Vertical Cavity Surface Emitting Lasers (VCSELs):
Technology Readiness Overview (TRO)

Applications:

Emerging photonics technologies will be critical for next generation high performance spacecraft which may include sensor applications generating unprecedented amounts of data. For example, future high resolution multi-wavelength sensor systems will require intensive data transfer and routing on-board satellites. Optical based data busses will have higher performance (e.g. bandwidth, size, etc.), lower weight and power, and reduced sensitivity to electromagnetic effects than copper-based alternatives. Experience at NASA has shown that fiber optic busses also make integration of a spacecraft easier and more efficient, resulting in significant cost savings. A specific photonics technology that shows great promise for high speed intra-satellite data transfer applications is the Vertical Cavity Surface Emitting Laser diode (VCSEL). It is a semiconductor device with light emission perpendicular to the chip surface. The vertical lasing cavity is produced by sequentially grown epitaxial semiconductor layers.

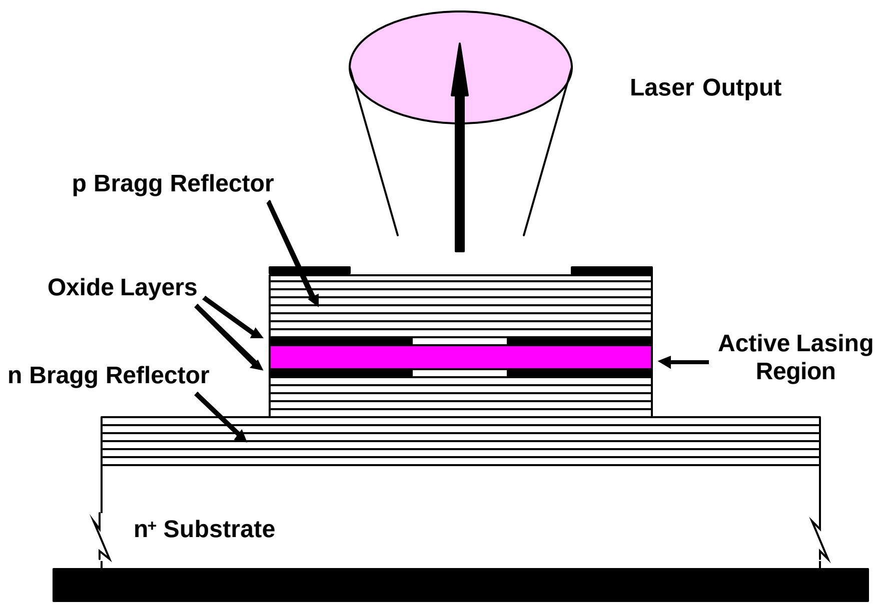

Figure 1 Pictorial of VSCEL. Note the vertical resonant cavity confined by the two Bragg reflectors. The lasing current is laterally confined by the oxide layers. The active region generally consists of a number of quantum wells to achieve sufficient power. VSCELS exhibit

very low threshold voltages. Different material systems are employed for various wavelength outputs.

VCSELs are becoming the component of choice for numerous applications, supplanting both LED- and edge-emitting sources, for diverse applications including data communication, optical interconnections and memory, sensors, etc. There are significant performance, producibility, and packaging advantages in the technology. For example, lower operating currents (mA's) and power dissipation/emission (mW's) at Gbit/s data rates; high reliability (> 10^7 Hrs MTTF), wafer-level batch fabrication and on-wafer testability, and utilization of the existing LED infrastructure; increased fiber coupling efficiency (> 90% as a result of the uniform single mode beam profile), and simplified drive electronics, which translates into a significant cost advantage. Additionally, VCSELs are suitable for 1- and 2-dimensional array integration for parallel optical interconnects.

There are both proton implant confined vertical cavity surface emitting lasers oxide confined VCSELs available commercially. An oxide confined VCSEL is desirable for 3.3 V (as opposed to 5V) transceiver applications due to its higher slope efficiency and lower operating voltage compared to proton implant confined VCSEL.[1] Although reliability issues remain important for the longer wavelength lasers required in some long reach (>500m) communications, satellite needs can be met with the more mature 850 nm technology.

<u>Radiation Response of VCSEL Technology</u>:

The Radiation Effects and Analysis Group (REAG) at NASA-GSFC has performed cobalt 60 and proton radiation testing on a variety of commercial VCSELs and VCSEL-based data links, and found them to be very robust in each case.[2] The Honeywell HFE-4080 ion implanted 850 nm VCSEL as well as a series of developmental oxide confined Honeywell VCSELs were exposed to multi-megarad levels of 63 MeV protons with only small threshold current shifts as well as some reduction in the slopes of the light output versus drive current curves (i.e. the differential quantum efficiency) at the higher proton fluences. In the case of the oxide-confined lasers we found that the smallest threshold current shifts were observed for the smaller aperture lasers as expected. These results are consistent with other observations in the literature.[3,4,5]

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[1] K.L. Lear, K.D. Choquettee, R.P. Schneider Jr., S.P. Kolcoyne, and K.M. Geib, "Selectivity oxidised vertical cavity surface emitting lasers with 50% power conversion efficiency," *Electron. Lett*., vol 31, pp. 208-290, 1995.

[2] M.V. O'Bryan, K.A. LaBel, R.A. Reed, J.W. Howard Jr., R.L. Ladbury, J.L. Barth, S.D. Kniffin, C.M. Seidlick, P.W. Marshall, C.J. Marshall, H.S. Kim, D.K. Hawkins, A.B. Sanders, M.A. Carts, J.D. Forney, D.R.Roth, J.D. Kinnsion, E. Nhan, and K. Sahu, "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics," 2000 IEEE Radiation Effects Data Workshop, July 2000, pp. 106-122.

[3] A.H. Paxton, R.F. Carson, H. Schone, E.W. Taylor, K.D. Choquette, H.Q. Hou, K.L.Lear, and M.E. Warren, "Damage from Proton Irradiation of Vertical-Cavity Surface-Emitting Lasers," IEEE Trans. Nucl. Sci., Vol. 44, No. 6., pp. 1893-1897, 1997.

It is important to note that many lasers exhibit a form of annealing that requires operating conditions to be controlling during and after irradiation in order to obtain meanigful results. For example, the act of measuring device properties after irradiation can cause damage to partially anneal as a result of the high power densities during laser operation. Given the relative hardness of the technology one may simply chose to perform a worse case radiation test in which the laser diode is irradiated unbiased and then immediately characterized using pulsed measurments with current limits. Further discussion of the annealing issues may be found in [5], and references therein.

REAG at NASA-GSFC has also characterized the proton response of a number of commercial off the shelf gigabit ethernet transceivers that employ 850 nm VCSEL-based transmitters. They were found to be quite robust out to ~25 krad(Si) of 63 MeV protons [2] during single event effect testing. Note that the VCSELs themselves would have been expected to operate satisfactorily to more than 200 krad(Si).

Summary:

Both oxide-confined and implant-defined 850 nm VCSELs are expected to perform well to over a megarad (Si) and hence should be applicable to any foreseeable NASA mission. Although the radiation response of longer wavelength VCSELs has not been measured, they are also expected to have robust performance in a radiation environment.

