 2), the capacitor in a conventional DRAM cell is replaced by two RTDs. This combination has two stable voltage states provided that the RTD peak current is larger than the sum of the HFET leakage current plus an RTD valley current. The voltage at the storage node latches to one of these two stable states (Figure 3), depending on the previously written bit signal. Read and write operations are analogous to conventional DRAM, with charge being stored by the high intrinsic capacitance of the RTD pair. However, the memory is static due to the bistability of the voltage states, removing the need for a refresh cycle.

Using RTDs with a peak current density of less than $1\text{A}/\text{cm}^2$, the standby power dissipation to maintain bistability is extremely low, and was measured at 50nW before downscaling, representing a 200x improvement over the previously reported GaAs 6-transistor cells [8]. The two-state TSRAM cell has an area of around $150\text{ }\mu\text{m}^2$.

Further sophistication comes from the use of symmetric RTDs, which exhibit NDR in both directions. By placing 2 RTDs back to back, which allows current to flow top-down in one RTD to the storage node and then bottom-up through the other, an interconnect is eliminated

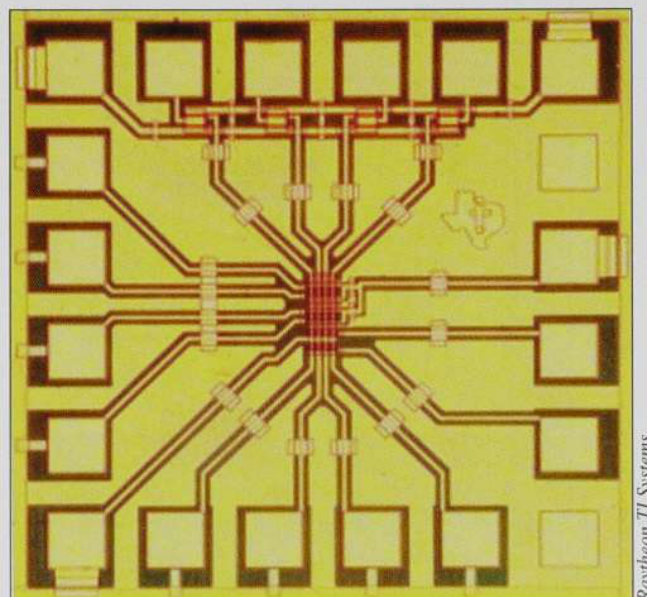


Figure 4. Fabricated 4x4 single-transistor cell TSRAM array. Improved designs should lead to delay circuits with 10x lower power and 100GHz speed.

Box A. Tunnel Diode Tutorial

Tunnel diodes function as a result of the quantum mechanical effect by which a wavefunction is able to partially penetrate a classically forbidden region such as a potential energy barrier. This enables electrons to 'tunnel' through the barrier without paying the associated energy penalty. In the original type of tunnel diode, discovered by Esaki, the barrier is the space-charge depletion region of a p-n junction formed in Si or Ge. More sophisticated structures involve the use of heterojunctions.

Resonant Tunneling Diodes (RTDs) feature a double barrier region, in which the quantum well enclosed by the barriers acts in a manner analogous to an optical Fabry-Perot cavity, enhancing the tunneling effect by resonant build-up of the wavefunction. A schematic diagram of the conduction band energy profile of a typical RTD is shown in Figure A1. As the device is biased, subbands with energy $E_{x,res}$ are pulled below the Fermi level (E_F) in the emitter. Where these subbands align with states in the well, tunneling can occur through the barrier region. Eventually, the resonant energy $E_{x,res}$ drops below the emitter conduction band energy and tunneling ceases, so that the current falls from its peak value to a minimum (the valley current - see Figure 1), determined by thermionic emission and scattering processes.

Figure A2 shows the energy band diagram of a GaSb/AlSb/InAs Resonant Interband Tunneling Diode (RITD) [14]. In this device, tunneling occurs from the conduction band in the InAs emitter at left, through the light hole 2DEG in the valence band of the GaSb well, and back into the InAs conduction band at right. As the bias is increased the hole 2DEG level eventually drops below the emitter conduction band and NDR is observed in the I-V curve. The characteristics of most interest for tunnel devices are the peak current density and the peak-to-valley current ratio (PVCRR). For high speed applications such as logic, high current density is required for fast charging and discharging of the circuit capacitances. For low power operations such as memory, low current density is needed to minimize the static power dissipation. For a comparison of tunnel diode properties, see [15].

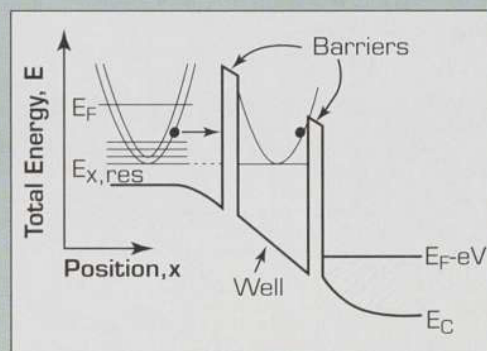


Figure A1. Conduction band profile of a Resonant Tunneling Diode (RTD). Where a 2D emitter subband parabola (of energy $E_{x,res}$) aligns with a state in the well, tunneling can occur.

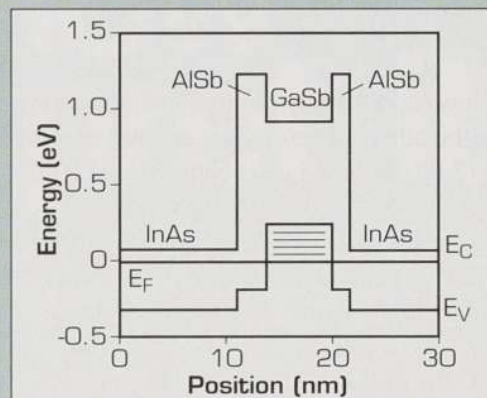


Figure A2. Energy band diagram of a typical Resonant Interband Tunneling Diode (RITD).

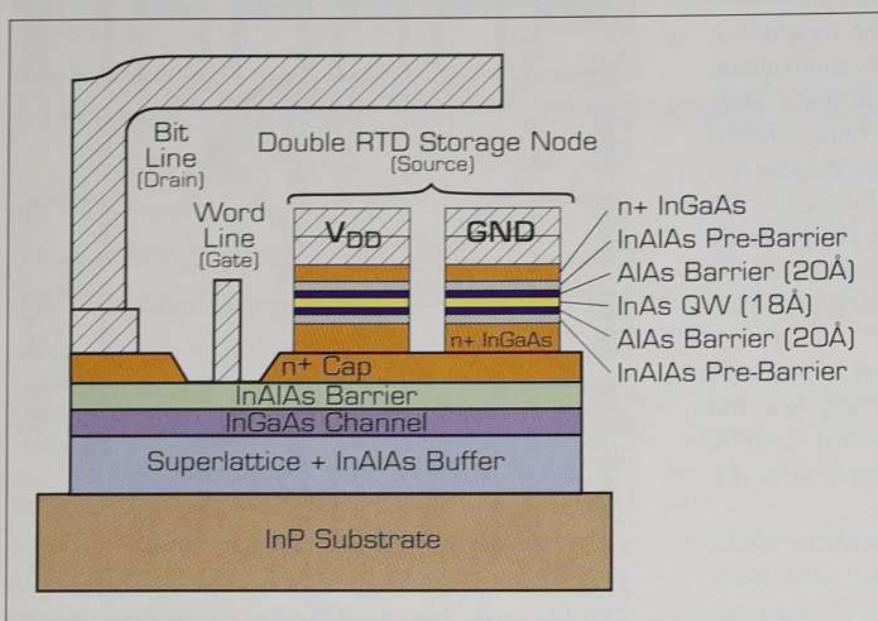


Figure 5. Schematic cross-section of single-transistor TSRAM cell, showing the device epilayers grown by MOMBE. Two RTDs are fabricated on the source region of the underlying HEMT, with a self-aligned gate forming the word line of the storage cell. The HEMT drain connects to the bit line.

Memory Technology	Speed (GHz) 1-2 μm pitch	Density (Mb/cm ²)	Standby Power(W/Mbit)
E/D HFET SRAM	1.0	0.1-0.4	0-200
H I2L HBT SRAM	0.05-0.2	0.03	200-1000
1-T HFET TSRAM	0.5	1.7-4.4	0.01
2-T HFET TSRAM	1.0	1.0-2.0	0.01
Si DRAM	0.03-0.2	10	10^{-7}
Si DRAM	0.01-0.04	150*	10^{-6} **
1-T Si TSRAM	0.01-0.04	50*	10^{-9} **

Table comparing of III-V and silicon memory with tunneling-SRAM (TSRAM) alternatives, showing in particular the huge power savings gained using TSRAM technology.

*Based on layouts with 256Mb CMOS/RTD DRAMs.

**Based on experimental 64Mb DRAM.

which was previously required using asymmetric RTDs to tie one RTD emitter to the other collector. This enables a further increase in cell density. Three-state (2 bit) TSRAM cells containing 4 RTDs have also been fabricated, with a power dissipation of 100nW/cell [3].

Figure 4 shows a photo of a fabricated 4 word x 4 bit TSRAM array. Tests and SPICE simulation on such arrays show that the cell charge can be sensed dynamically with sub-nanosecond access times. This results from the high storage node capacitance of 8fF per μm^2 RTD area and a reduced bit line length due to the compact cell size.

Raytheon predicts that TSRAM technology could ultimately yield SRAM on InP or GaAs at a density of 2Mbit/cm², with sub-nanosecond access times and a static power dissipation of 5mW/Mbit. This power loss figure represents a reduction of some 3,600x over the best III-V SRAM cells.

Device Growth and Processing

The TSRAM cell was constructed on a single die fabricated using an integrated RTD/HFET process on 50mm or 75mm InP substrates [9]. The schematic diagram in Figure 5 shows the RTD structure vertically integrated on the source of the HFET. The device layers were assembled in a single growth by metalorganic molecular beam epitaxy (MOMBE). The process consists of 10 mask levels and one e-beam gate definition step.

Silicon Also Benefits

The TSRAM cell concept will also apply to silicon when a low current density Si-based RTD or other NDR device becomes available, with tremendous implications for the future of DRAM. Standby power savings of up to 100x might be achieved by converting DRAM into refresh-free TSRAM, with power dissipation close to current non-volatile memories. Also, the RTDs create a self-adjusting leakage-compensating circuit that can overcome variations in the transistor leakage current, thus relaxing the transistor performance specification. Integration of Si-based RTDs with MOS technology could allow introduction of memory ICs that will store multiple full-length motion pictures.

Mixed-Signal Applications

Analog-to-digital converters (ADCs) are basic elements in mixed signal systems. Both flash [1] and folded [11] RTD/HFET ADCs and analog-to-multi-level quantizers [12] have now been demonstrated. For A-D conversion at clock frequencies above 10GHz, ADC resolution can become limited by raw device speed, so the switching time-constants as low as 1.5ps measured for RTDs [13] should enable ultrawideband ADC systems. Modelled performance for this technology is predicted to ultimately yield 6 bit ADCs operating at 25GS/s and 16W.

Signal Processing

As digital RF receivers are extended into the X-band, tapped shift registers with input data rates exceeding 20GHz will be needed to provide demultiplexed, parallel outputs at clock rates compatible with silicon signal processors. RTD/HFET shift registers have been demonstrated in which data is clocked onto the RTD latch on the first clock half-cycle and moved out on the subsequent half-cycle to the next stage. Power dissipation per stage is approximately 9mW.

[continued on page 40]

You've taken the X-ray data...

