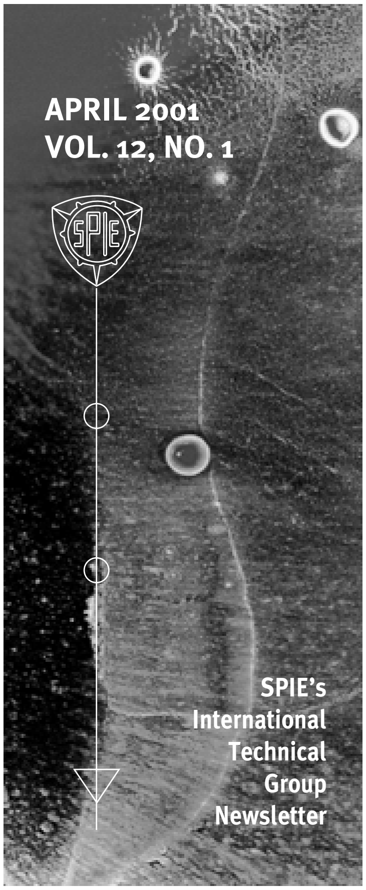
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(FORMERLY OPTICAL PROCESSING AND COMPUTING)

Special Issue:

VCSELs in Information Systems

Edited by **Kent D. Choquette,** University of Illinois at Urbana-Champaign and **Jan Danckaert,** Vrije Universiteit Brussel

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Full wafer VCSEL/PD integration on Si-CMOS LSI

Optical interconnection is increasingly needed to connect massively-parallel high-bitrate signal lines from frame to frame, board to board, and chip to chip with low power consumption and low crosstalk. Even inside chips, there is some possibility that optical interconnection will be introduced in extremely high-bit-rate clock or data lines. To realize such optical interconnection practically, one of the key issues is how to simultaneously integrate numerous III-V compound semiconductor-based optoelectronic devices, such as vertical-cavity surface-emitting lasers (VCSELs) and photodiodes (PDs), on a Si-based LSI.

The typical conventional approach to such integration is the flip-chip bonding technique.[1] After optoelectronic devices are processed completely, they are bonded chip by chip using solder bumps. Optoelectronic device chips can be tested beforehand, so only those that pass are chosen for bonding. However, it is difficult to bond large numbers of optoelectronic devices to exactly the correct sites of a SiLSI at the same time. Furthermore, the bonding of two or more optoelectronic devices with different thickness is practically impossible.

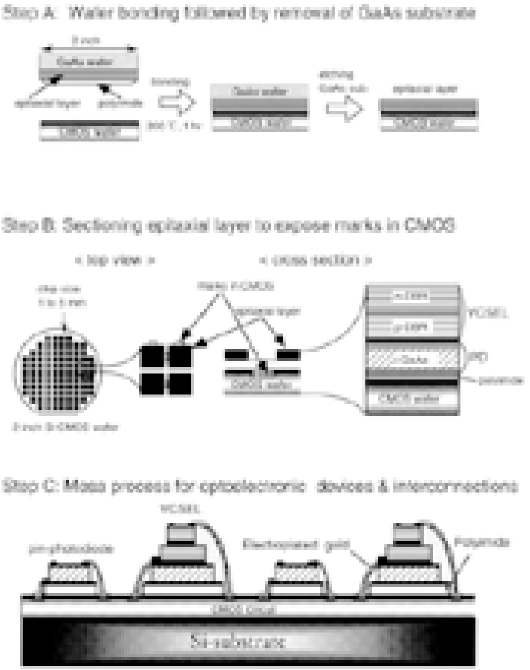

Figure 1. Polyimide bonding process.

We have developed a full-wafer bonding technique between an optoelectronic device wafer and a Si-LSI wafer, and demonstrated the simultaneous integration of large numbers of VCSELs and PDs with a Si-CMOS LSI.[2] Figure 3 shows the procedure, which has three steps.

- **Bonding**
  GaAs/AlGaAs-based VCSEL and PD structures are monolithically grown in tandem on a 2in GaAs substrate. Meanwhile, a 2in Si-CMOS wafer is punched out from a larger (6in) one. The circuit side is planarized with polyimide, where flatness within 0.1mm can be obtained. Both wafers are patched by another polyimide coating. After both wafers are bonded by heat treatment, the GaAs substrate is completely removed by chemical etching. An InGaP stop-etching layer is inserted between the epitaxial layer part and the GaAs substrate, so a smooth epitaxial layer surface is obtained over the entire 2in Si-CMOS wafer.
- **Sectioning**
  In order to locate VCSEL and PD elements at correct positions on the Si-LSI circuit, the marks on the Si-

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VCSEL-based optical data links

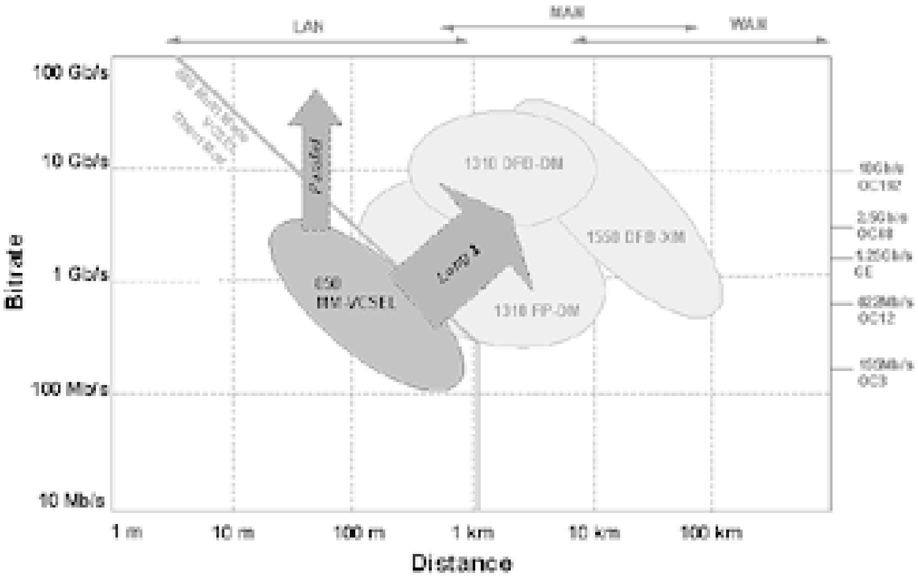

Figure 1. A bandwidth-distance map of various transceiver technologies.

It is estimated that between the years 2000 and 2003, the number of online Internet users will grow from 250 million to 500 million. This growth, added to growth in per-user Internet use, has resulted in rapidly increasing demand for fiber-optic communications bandwidth. This demand occurs at all levels: in the fiber-optic core backbones as well as in the metro-area networks (MAN), access networks, and local area networks (LAN).