This project will help demonstrate the feasibility of multi Gbps VCSEL-based serial and parallel optical fiber links for use in a space environment by evaluating the radiation response of key components. The proposed link technology uses several emerging technologies including vertical cavity surface emitting lasers (VCSELS), high speed metal-semiconductor-metal (MSM) photodetectors, and low-power gallium arsenide (GaAs) complementary heterojunction insulated gate field effect transistor (C-HIGFET) support circuitry which are expected to be robust to radiation. The Honeywell High Technology Center (HTC) will provide individual link components, and radiation effects testing and analysis will be performed by the Radiation Effects and Analysis Group (REA) at NASA-GSFC.

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[4] C.E. Barnes, J.R. Schwank, G.M. Swift, M.G. Armendariz, S.M. Guertin, G.L. Hash, and K.D. Choquette, "Proton irradiation effects in oxide-confined vertical cavity surface emitting diodes," presented at the RADECS99 Conference, Abbaye de Fontevraud, France, Sept 13-17, 1999, Paper L-O-2.

[5] A.H. Johnston, T.F. Miyahira, and B.G. Rax, "Proton Damage in Advanced Laser Diodes," IEEE Trans. Nucl. Sci., Vol. 48, No. 6., pp. 1764-1772, 2001.

VCSELs

Ion implanted 850 nm VCSELs were delivered to NASA/GSFC and tested at TRIUMF in May 1999. Further tests at lower proton energies will be completed at Davis in June 1999. Oxide confined VCSELs with 4 μm, 5 μm and 10 μm aperture sizes will be delivered to NASA/GSFC shortly for proton testing in June 1999. In both cases, the electrical connections will be via a TO46 can, and the optical connections will be SC. This packaging will allow reproducible optical power measurements at the proton accelerator site. In the case of the oxide-confined VCSELS, there was no standard burn-in procedure. Honeywell used the standard proton-implanted VSCEL burn-in with the current adjusted to account for the lower threshold current in the oxide aperture VCSEL.

Two proton-isolated VCSELs were gamma tested at the NRL gamma source in order to verify that the Ultem spherical plastic lens would not darken in response to TID exposure. The VCSELs were exposed to a total of ~1.8 Mrad(Si) at a dose rate was 0.38 krad(Si)/s. The turn-on threshold remained constant at ~5mA. The same two devices plus a third virgin device were exposed to 70 and 225 MeV protons at TRIUMF and no evidence of injection annealing was observed. Dosimetry was performed using Al activation foils. The devices degrade primarily via a shift in the threshold currents. As expected, they were extremely robust. The results for all proton energies will be presented together once the Davis data is acquired.

At Crocker, we will irradiate both VCSEL types until a significant threshold shift is observed (around $1\text{-}2\times10^{13}$ cm^{-2} at 63 MeV), and characterize the forward biased annealing at around 7 mA and 12 mA drive current for devices at high damage levels.

CHFET Shift Resisters

Both LT and non-LT shift registers are probed at wafer-level for the complementary HIGFET and feed forward logic (FFL) families (all die on all wafers). The Triquint packages from Kyocera arrived at Honeywell. The CHFET shift registers (on both LT and non-LT substrates) are expected at NASA/GSFC any day. The test board is almost complete in preparation for a June 1999 proton test at Davis. The “shift registers” are a very different design than we expected. As a result we must develop new software and run the test using the Anritsu bit error test receiver. The devices would more accurately be designed as divide by two cicuits. A heavy ion test is planned for August 1999.

3.3 Task 3: Characterization of Very High Speed Photodetectors for Fiber Optic Data Bus (FODB) Applications

Purpose: To quantify the proton upset response of MSM devices for both direct ionization and nuclear reaction events to support on-orbit predictions.

Background:

Higher speed FODBs are important for future satellite applications, and ultimately single mode (SM) systems will be necessary for efficient light collection onto the very small (low capacitance) photodetectors that will be necessary. In the drive for performance, monolithic receivers are also being developed, and MSM detectors have the advantage of compatibility with standard planar processes used for the associated amplification circuitry. They can reach higher speeds than other detector technologies such as PINs because they are a majority carrier device. The speed of operation is determined by the finger spacing but speeds in excess of 10 GHz are readily obtained. Research devices exist with speeds in excess of 100 GHz.

Progress:

No new developments.

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After the successful market introduction of proton implant confined vertical cavity surface emitting laser (VCSEL) based 5 V gigabit transceiver modules a few years ago,[1] oxide confined VCSELs arc being developed for 3.3 V gigabit transceiver modules. An oxide confined VCSEL is desirable for 3.3 V transceiver applications due to its higher slope efficiency and lower operating voltage compared to proton implant confined VCSEL[2]:. Here we report the commercialization of oxide confined VCSELs at Hewlett Packard.

The VCSELs are grown using a multi-wafer organometallic vapor- phase epitaxy (OMVPE) reactor. The 850 nm oxide VCSEL structure consists of a lower 40 pair AlGaAs DBR, a full wave cavity with three GaAs quantum wells in the center, followed by a thin $A1_{0.97}Ga_{0.03}As$ layer for oxidation, and an upper 25 pair AlGaAs DBR and capped by a heavily doped GaAs contact layer. The DBR interfaces are graded to reduce the series resistance of the devices.

After epitaxial growth, the VCSEL wafers are first characterized by reflectivity measurements to determine layer thickness and by Polaron capacitance-voltage measurements to determine doping level. The VCSEL devices are then formed by oxidation and front and back metallization. After the wafer fabrication, the VCSELs are first tested in wafer form for DC performance, and the wafers are then scribed and broken, and the lasers are mounted on TO-46 headers for burn-in and life test.

The oxide VCSEL performance yield per product specification is largely determined by the control of the uniformity of the epitaxial layer thickness, doping and the oxide VCSEL emission aperture size. Typically, the Fabry-Perot wavelength uniformity can be controlled to within ±0.6% over 80% area of a 2-inch diameter wafer, which translates into a lasing wavelength range of around 10nm. The oxide VCSEL emission window is defined by the lateral wet oxidation process of the buried $Al_{0.97}Ga_{0.03}As$ layer and the aperture size is controlled by the combination of oxidation rate and oxidation time. The oxide aperture size map across a 2-inch wafer is shown in Fig. 1. The oxide aperture is measured at ¼ intervals across the wafer for a total of 37 evenly spaced points. The aperture size across the wafer is 15.8 ± 0.3μm where ± 0.3mm (± 0.2%) is the standard derivation of the aperture size variation.

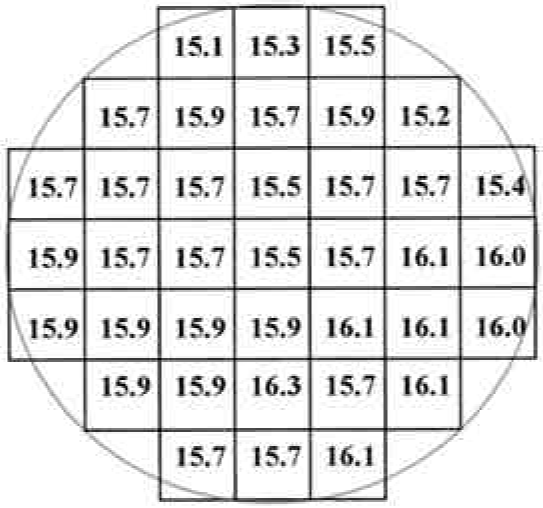


Figure 1. *Oxide VCSEL aperture size map across a 2-inch wafer.*

Figure 2 shows oxide VCSEL performance at the 37 evenly spaced points across a 2-inch wafer. The performance variation across the wafer is contributed by the combined variation of the layer thickness, doping and the aperture size. Excellent device performance has been achieved with low operating voltage, high power, and fast modulation speed. The operating voltage across the wafer at2 mW power is below 2 V, which is suitable for 3.3 V transceiver module applications.