Position	Count	29.32028	80.00	30.66057	92.00	32.00085	69.50	33.34114	83.50	34.68143	73.00	36.02171	69.50	37.36200	133.50	38.70229	68.50
28.00000	71.00	29.34029	64.00	30.68057	83.00	32.02086	68.50	33.36115	72.50	34.70143	63.00	36.04172	68.00	37.38200	125.50	38.72229	59.50
28.02000	62.00	29.36029	80.50	30.70058	97.00	32.04086	71.50	33.38115	67.00	34.72144	72.00	36.06172	73.00	37.40201	137.50	38.74229	67.00
28.04001	72.50	29.38029	67.00	30.72058	84.50	32.06087	70.50	33.40115	93.50	34.74144	79.00	36.08173	56.50	37.42201	148.50	38.76230	62.50
28.06001	68.50	29.40030	75.50	30.74059	86.50	32.08087	61.00	33.42116	74.50	34.76144	61.50	36.10173	69.00	37.44202	134.00	38.78230	62.50
28.08002	76.00	29.42030	70.00	30.76059	78.00	32.10088	68.50	33.44116	72.00	34.78145	71.00	36.12173	70.50	37.46202	143.00	38.80231	60.00
28.10002	67.50	29.44031	59.50	30.78059	76.00	32.12088	62.50	33.46117	89.00	34.80145	76.50	36.14174	68.00	37.48203	116.00	38.82231	64.50
28.12003	68.50	29.46031	64.00	30.80060	81.50	32.14088	65.00	33.48117	81.00	34.82146	83.00	36.16174	71.00	37.50203	136.00	38.84232	65.50
28.14003	71.00	29.48032	74.00	30.82060	72.50	32.16089	69.50	33.50117	88.00	34.84146	65.50	36.18175	66.00	37.52203	127.00	38.86232	66.00
28.16003	64.00	29.50032	66.00	30.84061	65.50	32.18089	63.50	33.52118	78.50	34.86147	76.00	36.20175	68.00	37.54204	109.50	38.88232	54.50
28.18004	74.50	29.52032	72.50	30.86061	79.50	32.20090	61.50	33.54118	86.50	34.88147	59.50	36.22176	67.00	37.56204	99.50	38.90233	70.50
28.20004	66.00	29.54033	66.50	30.88062	75.00	32.22090	79.00	33.56119	91.50	34.90147	81.00	36.24176	64.50	37.58205	95.00	38.92233	70.00
28.22005	66.50	29.56033	72.50	30.90062	62.50	32.24091	72.00	33.58119	97.00	34.92148	66.00	36.26176	67.50	37.60205	94.00	38.94234	77.00
28.24005	70.50	29.58034	65.00	30.92062	71.00	32.26091	68.50	33.60120	105.00	34.94148	70.50	36.28177	69.50	37.62206	98.00	38.96234	78.00
28.26006	70.00	29.60034	66.50	30.94063	68.50	32.28091	68.00	33.62120	103.00	34.96149	71.00	36.30177	66.50	37.64206	85.00	38.98235	73.50
28.28006	60.00	29.62035	70.00	30.96063	71.00	32.30092	64.50	33.64120	107.50	34.98149	70.00	36.32178	57.00	37.66206	76.50	39.00235	82.00
28.30006	69.50	29.64035	55.50	30.98064	67.50	32.32092	83.00	33.66121	96.00	35.00150	68.00	36.34178	67.50	37.68207	88.00	39.02235	81.00
28.32007	68.50	29.66035	69.50	31.00064	72.50	32.34093	71.00	33.68121	104.00	35.02150	70.00	36.36179	61.50	37.70207	84.50	39.04236	78.00
28.34007	63.50	29.68036	61.00	31.02065	72.50	32.36093	61.00	33.70122	118.00	35.04150	70.50	36.38179	68.50	37.72208	72.50	39.06236	82.50
28.36008	68.50	29.70036	71.50	31.04065	64.50	32.38094	80.00	33.72122	110.00	35.06151	67.00	36.40179	62.50	37.74208	82.50	39.08237	72.00
28.38008	74.50	29.72037	62.50	31.06065	69.00	32.40094	60.50	33.74123	132.00	35.08151	63.50	36.42180	60.50	37.76208	68.50	39.10237	78.50
28.40009	72.00	29.74037	69.00	31.08066	72.50	32.42094	76.00	33.76123	167.50	35.10152	82.00	36.44180	53.00	37.78209	73.00	39.12238	86.00
28.42009	65.50	29.76038	62.50	31.10066	67.50	32.44095	66.50	33.78123	186.00	35.12152	71.50	36.46181	58.50	37.80209	67.50	39.14238	81.00
28.44009	70.50	29.78038	68.50	31.12067	72.50	32.46095	61.50	33.80124	211.00	35.14153	67.50	36.48181	74.50	37.82210	79.50	39.16238	81.00
28.46010	72.50	29.80038	57.00	31.14067	66.50	32.48096	74.00	33.82124	224.00	35.16153	68.00	36.50182	61.50	37.84210	65.00	39.18239	76.50
28.48010	64.50	29.82039	64.50	31.16068	76.50	32.50096	70.00	33.84125	246.00	35.18153	62.00	36.52182	67.00	37.86211	68.50	39.20239	75.50
28.50011	67.50	29.84039	73.00	31.18068	71.00	32.52097	72.50	33.86125	284.50	35.20154	67.50	36.54182	54.50	37.88211	57.50	39.22240	68.50
28.52011	81.00	29.86040	73.50	31.20068	67.00	32.54097	74.50	33.88126	301.00	35.22154	61.00	36.56183	64.00	37.90211	64.00	39.24240	74.50
28.54012	73.00	29.88040	88.00	31.22069	74.00	32.56097	72.50	33.90126	331.50	35.24155	67.00	36.58183	71.00	37.92212	50.00	39.26241	70.50
28.56012	80.50	29.90041	74.00	31.24069	65.50	32.58098	64.50	33.92126	316.00	35.26155	66.00	36.60184	58.00	37.94212	70.00	39.28241	61.00
28.58012	71.50	29.92041	81.50	31.26070	68.00	32.60098	72.00	33.94127	356.50	35.28156	63.00	36.62184	59.50	37.96213	65.00	39.30241	62.00
28.60013	86.00	29.94041	81.00	31.28070	66.50	32.62099	58.00	33.96127	345.50	35.30156	69.00	36.64185	58.00	37.98213	61.50	39.32242	68.50
28.62013	82.50	29.96042	81.50	31.30070	67.50	32.64099	68.00	33.98128	319.00	35.32156	68.00	36.66185	63.00	38.00214	68.50	39.34242	63.50
28.64014	74.00	29.98042	80.00	31.32071	72.00	32.66100	68.50	34.00128	329.50	35.34157	68.00	36.68185	64.50	38.02214	62.50	39.36243	60.00
28.66014	75.00	30.00043	96.00	31.34071	59.50	32.68100	70.50	34.02129	317.50	35.36157	75.50	36.70186	62.00	38.04214	64.00	39.38243	68.00
28.68015	70.50	30.02043	82.50	31.36072	59.00	32.70100	69.50	34.04129	280.00	35.38158	62.50	36.72186	54.50	38.06215	54.00	39.40244	67.50
28.70015	70.50	30.04044	113.00	31.38072	67.50	32.72101	72.50	34.06129	261.00	35.40158	75.50	36.74187	63.00	38.08215	68.00	39.42244	66.50
28.72015	76.50	30.06044	98.00	31.40073	78.50	32.74101	73.00	34.08130	213.00	35.42159	73.50	36.76187	75.00	38.10216	66.50	39.44244	56.50
28.74016	69.50	30.08044	106.00	31.42073	65.50	32.76102	70.00	34.10130	185.00	35.44159	66.50	36.78188	64.50	38.12216	51.50	39.46245	53.50
28.76016	68.00	30.10045	115.50	31.44073	71.00	32.78102	61.50	34.12131	159.50	35.46159	71.50	36.80188	78.50	38.14217	63.50	39.48245	69.00
28.78017	72.50	30.12045	117.00	31.46074	61.00	32.80103	58.50	34.14131	145.00	35.48160	73.00	36.82188	69.00	38.16217	59.00	39.50246	69.00
28.80017	83.00	30.14046	127.00	31.48074	73.50	32.82103	72.00	34.16132	122.50	35.50160	71.00	36.84189	60.50	38.18217	66.00	39.52246	59.00
28.82018	73.00	30.16046	137.00	31.50075	79.00	32.84103	68.50	34.18132	101.00	35.52161	64.00	36.86189	66.50	38.20218	63.50	39.54247	63.00
28.84018	75.00	30.18047	157.00	31.52075	59.50	32.86104	77.50	34.20132	94.50	35.54161	71.50	36.88190	60.00	38.22218	73.00	39.56247	64.00
28.86018	82.00	30.20047	179.00	31.54076	74.00	32.88104	65.00	34.22133	85.00	35.56161	76.00	36.90190	68.50	38.24219	64.00	39.58247	69.50
28.88019	71.50	30.22047	222.00	31.56076	80.00	32.90105	73.50	34.24133	79.50	35.58162	61.50	36.92191	68.00	38.26219	55.00	39.60248	70.00
28.90019	76.50	30.24048	173.50	31.58076	73.00	32.92105	92.00	34.26134	83.50	35.60162	76.00	36.94191	71.50	38.28220	54.50	39.62248	63.00
28.92020	72.50	30.26048	206.00	31.60077	64.50	32.94106	70.50	34.28134	74.50	35.62163	63.00	36.96191	69.50	38.30220	76.50	39.64249	63.00
28.94020	76.00	30.28049	245.00	31.62077	75.00	32.96106	63.50	34.30135	81.00	35.64163	65.00	36.98192	65.50	38.32220	63.00	39.66249	60.00
28.96021	69.50	30.30049	243.50	31.64078	77.00	32.98106	57.00	34.32135	80.50	35.66164	61.50	37.00192	67.50	38.34221	67.50	39.68250	57.00
28.98021	66.50	30.32050	233.00	31.66078	66.00	33.00107	72.50	34.34135	76.50	35.68164	76.50	37.02193	61.50	38.36221	72.00	39.70250	60.50
29.00021	65.00	30.34050	270.50	31.68079	68.00	33.02107	81.50	34.36136	67.00	35.70164	69.50	37.04193	75.00	38.38222	66.00	39.72250	66.00
29.02022	70.50	30.36050	254.50	31.70079	63.50	33.04108	69.00	34.38136	87.00	35.72165	80.00	37.06194	78.50	38.40222	65.00	39.74251	63.00
29.04022	77.50	30.38051	237.50	31.72079	65.50	33.06108	68.00	34.40137	67.00	35.74165	65.50	37.08194	69.50	38.42223	61.00	39.76251	56.50
29.06023	64.50	30.40051	246.50	31.74080	71.50	33.08109	78.50	34.42137	72.00	35.76166	64.50	37.10194	76.50	38.44223	66.50	39.78252	68.00
29.08023	75.00	30.42052	270.50	31.76080	56.00	33.10109	74.00	34.44138	73.00	35.78166	75.50	37.12195	78.50	38.46223	59.00	39.80252	71.00
29.10023	65.00	30.44052	244.50	31.78081	64.50	33.12109	75.50	34.46138	66.00	35.80167	60.00	37.14195	74.50	38.48224	58.00	39.82253	58.00
29.12024	82.50	30.46053	198.00	31.80081	73.00	33.14110	74.00	34.48138	59.00	35.82167	63.50	37.16196	94.50	38.50224			

More RTD Research News

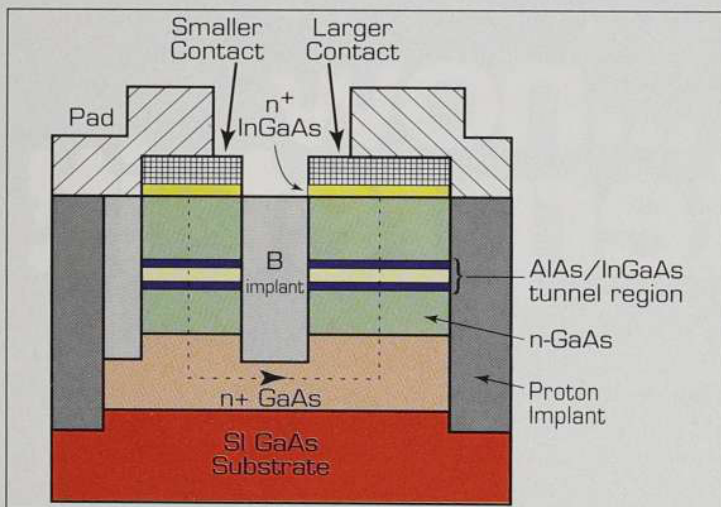
Planar Self-aligned RTD Fabrication

[C. Chen et al, IEEE Electron Device Lett., 1997, 18(10), 489]

Researchers at MIT Lincoln Laboratory have developed a self-aligned technology, which overcomes two disadvantages of conventional mesa-etched structures. The first arises from the undercut of the mesa etch, which can make the active device area difficult to control, while the second problem concerns the height difference between the two ohmic contacts. This can significantly increase the difficulty of interconnection and limit the packing density and complexity of the IC.

MIT Lincoln Lab's planar technology, which is compatible with conventional silicon processing, is based on self-aligned boron and proton implantation. As shown below, the RTD consists of a double-barrier AlAs/InGaAs heterostructure, surrounded by n-GaAs. A surface layer of InGaAs was included to permit the use of non-alloyed TiW contacts rather than Au. The TiW contact layer was sputtered across the whole planar surface and patterned using optical lithography and reactive ion etching. The active areas of the RTDs were defined by a shallow, self-aligned B implant, using the smaller TiW contact as a mask, whilst the devices were isolated by a proton implant defined by a conventional photoresist mask.

The fabricated structure is equivalent to two RTDs of different sizes connected in series. The smaller RTD determines the peak current and voltage, whilst the larger device is effectively a resistor since it does not reach its peak current under normal operating conditions. No degradation of performance was observed compared to mesa-etched RTDs, and as this technique does not require critical alignment, small geometries can be obtained, limited by the resolution of optical lithography tools.



Schematic cross-section showing two series RTDs separated by a B implant and isolated with a proton implant to give a planar structure. When operational, current flows in the device as shown in the dotted line.

Static Frequency Dividers using RTDs

[K. Arai et al, IEEE Electron Device Lett., 1997, 18(11), 544]

Raytheon TI Systems are not the only company to have integrated RHEMTs and RTDs. Researchers at NTT have also developed a process to monolithically integrate such devices using MBE growth on an InP substrate. In this case, the devices are connected in parallel. The bottom HEMT layers include an undoped InGaAs channel, whilst the RTDs contain an InGaAs/InAs/InGaAs strained QW with AlAs barriers. These heterostructures are used as the basis of static binary frequency dividers with greatly reduced complexity compared to conventional circuits.

The frequency divider has two sub-circuits consisting of a load element (an RTD) and a driver element, which is the monolithically integrated RTD and HEMT connected in parallel. This sub-circuit is a monostable-bistable transition logic element, or MOBILE. It effectively functions as a D-latch and has only 3 components, compared to the 15 required in conventional SCFL technology. This should help to reduce the transmission delay time in complex frequency divider circuits operating at speeds of up to 40GHz. The total power consumption of the frequency divider circuit is about 25mW, which is expected to lead to reduced power at higher frequencies.

[continued from page 38]

Other Applications - Logic and Optoelectronics

In general, RTDs can enhance the performance of any transistor technology since RTD/transistor circuits can typically be designed with fewer components, lower power dissipation and higher circuit speed than transistor-only circuits. (See, for example, the paper by Arai et al. described below). The wide applicability of RTDs beyond memory is shown by a number of circuit examples [9], such as 3GHz (40dB spur free dynamic range) clocked quantizers, and redundant number systems enabling high speed carry-free addition for multistate logic. Compact, optically switched resonant-tunneling photo-detectors have been demonstrated at speeds as high as 2Gb/s with low switching energy (30fJ) [10]. Such devices can be used to provide micron-sized optical clock and photoreceiver functions and allow interwafer communications at gigabit per second rates.

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Box B. Basic memory concepts

Large memory arrays, whether Random Access Memory (RAM) or Read-Only Memory (ROM), are constructed of rectangular arrays of cells contacted by horizontal (word) and vertical (bit) lines, which enable each cell to be individually addressed. The cells store information, which in the case of ROM is written permanently into the cells in the factory, whilst in other versions such as EPROM (Electrically Programmable ROM) and EEPROM (Electrically Erasable Programmable ROM), modifications can be made at a later stage, external to the computer. These types of memory are termed non-volatile, since the information is retained even when the power supply to the computer is switched off. Other types of non-volatile memory include flash RAM, and some types of magnetic and ferroelectric memory.

RAM allows continuous writing, reading and erasing of information in the cell; most types of RAM are volatile. In Static RAM (SRAM), information stored in the cell is retained until the cell receives another signal, whereas in Dynamic RAM (DRAM), the information must be continuously 'refreshed'. The basic DRAM cell is shown in Figure B1. When the word and bit lines are high, charge is stored on the capacitor C, and this drives the word line when the cell is subsequently read. Charge leakage from the capacitor necessitates the refresh cycle. DRAMs are extremely dense and fast, and are thus in widespread use despite the excess power consumption associated with the refresh operation. DRAMs currently hold about 75% share of the total semiconductor memory market, and are moving towards 1Gb memory arrays with a feature size of $<0.25\mu\text{m}^2$.

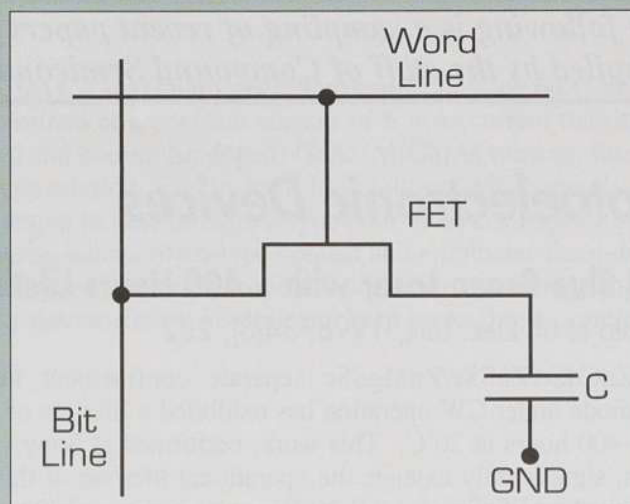


Figure B1. Basic conventional DRAM cell

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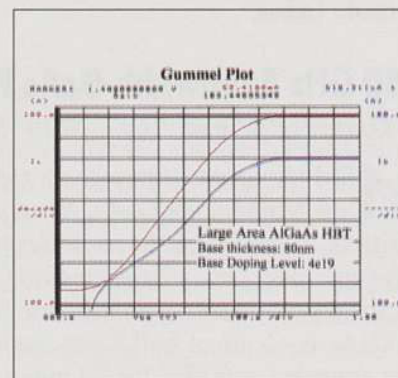
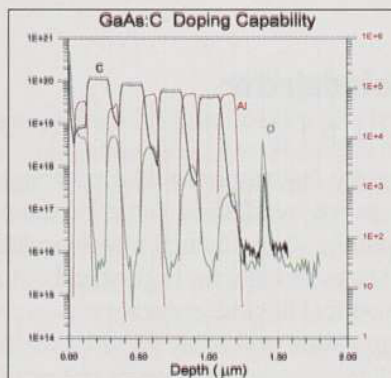
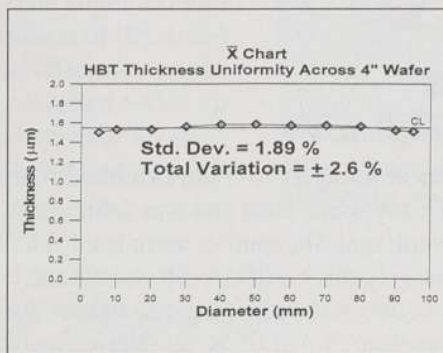
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Research Review

The following is a sampling of recent papers from a variety of international journals, compiled by the staff of Compound Semiconductor.