As illustrated in Figure 1, these levels are distinguished by the bandwidth-distance product of the fiber-optic link that they serve. At one extreme, the single-mode fiber-optic core supports single-wavelength bandwidth-distance products on the order of 100Gbps-km; at the other extreme, multimode fiber-based LANs support bandwidth-distance products on the order of 0.1Gbps-km. The requirements on the transceivers for these different bandwidth-distance products also varies: at the fiber-optic core, quality of service is paramount; as the optical communications infrastructures get closer to consumers, cost of deployment becomes more important.

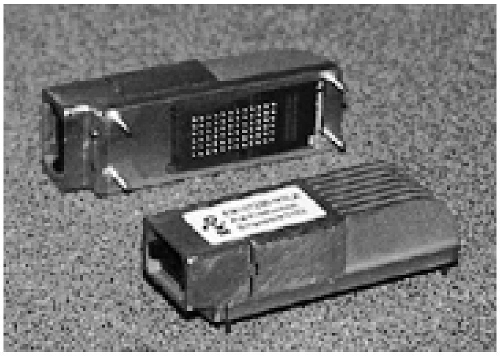

Figure 2. A twelve-channel parallel 850nm VCSEL transceiver module.

The current generation of VCSEL-based transceivers targets the low end of the bandwidth-distance-product space, where high performance at the lowest possible cost is critical. In this space, 850nm VCSELs have a number of advantages over CD lasers that had previously been used. Because of their unexposed active regions, they are significantly more reliable than CD lasers, even without hermetic packaging. They operate more cleanly at high (1-10Gbps) speeds than do CD lasers, which have been engineered to self-oscillate in the GHz range so as to reduce laser noise due to light feedback. And, their costs are approaching those of light-emitting diodes (LEDs). As a consequence, 850nm multimode VCSELs have largely replaced CD lasers for multimode-fiber-based optical transceivers. An example of a VCSEL-based transceiver is shown in Figure 2, along with an eye diagram at 1.25Gbps operation. In practice, VCSEL-based transceiver footprints and form factors range from standard 1×9 and Gigabit Interface Card (GBIC) transceivers with SC duplex connectors, to the increasingly popular small-form-factor (SFF) and small-form-pluggable (SFP) transceivers with LC and MT-RJ connectors.

In the coming years, continuing technology advances will enable VCSEL-based transceivers to widen their bandwidth-distance product space significantly. As this occurs, the markets for these transceivers are estimated to grow from about $0.4B in 2000 to $1.4B in 2003.

One advance will be to go parallel, relying on the array capability of VCSEL technology. For example, we have demonstrated a four-channel 2.5Gbps-per-channel VCSEL transmitter with an aggregate 10Gps bandwidth. This parallel module with four LC-connectors may be used to interconnect OC192 SONET equipment in a computer room or a central office for less than one-tenth the cost of current solutions. Soon, twelve-and-higher-channel VCSEL-based transceivers, as illustrated in Figure 2, will become commercial, and will enable interconnections across the network equipment backplane, where high port density is required to support Terabit routers and switches.

Another advance will be to go to the longer (1310nm and 1550nm) wavelengths with lower dispersion and attenuation in single-mode optical fiber. Currently, Metro and Metro Access Networks are dominated by 1310nm and 1550nm Fabry-Perot (FP) and distributed feedback (DFB) lasers. A long wavelength VCSEL (LW-VCSEL) would be an ideal low-cost alternative to the DFB laser, particularly for 10Gigabit Ethernet applications whose standards are currently under development by the IEEE 802.3ae working group. However, the performance specifications for such LW-VCSELs are challenging. If they are to be built into low-cost transceivers, they must operate over the 0 to 70˚C temperature range for indoor applications and over the –40 to 85˚C range for outdoor applications: without external temperature stabilization. The laser power launched into the single mode fiber must usually be more than 0.5mW in order to support transmission distances of 10km at 10Gbps. Currently, of the two major classes of LW-VCSELs—optically-pumped and electrically-pumped—only the optically-pumped class has the required transceiver power, although its manufacturability is still a challenge. Despite intense research effort, the electrically-pumped class has not yet met the requirements for commercial applications, though its potential value, if successfully developed, will be large.

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High-speed VCSEL arrays for datacom applications

Triggered by the rapidly increasing bandwidth requirements in datacom applications, there has been a strong focus on the development of short-wavelength high-speed VCSELs in recent years. These devices are considered to be the lightsources of choice for single channel as well as parallel datacom links. This is mainly due to their low-cost fabrication, efficient fiber-coupling, low threshold currents and high speed capabilities. Meanwhile, these VCSELs have matured and have become established as a reliable wafer-scale manufactured product.

A commercially available 1×4 VCSEL array from Avalon Photonics is shown in Figure 1. The multimode VCSELs are top-emitting at 850nm and are fabricated using advanced manufacturing techniques. Typical performance characteristics include a threshold current of 2.0mA and a slope efficiency of 0.5W/A, which yields an output power of 1.0mW at 4mA. At this operation point, the bandwidth is higher than 3GHz. Moreover, these VCSELs have proved to be very reliable. Thus far we have observed no failures out of 500 lasers tested at 75˚C and 100˚C. The failure criterion used was a –2dB drop in optical output power at 5mA injection, measured at 25˚C. Using the standard models for failure acceleration, we estimate the mean time to failure of our devices to be in excess of 10 years at 70˚C.

The high intrinsic speed and the low electrical parasitics (~50W series resistance, ~0.8pF capacitance) enable error-free data transmission up to 3.125Gbit/s. Figure 2 shows an eye-diagram at 3.125Gbit/s PRBS modulation obained from an optical link using Avalon Photonics VCSELs driven by Helix current drivers. The Helix drivers are fabricated in a commercial BiCMOS process technology and operate with a 3.3V supply. The Helix drivers are available as 4×3.125Gbit/s or 12×3.125Gbit/s modules.

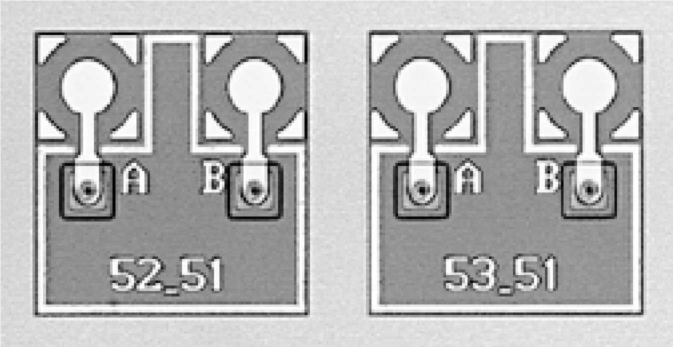

Figure 1. Avalon Photonics 850nm high-speed VCSEL arrays.