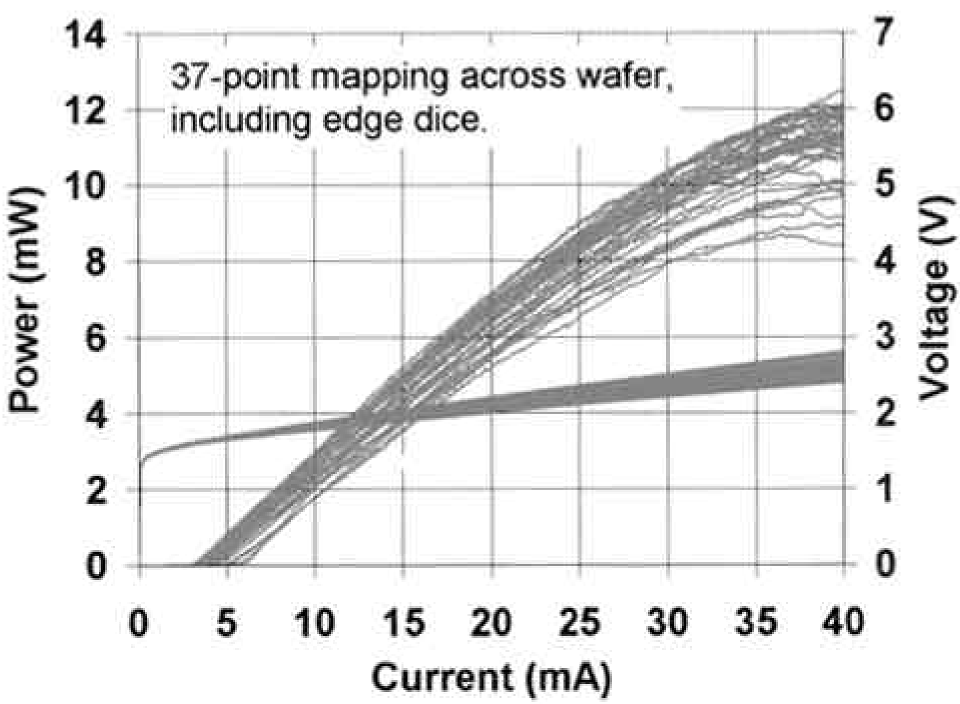


Figure 2. *Oxide VCSEL performance at the 37 evenly spaced points across a 2-inch wafer.*

One of the greatest concerns of developing oxide VCSELs is its reliability due to the strain and defects introduced in the VCSEL structure during oxidation. Preliminary reliability of the oxide VCSELs is investigated by studying both the random failure rate and the wearout lifetime. The random failure rate is established by stressing the devices at a constant output power of 2mW at 70ºC ambient. Four hundred sixty units were stressed up to 6000 hours to achieve over 2.2 million cumulative device hours. One device failed at 5000 hours and all the rest units remain stable. The long-term wearout tests are conducted at various currents and temperatures to determine the activation energy. The stress results show that the activation energy and the wearout lifetime of oxide VCSEL are similar to that of implant VCSEL emitting the same amount of output power.

In summary, we have developed a commercially manufacturable oxide VCSEL process. Good uniformity control in epitaxial thickness and oxide aperture is found to be important in achieving high yield. The manufactured VCSELs have superior performance with operating voltage less than 2V. Preliminary results show that oxide VCSEL reliability is similar to that of proton-implanted VCSELs.

1. C. Lei, L.A. Hodge, J.J. Dudley, M.R. Keever, B. Liang, J.R. Bhagat and A. Liao, “High performance vertical-cavity surface emitting lasers for product applications,” in *Proc. SPIE Conf. Vertical Cavity Surface-Emitting Lasers*, vol. 3003, pp. 28-33, San Jose, California, 1997.

2. K.L. Lear, K.D. Choquettee, R.P. Schneider Jr., S.P. Kolcoyne, and K.M. Geib, “Selectivity oxidised vertical cavity surface emitting lasers with 50% power conversion efficiency,” *Electron. Lett*., vol 31, pp. 208-290, 1995.

Vertical Cavity Surface Emitting Laser diodes (VCSELs) are semiconductor devices with light emission perpendicular to the chip surface. They are highly attractive for applications in optoelectronics, since they offer several advantages compared to conventional edge-emitting (in-plane) laser diodes, such as low electric power consumption, capability of on-wafer testing, simplified fiber coupling and packaging, longitudinal single-mode spectra, and suitability for 2D-array integration.

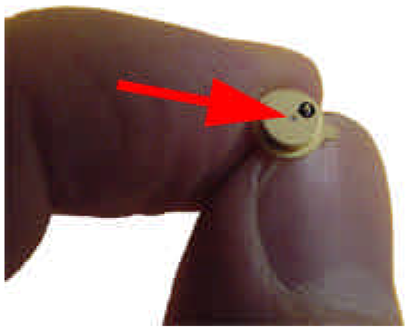


Fig. 1: BTJ-VCSEL on mount

In the past years, several projects have been concerned with the development and optimization of GaAs-based VCSELs in the near infrared (<1.3µm) at the Walter Schottky Institute. Different concepts for current confinement have been realized such as blocking layers and selective oxidation, and also VCSELs with quantum dots as active material have been demonstrated in continuous-wave mode operation at room temperature.

Particular interest with respect to fiberoptical communication systems exists for those VCSELs that are able to emit at wavelengths around **1.31µm** or **1.55µm** (Fig. 1) because of minimum dispersion or absorption, respectively, in silica fibers. Eligible material systems of compound semiconductors are (GaIn)(NAs) on GaAs substrate for 1.31µm VCSELs; on InP there are (InGaAl)As, (InGa)(AsP) and (AlGa)(AsSb) potential for both 1.31µm and 1.55µm. The realization of VCSELs with reasonable characteristics, however, suffers from several technological challenges related to the required materials, especially in the 1.55µm wavelength case:

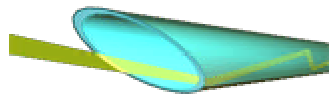
- Low refractive index-contrast of Distributed Bragg Reflector (DBR) mirrors.
- Poor thermal conductivity of ternary- (quaternary-) compound semiconductor DBRs.
- Problematic light amplification performance at elevated temperatures.
- Selective Oxidation (of InAlAs) expected to cause material damage.

To overcome these obstacles, the device concept of VCSELs with a Buried Tunnel Junction (**BTJ**) in conjunction with a dielectric DBR has been developed at the WSI within project B11 of the *Sonderforschungsbereich 348* "Nanometer Semiconductor Devices" which is supported by the Deutsche Forschungsgemeinschaft. Today, the project continues under designation B15.

Etc., etc.
Applications

In most areas of application for long-wavelength VCSELs - fiberoptical communication and gas monitoring - single-mode emission is required not only longitudinally, what is accomplished with any VCSEL, but also transversally (eg. fig. 8), which means that in a cross-section of the laser beam the intensity should be distributed like in the upper half of fig. 9. In addition, the optical field's polarization must be pure and stable. This is supported by elliptically shaped BTJs that are easy to manufacture since they are defined by standard photomask lithography.