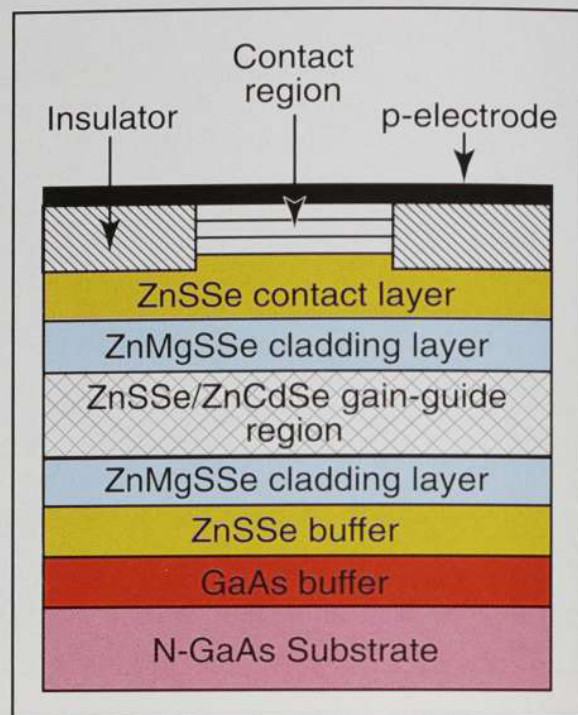
Optoelectronic Devices

II-VI Blue-Green Laser with > 400 Hours Lifetime

E. Kato et al, Elec. Lett., 1998, 34(3), 282

A ZnCdSe/ZnSSe/ZnMgSSe separate confinement heterostructure laser diode under CW operation has exhibited a lifetime of >140 hours at 40°C and ~400 hours at 20°C. This work, performed at Sony's Research Center in Japan, significantly extends the operational lifetime of this class of laser. The previous best lifetime for a II-VI laser was just over 100 hours at room temperature. The 514 nm laser operated with an output of 1 mW, and was fabricated from the layer structure shown opposite. A key step to increasing the device lifetime is to reduce the dark spot density to a value of $<10^3$ per cm^2 . At this level, degradation is due to microscopic point defects rather than macroscopic features such as stacking faults and threading dislocations originating at the III-V/II-VI interface. To enable this situation, S and Se cracker cells were used to control and optimize the II-VI ratio in the growth of the gain-guide region layers.

Schematic structure of the laser structure. The gain-guide region contains a single ZnCdSe QW with ZnSSe guiding layers. The contact region contains ZnSe/ZnTe MQWs to reduce the operating voltage.



50 A/cm² SQW Antimonide Lasers

G. Turner et al, Appl. Phys. Lett., 1998, 72(8), p.876

Strained SQW GaInAsSb/AlGaAsSb lasers emitting at 2.05 μm exhibited room temperature threshold current densities as low as 50 A/cm². This value is among the lowest for any diode laser and was achieved due to improved material and structural quality enabled by MBE. A valved As cracker and two conventional Sb₄ sources were used. The laser structure had a single Ga_{0.78}In_{0.22}As_{0.99}Sb_{0.01} QW with AlGaAsSb barriers. Lightly doped, relatively thick, AlGaAsSb waveguide layers were introduced to help reduce free-carrier optical losses. Compositionally graded regions between the cladding and barrier AlGaAsSb layers were also used, to reduce series resistance. The devices had a characteristic temperature (T_0) of 65 K, an internal quantum efficiency of 95% and an internal loss coefficient of 7 cm⁻¹. Single-ended CW power of 1 W was obtained from a 100 μm aperture device operating at 4.2 A. (Work carried out at MIT Lincoln Labs).

550 GHz Bandwidth GaAs Photodetector

P. Kordos et al, Elec. Lett., 1998, 34(1), p.119

MSM photodetectors with an extremely fast response time corresponding to a bandwidth of 550 GHz, have been fabricated from low temperature GaAs. Material grown by MBE at substrate temperatures between 150-350°C is non-stoichiometric and highly resistive. It can be used as a buffer to reduce short channel effects in MESFETs, or as an insulator in MISFETs. The high defect density (up to 10^{18} per cm^3) also makes LT GaAs suitable for high-speed opto-electronic applications. As the substrate temperature decreases, the defect density increases, but the critical thickness decreases - at 200°C, the critical thickness is 0.6 μm . As the absorption length in GaAs is ~1 μm at $\lambda=0.8 \mu\text{m}$, the temperature and other growth conditions have to be carefully optimized. Material grown at 200°C and annealed at 600°C for 10 minutes had a carrier lifetime of 0.2 ps. The interdigitated finger devices had rise and fall times of 0.4 ps and 0.6 ps respectively, and a unit area capacitance of 0.014 fF/ μm^2 . (Work carried out at the Institute for Thin Film and Ion Technology, Julich, Germany).

Double-fused 1.5 μm VCSELs

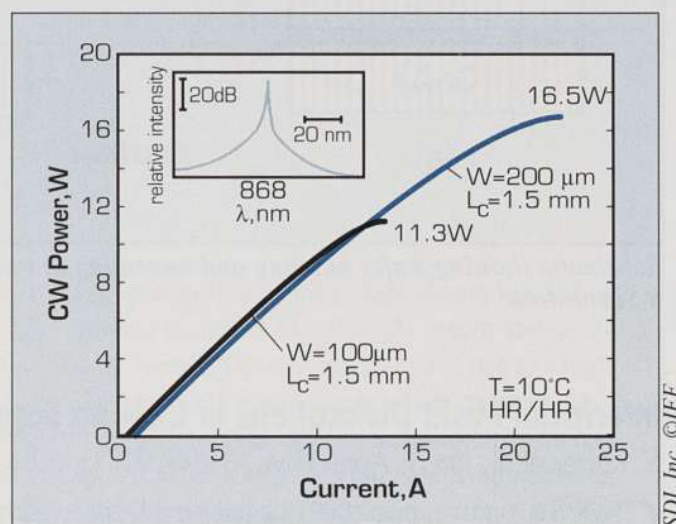
N. Margalit et al, Elec. Lett., 1998, 34(3), p.285

1.5 μm VCSEL structures fabricated by researchers at UC Santa Barbara have a maximum operating temperature of 64°C and an extended lifetime of >4000 hours at 15°C. The aging experiment was performed at a constant current of 6 mA (current density 10 kA/cm²) and an output power of 100 μW . The structures features top (p-type) and bottom (undoped) GaAs/Al(Ga)As mirrors, fused to the InP/InGaAsP MQW active region, with a buried oxide layer for current constriction. The device is top-emitting, which greatly simplifies packaging requirements. Previous similar devices have required the output to pass through n-type bottom layers, requiring both flip-chip bonding and limiting the output power. The present device features an intercavity n-type contact and eliminates the n-doped mirror, increasing the efficiency, lowering the threshold gain, and allowing higher temperature operation. A wide operating temperature range from -40 to +85°C is required in VCSELs to eliminate the need for thermoelectric cooling and keep packaging requirements simple.

16.5 W from an 870 nm AlGaAs Laser

S. O'Brien et al, Elec. Lett., 1998, 34(2), p. 184

Wide aperture AlGaAs-based lasers have been fabricated by SDL Inc. with CW output powers of 11.3 W and 16.5 W for 100 μm and 200 μm wide apertures respectively (see figure). The maximum CW output power of broad-area lasers is typically limited by the onset of catastrophic optical mirror damage (COMD), a thermal runaway effect. The onset of COMD was delayed in these devices by reducing internal losses and series resistance, combined with low defect densities. The structures were grown by MOCVD and featured a GaAs QW active region and AlGaAs separate confinement heterostructure. A 1.5 mm x 100 μm device with a maximum power of 11.3 W exhibited a T_0 of 145 K, a slope efficiency of 1.05 W/A (74%), and a threshold current of 0.4 A, corresponding to a threshold current density of 270 A/cm². The larger 2.0 mm x 200 μm device failed at 16 W, and had a threshold current of 0.8 A and a slope efficiency of 1.03 W/A. The total conversion efficiency of the 200 μm laser peaked at 52% with a current of 7 A and remained >45% up to 13.5 A (~12 W CW). These types of high power device have a variety of applications in diode-pumped solid-state lasers, fiber laser pumps, thermal printing and materials processing.



CW L-I curves for 100 x 1500 μm and 100 x 2000 μm lasers. Inset shows spectrum at 0.5 W CW output power, indicating operation at 868 nm.

Compound Semiconductor Materials

GaN/SiC n-p Heterojunctions

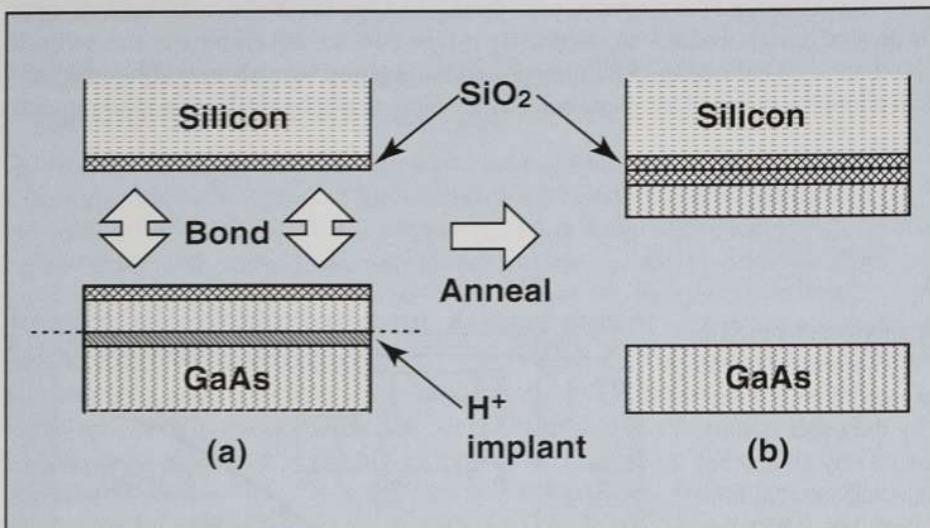
J. Torvik et al, Appl. Phys. Lett., 1998, 72(8), p.945

Wide bandgap n-p hetero-junctions formed between n-type GaN and p-type SiC have been used as the emitter-base junction in high temperature transistors, with high current gain and high power densities. However, these diodes have a low forward turn-on of ~1.15 V, rather than the 2.5 V expected from drift/diffusion theory. This work, carried out by Astralux Inc., Boulder, CO, provides evidence for the existence for a deep defect level located about 1.25 eV above the valence band edge in p-type 6H-SiC. The low turn-on voltage can be attributed to tunneling from the conduction band edge of GaN into this defect level. PL measurements on n-type 6H-SiC showed luminescence at 1.80 eV and 1.25 eV, corresponding to radiative transition from the conduction band to the deep level, and from the deep level to the valence band, respectively (the bandgap of 6H-SiC is 3.03 eV). Electroluminescence spectra from GaN/SiC n-p hetero-junctions showed peaks at 1.25 eV and 1.75 eV. The 1.25 eV EL represents tunneling of electrons from the conduction band in GaN to the defect level in p-type SiC. The 1.75 eV peak indicates some electrons are injected from the GaN to the conduction band of the SiC and subsequently undergo a radiative transition to the defect level (the value is shifted slightly compared to the PL measurement). The origin of the defect level is unclear but could be due to molybdenum, which acts as a deep acceptor in 6H-SiC; other possibilities are surface/interface states, or donor to acceptor transitions.

Transfer of 3 Inch GaAs Films to Silicon

E. Jalaoui et al, Elec. Lett., 1998, 34(4), p. 408

Hetero-epitaxy of GaAs on Si suffers from a high density of threading dislocations, but bonding techniques allow the transfer of GaAs films to Si substrates. This work, by LETI-CEA in Grenoble, France, is a technique for transferring large GaAs films, up to 3 inches thick, to Si wafers using a proton implantation process. After hydrogen implantation into GaAs at 100 keV with a dose in the



Schematic showing wafer bonding and annealing to transfer a GaAs thin film to a Si substrate

range $5 \times 10^{16} \text{ cm}^{-2}$ to $1 \times 10^{17} \text{ cm}^{-2}$, blisters appear when the wafer is annealed at 400-700°C (the exact temperature relates to the implant level). Blistering is indicative of the formation of hydrogen-induced microcracks. XTEM revealed different types of cavities in blistered GaAs layers as well as micron-sized cracks parallel to the (100) surface, which subsequently lead to splitting.

A hydrogen-implanted GaAs wafer and a Si wafer, each with a surface silicon dioxide layer grown by PECVD, are joined by room temperature hydrophilic bonding (see figure a). The bonding is enhanced by annealing at 350°C, while further annealing at 400-700°C causes the implanted wafer to split (figure b). The result is a Si substrate with a thin, monocrystalline GaAs film. As the thin film is unable to deform elastically, some splitting of the underlying substrate is observed.

Interfacial Misfit Dislocations in GaN on Sapphire

S. Kaiser et al, Jpn. J. Appl. Phys., 1998, 37(1), p.84

GaN films grown on a (0001) sapphire substrate without a buffer layer were studied by transmission electron microscopy (TEM). 1 μm thick layers were grown by plasma-induced MBE at a substrate temperature of 810°C. A high density of defects ($10^{10} - 10^{11} \text{ cm}^{-2}$) was observed in the interfacial region. Selected area electron diffraction indicated that the (0001) directions were parallel in the layer and the substrate, but the (1010)-direction in GaN was parallel to the (1120)-direction in sapphire. The difference in lattice constants between epilayer and substrate results in a mismatch of -13.9%. The TEM studies reported here show that -11.8 $\pm$ 0.9% of the mismatch is compensated by the formation of defects confined directly at the GaN/Al₂O₃ interface. The misfit dislocations are formed parallel to the interface plane and do not extend into the GaN layer. This relaxation process at the interface allows epitaxial growth with a density of non-confined dislocations of about 10^{10} cm^{-2} . These dislocations reduce the residual strain from -2.1 $\pm$ 0.9% near the interface, as measured by TEM, to -0.2 $\pm$ 0.1% measured by DXRD in the surface region. Different types of non-confined dislocations are discussed fully. (Work carried out at the Universities of Regensburg and Karlsruhe and the Walter Schottky Institute).

Microelectronic Devices and Circuits

1.2 V FETs for Digital Cellular Phones

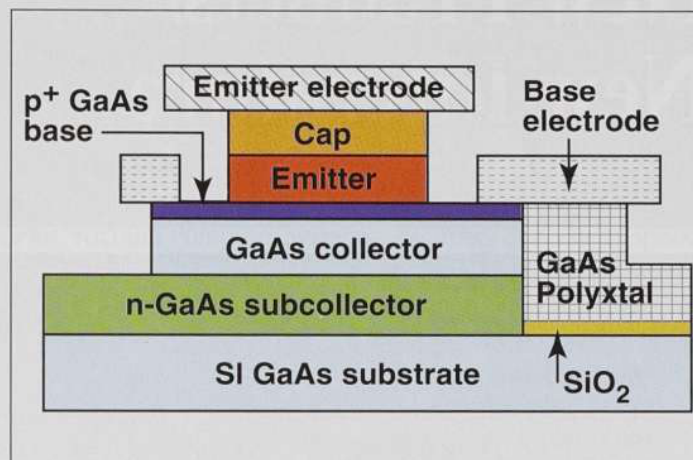
Yamaguchi et al, IEEE Trans. Elec. Dev., 1998, 45(2), p.361

A 0.8 μm gate-length n-AlGaAs/InGaAs/n-AlGaAs heterojunction FET with 1.2 V drain bias operation has been demonstrated by ANEC Corporation for personal digital cellular (PDC) applications. Low power consumption in the microwave power amplifier is a key issue to reducing the battery cell number and therefore the size and weight of handsets. The current device structure, grown on SI GaAs, features a 13.5 nm In_{0.2}Ga_{0.8}As undoped channel between two n-type Al_{0.22}Ga_{0.78}As barriers. The 0.8 μm gate length device exhibited on-resistance on 2.1 Ωmm and a maximum drain current of 640 mA/mm. At the PDC operating frequency of 950 MHz and 1.2 V drain bias, the 28 mm gate width HFET achieved P_{out} of 30.0 dBm and PAE of 51.5%.

Reduced Collector Capacitance in InGaP/GaAs HBTs

Mochizuki et al, IEEE Elec. Dev. Lett., 1998, 19(2), p. 47

HBTs with polycrystalline GaAs buried beneath the base electrode (see diagram) had a collector capacitance up to 28% lower than devices without the polycrystalline layer. The devices were grown by gas-source MBE at 430°C, on a GaAs substrate patterned with SiO₂. Polycrystalline material was deposited on this mask. The vertical interface between single- and poly-crystalline material was achieved with a surface roughness of < 70 nm. For 0.7 x 8.5 µm HBTs, figures of $f_T = 120$ GHz and $f_{max} = 230$ GHz were measured. Compared to HBTs without the polycrystal layer, the maximum stable gain was improved by 1.2 dB due to complete carrier depletion. This work, carried out at Hitachi Central Research Labs, shows the potential of these devices for high-speed digital and broadband amplifier applications



Hitachi's HBT structure with polycrystalline GaAs beneath the base electrode. The emitter is In_{0.5}Ga_{0.5}P.