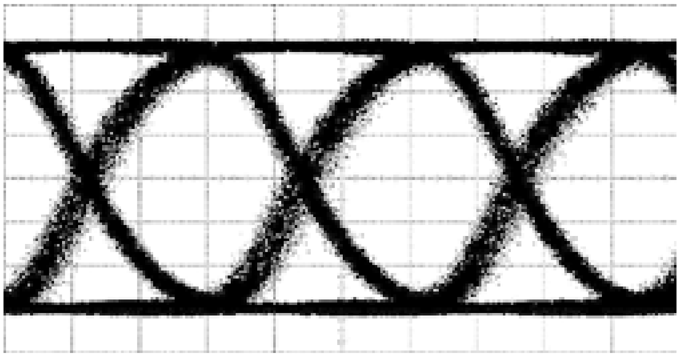

Figure 2. 3.125 Gbit/s eye-diagram of an complete optical link.

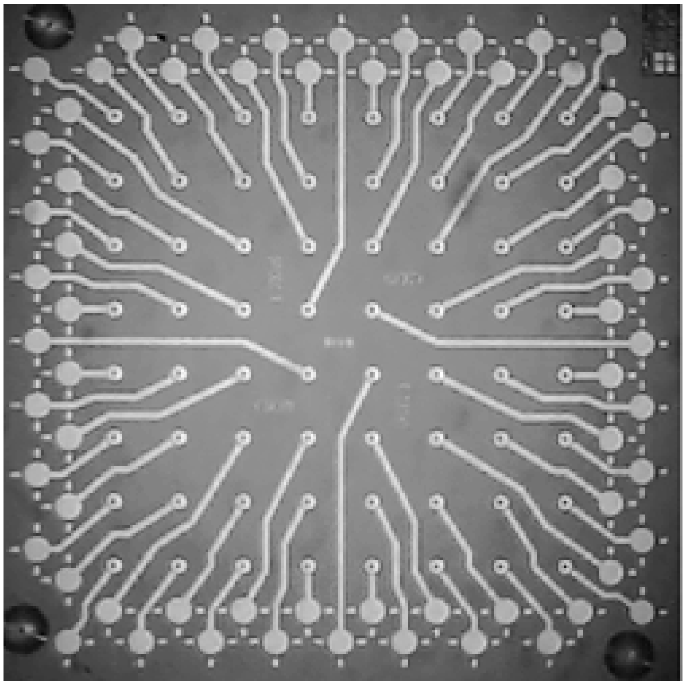

Figure 3. Individually-addressable high-performance 8×8 VCSEL array.

High-performance two-dimensional VCSEL arrays

In future, the advantages of VCSELs will also be used for waveguide-based or freespace two-dimensional (2D) optical interconnects, which are expected to replace electrical interconnects in shorter distance (<1m) high-density applications from interboard, interchip, down to intra-chip communication. This development is mainly driven by the bandwidth limitation of electrical interconnects, taking the rapidly increasing clock speed and input/output requirements of Si-chips into account. These applications not only benefit from the simple monolithic fabrication of the VCSELs in large 2D arrays, but also from the circular emitted beams that can be collimated to a small diameter with low divergence. For these future high-density communication needs, however, system designers are asking for further improvement in VCSEL performance to reduce the thermal and electrical load of the whole array. This requires a high efficiency in the low output power range. Moreover, the VCSELs need to be faster at these low powers.

To meet this future communication need, prototypes of individually addressable high-performance 8×8 VCSEL arrays were fabricated (Figure 3). The pitch between the individual devices is 250µm and the total array area is 2.8×2.8mm^2. The output power, voltage and wallplug efficiency versus current characteristics of all 64 individual devices of an optimized array are plotted in Figure 4. The mean threshold current is only 0.25mA and the mean threshold voltage is 1.42V. These low threshold properties correspond to a low threshold power, which enables high efficiency values shortly above threshold: an efficiency per element of 20% has already been achieved for an output power level of 150µW, which corresponds to a dissipated power of only 600µW. As mentioned above, high efficiency in the low power range is a key attribute for future high density interconnects, since these applications typically require only low output powers but the power dissipation per area (thermal load) is a critical issue. Variation of all characteristic electrical and optical performance parameters across the array are below 3%,

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Short distance optical interconnects: LEDs or VCSELs?

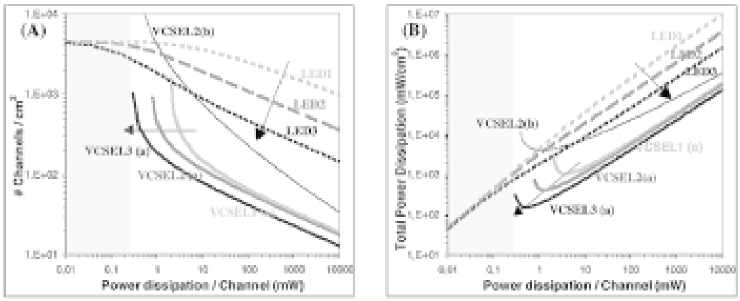

Figure 1. (A) Number of parallel optical channels and (B) total power dissipation to obtain a throughput of 1TB/s as a function of the power dissipation in each emitter. The arrows indicate the trends where device characteristics are improved. For VCSELs, a bias current above (below) threshold is indicated by parentheses: (a) ((b)).

Table 1. VCSEL and LED performance.

VCSEL Parameters	VCSEL1 [2]	VCSEL2 [3]	VCSEL3 [4]
Threshold current (mA)	1	0,4	0,155
External efficiency (%)	50	45	40
Diameter (µm)	10	3	2
Bandgap (eV)	1.27	1.27	1.27
LED Parameters	**LED1 [5]**	**LED2 [6]**	**LED3 [7]**
External efficiency (%)	12	18	20
Diameter (µm)	52	22	15
Active layer thickness (nm)	20	30	10
Bandgap (eV)	1.27	1.45	1.45

Fiber optics and free-space optoelectronic technologies have been widely investigated to alleviate data communication bottlenecks at different levels of the computer hierarchy. Recent breakthroughs in the fabrication of arrays of optoelectronic devices and their heterogeneous integration with Si-CMOS now also encourage the use of photonics as a wire replacing technology at the inter- and intra-MCM level.[1]

These future short-distance optical interconnects will make use of new components such as arrays of VCSELs,[2-4] micro-cavity LEDs[5] or non-resonant LEDs.[6,7] At present there is still much debate concerning which type of optical source is most suitable to provide the necessary bandwidth and parallelism in order to outperform electrical interconnects. Therefore, we have compared[8] state-of-the-art LEDs and VCSELs for short distance optical interconnects based on simple rate equations and trade-offs between the bandwidth, power dissipation, and channel density.