Annealing studies of irradiated VCSELs



Four MITEL VCSELs type 1A444 were irradiated at ISIS/Rutherford Appleton Laboratories (RAL) with a fluence of (2.9+/-0.8) $x10^{15}$ n/cm^2.
Since these VCSEL are GaAs devices the highest required effective 1 MeV neutron fluence is $2.5x10^{15}$ n/cm^2 (1st layer total fluence over 10 years [1], [2]).

All four VCSEL survived the irradiation and recovered reasonably quickly.

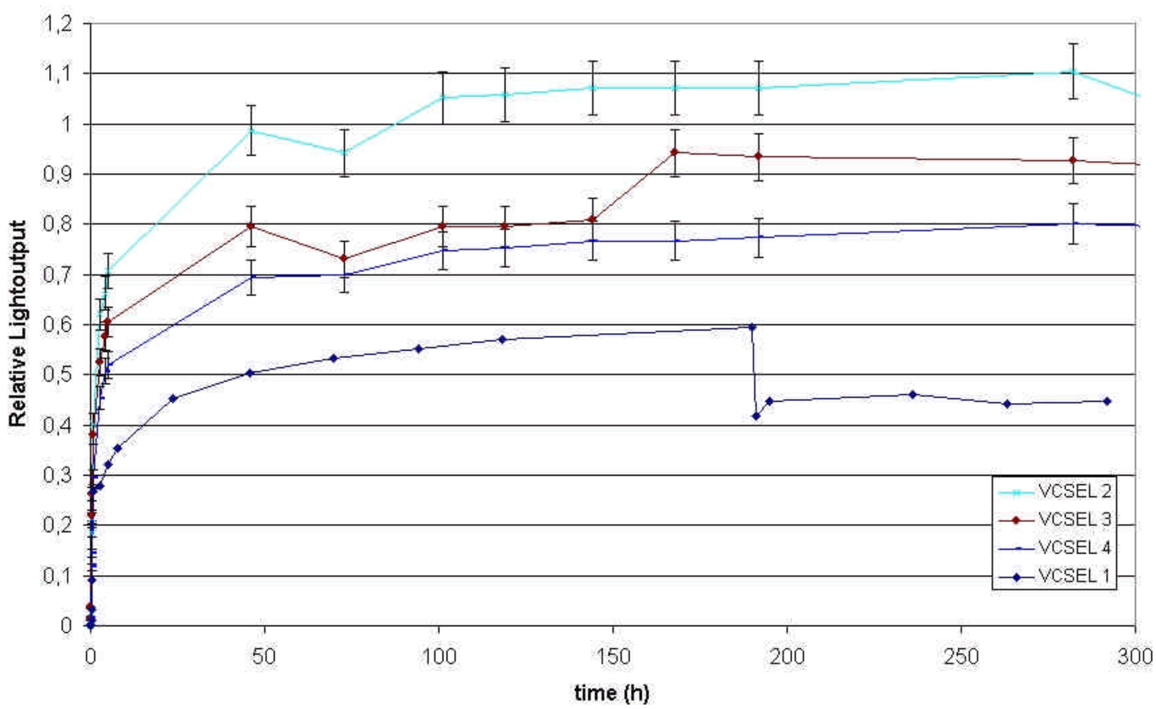


Figure Figure 1: Light output vs. time of 4 MITEL VCSEL type 1A444 irradiated with $2.9x10^{15}$ n/cm^2 annealing with 20mA. The VCSELs were not operated during

Figure 1 shows the recovery during the first 300 hours after turning on the forward current. Th VCSELs were connected in series and biased with a forward current of 20 mA.

The first 5 hours of this annealing period are shown in close up (figure 2 below). The drop in the light output of VCSEL 1 appeared after this VCSEL was handled and is probably due to damage.

Twenty further MITEL VCSELs of the same type were irradiated at ISIS in order to test their lifetime after a sufficient annealing time. The fluence was $(4.1 +/- 1.39)*10^{14}$ n/cm^2. Figure 3 (below) shows the relative light output of these 20 VCSELs vs. time. These 20 VCSELs were devided into 4 groups. Each group was driven with a different forward current: 10, 15, 20 and 25 mA. The 5 curves always show the group average.

VCSELs which were irradiated with a fluence of $4.1x10^{14}$ n/cm^2 annealed within seconds when they were driven with 20mA. Also the VCSEL irradiated with $2.9x10^{15}$ n/cm^2 annealed to an acceptable level in a reasonable time when driven with 20mA (order of 24 hours).

The VCSEL irradiated with $4.1x10^{14}$ n/cm^2 driven with 10 and 15 mA annealed rapidly. But they only annealed up to a level of 80%. There is no evidence of further annealing after the first minutes. Whereas driven with 20 mA they anneal within seconds up to 100%.

To determine whether these VCSELs anneal slowly just because the drive current was less than 20 mA, the current was turned up to 20 mA and they annealed to a level of 100% (marked with an arrow in figure 3). The VCSELs driven with 10 mA appear to reach the 100% level very slowly. This is due to one slowly annealing VCSEL. The light outputs of the rest of this group rose directly up to 100%.

Conclusions:

The annealing behaviour of irradiated VCSELs driven with currents between 10 and 25 mA was studied. It seems that VCSELs driven with a current of 10 or 15 mA anneal slower. We conclude that 20 mA are required for safe annealing. Further measurements will be done, because of an error in the first measurement.

Reference:

[1] ATLAS Pixel TDR May 1998, table 4-1

[2] INDET-NO-182

[3] Andreas Kootz " Lebensdauertest von bestrahlten VCSEL fuer den ATLAS Pixel Detektor" Lifetimetest of irradiated VCSELs for the ATLAS Pixel Detector, Diplomathesis in preparation

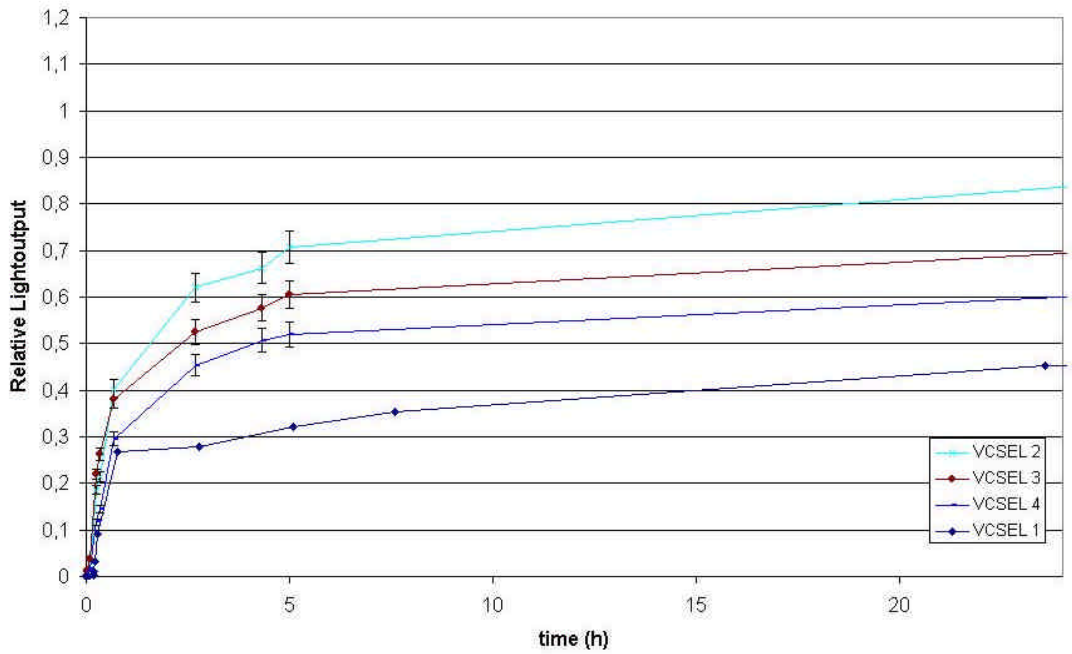


Figure 2: Light output vs. time of 4 MITEL VCSEL type 1A444 irradiated with 2.9x10^{15} n/cm^{2} annealing with 20mA. The VCSELs were not operated during (first 25 hours)