Progress in GaN/AlGaN heterostructure FETs

Y-F. Wu et al, IEEE Electron Dev. Lett., 1998, 19(2), p.50

Q. Chen et al, IEEE Electron Dev. Lett., 1998, 19(2), p.44

A. Ping et al, IEEE Electron Dev. Lett., 1998, 19(2), p.54

AlGa_{0.5}N/GaN Field Effect Transistors are of great interest for high speed, high power and high temperature applications. Researchers at UC Santa Barbara have investigated the effect of increasing the Al mole fraction in AlGa_{0.5}N/GaN MODFETs. These device structures have an undoped GaN channel, separated from the n-type AlGa_{0.5}N donor layer by an undoped spacer. A higher Al mole fraction increases the bandgap in AlGa_{0.5}N and hence the composite breakdown field. Also, the conduction band discontinuity and piezoelectric effect are both increased, resulting in improved carrier confinement and increased mobility in the channel. The saturation velocity of carriers in the GaN channel is largely unaffected by the Al composition, and should remain high.

Al compositions in the range 25-50% were investigated. The sheet carrier density in epilayers increased from 8×10^{12} cm⁻² at 15% Al to 1.2×10^{13} cm⁻² at 35%, although reduced doping efficiency was observed at higher Al composition. The room temperature mobility showed little degradation with increasing Al-content up to 50%, and was 2500 cm²/Vs at this Al composition. 0.7 µm gate length Al_{0.5}Ga_{0.5}N/GaN MODFETs exhibited an ultrahigh three-terminal I-V product up to 200 VA/mm, and values of $f_T = 17.5$ GHz and $f_{max} = 44$ GHz were measured. CW power densities of 2.84 and 2.57 W/mm at 8 GHz and 10 GHz respectively were achieved. These values, measured on sapphire substrates without thermal management, are close to the 3.3 W/mm measured for pulsed SiC MESFETs.

Another approach is to use a doped-channel structure.

Chen et al fabricated devices with a GaN channel doped at $\sim 2-5 \times 10^{17}$ cm⁻³, an undoped Al_{0.15}Ga_{0.85}N spacer and an n-type Al_{0.15}Ga_{0.85}N barrier. Optimal doping gave rise to a high sheet charge density while maintaining a high channel electron mobility. The sheet carrier density times electron mobility product was 1.6×10^{16} /Vs. 0.25 µm gate length devices also exhibited high gain (>4 dB) at moderate input powers (10 dBm) over a wide range of frequencies (8-18 GHz). At a drain bias of 18 V and drain bias current of 46 mA, these 100 µm wide devices exhibited high gain at 8.4 GHz with a power density reaching 1.73 W/mm. The drain efficiency was 21% and the power added efficiency was 15%. (Work carried out at APA Optics, Rensselaer Polytechnic, Rockwell and Illinois University).

SiC has a higher thermal conductivity than sapphire and reduced thermal mismatch with respect to growth of GaN-based devices. AlGa_{0.5}N/GaN FETs grown on SiC might be expected to have improved high power performance. Ping et al grew doped-channel FETs with 20% Al in the spacer and barrier layers. The sheet carrier concentration and mobility were 1×10^{13} cm⁻² and 1500 cm²/Vs respectively. 0.25 µm gate length devices exhibited a source-drain current of 1.4 A/mm at 20 V, with minimal self-heating effects apparent from the I-V characteristics. These devices also demonstrated a high transconductance of 229 mS/mm, an f_T of 53 GHz and an f_{max} of 58 GHz. The value of f_T is the highest reported for a GaN-based FET grown on a SiC substrate. (Work carried out at the University of Illinois and APA Optics).

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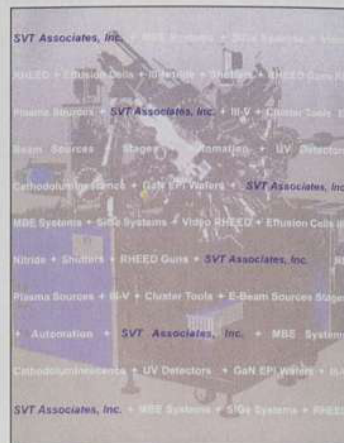
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Phosphorus Source for MBE

East Grinstead, West Sussex, UK. VG Semicon has expanded its MBE component offerings to include a Compound Phosphorus Source. The source is designed to provide 100% P_2 species by evaporating P_2 from the solid compound GaP. Gallium molecules are removed from the flux by a simple baffle arrangement. Flux control is easily achieved by rapidly adjusting the temperature of the source.

The Compound Phosphorus Source is the first commercially available MBE cell which claims 100% P_2 without using thermal cracking. Its design and operation is much simpler than that of thermal crackers, especially valved crackers. "Complex construction is the Achilles heel of the valved thermal cracker. It is just too complicated, especially for use in production MBE where reliability is paramount," commented Philip Sullivan, General Manager of VG Semicon USA. "Our new component is available to all of our MBE system users. It provides our customers who wish to explore phosphorus containing semiconductors with a simple, reliable, inexpensive and very controllable source of pure P_2 ."

The source has been tested at a number of sites worldwide, and compared to valved crackers has demonstrated significant improvements in safety, reliability, material purity and cost. In addition, it has been used to grow very abrupt phosphide/arsenide interfaces - a prerequisite of many advanced device structures.

"Users who are involved in commercially mature manufacture of MBE material are continually pushing us to provide more production-worthy solutions for the MBE process," said David Williams, Managing Directory of VG Semicon. "We see this as a significant incremental step towards the safe and reliable integration of phosphides into the production MBE environment."

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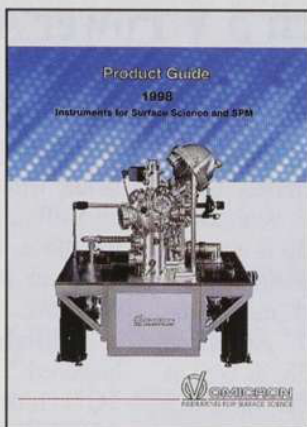
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CTI-Cryogenics Introduces On-Board TurboPlus Vacuum Pumping Systems

Mansfield, MA. CTI-Cryogenics, a division of Helix Technology Corporation, announces the introduction of its new On-Board TurboPlus Vacuum Pumping Systems. By integrating high-speed water pumping with a compound turbomolecular pump, deposition processes can be performed with superior film quality and higher yield than with turbo pumping alone. On-Board TurboPlus Vacuum Pumping Systems are also very effective for load lock application requiring minimum water contamination. Available with 6" (150mm) and 8" (200mm) ID vacuum ports, net speeds of over 3000 l/s can be obtained at much lower net cost than comparably sized turbo pumps.



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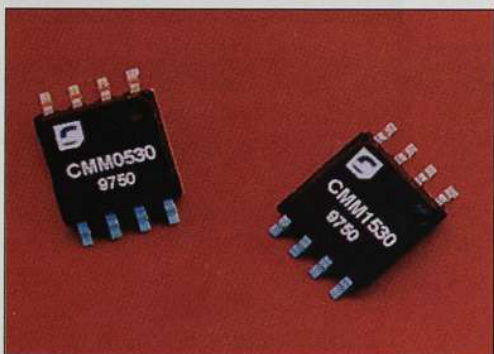
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Abstract Deadline: May 30, 1998

Anadigics, Celeritek, TriQuint Launch 3 V Power Amplifiers for Cellular Handsets

Three GaAs IC manufacturers recently announced power amplifiers capable of operating from a 3 V supply, to enable cellular phone handset designers to develop phones with very low power consumption. Both Anadigics and TriQuint have used a low voltage MESFET process, whereas Celeritek's new products are based on PHEMTs.

The trend is towards lower voltage operation to accommodate newer batteries, such as lithium-ion, which operates at 2.7 V. Another continuing trend is for dual-mode phones, to utilize the cheaper airtime charges and improved features offered by 1.7-1.9 GHz Personal Communications Services (PCS)/ Digital Communication Systems (DCS) systems, yet maintain coverage within the 800-950 MHz cellular locales where PCS/DCS is not available.



Celeritek's PHEMT-based, dual-band 3.0 V power amplifiers feature 8-pin plastic packaging for improved thermal characteristics and a small footprint.

Santa Clara, CA. Celeritek's new products are the latest members of its Trinita DX Pro family of 3 volt power amplifier MMICs. CMM0530 is a multi-mode PA for handsets operating in the 824-928 MHz range, and meets the requirements for cellular Advanced Mobile Phone System (AMPS) as well as the CDMA and TDMA digital standards. Performance features include 27 dB gain, 45% linear power added efficiency (PAE), and 55% PAE at 32 dBm P_{sat} . CMM1530 is a linear PA designed for PCS handsets and base stations in the 1.85-1.91 GHz range. The device will meet the requirements of PCS-1900, IS-136 (TDMA), J-STD-18 (CDMA) and DCS-1800 systems. Features include 40% PAE under linear operation and 30 dB gain.

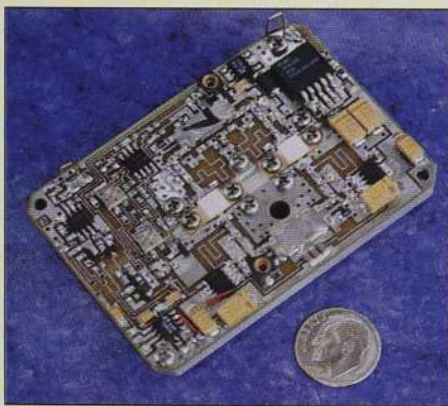
Santa Clara, CA. Anadigics' new 3V product line features dual and single mode power amplifiers to address all the major cellular standards. Nominal performance is at 3.6 V, although the PAs are designed to meet cellular specifications at voltages as low as 2.7 V. AWT936 and AWT937 are single-mode PAs for GSM and AMPS respectively. AWT936 has a typical PAE of 60% at 3.6 V and P_{out} of 35 dBm, AWT937 has a PAE of 70% at P_{out} of 31.5 dBm. AWT938 and AWT939 are dual-mode; the former is for 800 MHz AMPS/CDMA applications. PAE for CDMA modulation is 42% at 28 dBm, while in the AMPS mode, PAE is 60% with 8 dBm input power and P_{out} at 31.5 dBm.

AWT939 is for AMPS only; in digital mode, with of 28.5 dB gain and P_{out} of 28.5 dBm, the efficiency is 45%. In analog mode, output power of 31.5 dBm is achieved with 8 dBm input power and 60% PAE.

Hillsboro, OR. TriQuint has launched 5 new 3 V, single supply PAs. TQ7111, designed for analog operation of AMPS (IS-19) handsets in the 824 - 849 MHz cellular band is a two-stage amplifier with a typical P_{out} of 31.5 dBm and PAE of 60%. TQ7541 and TQ7641 are three-stage PAs designed for DCS-1800 (1710-1785 MHz) and US PCS-1900 (1850-1910 MHz) handsets respectively. TQ7541 has a PAE of 45% at P_{out} of 32.5 dBm.

TriQuint also has two new products for TDMA applications. TQ7121 is a dual mode PA operating in the digital TDMA or an analog AMPS mode. In AMPS mode, P_{out} is 31.5 dBm with 50% PAE. In TDMA mode, the adjacent channel power (ACP) is -29 dBc/30 KHz, with alternate channel power (ALT) of -49 dBc/30 KHz, and PAE of 42%. TQ7621 is optimized for digital TDMA (IS-136) operating in the PCS (1850- 1910 MHz) band. The on-chip negative supply generator (charge pump) can be switched off between transmit time slots when the PA is used in TDMA systems, to extend the available talk time. At a rated power of 30 dBm, TQ7621 meets typical ACP of 29 dBc/30 kHz and ALT of -49 dBc/30 kHz with PAE of 30%.

10 W Power Amplifier Module from Celeritek



Santa Clara, CA. The PCS-19010MA solid-state 10 W PA module from Celeritek is designed for digital PCS base station transmit applications operating in the 1930-1990 MHz range. The product uses a single +12 V power supply and meets the high dynamic range requirements of CDMA and TDMA modulation schemes, as well as DCS-1800/PCS-1900 applications. A

compact, unobtrusive and cost effective module is required to meet the demands of expanding PCS infrastructure coverage. Celeritek's new product measures 3" x 2" x 0.5" high and is a suitable 10 W solution for microcells, picocells, repeaters and pole-top designs. The module uses GaAs FET-based technology and is priced at \$250 in 1,000 piece quantities.

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New GaAs ICs for Telecommunications

Multilink Launches GaAs Products For Fiber-Optic Networks

Santa Monica, CA. Multilink Technology Corporation recently unveiled their large family of GaAs mixed-signal ICs for applications in fiber-optic networks. Under a strategic agreement between Multilink and TRW, Multilink's proprietary MMIC designs are fabricated using TRW's HEMT and HBT processes. TRW owns a minority interest in the privately held Multilink. 'Multilink's products will extend TRW's high-speed GaAs and InP technologies into the dynamic market segment of wired telecommunications, complementing our rapidly growing business in MMICs and modules for wireless telecom', says David B. Vandervoet, TRW vice president and general manager of the company's Telecommunications Programs Division. The wireless market is being tackled through TRW's strategic venture with RFMD.

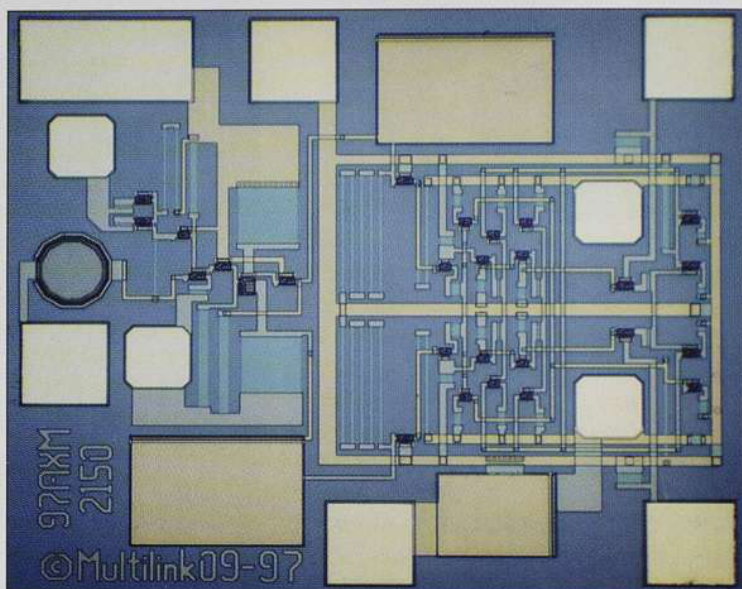
The announcement marks Multilink's first major product introduction since partnering with TRW, says Multilink president Richard N. Nottenburg. 'Our new family of products will drive down the cost of operating fiber-optic networks, while providing operators with the greater information carrying capacity they seek'. At present, the products are all GaAs-based, although InP-based products 'are in advanced stages of development'.