Our comparison relies on the characteristics of a number of VCSELs and LEDs reported in the literature. The values presented in Table 1 are only used to clarify the performance differences between LEDs and VCSELs and are likely to be improved in future devices. Whereas LEDs have been improved, yielding higher modulation frequencies (few GHz) at reasonable efficiencies,[5-7] VCSELs have seen a further decrease in threshold current without sacrificing their efficiency.[2-4]

To compare VCSELs and LEDs we have plotted, in Figure 1, the number of parallel optical channels and the total power dissipation of the source array necessary to obtain an aggregate bandwidth of 1Tb/s from an area of 1cm^2. As can be seen from Figure 1A, this aggregate bandwidth can be reached either with a small amount of fast channels or a large number of parallel channels all working at a moderate speed. The data presented in Figure 1 does not take into account an upper value for the current nor the limitations imposed by parasitic capacitances. For VCSELs, a minimum amount of power dissipation per channel is required because of the threshold current. This limits the operational parameter domain of VCSELs for 1Tb/s aggregate bandwidth applications as indicated by the shaded region in Figure 1.

From Figure 1B it can be seen that, for VCSELs, there is an optimal working point that allows the total power dissipation to be minimized. This working point corresponds to a moderate current and channel density, and scales to lower power dissipation values when the threshold current is reduced. The performance of LEDs is comparable to that of VCSELs biased below threshold (see VCSEL2(b) in Figure 1). However, when compared to VCSELs biased above threshold, LEDs only have an advantage at very high channel densities. When the VCSEL is biased, power will be dissipated even when a logical zero is transmitted. But this additional power dissipation is compensated for by the vast increase in modulation speed. Note that, as the efficiency of LEDs and VCSELs is comparable, they emit approximately the same amount of optical power.

In this comparison between LEDs and VCSELs, one should also consider the type of optical interconnection system (e.g. free-space, POF- or fiber-image-guide-based). In the case of parallel free-space optical interconnects, the maximum interconnection distance will be limited by diffraction and cross-talk. Hence, a source with a small divergence angle is needed and only VCSELs can be used. But even with VCSELs, care has to be taken to limit their FWHM divergence angle to about 10°.[9]

For a POF-based or fiber-image-guide system, both VCSELs and LEDs can be used. The LED approach only offers a clear advantage for high channel densities, corresponding to a pitch smaller than approximately 100µm. Such a small pitch, however, will most likely cause cross-talk problems in the optical system. VCSELs biased above threshold will therefore provide the best solution, while LEDs may still be preferred, because of their simpler device structure, in cases where only moderate data-rates and channel densities are needed.

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VCSELs in information systems: 10Gbps^{-1} oxide VCSELs for data communication

Parallel-fiber optical data communication over short distances (less than a kilometre) is a rapidly growing market, with applications in high-density switching and routing systems. A major requirement is to provide increased board-level bandwidth density (Gbps/inch) while maintaining low cost (Gbps^{-1}/\$). This has been made possible by constructing optical modules based on the use of low-assembly-cost multimode parallel fiber ribbon, along with 850nm Vertical Cavity Surface Emitting Lasers (VCSELs).

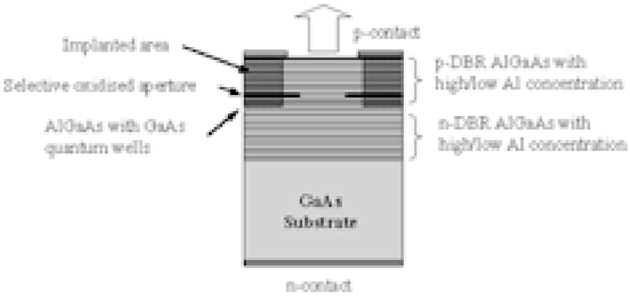

Figure 1. Cross-section of selectively-oxidised VCSEL structure.

Today, optical links with per-channel operating bit-rates of 2.5Gbps^{-1} are available on the market: Mitel, for example, offer 12-channel modules with 30Gbps^{-1} total data throughput.[1] Work is already well underway at many companies on the next generation of such parallel optical links, where per-channel bit-rates of 10Gbps^{-1} will be required. Selectively-oxidised VCSELs are very attractive candidates to achieve these desired bit-rates at the required low cost, because they are easy to manufacture and on-wafer screening can be performed. 10Gbps^{-1} VCSEL operation has been successfully demonstrated.[2] The selectively-oxidised VCSEL has many advantages compared to the more common, implanted VCSEL: low threshold current and a high optical and electrical efficiency among them. Importantly, they have also demonstrated the ability to operate at high speeds, and their excellent device-to-device uniformity makes them very suitable for arrays.

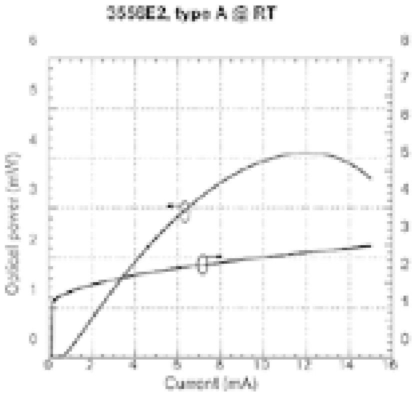

Figure 2. LIV curve at room temperature for a selectively-oxidizedVCSEL with a 4μm aperture.

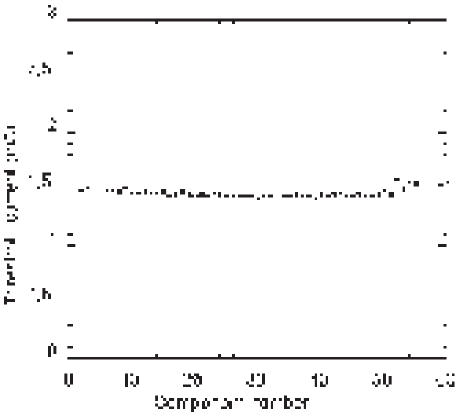

Figure 3. Threshold current for 60 devices taken adjacent with 12μm aperture measured on wafer at room temperature.

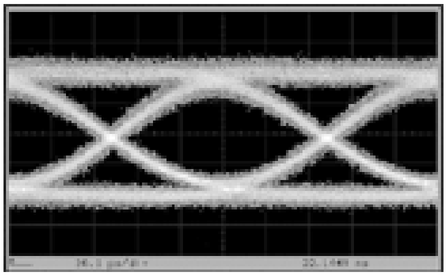

Figure 4. 10 Gbps^{-1} measured back-to-back on chip at 3mA average drive current.