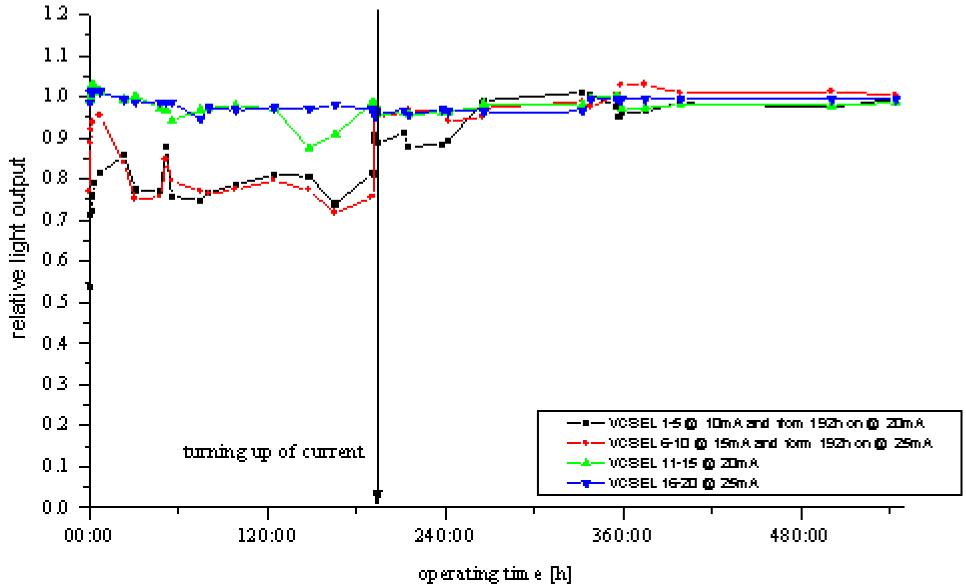


Figure 3: Light output vs. time of 20 MITEL VCSELs irradiated with $4.1x10^{14}$ n/cm^2 and annealed with different currents.

last modified : 28 May 1999

Radiation Hardness and Life Time Studies of LEDs and VCSELs

Introduction

One of the technologies proposed for the readout of the ATLAS SemiConductor Tracker (SCT) uses **optical links** based on Light Emitting Diodes (LEDs) or Vertical Cavity Surface Emitting Laser Diodes (VCSELs). Mounted near the detector modules close to the interaction point, these devices would be subject to fluences on the order of 10^{14} charged hadrons and 10^{14} neutrons per cm^2, and to an ionizing dose of about 10^5 Gy during 10 years of operation at the Large Hadron Collider (LHC). Obviously, both the **radiation hardness** and the **lifetime** of LEDs and VCSELs must be studied carefully before they can be used in such an environment.

Results and Publications

- J. Beringer et al., *Radiation Hardness and Life Time Studies of LEDs and VCSELs for the Optical Readout of the ATLAS SCT,* Nuclear Instruments and Methods **A435** (1999) 375-392
- J. Beringer et al., *Final Results of Radiation Hardness and Life Time Studies of LEDs and VCSELs for Optical Links of the ATLAS Inner Detector,* Proceedings of the Third Workshop on Electronics for LHC Experiments (London, UK, 1997), CERN/LHCC/97-60 (1997), p. 265

- J. Beringer et al., *Radiation Hardness and Life Time Studies of LEDs and VCSELs for the Optical Readout of the ATLAS SCT,*
  ATLAS Internal Note No. 183, September 16, 1997 (approx. 1.8MB without photographs)
  ATLAS Internal Note No. 183, September 16, 1997 (approx. 11MB, compressed, with photographs)
- R.K. Mommsen, *Life Time Studies of Irradiated LEDs and VCSELs for the ATLAS Experiment at the Large Hadron Collider,* diploma thesis, University of Bern (1997)
- J. Beringer et al., *First results of a comprehensive life time test of irradiated LEDs and VCSELs*, Proceedings of the Second Workshop on Electronics for LHC Experiments (Balatonfüred, Hungary, 1996), CERN/LHCC/96-39 (1996), p. 382, also available as preprint BUHE-96-7 (1996)
- J. Beringer, *Studies for the Inner Detector of the ATLAS Experiment at the Large Hadron Collider*, PhD thesis, University of Bern (1996)

Further Informations

- Results of a first life time test of a small number of neutron irradiated LEDs
- The scanning machine, an automatic measurement system for long term tests of up to 448 LEDs or VCSELs

Links to related information

- Homepage of the ATLAS Working Group on Front-end Links
- SCT links home page at CERN

Vertical-Cavity Surface-Emitting Lasers (VCSELs) Characterisation and Modeling for Parallel Optical Interconnects Applications

A. Overview

1. Purpose

The purpose of this project, initiated by the IBM Zürich Research Labs, is to realize within the next four years a complete solution for short to medium distance parallel interconnects. Each of the 100-500 channels should have 10Gbit/s capacity, resulting in an aggregate data rate of 1-5Tbit/s.

2. Fundamental Limitations

The Semiconductor Industry Association predicts for the year 2012 logic chips with 1.4 billion transistors and more than 20km interconnection lines (35nm lines), distributed over 9 layers. By 2005, the interconnects are expected to become the dominant source of power dissipation and of delay time.
This is due to the intrinsic physical limitations of electrical interconnection lines [1]. Furthermore, as a consequence of the parasitic capacitance of the lines, crosstalk will increase dramatically as the lines will get more densely packed.
The MEL-ARI optoelectronics technology roadmap 1998 [2] says: *"Future IC generations will be designed by placing the signal paths and fitting transistors in between"*.
Although the initial purpose of this project is not the realization of intra-chip interconnects, this shows that electrical interconnections will become more and more the critical issue in chip design. Furthermore, the intrinsic limitations of electrical interconnections become more obvious as the interconnection length increases. For example, the electrical interconnection technique has already reached a bottle neck for board-to-board interconnections [3]. This is also the reason why the telecom industry already made the step towards optical transmission lines for very long distances.