The products are a series of GaAs-based MMICs and modules, designed for networks operating at 2.5 Gbit/s or 10 Gbit/s. They are fabricated using either TRW's HBT process, with an f_T of 45 GHz, or the HEMT process with a 0.15 μm gate length and f_T of 80 GHz. The products include;

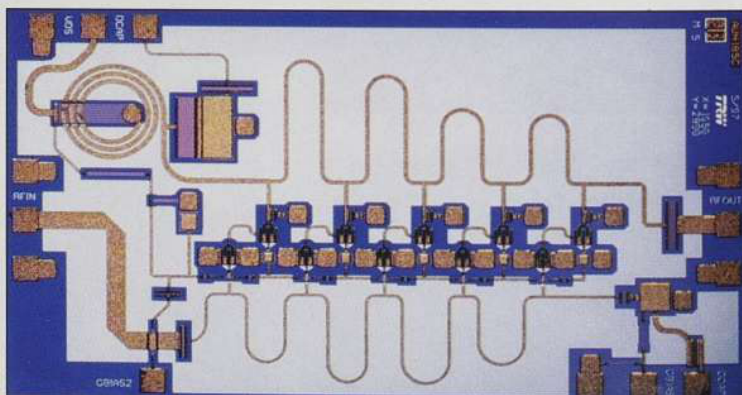
- MTC1203/1204 - 16 bit mux and demux chipsets fabricated using the HBT process to minimize power dissipation.
- MTC2040 - A VCSEL driver IC operating from DC to 2 Gbit/s, with up to 30 mA peak current. The MMIC provides both bias and modulation current adjustment to match the temperature characteristics of most VCSEL devices. Total power consumption is less than 125 mW.
- MTC2150 - A fully monolithic receiver integrating a GaAs PIN photodiode, a low noise transimpedance amplifier and a differential limiting amplifier on a die that measures 0.9 x 0.8 mm. The detector has an active diameter of 75 μm and requires no external bias for data rates up to 1.25 Gbit/s. A robust design and the GaAs HBT process, utilizing backside vias, enables easy packaging with a minimal number of external bypass capacitors.
- MTC5510 - A 30 KHz - 15 GHz medium power amplifier suitable for driving external modulators, particularly LiNbO_3 where a large extinction coefficient is required. The module has a flat linear gain response, low internal jitter and consumes 4 W of power.

- MTC5520 - A 10 GHz transimpedance amplifier manufactured using the GaAs HEMT process. The transimpedance gain is 750 Ω and the amplification remains linear for peak input currents up to 2 mA. The die size is 1.5 x 1.4 mm.

Other products fabricated using the HEMT process include; a DC to 12 GHz linear gain block, a 30 KHz-10 GHz variable gain amplifier, a 2-12 GHz MMIC distributed amplifier and a 2-15 GHz MMIC power amplifier.



Multilink Technology's MTC2150 is a fully monolithic receiver which integrates a GaAs PIN photodiode (annular structure at left), a low noise transimpedance amplifier, and a differential limiting amplifier on a die measuring 0.9 x 0.8 mm.



Multilink Technology's MTC5520 is a 2-15 GHz MMIC power amplifier fabricated using TRW's 0.15 μm GaAs HEMT technology.

Anadigics Offers 10 Gbit/s GaAs PHEMT ICs

Warren, N.J. Anadigics announced transimpedance and limiting amplifiers operating at 10 Gbit/s as their first ever products to be fabricated using a GaAs PHEMT process. PHEMTs reportedly offer better sensitivity and bandwidth than conventional MESFET devices. The PHEMT process starts with 4" GaAs-based epitaxial wafers purchased from a commercial vendor, but has many subsequent fabrication steps in common with the MESFET process.

The ATA90000 is a 10 GHz TIA with a minimum 450 ohm transimpedance, output return loss of 14 dB, low distortion and typical gain flatness of ± 0.5 dB. The price in die form is \$500 in quantities of 1,000. The ALA90000 is a 3-stage, DC-coupled differential amplifier IC with a small signal gain of 25 dB, input sensitivity of 7 mV (differential) and an output drive of 700 mV into 50 ohms. 'It also offers built-in DC input offset cancellation which automatically biases the input stage in the optimal high gain region', says Tony Jakumar, Program Design Manager.

Rockwell Enters SONET/SDH Market With GaAs HBTs

Newport Beach, CA. Rockwell Semiconductor Systems announced the availability of GaAs HBT ICs, supporting SONET and SDH digital data transmission standards. A complete front-end transceiver solution for 2.5 Gbit/s fiber-optic data transmission is offered, along with related high-speed devices for 622 Mbit/s applications. Rockwell initially developed and manufactured this family of ICs on an exclusive basis for a single customer, and is now making the devices available to the merchant market. HBTs were chosen in preference to MESFETs for these applications, due to superior performance characteristics. "We optimized these high performance devices to achieve both low jitter and low power consumption using our 50 GHz GaAs HBT process," said K. Joseph Sikias, senior product marketing manager.

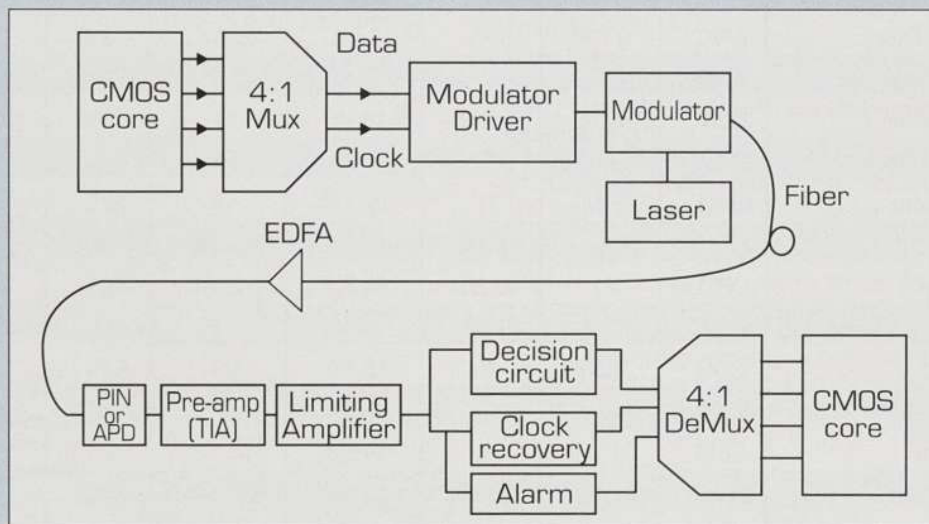
The RS701/RS702 16-bit mux/demux chipset consists of parallel-to-serial and serial-to-parallel digital data conversion ICs capable of serial rates up to 3 Gbit/s. Rockwell's advanced GaAs process yields high margins and very fast edge rates, and fully differential internal logic minimizes skew and jitter. These ICs feature a low typical power dissipation of 1.3-1.5 W. The R1901 transimpedance amplifier (TIA) features a high dynamic range from 5 to 1200 mA, high transimpedance gain of 62 dB Ω , and low power consumption of 160 mW.

The R1902 Clock and Data Recovery unit integrates a limiting amplifier, clock recovery and a decision circuit into a single chip solution with power consumption of 900 mW. The R1903 laser driver can achieve a maximum output driving current of 80 mA with a 25 Ω load. Power consumption is less than 400 mW.

Along with similar devices supporting 622 Mbit/s applications, Rockwell also offers the RI61010 12-bit digital-to-analogue converter (DAC) and RI4140X family of 10 GHz pre-scalars that can divide data signals by 2, 4, 8 and 32.

Electronic Components in Optical Networks

The main electronic components in optical transmission systems (see Figure) operate as follows. Low data rate signals from the CMOS core processor are combined using TDM (Time Division Multiplexing) in several stages to achieve a single data stream at the appropriate bit rate. In the example shown, the 4:1 mux IC combines 4 signals at 622 Mbit/s into a 2.5 Gbit/s output, and also generates a clock signal. The data and clock feed into a laser driver IC (for direct modulation) or to the modulator driver controlling an external III-V or lithium niobate modulator. At this stage, different wavelengths can be combined if desired using WDM and separated at the other end of the route. In the receiver, the incoming optical signal is detected by a PIN photodiode or an APD. The pre-amplifier stage of the receiver is frequently a transimpedance amplifier (TIA) which converts the weak electrical current from the detector into a voltage output. The limiting amplifier then further amplifies this voltage and also limits its amplitude to keep it within the limits of the next stage. The data and clock recovery chip contains a decision circuit that decodes the signal into a digital logic output of ones and zeros matching the original data stream. The clock recovery circuit extracts a timing signal matched to the data, and the alarm circuit generates a suitable logic-level output under a loss-of-signal condition. The data and clock signals are then demultiplexed down to a suitable data rate for processing by the CMOS system core.



GaAs IC Business Loses Some of Its Glamour

MARIE MEYER

Last fall (CS 3(5), p. 44) we published a chart showing the excellent progress being made in Anadigics', TriQuint's and Vitesse's market capitalization. (Market capitalization or 'market cap' is determined by multiplying the number of shares outstanding by current share price - in other words, it is the 'paper value' of a publicly traded company.) At that time, the companies appeared to be marching inexorably forward, though not in lock-step: Vitesse has consistently outpaced all of the other companies in the Compound Semiconductor Portfolio for the past two years.

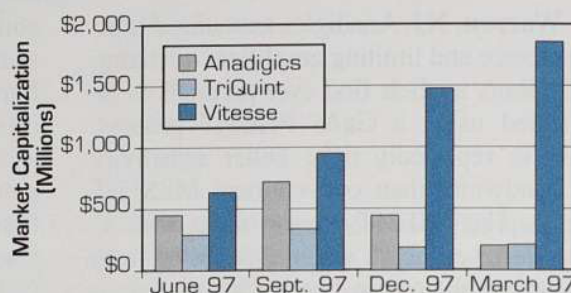
But while Vitesse has continued to impress, with a current market cap of around \$1.85 billion, the other two have sunk over 60% in the past six months. See Chart. Both are experiencing soft business with some of their major OEM cus-

tomers and increasing competition from other suppliers. And while the forecast is not completely gloomy, and the companies do seem to have the potential to bounce back, on the whole this sector seems quite a bit less glamorous than it did just a few months ago.

Kopin Wafer Sales Up

Kopin's epiwafer sales were up 43% in 1997, falling just slight short of \$12 million. The increase was primarily due to the increased demand from various wireless telecommunications sectors, with the bulk of the material going to Kopin's major customer, Rockwell. Total revenues for the year were \$16,393,018 compared to \$18,018,253 in 1996, a decrease of \$1,625,235, due largely to a decline in government research funding.

Market Caps for GaAs IC Fabs



While the epiwafer division is doing well, overall the company continues to struggle as it tries to find high volume markets for its display products. It has not been profitable in any quarter of its last five fiscal years, ringing up an accumulated deficit of \$54,518,912. The net loss for 1997 was \$6.2 million, compared to \$21.5 million in 1996.

Asian Fiscal Crisis Hurting Ortel

Ortel reported a steep decline in revenues and profit for their fiscal quarter ended January 31, 1998. Revenues were \$18.8 million, down 18% from the year-ago-period, and net income was down 80%, to \$0.4 million.

"While our international sales are up 57% year-to-date compared with the prior year, the continuing Asian economic crisis, coupled with weakness in Europe, adversely impacted Ortel's international business in the most recent quarter and, in turn, the company's operating results for the quarter," said Wim H.J. Selders, Ortel's president and chief executive officer. He said the company is expecting further weakness in international sales in the next quarter, which is expected to result in a loss.

But Selders added that company is encouraged by its recent introduction of new products, including a new family of 1310 nm lasers, and 980 nm pump lasers.

Company	Symbol	52 - Week		Closing Price		Change	Volume (000's)	P/E Ratio
		Hi	Lo	Jan 2	March 27			
Alpha	AHA	20 5/8	5 1/2	15 3/4	14 7/8	-6%	71	◆
Anadigics	ANAD	54 1/4	13 1/4	29 2/3	13 1/2	-55%	402	13
APA Optics	APAT	9 1/4	5 1/4	8 5/8	5 3/4	-33%	7	◆
ATMI	ATMI	42 1/4	15 3/4	23 1/8	30 5/16	31%	253	■
Celeritek	CLTK	18 3/8	9 1/2	13 1/2	11	-19%	33	19
Cree Research	CREE	29 1/2	9 1/2	17 3/4	16 3/4	-6%	194	56
Emcore	EMKR	25 1/4	11	19 1/4	15	-22%	48	◆
Kopin	KOPN	29	10 1/2	16 2/3	17 3/8	4%	118	◆
Ortel	ORTL	25	10 2/3	15 3/4	12 3/4	-19%	65	26
RF Micro Devices	RFMD	23 3/4	9 3/4	13	14 1/2	12%	201	◆
SDL	SDLI	25 3/8	8	15 1/8	23	52%	93	◆
SLI	SLIC	6 3/4	1/2	1 3/4	1 3/4	0%	118	◆
Spire	SPIR	24 3/4	4	14 5/8	14 1/8	-3%	21	27
TriQuint	TQNT	45 1/2	17 3/8	20 1/4	22 7/8	13%	102	30
Vitesse	VTSS	56 1/2	24	35 5/16	47 1/2	35%	609	49

Notes ◆ = loss in most recent 4 quarters ■ = P/E ratio greater than 100

PATENTS

Patents related to compound semiconductors issued from February 6, - March 11, 1998
Headlines contain Patent # / Date Issued / Assignee.

Sources:

"05..." = U.S. Patent Office; "EP..." = European Patent Office;

"WO..." = World Intellectual Property Organization

Now
includes
International
Patents

Electronic Circuits & Devices

**W09808259 / 1998 02 26 / ABB Research
Bakowski, M.; Bleichner, H.; Gustavsson,
U.**

A Bipolar Semiconductor Device Having Semiconductor Layers Of SiC. A bipolar semiconductor device having semiconductor layers of SiC and at least one pn-junction with charge carrier transport there across between two subsequent such layers in a conducting forward state of the device has a member having such a resistance that it substantially lowers the current as of which the voltage drop over the device increases with the temperature and which is arranged in series with said pn-junction.

**05719409 / 1998 02 17 / Cree Research
Singh, R & Palmour, J.**

SiC MISFET. A (SiC) metal-insulator semiconductor field effect transistor having a u-shaped gate trench and an n-type SiC drift layer is provided.

**05721438 / 1998 02 24 / Motorola
Tang, Z; Ford, J; Steele, J**

Heterojunction Semiconductor Device And Method Of Manufacture. A HBT is formed to have a germanium composition profile in a base region (that improves the tolerance of the HBT device to manufacturing variations and reduces the sensitivity to emitter/base biases. A first region of essentially constant germanium composition is formed at the interface of an emitter region and the base region. The germanium composition profile also has a second region in which the germanium composition is increased linearly to provide an acceleration field by reducing the band gap in this second region. The acceleration field reduces the transit time of carriers and increases the frequency response of the HBT device.

**05723376 / 1998 03 03 / Nippondenso Co.
Takeuchi, Y et al.**

Method of Manufacturing SiC Semiconductor Device Having Double Oxide Film Formation To Reduce Film Defects. The present invention relates to a method of manufacturing a silicon carbide semiconductor device. The method is suitable as a manufacturing method of, for example, an insulated gate type of electric field effect transistor, specifically a high power vertical type of MOSFET.

**05717228 / 1998 02 10 / NTT
Matsuoka, Y & Yamahata, S**

HBT with Crystal Orientation. A self-aligned heterojunction bipolar transistor is disclosed. The emitter region has an undercut mesa structure and its crystal orientation is defined in a direction other than that parallel to the [011] direction. In neither the [001] direction nor the [011] direction has the transistor any outwardly slanted structure that could cause leakage current between the emitter and base and, hence, the transistor has improved electric isolation between the emitter and base although it is self-aligned.

**05726468 / 1998 03 10 / Mitsubishi Denki
Oku, T. et al**

Compound Semiconductor Bipolar Transistor. A semiconductor device includes a semiconductor substrate; a first active layer disposed on the semiconductor substrate; a second active layer disposed on the first active layer; a first electrode including a lower stage disposed on the second active layer and an upper stage disposed on the lower stage and having an overhanging portion protruding from the lower stage; an insulating film continuously covering a surface of the second active layer, a side surface of the lower stage of the first electrode, and a lower surface and a side surface of the overhanging portion of the upper stage; and a second electrode disposed on the surface of the first active layer at opposite sides of the second active layer, self-aligned with the second active layer. The distance between the second electrode and the second active layer is minimized and the thickness of the second electrode can be about 7000 angstrom, minimizing the resistance of the first active layer and improving high frequency characteristics. Electrical separation between the first and second active layers can be achieved reliably. Recombination at the surface of the second active layer is suppressed.