The oxidised VCSEL at Mitel is constructed by using alternate layers of high and low Al concentration AlGaAs layers to form the top and bottom quarter-wave mirrors, with a cavity containing an active region of GaAs quantum wells. A higher Al layer placed in the top mirror near the cavity is selectively oxidised to form apertures of 4μm and 12μm diameter. When the layer oxidises, it becomes insulating which confines the injected current within the non-oxidised aperture. In Figure 1, a cross-section of the VCSEL structure is shown. Implantation is used to reduce the parasitic capacitance in the component, and thereby improve the high-speed performance.

A typical LIV curve for a 4μm-aperture device is shown in figure 2. As we can see, it exhibits a threshold current of 0.7mA, slope efficiency of 0.58mW/mA at low currents, and a forward voltage at threshold of 1.8V. Up to 85˚C, the VCSEL lases with a relatively small variation of threshold current and of output power. These variations over temperature are important parameters for the complexity of the driver circuit within the module. As good uniformity is necessary for parallel fiber modules, oxidised VCSELs are a perfect choice, as can be seen in Figure 3. The threshold current varies by only 3% from the mean-value.

In Figure 4, the large signal modulation results are shown in the form of an eye-diagram at 10Gbps^{-1} using a 2^{31}-1 PRBS (Pseudo Random Bit Sequence) and a 10Gigabit Ethernet receiver. The same 4μm oxide VCSEL presented in Figure 2 is used for this experiment, with an average bias of 3mA. From the diagram we see that the 10Gbps^{-1} performance of the component is excellent.

To sum up, superb performance is obtained for oxidised 850nm VCSEL, sub-mA threshold current, high efficiency, good device-to-device uniformity and excellent dynamic results at speeds up to 1Gbps^{-1}.There seems no doubt that selectively oxidised VCSELs will be the laser of choice for future cost-effective parallel-optical short-haul data communication.

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VCSELs for high-throughput, very-short-reach optical interconnects

The vertical-cavity surface-emitting laser (VCSEL) is a fine specimen of a novel compound semiconductor device that has been successfully commercialized in the last few years. Among the various applications for this laser, optical datacom is the primary driving field. In particular, Gigabit Ethernet (GbE) and related transceivers for graded-index multimode fiber (MMF) data transmission have become inexpensive mass products by relying on 850nm short-wavelength VCSEL technology. Meanwhile, work toward the successor of GbE is well under way and the current 10-GbE proposal is expected to be adopted as a standard termed IEEE 802.3ae by the end of this year.[1] Important milestones have been reached with the demonstrations of VCSEL-based 10Gbit/s transport over up to 2.8km of a new-generation 50µm-core-diameter MMF[2] and even 40Gbit/s over 310m of the same fiber type.[3] In the latter case, a 4-channel coarse wavelength-division multiplexing system was implemented to increase the aggregate data rate.

In very-short-reach optical interconnects, with link lengths of less than about 100m, space-division multiplexing—where signals are transported in parallel through different optical waveguides—is a straightforward means of achieving higher data throughput. Parallel link modules for data rates up to 2.5Gbit/s per channel have been announced by several vendors. Figure 1 shows a photograph, bit-error-rate (BER) characteristics, and an eye diagram of a 10× 10Gbit/s-VCSEL array that is being developed for next-generation parallel optical transceivers. In this experiment, 850nm-wavelength, 2.5µm-active-diameter, selectively-oxidized, single-mode VCSELs, with an average threshold current of about 350µA, have been driven at identical 1.65mA bias currents and 0.65V_{pp} modulation voltage,[4] yielding a dynamic on-off ratio of 6dB. Figure 1 reveals that the BER curves thus obtained for back-to-back operation almost coincide, and that error rates of 10^{-9} are reached with less than –15dBm received optical power. These results confirm that 10Gbit/s-compatible prototype VCSEL arrays are available today, leaving the realization of complete interconnect modules to the dense integration of high-speed electronics and sensitive detector arrays as the main challenge.

Single-mode VCSELs, as shown in Figure 1, offer numerous advantages over transverse multi-mode devices[5] like reduced driving current, lower noise operation, or better large-signal dynamics. However, in high-efficiency oxide-confined VCSELs, single-mode emission is often achieved by creating a very narrow current aperture of less than 4µm diameter with associated problems of increased differential resistances and high current densities that might lead to reduced long-term reliability. We have devised two possible routes to circumvent this problem. The first relies on the incorporation of a several-µm-long spacer layer into the laser resonator so that higher-order transverse modes suffer from increased diffraction and scattering losses.[4] Using this technique, a 7µm-aperture, 4µm-long-spacer VCSEL, with a series resistance of less than 100Ω, was shown to emit up to 5mW single-mode power. Our second viable method involved the introduction of a surface relief VCSEL[6] as illustrated in Figure 2. By etching a shallow donut-shaped trench into the uppermost layer of the Bragg reflector, the threshold gains of higher order modes are dramatically increased. In the bottom part of Figure 2, optical spectra of regular and 3µm-etch-spot-diameter surface-modified VCSELs, both with 6.5µm oxide aperture diameter, are compared for the same 4mW output power. As intended, a dramatic narrowing of the spectrum is observed, with more than 40dB side-mode suppression in case of the surface-relief VCSEL. The differential resistance of the devices is about 90Ω.

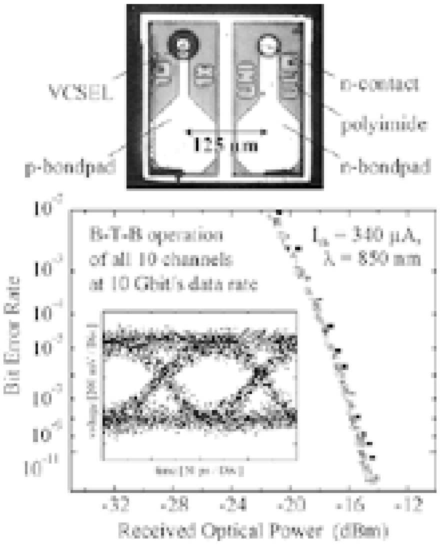

Figure 1. Cleaved unit cell of a linear 1×10, 250µm-spacing VCSEL array with co-planar, 125µm-pitch contact arrangement (top). Bit-error-rate characteristics for back-to-back (B-T-B) operation of all 10 channels at 10Gbit/s modulation with a representative eye diagram (on a 200ps time scale) in the inset (bottom).