3. Electrical vs. optical Interconnects

Table 1 compares some essential properties of electrical and optical interconnection lines:

Table 1: Electrical vs. optical interconnects

electrical interconnects
optical interconnects

Physics
density

- overlapping or crossing of lines NOT allowed
- size of the beam limited by the wire
- planar technology
- overlapping and crossing allowed (free-space)
- size of the beam limited by diffraction
- 3D allowed (free-space and fiber)

delay

- max. signal propagation speed ~= 0.1mm/ps
- signal propagation speed ~1/C' ~ interconnection density
- max. signal propagation speed ~= 0.3mm/ps
- the signal propagation speed doesn't depend on the interconnection density

bandwidth

- the density of electrical interconnections is affected by the bandwidth carried by each connection (because of parasitic C' and L' effects)
- the density of optical interconnections is NOT affected by the bandwidth carried by each connection

power

- matching impedance needed at the end of the line to avoid reflections => large power expenditure
- power requirements mainly limited by the sensitivity of the photodectors, the efficiency of the conversions and the transmission efficiencies

noise

- high noise features
- low noise features

Technology
material

- all Si possible
- all Si impossible

technology

- easy (CMOS)
- complicated (III-V materials, hybrid integration,...)

alignment

- low sensitivity to misalignment
- extremely sensitive to misalignment

To summarize the above results, one can say that electrical interconnects show clear physical limitations, while the limitations of optical interconnects are more on the technological side.

4. Key Technologies

Vertical Cavity Surface Emitting Lasers (VCSELs) [4] are a key technology towards such a parallel optical interconnects solution [5]. Some of their most remarkable features are monolithic 1D or 2D arrays processing and on wafer testing capability, circular output beam, single longitudinal mode, low threshold current and high speed direct modulation capability. However, although VCSELs represent a major breakthrough towards parallel optical interconnects, some major issues must still be solved before an efficient and cheap optical interconnects solution comes to the market. Some other required key technologies are:

- chips (CMOS?) able to drive each of the densely packed lasers at high frequency with minimum electrical crosstalk and power consumption
- arrays of fast, cheap and sensitive detectors, either monolithically integrated with the VCSELs arrays, or realized in the same technology as the driver
- an efficient technique for aligning the waveguides to the emitter / receiver

5. Project Evolution

My specific contribution in this project first consists in the characterization of VCSELs in order to acquire a better understanding of the laser's underlying physics, so that structures could be optimized for that specific application. The second part, which is actually conducted in parallel, is the development of an efficient model to simulate the VCSEL's behavior under direct modulation. The requirements for such a model are:

- high computational efficiency
- typical large signal modulation figures of merit in good agreement with measurements (BER, eye diagrams, noise, chirp, ...)
- an efficient fitting procedure to extract parameters from real world devices
- the ability of being implemented in an electronic circuit simulator ("Spice-like"), in order to simulate and optimize an entire channel (driver, laser, waveguide, detector, parasitics, optical coupling,...)

6. References

[1] D.A. Miller and H. M. Ozaktas, "Limit to the Bit-Rate Capacity of Electrical Interconnects from the Aspect Ratio of the System Architecture", *Journal of Parallel and Distributed Computing*, p. 42-52, 1997

[2] European Commission ESPRIT program, Microelectronics Advanced Research Initiative (MEL-ARI OPTO), Technology roadmap, *Optoelectronics Interconnects for Integrated Circuits*, June 1998

[3] R. A. Nordin, W. R. Holland and M. A. Shahid, Advanced Optical Interconnection Technology in Switching Equipment, *J. Lightwave Technol.*, vol. 13, no. 6, 1995

[4] K. Iga, "Surface-Emitting Laser - Its Birth and Generation of New Optoelectronic Fields", *IEEE J. Select. Topics Quantum Electron.*, vol. 6, pp. 1201-1215, 2000

[5] D.A. Miller, "Rationale and Challenges for Optical Interconnects to Electronic Chips",*Proc. IEEE*

VCSELs continue to push back technological barriers

VCSELs are still developing quickly despite the challenges of manufacturing large arrays and the reliability of the materials used in long-wavelength lasers for optical networking, as Richard Dixon discovered at the recent Photonics West conference in San Jose, California.

The large number of presentations that made up the VCSEL sessions held during this year's Photonics West event (January 20-25) testified to the continued high interest in 850 nm lasers for short-reach (i.e. less than 500 m) communications links.

Papers on 1310 and 1550 nm VCSELs also generated great interest. Long-wavelength devices are eagerly anticipated as cost-effective replacement sources for edge emitters. These devices are slated for 10-40 km optical links in high-growth areas at the edge of the network, including metro access and enterprise communications.

Manufacturing

In his invited talk, Honeywell's Jim Tatum suggested doing away with proprietary packaging in favor of standardized packages. This should enable VCSEL makers to move on to the next step of automated assembly and manufacturing. The standardization of packaging will enable the vendors of automated manufacturing tools to design products specifically for VCSEL producers if the market is large enough. Currently, each manufacturer has its own package, and the number of variations may be slowing market development.

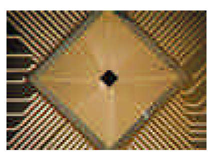


Figure 1

Tatum also considered replacements for the traditional TO-46 can, which still features leads that can reflect power during 2.5 GHz operation. Controlled-impedance ceramic packages could be the answer owing to their essentially flat impedance response up to 12 GHz, which would be adequate for 10 Gbit/s applications. Tatum said he would also like to see an industry consensus on a 10 Gbit/s integrated VCSEL/TIA/*pin* photodetector package.

Flip-chip arrays

B Schneider of ULM Photonics stressed the importance of flip-chip bonding to large-scale VCSEL array manufacturing (see figure 1). Flip-chip processing is seen as vital to the manufacture of large arrays: it simplifies assembly and test, and eliminates complicated wire-bonding and bond-pad schemes. ULM's 850 nm VCSELs employ a coplanar waveguide structure that allows all the contacts to be placed on the top, while bottom emission requires removal of the GaAs substrate.

The company's devices exhibit a series resistance of 70 O at 4 mA, and provide an output power of 2 mW. The threshold current is typically 1 mA, and even after substrate removal thermal resistance is only 2.6 K/mW.

Large-scale arrays undergoing accelerated aging at 160 °C and 7 mA drive current typically fail at around 1350 hours, which extrapolates to more than 10 million hours at room temperature. Schneider concluded by saying that singlemode operation at 10 Gbit/s is still desirable, and that processing and reliability issues still remain the main challenges for VCSELs to overcome.

Long-wavelength VCSELs

Long-wavelength VCSELs have developed more slowly than their shorter-wavelength 850 nm cousins as a result of fundamental materials issues. Mirror structures with high reflectivity can be grown on GaAs, but 1300 nm active regions are difficult to grow in this material system. However, good InP-based long-wavelength active regions can be grown, but at the expense of good mirrors.

One way around this is to use wafer bonding to fuse the different materials that give the desired emission wavelength and high-reflectivity mirrors. Alternatively, quaternary alloys such as InGaAsN can be used in the active region to overcome the problems of lattice matching GaAs-based mirrors to InP.

J Klem of Sandia National Laboratories discussed advances in 1300 nm VCSELs based on InGaAsN with nitrogen contents up to 1.5%. Sandia's devices are grown by MBE on 3 inch GaAs substrates. Several new oxide-confined monolithic VCSEL designs were also described. These incorporated compositionally graded mirror interfaces and doping profiles, which reduce the operating voltage to 4.3 V. Adding nitrogen allows the indium content to be increased in the InGaAs QWs, although too much indium causes strain relaxation and limits the number of QWs that can be introduced. Sandia has thus opted for 34% indium in InGaAsN wells that are 6 nm thick.