**05719415 / 1998 02 17 / Sharp
Yagura, M et al**

Hetero-Junction Bipolar Transistor. A hetero-junction bipolar transistor includes: a substrate; a first conductive type collector layer disposed on the substrate; a second conductive type base layer having an external base region; and a first conductive type emitter layer having a bandgap larger than the

bandgap of the base layer disposed in this order, wherein the emitter layer includes a first emitter layer, an etching stop layer, and a second emitter layer disposed in this order starting from the substrate side; a base electrode is formed on the etching stop layer or the first emitter layer disposed on the external base region; a region of the first emitter layer on the base layer has a thickness such that the region is substantially depleted at all voltages applied when the transistor is normally operated; the second emitter layer has an electron affinity equal to or smaller than an electron affinity of the first emitter layer; and the etching stop layer has an electron affinity larger than the electron affinity of the first emitter layer, and has a thickness of approximately 3 nm.

**05721437 / 1998 02 24 / Sharp
Twynam, J et al**

HBT with Ballast Resistance Layer. A heterojunction type AlGaAs/GaAs bipolar transistor includes an n-GaAs collector layer, a p+ GaAs base layer and an n-AlGaAs emitter layer formed in a stack, and an n-AlGaAs ballast resistance layer formed on the emitter layer. The ballast resistance layer has an Al concentration y in the range of $0 < y < 0.4$, and a resistance higher than that of the emitter layer.

**EP0825452 / 1998 02 25 / TRW
Lo, C-W et al**

Monolithic, Low-Noise, Synchronous Direct Detection Receiver For Passive Microwave/Millimeter-Wave Radiometric Imaging Systems. A direct detection receiver for a passive microwave and millimeter wave radiometric imaging system. The receiver includes a balanced switch low-noise amplifier (BSLNA). A front-end, low-noise amplifier (LNA) is inserted before the BSLNA to achieve a low-noise figure, as well as provide sufficient gain to minimize the input noise figure degradation due to loss of the BSLNA. A high-electron mobility transistor (HEMT) diode is used as a power detector. The front-end amplifier, BSLNA and diode are process compatible for monolithic integration.

Laser Diodes

05717711 / 1998 02 10 / Alcatel Optonics Doussiere, P & Riant, I

Laser Device For Optical Pumping. In a laser device, notably for optical pumping, the wafer includes an expansion segment adjacent the exit to prevent degradation of the exit facet of the semiconductor wafer that constitutes the amplifying part of the laser. The other facet is reflective and a Bragg grating is formed in a coupling fiber disposed near the exit facet. Applications include optical pumping of erbium-doped fiber amplifiers.

05724376 / 1998 03 03 / Hewlett-Packard Kish, Jr., F & Schneider, Jr., R.

Transparent Substrate VCSEL Fabricated by Wafer Bonding. A method for fabricating transparent VCSEL's using wafer bonding is described. The VCSELs have their active layers located much more closely to a heat sink than is possible in known absorbing substrate VCSELs. The improved heat transport from the active layer to the heat sink permits higher current operation with increased light output as a result of the lower thermal impedance of the system. Alternatively, the same light output can be obtained from the wafer bonded VCSEL at lower drive currents. Additional embodiments use wafer bonding to improve current crowding, current and/or optical confinement in a VCSEL and to integrate additional optoelectronic devices with the VCSEL.

05721750 / 1998 02 24 / KAIST

Laser Diode for OEIC. The present invention relates to a laser diode for optoelectronic integrated circuit with a rooftop reflector which can be operated by means of a low driving current and a process for preparing the same.

05719077 / 1998 02 17 / Lucent Chakrabarti, U et al

Apparatus And Method For Cleaving A Semiconductor Bar And Coating The Cleaved Facets Within A Vacuum Environment. The fixture cleaves the semiconductor samples in a manner that reduces semiconductor sample waste and also allows the processing environment requirements to be reduced compared to other cleaving and coating techniques.

05727012 / 1998 03 10 / Lucent Baillargeon, J; Cheng, K-Y; Cho, A. Y.

Heterostructure Laser. The specification describes a heterostructure laser utilizing GaAs based materials that emits at 0.98 micron and is thus suitable for pumping an erbium doped fiber waveguide amplifier. The composition of the cladding layers of the laser is designed to give exceptional electrical and optical confinement without the high levels of aluminum that are found to reduce the lifetime of high performing prior art devices.

05717710 / 1998 02 10 / Mitsubishi Denki Miyazaki, Y et al

Optical Semiconductor Device. In an optical semiconductor device including a DFB laser and a light absorption modulator, a semi-insulating semiconductor layer is disposed between a carrier blocking layer and an upper cladding layer, the upper cladding layer having an opposite conductivity type from that of the semiconductor substrate and disposed on a buried waveguide and the carrier blocking layer. The capacitance between the carrier blocking layer and the upper cladding layer is reduced. Therefore, mutual interference between the DFB laser and the light absorption modulator through the carrier blocking layer is reduced.

05721752 / 1998 02 24 / Mitsubishi Denki Takagi, Kazuhis

Semiconductor Laser Device. A semiconductor laser device includes an active layer from which laser light is emitted, a front facet reflection film, a back facet reflection film, and a resonator including the front and back facet reflection films, at least one of the front and back facet reflection films includes a saturable absorber to the laser light. Independently of a difference in optical confinement coefficient and in differential gain between a region where a current flows and a region where no current flows in the active layer, self-pulsation in which the emitted light is pulsed light having high frequency occurs easily, whereby a self-pulsation semiconductor laser device having good laser characteristics, such as a transverse mode characteristic and a threshold current characteristic, is obtained. Consequently, a wider margin of device design is afforded than in the prior art device, whereby the device is stably fabricated with a good yield.

05719893 / 1998 02 17 / Motorola Jiang, W; Claisse, P; Lebby, M

Passivated VCSEL. A passivated vertical cavity surface emitting laser including a first stack of distributed Bragg reflectors disposed on the surface of a semiconductor substrate, a first cladding region disposed on the first stack, an active region disposed on the first cladding region, a second cladding region disposed on the active region, and a second stack of distributed Bragg reflectors disposed on the second cladding region. A passivation layer having an optical thickness of an integral multiple of approximately one half of the wavelength of emitted light is disposed on the vertical cavity surface emitting laser.

EP0827241 / 1998 03 04 / NEC Nakamura, T.

Semiconductor Laser. A semiconductor laser is disclosed which comprises an active layer and SCH layers which sandwich the active layer from upper and lower sides,

wherein the SCH layer comprises a multi-layer structure of or more layers and this multi-layer structure is constituted so that the band gaps of the respective layers may increase as the multi-layer structure is apart from the active layer.

05726078 / 1998 03 10 / Northwestern Univ. Razeghi, M.

Buried-ridge Laser Device. A buried-ridge structure of the quaternary/tertiary structures of $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}/\text{InGaP}$ (x and $y < 1$) are grown on a GaAs substrate by Low Pressure Metalorganic Chemical Vapor Deposition (LP-MOCVD) in a two-step process. The process comprises steps of growing and doping the requisite epitaxial layers, etching these layers so that stripes or mesas of material remain and then regrowing the material by gas molecular beam epitaxy (GSMBE). The structures are then processed into devices.

05721751 / 1998 02 24 / NTT Itaya, Y & Matsumoto, S

Semiconductor Laser. A semiconductor laser includes a mesa stripe portion having a multilayer structure and a buried current blocking layer arranged on both sides of the mesa stripe portion and a contact layer. The contact layer includes a first contact layer contacting the clad layer and a second contact layer provided on the first contact layer. The first contact layer has an energy gap smaller than that of the clad layer and larger than that of the second contact layer. Preferably, the first contact layer is an InGaAsP semiconductor layer having an energy gap within the range of from 0.82 eV to 1.12 eV, the second contact layer is selected from the group consisting of an InGaAs semiconductor layer and an InGaAsP semiconductor layer which has an energy gap of 0.8 eV, and the clad layer contacting the first contact layer is an InP layer.

05719894 / 1998 02 17 / Picolight & 05719895 / 1998 02 17 / Picolight Jewell, J & Temkin, H

Extended Wavelength Strained Layer Lasers Having Nitrogen Disposed Therein. Several methods are used in novel ways with newly identified and viable parameters to decrease the peak transition energies of the pseudomorphic InGaAs/GaAs heterostructures. These techniques, taken separately or in combination, suffice to permit operation of light emitting devices at wavelengths of 1.3 micron or greater of light-emitting electro-optic devices. These methods or techniques, by example, include: (1) utilizing new superlattice structures having high In concentrations in the active region, (2) utilizing strain compensation to increase the usable layer thickness for quantum wells with appropriately high In concentrations, (3) utilizing appropriately small amounts of nitrogen (N) in the pseudomorphic InGaAsN/GaAs laser struc-

Laser Diodes, cont.

ture, and (4) sue of nominal (111) oriented substrates to increase the usable layer thickness for quantum wells with appropriately high In concentrations.

EP0828324 / 1998 03 11 / Sanyo Shono, Masayuki et al

Semiconductor Laser Device. A semiconductor laser device comprises an n-type cladding layer, an active layer formed on the n-type cladding layer and having a quantum well structure including one or a plurality of quantum well layers, a p-type cladding layer comprising a flat portion formed on the active layer and a stripe-shaped ridge portion on the flat portion, and a current blocking layer formed on the flat portion so as to cover the side surface of the ridge portion and formed on a region on the upper surface of the ridge portion from one of facets of a cavity to a position at a predetermined distance therefrom.

P0826256 / 1998 03 04 / Siemens Stegmüller, B; Matz, R.

Process For Producing A DFB Laser Diode With Coupled Waveguide And DFB Laser Diode Film Structure. Abstract not available.

EP0827242 / 1998 03 04 / Sony Hirata, Shoji et al.

Semiconductor Laser. An AlGaInP-based buried-ridge semiconductor laser includes an n-type GaAs current blocking layer buried in opposite sides of a ridge stripe portion which is made of an upper-layer portion of a p-type AlGaInP cladding layer, p-type GaInP interme-

diate layer and p-type GaAs contact layer. The ridge stripe portion includes tapered regions having the length of L1 at cavity-lengthwise opposite ends of the ridge stripe portion.

05727016 / 1998 03 10 / U.S.A.F. Paxton, Alan H.

Spatially Coherent Diode Laser With Lenslike Media And Feedback From Straight-Toothed Gratings. In a surface emitting semiconductor laser, a variable index of refraction layer having an approximately parabolically shaped trough therein is positioned adjacent the active lasing region and a straight toothed second order diffraction grating coats with the refraction layer to produce a broad spatially coherent output beam.

W09808278 / 1998 02 06 / W.L. Gore Jayaraman, Vijaysekhar

VCSELs Using Patterned Wafer Fusion. In the fabrication of VCSELs, patterned wafer fusion promotes low-loss refractive index guiding combined with a mechanically robust and reproducibly fabricatable structure.

05724375 / 1998 03 03 / W.L. Gore Peters, F.

VCSEL With Enhanced Second Harmonic Generation. A vertical cavity surface emitting laser is constructed on a semiconductor substrate, and includes a second mirror stack disposed on the substrate, a gain region with an active material within the second mirror stack capable of emitting electromagnetic radiation at a fundamental wavelength, a non-linear element disposed above the second mirror stack capable of emitting electromag-

netic radiation at a harmonic of the fundamental wavelength in response to the electromagnetic radiation at the fundamental wavelength, and a first mirror stack disposed above the non-linear element. The gain region within the second mirror stack and the non-linear element are separated by a preselected distance. The first mirror stack is organized to be reflective of electromagnetic radiation at the fundamental wavelength and partially transmissive of electromagnetic radiation at the harmonic of the fundamental wavelength.

05717707 / 1998 02 10 / Xerox Beernink, K et al

Index Guided Semiconductor Laser Diode. An index-guided semiconductor laser diode made by impurity-induced layer disordering (IILD) of AlInP, GaInP and AlGaInP heterostructures. Several techniques for reducing parasitic leakage current via the n-type IILD regions, are described.

The full text of any of these patents can be obtained by e-mail from MicroPatent for \$2.00 each. See <http://www.micropat.com> and select the "PatentWEB™ option.

Other Optoelectronics

EP0826246 / 1998 03 04 / Cree Research Edmond, J. & Kong, H-S

Double Heterojunction Light Emitting Diode With Gallium Nitride Active Layer. Abstract not available.

05721429 / 1998 02 24 / Hughes Electronics Radford, W & Wilson, J

Self-focusing Detector Pixel Structure. An array of photodetectors is constructed of IR radiation-responsive Group II-VI alloy semiconductor material, such as HgCdTe. A novel photodetector structure utilizes internal reflections from mesa sidewalls and/or from reflective material that is applied to the mesa sidewalls to achieve a concentration of incident infrared radiation into a significantly smaller radiation absorbing region.

05717226 / 1998 02 10 / ITRI Lee, B; Chang, C & Jou, M.

Light-Emitting Diodes. The present invention relates to the structure of a light-emitting diode (LED) and method of manufacturing the same, which uses the contact between the bonding metal and the semiconductor as a Schottky barrier to block and spread the current therein.

EP0828299 / 1998 03 11 / Matsushita Electric Wada, Takahiro et al.

Compound Semiconductor And Thin Film Solar Cell. This invention provides a compound semiconductor which can be used for an absorbing layer of a thin-film solar cell. The compound semiconductor is character-

ized in that it belongs to a II-VI space group with a stannic structure and is from the CuInGaSeS material system. It has a larger band gap than the corresponding compound semiconductor having a chalcopyrite structure.

05717709 / 1998 02 10 / Sharp Sasaki, K & Yamamoto, O.

Semiconductor Light-Emitting Device. The object of the present invention is to provide a semiconductor light-emitting device having a current constrictive layer which has improved performance characteristics, and a method of making the same. Semiconductor light-emitting devices to which the invention is directed include, in particular, semiconductor laser devices and light-emitting diodes.

Materials

05718761 / 1998 02 17 / Canon Tokunaga, H; Hanna, J; Shimizu, I

Method Of Forming Crystalline Compound Semiconductor Film. This invention relates to a method of forming a II-VI compound thin film by MOCVD using an organometallic compound starting material.

W09808780 / 1998 03 05 / Chorus Corp. Colombo, P & Donadio, R.

Unibody Crucible And Effusion Source Employing Such A Crucible. A unibody, monolithic, one-piece negative draft crucible for an MBE effusion source. The crucible maximizes capacity, uniformity and long-term flux stability, and minimizes oval defects, depletion effects, and short-term shutter-related flux transients. The invention also includes an effusion source employing such a crucible, as well as a method and mandrel apparatus for making a unibody containment structure, such as a crucible formed of PBN, having a negative draft, via chemical vapor deposition.

05726294 / 1998 03 10 / Florida State Univ.

Metalorganic Chemical Vapor Deposition Method For Depositing F-Series Metal Or Nitrogen And Metal Amides For Use In MOCVD. A MOCVD method for depositing an F-series metal onto a semiconductor or other substrate or for incorporating nitrogen as a p-type dopant in Group II-VI semiconductor materials. The MOCVD method utilizes an F-series metal amide or zinc amide composition as the source compound for the F-series metal or nitrogen, respectively. Novel erbium amide and zinc amide compositions are disclosed along with methods for preparing the metal amide compositions.

EP0828296 / 1998 03 11 / IBM Chu, Jack Oon et al

High Temperature Superconductivity In Strained Si/SiGe. A structure based on strained Si/SiGe that has high temperature superconductivity is disclosed. The structure for carrying superconducting current includes a substrate; a first epitaxial P type semiconductor layer, which is under compressive strain, for transporting holes; a second epitaxial barrier layer positioned on the first layer; and a third epitaxial N type semiconductor layer, which is under tensile strain, for transporting electrons. The barrier layer is thick enough to restrict recombination of electrons and holes, yet the barrier layer is thin enough to permit coulomb force attraction between the electrons and holes to form electron-hole pairs. The first and second layers include SiGe, such as Si(1-x)Ge_x, where x is 0.6-0.8 for the first layer, and 0.3-0.4 for the second layer. The third layer includes Si.