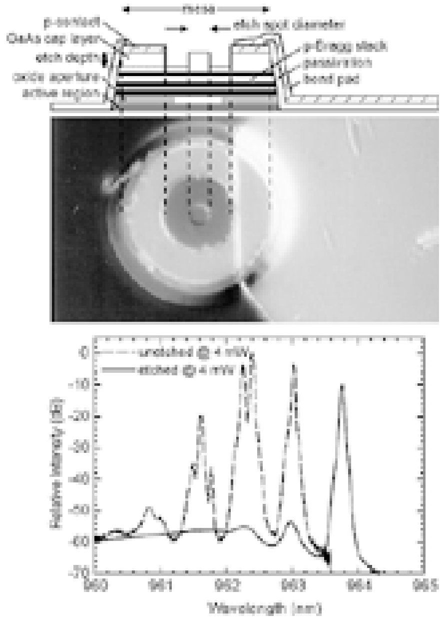

Figure 2. Schematic surface profile and photograph of novel large-area VCSELs for stable fundamental mode emission (top). The optical spectra compare regular and surface-etched devices of 6.5µm-diameter at identical 4mW output power (bottom).

In addition to silica MMFs, numerous data transmission experiments in the 10Gbit/s regime have been carried out lately using single-mode VCSELs over various multimode waveguides: graded-index perfluorinated plastic optical fibers (POFs),[4] two-dimensional step-index POF bundles and image POFs[7] for massively parallel optical interchip interconnection,[8] and one-dimensional polymer waveguide arrays hybridly integrated into conventional electrical printed circuit boards.[7] The underlying recent developments toward reliable single-mode emission thus suggest a bright future for the application of high-speed VCSEL arrays in very-short-reach optical interconnects.

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continued on p. 9

VCSELs in the information age

Vertical Cavity Surface Emitting Lasers (VCSELs) emerged from scientific curiosity into economic reality in 1996 when Honeywell introduced the world's first commercial products. The VCSEL was viewed as an enabling technology that quickly supplanted edge-emitting laser technology in the data communications market.[1,2] Edge-emitting lasers suffer from several inadequacies, such as poor reliability (both in the DC and AC sense), strong relaxation (turn on) oscillations, and poor coupling efficiency to optical fiber. Honeywell VCSELs have achieved reliability projections in excess of ten million hours of operation at nominal conditions while maintaining optical signal integrity during aging. In addition, the physics of the VCSEL microcavity ensure well-damped, extremely-high-frequency relaxation resonance, and they emit circularly-symmetric, non-astigmatic optical beams. This new laser source, coupled with the burgeoning optical communications, market has triggered a phenomenal increase in the number of VCSEL shipments. Most of the VCSELs in use today are for data communications systems operating on multimode optical fiber, and running at speeds up to 1.25GBd in applications supporting both ethernet and fiber channel.

As the Internet continues to grow, so does the seemingly insatiable demand for consumer bandwidth. With this growth, the lines between data communications and telecommunications applications continue to blur. The collision of these two markets is set to happen with the adoption of the IEEE 802.3ae standard, which will proliferate ethernet into traditional SONET markets at OC192 data rates. In addition, other standards, such as the Trade Association's Infiniband™ standard and Fiber Channel, are emerging with 10GBd systems. VCSELs are uniquely suited for this application in a number of ways.[3,4]

Since the optical beam is emitted perpendicular to the wafer surface, VCSEL arrays can be fabricated with photolithographic tolerances, making them ideal sources to mate with ribbon fiber interconnects. To date, most of the market has centered on either four elements operating up to 3.125GBd per channel, or 12 elements operating up to 1.25GBd per channel. The operating reach of a parallel interconnect is more than 100m, and is limited by the skew in the optical fiber. The use of parallel interconnects allows the user to custom design the network, using either fanout architectures or direct links, potentially eliminating the need for high-speed SERDES functionality. In other systems, serial data communication is more advantageous, and VCSELs have been operated at speeds in excess of 10GBd by direct modulation. Achievable link lengths are on the order of 75m over installed multimode optical fiber, with distances of 500m on 850nm optimized fiber such as Lucent's LazerSpeed™. The combination of VCSELs operating at 10GBd serial rates, and 12 element (and larger) arrays whets the appetite for 100GBd datacom systems.

While most applications to date have centered on the 850nm VCSEL operating on multimode optical fiber, researchers at numerous companies are working on VCSELs operating in the telecommunications wavelength windows of 1310nm and 1550nm. Fabrication of VCSELs at these wavelengths is plagued by several technical challenges. Among these are the poor index contrast of the material system necessary to form the Bragg mirrors, the necessity to maintain single spatial and longitudinal mode operation, the need for high power (several milliwatts), and the performance over temperature. Numerous approaches are under investigation to mitigate these technical risks but, to date, a viable long-wavelength VCSEL has not been demonstrated. While the technical risk is high, large amounts of money and resources are being poured into the development of VCSELs suitable for telecom applications on single mode fiber, and commercial products have been promised in 2002.

On the opposite end of the data communications spectrum, plastic optical fiber (POF) holds the promise of extremely low cost and high volume applications in the consumer marketplace. POF, made from PMMA, has a minimum absorption regime in the 660nm (visible) range. Current applications are served with low-cost LEDs where the required bandwidth is relatively low. While the huge market potential has not yet materialized, VCSELs are expected to play a significant role at speeds of 100MBd and higher. Fabrication of VCSELs at visible wavelengths suffers from many of the same problems described earlier for telecom-wavelength VCSELs.[2] The first commercial visible VCSEL products will be in the optical sensor market, and as scientist resolve technical issues, POF may fulfill its long anticipated market presence.

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High-speed VCSEL arrays for datacom applications

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among the best reported to date. A high uniformity is indispensible for many systems, since different operating points require individual channel control which is impractical for high density applications.

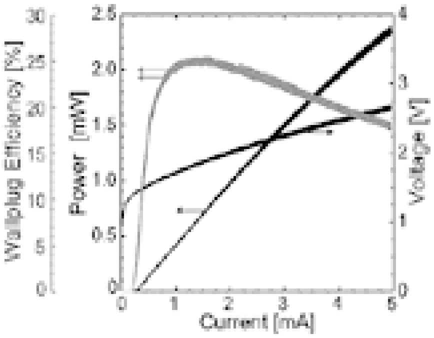

Figure 4. Characteristics of all individual devices of an 8×8 VCSEL array.

Additionally, 8×8 VCSEL arrays with improved high-speed performance show a maximum modulation bandwidth per element of higher than 13GHz at only 4mA (1.6mW optical output power). Moreover, open eyes were measured at 10 Gbit/s for these devices with a bit-error-rate (BER) smaller than 10^{-13}. All these fundamental performance improvements will enable the widespread use of 2D VCSEL-arrays in future low-power dissipation high-density optical interconnects.