One scheme discussed employed a monolithically grown GaAs tunnel junction and two n-type DBRs that are designed to reduce free-carrier absorption losses. This led to output powers of 2 mW at room temperature for large-aperture devices. A second design with a smaller aperture operated at a much lower voltage of 2.7 V. This device has a threshold current of 1.1 mA and demonstrated 0.68 mW of CW output power. The slope efficiency was reported to be 0.24 W/A.

T Miyamoto of the Tokyo Institute of Technology also discussed the fabrication of GaInAsN/GaAs VCSELs for telecom applications. Miyamoto described a process that involved growing the $Al_{0.7}Ga_{0.3}As$/GaAs DBRs (35 pairs on the bottom and 24 on top) by MOCVD, and depositing the three QWs separating the mirrors using CBE. Apertures of 9 μm^2 were formed using oxidation at 450 °C and devices exhibited 1 mW in CW mode at a wavelength of 1185 nm. The threshold current was 2.6 kA/cm^2, and the maximum pulsed power output was 4 mW for a slope efficiency of 0.22 W/A.

Miyamoto's colleague T Kondo described 1160 nm VCSELs based on an active region with three strained $In_{0.36}Ga_{0.64}As$ quantum wells. Using an aperture size of 9 μm^2, these devices achieved a threshold current of 3 mA and current density of 3 kA/cm^2. The output power was 2 mW and slope efficiency was 0.3 W/A at 25 °C. The dependence of current on temperature was nearly constant up to 70 °C, which led Konda to suggest that the devices could be used as uncooled sources in LAN applications.

Cielo ships a range of long-wavelength VCSELs that can be driven at up to 10 Gbit/s in eight- and twelve-channel arrays, while its singlemode devices give up to 1 mW output power. Lance Thomson gave an update on Cielo's latest 1300 nm device, which now offers 1 mW at temperatures up to 90 °C with a wavelength drift of 0.08 nm/°C. VCSELs operating at a current density of 35 kA/cm^2 and at 90 °C have functioned reliably for 1550 hours, he added.

Emcore's long-wavelength VCSELs

Hong Hou gave an overview of Emcore's 1300 nm singlemode VCSEL, which is intended for telecom applications. The device features an $In_{0.34}Ga_{0.66}As_{0.99}N_{0.01}$ QW active region surrounded by high-index GaAs/AlAs DBR mirrors (39 pairs on the bottom and 25 pairs on top).

A device with a wavelength of 1275 nm has been designed with an 8 µm aperture, and provides a threshold current of 3 kA/cm^2. The singlemode output is 0.4 mW, and more than 1 mW in multimode operation. The company's target is 0.7 mW for 2 km optical links.

Hou explained that higher-power singlemode devices still remain a major challenge, and that currently only around 60% of the optical power is coupled into a singlemode fiber with optics. In addition, the series resistance in the long-wavelength emitter needs to be reduced from its current level of 100 O to 30 O demonstrated by the company's 850 nm products. Emcore is also working to remove the wavelength's dependence on temperature.

Developments in 10 Gbit/s VCSELs

Swiss VCSEL specialist Avalon Photonics is manufacturing singlemode VCSELs for absorption spectroscopy applications, and developing 1 x 4 and 1 x 12 arrays using multimode fiber at rates of up to 3.125 Gbit/s (see *Compound Semiconductor* May 2001, p70).

John Humphries described Avalon's new 10 Gbit/s devices, which consist of small (4 µm) apertures designed to lower parasitic resistance and reduce power consumption at these high modulation rates. Humphries noted that reducing the dimensions of the oxide region could lower the series resistance from 100 O to around 40 O.

Avalon is targeting 10 Gigabit Ethernet applications, in addition to cable television and remote antenna addressing for mobile-phone systems. The last two applications use analog modulation schemes that require low noise, high linearity and fast modulation, and may benefit from Avalon's VCSELs, which feature a low relative intensity noise (RIN) of -130 dB/Hz at 10 GHz.

Figure 2

Emcore's Hou gave a paper on the company's VCSEL arrays, which together with single devices constitute a capacity of 1.5 million VCSELs per month. The company's roadmap includes 4 x 8 and 4 x 12 arrays, in addition to 32 x 32 arrays at 2.5 and 3.3 Gbit/s. VCSELs capable of 10 Gbit/s performance are also under development. Their mesa structure reduces series resistance, which is currently 60 O. The power output is 1 mW. Initial results of accelerated reliability studies (at 70 °C and 6 mA) for 10 Gbit/s 1 x 12 arrays led to lifetimes of 4 x 10^5 hours.

S Chiou reviewed United Epitaxy Company's (UEC's) recent VCSEL activities. Development began in October 2000, and GaAs-based VCSELs that operate in the 780-850 nm range were first announced last June (see *Compound Semiconductor* June 2001, p15). These devices are available as epiwafers on 3 inch GaAs substrates, or as chips. Red 650 nm devices are also being developed.

UEC now has a third facility at an industry park in Tainan, Taiwan and has a total of 30 MOCVD reactors, including five dedicated to nitride-based materials. By June this year, the company plans to offer 10 Gbit/s 850 nm single VCSELs and 4 x 2.5 Gbit/s arrays.

UEC's arrays contain VCSELs with 10 µm apertures placed at 250 µm intervals (figure 2). The measured series resistance is 35 O, and the devices deliver 2 mW of multimode output power at 5 mA for a forward voltage of 1.8 V. To date, these devices have operated at 5 mW for 1000 hours at 70 °C. In contrast with the multimode devices, UEC's singlemode 850 nm VCSELs have a relatively high series resistance of 75 O and an output of 1.5 mW at 5 mA. The threshold current lies at 1.5 mA and the singlemode suppression ratio is 40 dB.

VCSELs continue to push back technological barriers

AXT develops 10 Gbit/s VCSELs

One area of focus at AXT has been singlemode 850 nm VCSELs, which resulted in 3.125 Gbit/s devices last year (see *Compound Semiconductor* June 2001, p13). Other areas of development include all-important steps to automate packaging processes and to improve optical coupling to the fiber.

B Liang described new 10 Gbit/s multimode VCSELs that achieve 3 mW over the 5-75 °C range. AXT is currently sampling these devices, which deliver 12.5 GHz of bandwidth and feature a threshold current of 1.5 mA.

Reliability studies show failure rates (taken at the 0.1% level and using a 10 mA drive current) that extrapolate to lifetimes of 10^5 hours at 85 °C. The company is also working on large-area (8 x 8) arrays and singlemode devices for encoder and printing applications. Singlemode VCSELs have so far achieved 0.5 mW output at 3 mA, and a 0.25 W/A slope efficiency at 25 °C.

Figure 3

Zarlink looks to large apertures

Zarlink has commercialized 12 x 2.5 Gbit/s arrays and is developing 850 nm selectively oxidized designs for 10 Gbit/s operation. According to Thomas Aggerstam, the modulation characteristics of the company's VCSELs have been substantially improved by moving to InGaAs QWs, which exhibit better gain characteristics than GaAs QWs.

Grown by MOCVD, Zarlink's devices have both contacts on the top of the structure (figure 3), and are grown on semi-insulating GaAs substrates. The Bragg mirrors have alternating quarter-wavelength high- and low-index layers of AlGaAs. A high aluminum content layer above the active region and top p-DBR is oxidized to form the aperture.