5716450 / 1998 02 10 / Japan Energy Togawa, S & Okazaki, H

Growing method of GaN. In a method of growing a gallium nitride related compound semiconductor crystal on a single crystal substrate, the {011} plane or the {101} plane of rare earth group 13 (3B) perovskite is used as the single crystal substrate. As a result, a gallium nitride group semiconductor crystal excellent in crystallinity can be grown epitaxially.

EP0823498 / 1998 02 11 / Japan Science & Tech. Corp. Yoshida, Hiroshi

Process For Producing A Heavily Nitrogen Doped ZnSe Crystal. In a process for growing a ZnSe crystal by an MBE or MOCVD process, N₂ gas dissociated by electromagnetic waves and vapor In are prepared at a ratio of N:In being 2:1. The atomic gases may be prepared by decomposing InN at a high temperature with electromagnetic irradiation and adding N₂ gas to the decomposed product. The atomic gases are fed onto a substrate in a crystal growth region, so as to simultaneously dope ZnSe with In and N at a ratio of 1:2. A n-type dopant In substitutionally occupying a position of Zn makes a 1:1 couple with a p-type dopant N substitutionally occupying a position of Se, and another one N atom coordinates near the atomic couple and serves as an acceptor. As a result, the acceptor is kept in activated state up to higher concentration, and the ZnSe crystal can be heavily doped with the p-type dopant N.

P0825652 / 1998 02 25 / Sony E. Miyajima, T.

Ohmic Electrode And Method Of Forming The Same. There are provided an ohmic electrode capable of operating elements stably for a long period by making contact specific resistance smaller and also increasing thermal stability thereof and a method of forming the same. An electrode layer is formed on a p-type compound semiconductor layer composed of p-type GaN and so on through a contact layer composed of p-type GaN and so on. The contact layer is formed by an MBE method, and the hole density is set higher than that of the p-type compound semiconductor layer. The electrode layer is formed by laminating a transition metal layer composed of a transition metal other than gold or platinum, a platinum layer and a gold layer one after another and annealing the laminated layers thereafter. With this, the platinum layer is made to adhere closely to the p-type compound semiconductor layer by the transition metal layer while preventing gold from diffusing toward the p-type compound semiconductor layer with the platinum layer.

05723360 / 1998 03 03 / Sumitomo Electric Iwasaki; Takashi

Method Of Processing An Epitaxial Wafer Of InP Or The Like. Fine processing of InP epitaxial wafers including As, In and P for producing laser diodes, light emitting diodes or photodiodes. The InP epitaxial wafer is selectively covered with striped protection mask films. The wafer is etched by some etchant which forms normal-mesas or mountain-shaped stripes under the masks. Then the wafer is again etched by a gas of thermally dissolved AsCl₃ till the stripes have rectangle sections with erect surfaces. Buried layers of InP are grown on the eliminated parts of the wafer.

EP0827189 / 1998 03 04 / Sumitomo Electric Doi, Hideyuki

A Method Of Cleaning A Surface Of A Compound Semiconductor Crystal Of Group II-VI Elements. A surface of a compound semiconductor crystal of Group II-VI elements of Periodic Table can be cleaned to obtain a mirror surface suitable for epitaxial growth, without deteriorating the smoothness of the surface after etching

EP0826800 / 1998 03 04 / Sumitomo Electric Hirota, Ryu & Fujiwara, Shinsuke

A Method For The Heat-Treatment Of ZnSe Crystal. An object of the present invention is to provide a method for the heat-treatment of ZnSe crystal whereby a deterioration in crystallinity can be prevented and a crystal having a low resistivity, without the occurrence of precipitates, can be produced.

05716449 / 1998 02 10 / TI Klocek, Paul

Method Of Forming A Compound Semiconductor Material. This invention relates to a crystal growth process for producing large area group III-V compounds and particularly GaAs having controllable resistivity and the use thereof for fabrication of infrared window/domes with EMI/EMP protection.

The full text of any of these patents can be obtained by e-mail from MicroPatent for \$2.00 each. See <http://www.micropat.com> and select the "PatentWEB™ option.

1998 Conference on Lasers & Electro-Optics & The International Quantum Electronics Conference

CLEO/IQEC '98 will be held May 3-8, 1998 at The Moscone Center in San Francisco, CA.

Contact: Ms. Amy Hutto
OSA Conference Services
2010 Massachusetts Ave., NW
Washington, DC 20036-1023
TEL [1] 202 416-1980
FAX [1] 202 416-6100
Net or Web: cleo.info@osa.org
http://www.osa.org

193rd Meeting of the Electrochemical Society

The 193rd ECS Meeting will be held May 3-8, 1998 at the Sheraton San Diego Hotel & Marina in San Diego, California. Symposia include: I2 - State-Of-The-Art-Program On Compound Semiconductors (SOTAPOCS XXVII); K1 - Light Emitting Devices For Optoelectronic Applications

Contact: The Electrochemical Society
10 South Main Street
Pennington, NJ 08534-2896 USA
TEL [1] 609 737 1902
FAX [1] 609 737 2743
NET or WEB: ecs@electrochem.org
or http://www.electrochem.org

1998 Custom Integrated Circuits Conf.

The 20th Custom Integrated Circuits Conference (CICC) will be held May 11 - 14, 1998 in the Santa Clara, CA. This is the leading technical conference for design, fabrication and integration of ASIC and system-on-a-chip applications using CMOS and other technologies. Topics of interest for this year's meeting include: Analog Techniques; RF IC Technology; Wireless; DSP; Custom Design; Clocking and Low-Power Design Methodologies; Deep Submicron Design; Modeling and Interconnects; PLD architectures; System-on-a-Chip; and design success stories.

Contact: Melissa Winderkehr
CICC
101 Lakeforest Boulevard
Gaithersburg, Md. 20877 USA
TEL [1] 301 427 0902
FAX [1] 301 527 0994
Net or Web: cicc@his.com or
http://www.ieee.org/conference/cicc/

10th Int'l Conf. On InP and Related Materials

IPRM '98 will be held May 11-15, 1998 in Tsukuba, Japan. The scope of the conference will include optoelectronics, electron devices, processing, epitaxy, bulk growth and characterization, and new materials and nanos-

tructures.

Contact: IPRM '98
IEEE/LEOS
445 Hoes Lane
Piscataway, NJ 08854 USA
TEL [1] 908 562 3896
FAX [1] 908 562 8434
NET msarcone@calypso.ieee.org

22nd Workshop on Compound Semiconductor Devices and Integrated Circuits

WOCSDICE 98 will be held May 24-27, 1998 at the Pannonia Hotel in Zeuthen, Germany. The European Workshop on Compound Semiconductor Devices and Integrated Circuits aims to bring together scientists and engineers working in the area of III/V compound semiconductor devices and integrated circuits for microwave, mm-wave and optoelectronic applications. To encourage interaction between participants and to permit sufficient discussion, presentations are kept short and focused on the main results and new ideas presented by the participants. The Workshop is open to European and world wide participation.

Ferdinand-Braun-Institut
für Hochfrequenztechnik
Rudower Chaussee 5
D-12489 Berlin Germany
TEL [49] 30 6392 2690
FAX [49] 30 6392 2685
NET or WEB:
wocsdice@fbh-berlin.de
or http://www.fbh-berlin.de

1998 Electronic Components & Technology Conference on Optoelectronics

The 48th ECTC Optoelectronics Conference will be held May 25-28, 1998 in Seattle, WA. Papers are solicited on all topics pertaining to the design, development, and technology of packaging active/passive hybrid and integrated photonic components, devices, circuitry and systems.

Contact: Mark W. Beranek
The Boeing Company
PO Box 3999, M/S 2W-51
Seattle, WA 98124-2499
TEL [1] 253 657 5748
FAX [1] 253 657 8903

9th Int'l Conf. On Metal Organic Vapor Phase Epitaxy

ICMOVPE IX will be held May 30 - June 4, 1998 at the Sheraton Grande Torrey Pines in LaJolla, CA. Topics of interest include precursors, process design/communication issues; developing applications of MO compounds; growth technologies; advances in devices by MOVPE, and characterization.

Contact: Barbara Loitwood
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420 Commonwealth Drive
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TEL [1] 412 776 9000 x234
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NET kamperman@tms.org

10th Int'l Conf. on Semiconducting and Insulating Materials

SIMC-X will be held June 1 -5th 1998 in Berkeley, CA. This conference is the tenth in a series of bi-annual conferences which aim to bring together scientists and engineers interested in materials problems of compound semiconductors of relevance for the performance of electronic and optoelectronic devices. The purpose of the meeting is to discuss growth, characterization, theory, device applications, and materials problems related to semi-conducting and insulating compounds such as GaAs, InP, III-nitrides, II-VI compounds, SiC and SiGe. Special areas of interest for this Conference are: III-nitrides, III-oxides, and non-stoichiometric III-V compound semiconductors.

Contact: Dr. Zuzanna Liliental-Weber
Berkeley National Laboratory
1 Cyclotron Road MS 62-203
Berkeley, CA 94720, USA
Net:
zlw@ux5.lbl.gov or simc@ux5.lbl.gov

1998 MTT-S International Microwave Symposium

MTT '98 will be held June 7-12, 1998 at the Baltimore Convention Center in Baltimore, MD.

Contact: Mr. Steven Stitzer
Westinghouse Electric Corp.
P.O. Box 1521
MS 3T15
Baltimore, MD 21203
TEL [1] 410 765-7348
FAX [1] 410 993-7747

1998 IEEE Radio Frequency Integrated Circuits Symposium

RFIC '98 will be held Jun. 07, 1998 - Jun. 12, 1998 at the Baltimore Convention Center in Baltimore, MD (in conjunction with MTT '98).

Contact: Dr. Vijay Nair
Motorola Inc.
2100 E. Elliot Rd.
M/D EL508
Tempe, AZ 85234
TEL [1] 602 413-5922
FAX [1] 602 413-5934

European MRS 1998 Spring Meeting

The 1998 E-MRS Spring Meeting will be held June 16 - 19, 1998 in Stasbourg, France. Symposia include

Growth, Characterization and Applications of Bulk II-VI's; Thin Films, Epitaxial Growth and Nanostructures; and Nitrides and Related Wide Band Gap Materials.

Contact: E-MRS
BP 20
67037 Strasbourg Cedex 2
France
TEL [33] 3 88 10 65 43
FAX [33] 3 88 10 62 93
Net or Web:
emrs@phase.c-strasbourg.fr

4th International Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies

EXMATEC 98 will be held June 22-24, 1998 in Cardiff, Wales, UK. This conference aims to bring together research, development, and production specialists involved in compound semiconductor material physics, chemistry, process technology, and

Conference Notes

- Additional details, including the Abstract Submission Deadline, have been added for the North American MBE Conference, to be held at Penn State Oct. 4-7, 1998.
- The dates for the 3rd International Workshop on Novel Index Surfaces have changed to October 6 - 9, 1998.
- Additional details, including the Abstract Submission Deadline, have been added for the Fall MRS Meeting, to be held in Boston November 30 - December 4, 1998.

New Entries

- 6th Int'l Conf. on Terahertz Electronics, September 3- 4, 1998, Leeds, England
- First Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems, September 17-18, 1998, Ann Arbor, MI

device fabrication.

Contact: Cherrie Summers
Cardiff School of Engineering
PO Box 917, Newport Road
Cardiff, Wales
CF2 1XH UK
TEL [44] 1222 874000
FAX [44] 1222 874421
NET or WEB:
summersc@cardiff.ac.uk

1998 Device Research Conference

The 1998 DRC will be held at the University of Virginia in Charlottesville, VA on June 22 - 24, 1998

Contact: Emmanuel Crabbe
Tel: [1] 914 892-2056
Fax [1] 914 892-2568
Net or Web:
crabbe@watson.ibm.com

Third European GaN Workshop

EGW-3 will be held June 22-24, 1998 in Warsaw, Poland. This meeting will encompass all areas of research related to physical properties, crystal growth, epitaxy, doping, processing, device manufacturing and applications of nitride semiconductors.

Contact: Conference Secretariat
EGW-3
High Pressure Research Center
01-142 Warsaw, Sokolowska 29/37
Poland
TEL [48 22] 632 5010
FAX [48 22] 632 4218
Net or Web: stach@unipress.waw.pl
or http://www.unipress.waw.pl/egw-3/info.html

1998 Electronic Materials Conference

The 40th EMC will be held at the University of Virginia in Charlottesville, VA on June 24-26, 1997. This conference provides a forum for topics of current interest and significance in the areas of preparation and characterization of electronic materials. Individuals actively engaged or interested in electronic materials research and development are encouraged to attend this meeting, and papers in this general subject area are solicited.

Contact: Barbara Loitwood
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420 Commonwealth Drive
Warrendale, PA 15086 USA
TEL [1] 412 776 9000 x234
FAX [1] 412 776 3770
NET kamperman@tms.org

1998 IEEE Photovoltaics Specialist Conference

Wien, Austria July 6-10, 1998
Contact: JRC-Ispira
WCON2
Ispira (VA) Italy I-21020

TEL [39] 332 785 885
FAX [39] 332 789 646
Net or Web: wcon2.prog@jrc.it

OE Expo '98

The 1998 International Optoelectronics Exposition will be held July 11 - 14, 1998 in Taipei, Taiwan. The only annual optoelectronics exhibit in Taiwan, this conference provides an excellent introduction to this rapidly expanding market. Areas of interest include materials, optoelectronic components, equipment and systems, and processing equipment related to the optoelectronic industry.

Contact: Photonics Industry & Technology
Development Association
Taipei, Taiwan
FAX [886] 2 396 8513

ICCG-12 & ICVGE-10

The Twelfth International Conference on Crystal Growth in conjunction with the Tenth International Conference on Vapor Growth and Epitaxy will be held July 26 - 31, 1998 at the Renaissance Jerusalem Hotel in Jerusalem, Israel

Contact: Conference Secretariat
ICCG-12 / ICVGE-10
Int'l Travel and Congresses Ltd.
P.O. Box 29313, 9 Rothschild Blvd.
Tel Aviv 61292 ISRAEL
TEL [972] 3 5102538
FAX [972] 3 5160604
NET or WEB:
100264.2432@compuserve.com or
http://www.technion.ac.il/~iccg12

10th Int'l Conference on Molecular Beam Epitaxy

MBE-X will be held August 31 - September 4, 1998 in Cannes, France. This conference will cover the full spectrum of MBE-related topics, in the pleasant surroundings of the south of France. Topics of interest include: MBE growth of semiconductors, metals, insulators and other materials; applications and devices; alternative sources and methods; novel in-situ process control; nanostructure engineering; control of surfaces and interfaces; production technology and manufacturability issues.

Contact: Prof. Jean-Pierre Faurie
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Rue Bernard Gregory
F 06560 Valbonne France
TEL [33] 4 9395 4220
FAX [33] 4 9395 4142
NET or Web: org@mbe-x.unice.fr
http://www.crhea.unice.fr/mbe-x

6th Int'l Conf. on Terahertz Electronics

THz 98 will be held September 3- 4, 1998 in Leeds, England. This conference has established itself as the primary meeting for the terahertz elec-

tronics research community. Its main goal is to provide a forum for the exchange of information on the theory, technology and application of the emerging and interdisciplinary field of terahertz electronics, and to foster an appreciation of the capabilities and future directions of this technology.

Contact: Dr. Stavros Iezekiel
School of EEE
University of Leeds
Leeds, LS2 9JT, UK
Tel: [44] 113 233 2088
Fax: [44] 113 233 2032
Net or Web:
THz98@elec-eng@leeds.ac.uk or
http://www.elec-eng.leeds.ac.uk/THz98Picture

First Int'l School on Crystal Growth Technology

ISCGT-1 will be held September 5-16, 1998 at Beatenberg above Interlaken, Switzerland. This School will treat in 54 one-hour lectures, from leading crystal growth and epitaxy technology experts, the major technologies for fabrication of large commercial crystals including crystal machining, crystal growth machines, and saws. Emphasis will be on silicon, III - V and II - VI compounds, and sapphire. Posters are welcome.

Contact: Dr. Hans Scheel
Cristallogenese
Ch. de Bellerive 34
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Tel. (41) 21 693-4452
Fax. (41) 21 693-4750
Net or Web: Hans.Scheel@epfl.ch

1998 Conference on Lasers & Electro-Optics Europe & The 6th European Quantum Electronics Convention

CLEO EUROPE/EQEC will be held Sep. 13 - Sep. 18, 1998 at the Scottish Exhibition & Conference Center in Glasgow, Scotland.