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Long wavelength VCSEL on GaAs substrate

Large-scale networks and computing systems are increasingly incorporating optical technology: optical computing, optical interconnects, and parallel lightwave systems are a few examples. Progress in surface emitting lasers (SELs) and vertical cavity surface emitting lasers (VCSELs) has been rapid since the late 1990s and various applications into ultra-parallel optoelectronics have been considered. The importance of long-wavelength devices in such systems is currently increasing, because gigabit and several-km transmission capability is becoming necessary even in local area networks (LANs). Responding to this need,[1,2] our group demonstrated a 1300nm, room-temperature, CW device in 1993.[3]

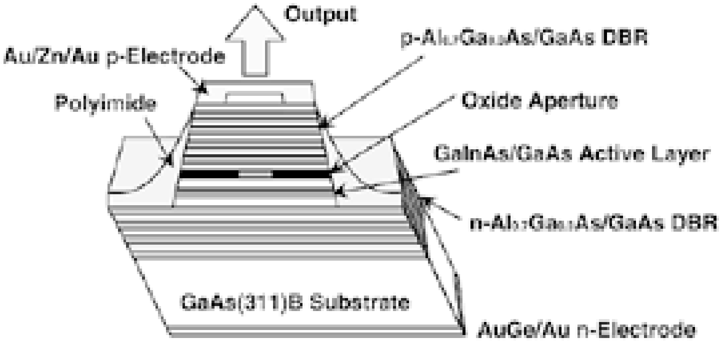

Figure 1. A vertical cavity surface emitting laser device fabricated on (311)B GaAs substrate.

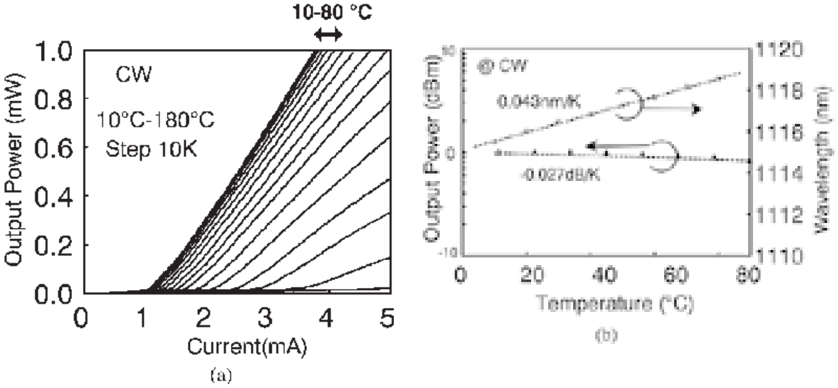

Figure 2. (a) Optical Power vs Current (P-I) characteristics and (b) temperature characteristics of a long wavelength VCSEL on (311)B GaAs.

More viable materials for long-wavelength emitters consist of those that can be deposited on a GaAs substrate:[4] in particular, GaAs/AlAs Bragg reflectors can be incorporated on such a substrate and AlAs oxidation employed. Some consideration of device design has already been discussed.[5] Another viable candidate is a GaInNAs system lattice-matched to GaAs.[6,7] Recently, we reported a GaInNAs VCSEL grown by MOCVD.[8] During our research into GaInNAs lasers, we found that a highly strained GaInAs/GaAs system with a large (40%) indium content can provide an excellent temperature characteristic,[9] operating at T_0- 200K. This system should be viable for λ>1200nm for silica-fiber-based high speed LANs.[10]

Most VCSELs grown on GaAs (100) substrates show unstable polarization states due to isotropic material gain and symmetric cavity structures. We have grown VCSELs on GaAs(311)B substrates using MOCVD,[11] and realized devices that operate simultaneously in both single transverse mode and polarization mode.

The schematic structure of a fabricated top emitting VCSEL grown on GaAs (311)B is shown in Figure 1.[11] The bottom *n*-type distributed Bragg reflector (DBR) consists of 36 pairs of $Al_{0.7}Ga_{0.3}As$/GaAs doped with Se. The top p-type DBR consists of 21 pairs of Zn-doped $Al_{0.7}Ga_{0.3}As$ / GaAs and a 70Å-thick AlAs carbon high-doping layer inserted at the upper AlGaAs interface by our own carbon auto-doping technique. The active layer consists of three 8nm-thick $In_{0.2}Ga_{0.8}As$ quantum wells and 10nm GaAs barriers surrounded by $Al_{0.2}Ga_{0.8}As$ to form a cavity. An 80nm-thick AlAs layer was introduced on the upper cavity spacer layer to form an oxide for confinement. We oxidized the 50μm^2 AlAs mesa at 480˚C for 5 minutes in an N_2/H_2O atmosphere, by bubbling in water at 80˚C, and formed an oxide aperture of 2.5μm×3.0μm.

Figure 2(a) shows typical current to optical power (I-P) characteristics under cw operation by changing the ambient temperature from 10˚C to 180˚C. The threshold current at room temperature is around 1mA or less, comparable to the value reported for non-(100) substrate VCSELs. The threshold and quantum efficiency did not change much The driving voltage is 1.5-2V and the tested maximum output power is >1mW at 4mA. In Figure 2(b) we show the change of output power and wavelength while maintaining the driving current at 3.7mA to provide 1mW(0dBm) output at room temperature. Note that we can achieve a very small change in power and wavelength even if we operate with a constant bias.[12] This implies the possibility of using VCSELs without any automatic power controller (APC) and thermo-cooler.

In other devices, we confirmed that a large side mode suppression ratio (SMSR) and orthogonal polarization suppression ratio (OPSR), both over 30dB, were simultaneously achieved throughout the entire tested driving range ($I< 16I_{th}$) . We have achieved an entirely single-mode VCSEL by employing most available advanced techniques. High speed modulation for several Gbits/s has been performed, as have transmission experiments that will be published elsewhere. In addition, Koyama[10] has suggested the possibility of single-mode transmission though a conventional, single-mode silica fiber using a 1200nm-VCSEL.

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continued on p. 10

Full wafer VCSEL/PD integration

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LSI surface have to be bared so that they can be clearly monitored in the next device process. Epitaxial layers are sectioned into 1mm to 5mm-square chips by chemical etching. This sectioning helps to avoid cracking of the thin epitaxial layers during device processing.

- **Mesa process**
  The normal mesa process for VCSELs and PDs can be applied as if they were on a GaAs substrate. It has been confirmed that the Si-CMOS circuit is resistant to heat treatments as high as 400˚C, such as for ohmic contact formation. VCSELs and PDs are electrically connected with the Si-CMOS circuit through contact holes of a polyimide layer by electroplated gold. Under the VCSEL elements, there are gold heatsinks that are deposited before planarization of the Si-CMOS wafers.