The active region contains a one wavelength thick AlGaAs/InGaAs MQW, and the top DBR is implanted to reduce the capacitance of the thin oxide layer. A benzocyclobutene insulator is also used to reduce parasitic capacitance from the bond pads.

Two apertures sizes were characterized: a 6 µm device achieved 4 mW and a bandwidth of 16.5 GHz, while the larger 12 µm emitter exhibited 18 mW at 13.6 GHz. Tests over 300 m fiber resulted in power losses of 0.5 dB, although no reliability data were available.

Reliability issues

T Lowes of Gore Photonics discussed the long-term testing of the VCSELs used in its commercially available 1.25 Gbit/s nLighten modules. Up to 1500 devices have been analyzed to date. According to Lowes, current-voltage curves stay the same over 9000 hours, although the threshold currents increase as the devices age. Gore's VCSELs exhibit lifetimes that exceed the requirements of most systems, with eventual failure occurring in the mirror regions.

Agilent's R Herrick noted that VCSELs in real situations can be affected by the modules' self-heating. This can increase the device-junction temperature by up to 20 °C. He also questioned the use of mean-time-to-failure (MTTF) data without failure distributions. Actual failure could occur two or three times more quickly than using data for only 1% of the MTTF specifications would predict.

Herrick gave an example of VCSELs in an air-conditioned room, which can experience a case temperature of .50 °C, which has led to a lifetime of around 32 years under certain operating conditions. Where rooms or modules lack adequate cooling, case temperatures can soar to 90 °C and cause the MTTF to drop to as low as four years.

Honeywell

VCSELS

Contact: Robert A. Morgan, Senior Principal Research Scientist

Within the last 2 years Vertical Cavity Surface Emitting semiconductor Lasers (VCSELs) have emerged from the research laboratory into the commercial marketplace at Honeywell's MICROSWITCH Division. VCSELs are becoming the component of choice for numerous applications, supplanting both LED- and edge-emitting sources, for diverse applications including data communication, optical interconnections and memory, sensors, printers, and so forth. The enormous success of VCSELs is attributed, in part, to their performance, producibility, and packaging perks. Namely, significantly lower operating currents (mA's) and power dissipation/emission (mW's) at Gbit/s data rates; high reliability (> 10^7 Hrs MTTF), wafer-level batch fabrication and testing, and utilization of the existing LED infrastructure; increased fiber coupling efficiency (> 90%), and simplified drive electronics, which translates into a significant cost advantage. Most of these attributes result directly from the laser's novel, but inherent, vertical geometry. This vertical cavity is essentially a zero-order thin-film Fabry-Perot transmission filter, utilizing integral quarter-wave high-reflectance (> 99%) semiconductor epitaxial interference stacks referred to as distributed Bragg reflectors (DBRs). In fact, much of the intricacy of commercial-grade VCSELs lies in their epitaxial structure. Over 200 AlGaAs hetero-layers, in excess of 7 µm thick, are required to construct the vertical cavity. In addition to fabrication advantages, the AlGaAs material system is chosen to obtain emission wavelengths≅850nm, compatible with low-cost Silicon and/or GaAs detectors. To obtain the low threshold currents (1-5mA), these VCSELs utilize small-volume, high-Finesse cavities. To obtain lasing from thin,≅200-Å thick, active regions (typically 1 - 3 quantum wells) very high reflectivity (> 99%) DBRs are needed necessitating >20 quarter-wave periods, >2.5µm thick. The gain-apertured area is typically defined by proton bombardment through the top DBR. Annular metal contacts are utilized to enable current injection concomitant with light transmission. The resulting planar structure diameter typically is between 10µm and 20µm. These commercial-grade VCSELs are designed to operate in a single longitudinal mode, determined from the Fabry-Perot resonance, but lase in multi-transverse modes. The resultant reduction in coherence is utilized to circumvent modal noise in multi-mode fiber data links.

In addition to this successful commercial-grade VCSEL structure, HTC is presently conducting advanced VCSEL research. This includes alternate material systems to span the emission range from the red (650nm and 780nm) into the near IR (850nm, 980nm, 1300nm, and beyond). Furthermore, both 1D and 2D VCSEL arrays have been demonstrated with excellent yield and uniformity. Alternate fabrication approaches are also being pursued to open up even further applications of high efficiency VCSEL- and VCSEL-array based technologies. Research-grade VCSELs, utilizing dielectric-apertures formed by selective oxidation of buried high Aluminum-containing AlGaAs layer(s) have been demonstrated. These efficient (wallplug efficiencies > 25%) VCSELs exhibit an order of magnitude reduction in the VCSEL diameter (< 2um) concomitant with a similar reduction in threshold current. Likewise, higher speeds are obtainable with lower drive power, less complicated and, hence, less costly drive electronics. These 0.1 mA-level threshold-current VCSELs are enabling multi-element VCSEL array applications. Promising applications being pursued include high-speed, parallel optical interconnects within and between computers, Terabyte-throughput smart-pixel-array modules, advanced sensor, printing and storage technologies.

Progress:

We have performed a vendor survey and identified several VCSEL-based commercial fiber optic links for proton characterization. We will perform a generic (no higher protocol) BER test on high-speed fiber link transceivers at Crocker Nuclear Laboratory the week of June 28, 1999. The test configuration will have two transceivers on a card with an optical fiber cable connecting them and ECL in/out connectors to the BCP bit error rate tester (BERT). The bit error cross sections will be characterized using a pseudo-random sequence as a function of optical power at two incident angles, and the radiation susceptibility of both the transmitter and receiver circuitry will be monitored. We are building a generic test board that will be able to handle the standard 1x9 fiber optic transceiver package with integral duplex SC multi-mode configuration.

The following transceivers are being considered for test. Three transceivers from the first two vendors (HP and Lasermate) will be evaluated during the June 1999 proton test run.

1. ***HP***: HFBR-53D5, a Gigabit Ethernet transceiver with 850 nm VCSEL, Si PIN detector, and a Si bipolar transimpedance amplifier (TIA).

2. ***Lasermate***: 155 Mbps transceivers TTC-155M4 (850 nm VCSEL transmit/1300 nm receive) and TTC-155M2 (850 nm VCSEL transmit/ 850 nm Si PIN receive). (Lasermate will have a 1 Gbps version soon.)

3. ***Cielo***: Giga-bit Interface Converter (GBIC) Standard VCSEL-based transceiver (Cielo now fabricates their own VCSELs. They used to be the component division of Vixel Corp.)

4. ***Applied Micro Circuits Corp. (AMCC)***: GSFC has proprietary agreement in place but will not be including their product in the June proton test.

5. ***AMP***: VCSELs supplied by Emcore.

6. ***Methode***: Methode (MDX-19 series 850 nm VCSEL, standard 1x9 Gbps unit)

7. ***Honeywell:*** Also has several series of ethernet transceivers.

8. ***Vixel:*** Giga-bit Interface Converter (GBIC) Standard Fiber Channel Tranceivers OE1063 series.

9. ***Picolight***: Picolight supplies VCSELs to the Univ. of CO free space optical link project which is DARPA funded.

10. ***Honeywell:*** Note that Honeywell no longer sells commercial fiber channel and ethernet fiber optic links. They will only supply components (VCSELs and photodetectors) in first-level packages to COTS customers. However, they are still very active in the development and supply of ruggedized FO links for aerospace and rad-hard customers.