Contact: Ms. Melissa K. Estrin
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445 Hoes Lane
Piscataway, NJ 08855-1331
TEL [1] 908 562-3896
FAX [1] 908 562-8434
Net or Web: m.estrin@ieee.org
http://www.ieee.org/leos/meet.htm

First Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems

The first IEEE sponsored topical meeting on Silicon Monolithic Integrated Circuits in RF Systems will be held September 17-18, 1998 at The University of Michigan, Ann Arbor, MI. The meeting is devoted entirely to silicon integrated circuits for RF systems and will cover material development, advanced devices, high frequency circuits, passive device development, reliability and

yield, and applications. Three copies of a full-length paper (up to 10 pages) are expected by the deadline. Abstract Submission Deadline: May 15, 1998.

Contact: George E. Ponchak
NASA Lewis Research Center
21000 Brookpark Rd., MS 54/5
Cleveland, OH 44135
TEL: [1] 216-433-3504
FAX: [1] 216-433-8705
Net or WEB:
george.ponchak@lerc.nasa.gov
http://www.eecs.umich.edu/RADLAB/SiGe.Conference.

1998 IEEE Bipolar/BiCMOS Circuits and Technology Meeting

BBCTM '98 will be held Sep. 27 - Sep. 29, 1998 in Minneapolis, MN. This meeting provides a forum for technical communication focused on the needs and interests of bipolar and BiCMOS engineers. Papers covering the design, performance, fabrication, testing and application of bipolar, BiCMOS and BiFET ICs, bipolar phenomena, and discrete devices are solicited.

Contact: Ms. Janice V. Jopke
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2nd Int'l Symposium on Blue Laser and Light Emitting Diodes

The 2nd ISBLLED Conference will be held September 29 - October 2, 1998 at the in Chiba, Japan. The main objective of this symposium is to provide a joint forum for both the GaN community and the ZnSe community to discuss common problems extending from the growth and characterization of materials to device performance and reliability.

Abstract Submission Deadline: May 15, 1998

Contact: Prof. F. Hasegawa
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1-1-1 Tennodai
Tsukuba, Ibaraki 305 Japan
TEL [81] 298 53 5287
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hasegawa@mat.ims.tsukuba.ac.jp
or http://www.etl.go.jp/etl/divisions/material/isblled2/isblled2.html

17th North American MBE Conference

NAMBE-17 will be held Oct. 4-7, 1998 on the Penn State campus in State College, PA. Researchers from all fields who use MBE in their work with all types of materials are invited

to attend. Papers presented at this conference describe recent advances associated with MBE in materials growth technology for research and production, measurement and control, materials characterization, electronic, photonic, and novel devices, and quantum structures.

Abstract Deadline: May 30, 1998.
Contact: David L. Miller

The Pennsylvania State University
121 E.E. East Building
University Park PA 16802
TEL [1] 814 865 2730
FAX [1] 814 865 7065
Net or Web: dlm15@psu.edu
<http://www.cde.psu.edu/C&I/MBE/Contact>

1998 IEEE/LEOS Semiconductor Laser Conference

The 1998 IEEE/LEOS Semiconductor Laser Conference will be held Oct. 5, 1998 - Oct. 10, 1998 at the Nara Public Hall in Nara, Japan. The scope of the meeting includes semiconductor laser physics; materials and processing; design and modeling; long & short wavelength laser; high power & high speed laser; VCSELs, novel laser structures; and integration and packaging.

Abstract Submission Deadline: May 8, 1998

Contact: Ms. Elsie L. Vega
IEEE/LEOS
445 Hoes Lane
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TEL [1] 732 562-3897
FAX [1] 732 562-8434
Net or Web: e.vega@ieee.org
<http://www.ieice.or.jp/es/islc98.html>

European Microwave Week (Including GAAS '98)

The new "European Microwave Week" event will be held October 5 - 9, 1998 in Amsterdam, The Netherlands. This event incorporates three previously existing conferences: The European GaAs Applications Symposium (GAAS '98), The European Microwave Conference (EuMC '98), and The MTT-S European Topical Congress on Technologies for Wireless Applications (MTT-S European Wireless '98).

Contact: David Roberts
Miller Freeman Plc
Microwave Engineering Europe
30 Calderwood Street
London SE18 6QH UK
TEL [44] 181 855 777 x 5953
FAX [44] 181 316 3174
Net or Web: droberts@unmf.com

25th Int'l Symp. on Compound Semiconductors

ISCS '98 will be held October 12 - 16, 1998 in Nara, Japan. This sym-

posium covers all aspects of compound semiconductors - including growth, processing, devices, ICs, and applications - and deals with III-V compounds such as GaAs, InP, and GaN; II-VI compounds such as ZnSe and ZnS; IV-IV materials such as SiC and SiGe; etc.

Abstract Submission Deadline: May 18, 1998

Contact: Kimiyoshi Yamasaki
NTT System Electronics Laboratories
3-1 Morinosato Wakamiya,
Atsugi, Kanagawa, 243-01 Japan
TEL [81] 462 40 2500
FAX [81] 462 40 2872
Net: kyama@aecl.ntt.co.jp
Web:
<http://www.ieice.or.jp/es/iscs98.html>

3rd Int'l Workshop on Novel Index Surfaces

NIS '98 will be held October 6 - 9, 1998, 1998 in La Casona (San Rafael), Spain. The scope of this conference is the growth, characterization and exploitation of epitaxial compound semiconductors on novel index surfaces. All communications in close relation with the topics of the workshop are welcome.

Abstract submission deadline: May 15, 1998

Contact: Mariano Gonz-lez
ETSI Telecomunicacion-UPM
Ciudad Universitaria
28040-Madrid, Spain
FAX [34] 1 336 73 23
Net or Web: mariano@die.upm.es
<http://www.die.upm.es/research/nis98.htm>

1998 IEEE GaAs IC Symposium

The 1998 IEEE GaAs IC Symposium will be held Nov. 01 - Nov. 04, 1998 at the Westin Peachtree Plaza in Atlanta, GA.

Contact: Dr. William Stanchina
Hughes Research Labs., RL61
Plasma Physics Lab.
3011 Malibu Canyon Rd.
Malibu, CA 90265
TEL [1] 310 317-5089
FAX [1] 310 317-5483

194rd Meeting of the Electrochemical Society

The 194rd ECS Meeting will be held November 1-6, 1998 at the Sheraton Boston Hotel & Tower in Boston, Massachusetts. Symposia include: I1 - III-V Nitride Materials And Processes; J1 - Fifth International Symposium On Quantum Confinement: Nanostructures; N1 - Compound Semiconductor Power Transistors; N3 - Sixth International Symposium On Long Wavelength Infrared Detectors And Arrays: Physics And Applications; N4 - State-Of-The-Art Program On Compound

Semiconductors (SOTAPOCS XXVIII); P1 - Photovoltaics For The 21st Century

Abstracts Submission Deadline: June 1, 1998

Contact: The Electrochemical Society
10 South Main Street
Pennington, NJ 08534-2896 USA
TEL [1] 609 737 1902
FAX [1] 609 737 2743
NET or WEB:
ecs@electrochem.org or
<http://www.electrochem.org>

45th National AVS Symposium

The 1998 AVS National Symposium will be held November 2-6, 1998 at the Baltimore Convention Center in Baltimore, MD. AVS Technical Divisions include: applied surface science; nanometer-scale science and technology; surface science; vacuum metallurgy; electronic materials and processing; plasma science and technology; thin film; and vacuum technology.

Abstract Submission Deadline: May 1, 1998

Contact: Marion Churchill
AVS
120 Wall Street
New York, NY 10005 USA
TEL [1] 212 248 0200
FAX [1] 212 248 0245
Net: marion@vacuum.org
Web: <http://www.vacuum.org>

6th Int'l Workshop on High Performance Electron Devices for Microwave and Optoelectronic Applications

EDMO '98 will be held November 23-24, 1998 in Manchester, UK. Its purpose is to act as a forum for microwave and optoelectronic device designers, fabricators, modellers and general users to discuss the synergy between system needs and advanced electronic devices and circuits. Contributions concerned with the application of electron devices for microwave and optoelectronics are welcomed.

Abstract Submission Deadline: September 1, 1998

Contact: Dr M Missous
UMIST, EE& E Dept.
PO Box 88
Manchester M60 1QD UK

TEL [44] 161 200 4797
FAX [44] 161 200 4770
Net or Web:
missous@fs4.ee.umist.ac.uk or
<http://www.ee.umist.ac.uk/new/edmo98.html>

1998 Fall MRS Meeting

The 1998 Fall MRS Meeting will be held November 30 - December 4, 1998 in Boston, MA. Symposia include: B) Growth Instabilities and Decomposition During Heteroepitaxy; D) Integration of Dissimilar Materials in Micro- and Optoelectronics; G) GaN and Related Alloys; H) IR Semiconductor Materials and Devices; and I) III-V and SiGe Processing Challenges for Commercial Applications.

Abstract Submission Deadline: June 8, 1998

Contact: Materials Research Society
506 Keystone Drive
Warrendale, PA 15086-7573 USA
TEL [1] 412 779-3003
FAX [1] 412 779-8313
Net or Web: webmaster@mrs.org or
<http://www.mrs.org>

1998 IEEE International Electron Devices Meeting

The 1998 IEDM will be held Dec. 06-09, 1998 in San Francisco, CA.

Contact: Ms. Phyllis Mahoney
Widerkehr & Associates
101 Lakeforest Blvd., Suite 270
Gaithersburg, MD 20877
TEL [1] 301 527-0900
FAX [1] 301 527-0994
Net or Web: pwmahoney@aol.com

Conf. on Optoelectronic and Microelectronic Materials and Devices

COMMAD '98 will be held December 14-16, 1998 in Perth, Australia.

Abstract Submission Deadline: August 31, 1998

Contact: Lorenzo Faraone
Univ. of Western Australia
EEE Department
Nedlands, WA 6907 Australia
TEL [61] 8 9380 3104
FAX [61] 8 9380 1095
Net or Web: faraone@ee.uwa.edu.au
<http://www.ee.uwa.edu.au/~COMMAD98>

If you would like your conference to be included in future issues, send the appropriate information by E mail to

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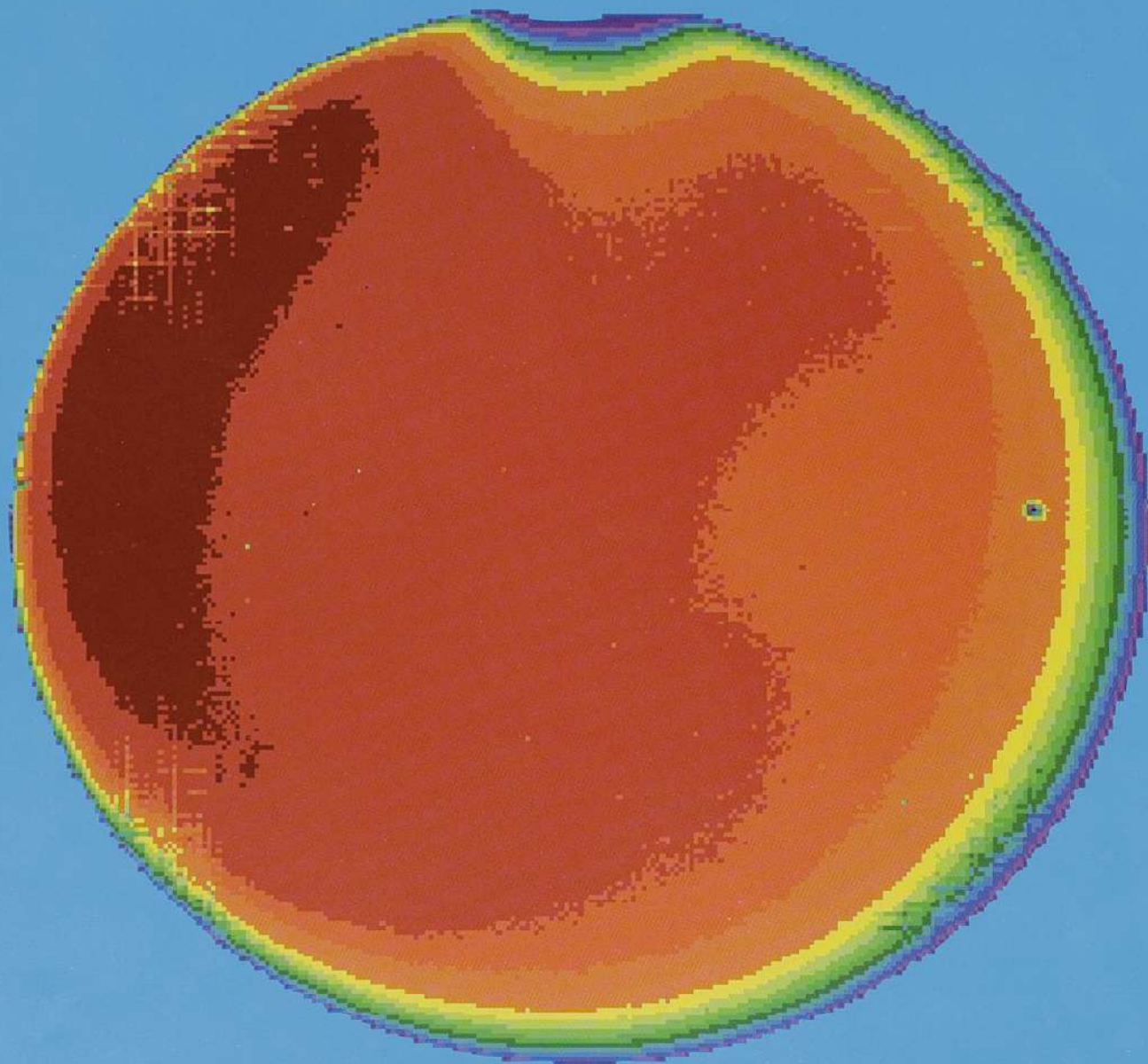
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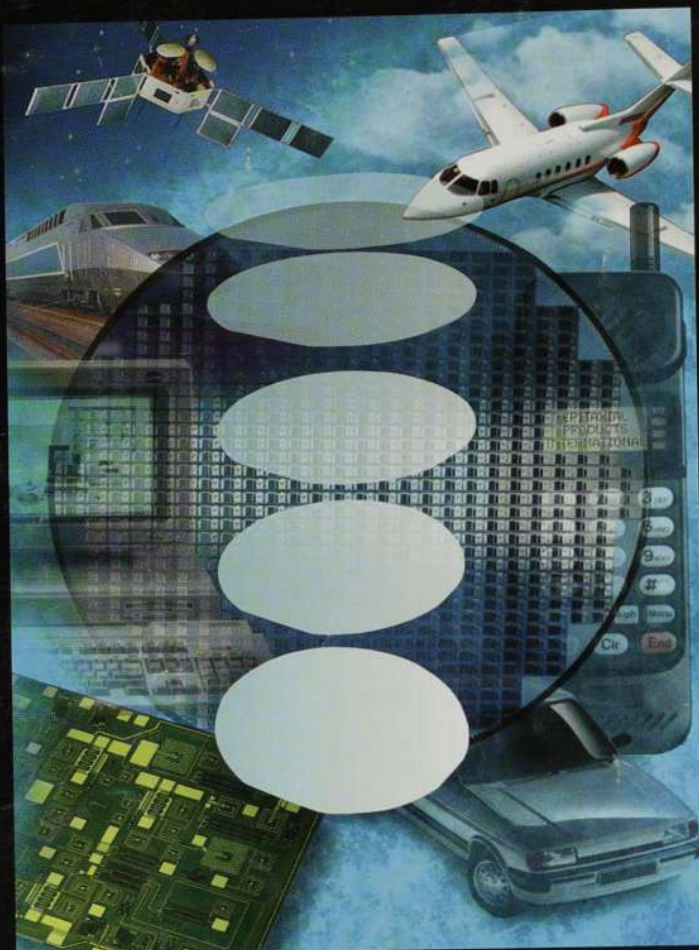
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