Figure 2 shows a photograph of the wafer after the above three-step process. The wafer consists of various circuits, such as receiver arrays, transmitter arrays, and 2×2 or 16×16 banyan switching circuits. Many PD and VCSEL elements are integrated over the entire wafer as O/E and E/O interfaces. Figure 3 shows a magnified view of a typical part of the wafer. 850nm GaAs/AlGaAs-based VCSELs with a diameter of 25mm and GaAs-pin PDs with a diameter of 60mm are periodically integrated onto the chip.[3] The pitch is 250mm for the two orthogonal directions. Each VCSEL and PD element is connected to CMOS driver and receiver circuits, respectively. It is clear that all of the elements are connected without any bonding pads and wires. We have confirmed that an integrated 850nm VCSEL element exhibits room-temperature CW operation with a threshold current of 20mA.

The typical feature of the integration is that the parasitic capacitance accompanying the bonding is negligibly small. This feature is important when the integration is applied to optical receivers. We have demonstrated high-speed Si-CMOS receivers integrated with GaAs pin-PDs by this bonding technique.[4] The input capacitance is 50fF, which is equivalent to the intrinsic capacitance of a PD. The operating speed (800Mb/s) is limited by the CMOS circuits: in this case, 0.8mm-rule CMOS LSI is used. So the bonding technique can be applied to achieve receivers with higher bit rates (>1Gb/s).

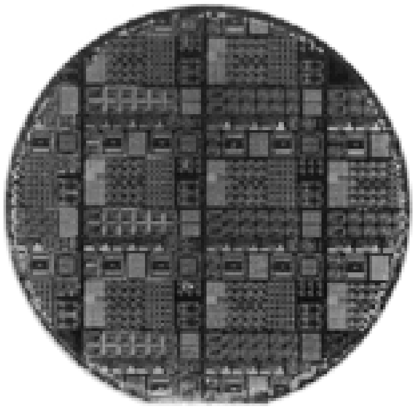

Figure 2.The Si-CMOS wafer integrated with GaAs VCSELs and PDs.

We have successfully integrated many VCSEL and PD elements with a Si-CMOS LSI simultaneously by polyimide bonding. This technique can be applied to, for example, a large-scale optical switch, where 16×16 banyan switch chips with PD and VCSEL arrays are connected with polymer waveguide circuits.[5]

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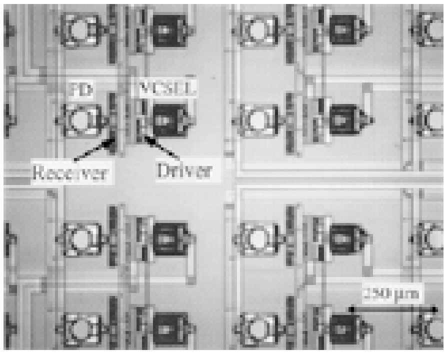

Figure 3. VCSEL and PD arrays integrated Si-CMOS driver and receiver circuits.[4]

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Buried tunnel-junction

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sers ideally suited for a large number of telecommunication applications.

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Buried tunnel-junction long-wavelength vertical-cavity surface-emitting lasers

Vertical-cavity surface-emitting lasers (VCSELs) with emission wavelengths from 1.3-1.55µm have been the subject of intensive research efforts during the past few years.[1,2] In future optoelectronic applications in the exponentially growing telecom and datacom markets, this kind of laser represents an indispensable component with respect to its potential for low-cost manufacturability and device properties. In contrast to high-performance commercially-available GaAs-based VCSELs with wavelengths below 1µm,[3] the device characteristics of their long-wavelength counterparts are still significantly inferior.

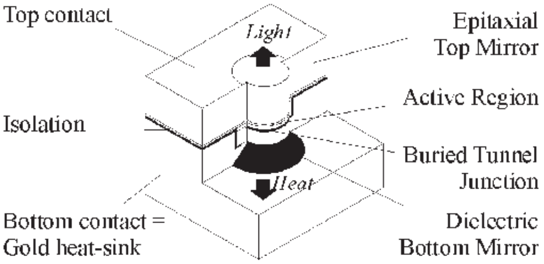


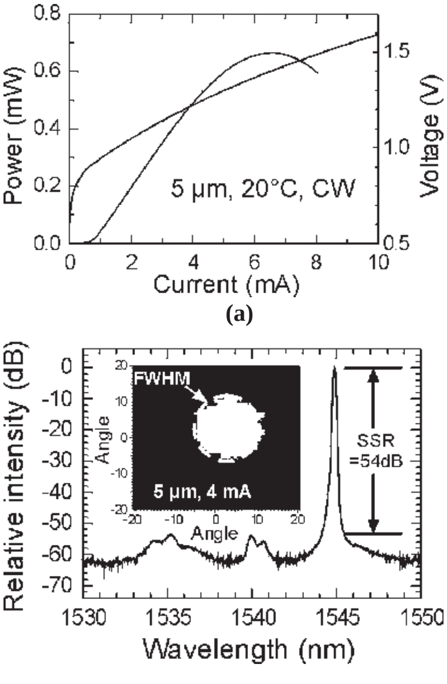
Figure 1. Schematic diagram of BTJ-VCSEL.

The objective of our research project at the Walter Schottky Institute is to realize InP-based VCSELs with emission wavelengths from 1.3-2 µm that show application-suitable output characteristics: particularly in terms of output power, temperature behavior and single-mode operation.

Device structure

The decisive problem for InP-based long-wavelength VCSELs stems from their unsatisfying thermal properties. These result in increased temperature sensitivity of the material gain in the corresponding active regions, leading to T_0-values of only 60-80 K and a low thermal conductivity for the alloy compositions commonly used for Bragg mirrors on InP substrates. Additionally, the technique of wet thermal oxidation of aluminum-rich layers to achieve simultaneous optical and electrical confinement is not applicable for the InP-based material systems.

The striking advantage of our device design, illustrated in Figure 1, is sharply reduced heating. This allows for increased output power and operating temperature and is accomplished by a small thermal resistance and reduced heat generation. The key element for the latter is the application of a buried tunnel junction (BTJ). By this means, it is possible to substitute high-resistive *p*-doped layers by low-resistive *n*doped material to obtain a substantially smaller *p*-side series resistance. Since the latter usually dominates the total device resistance it is consequently the main cause of the laser heating. A lateral structuring of the tunnel junction in our VCSEL to a well-defined extent, and subsequent regrowth, results in a buried tunnel junction (BTJ). With this technique, strong and self-aligned current confinement and indexguiding can be realized. To minimize the thermal resistance, our lasers are operated in an upside-down configuration in which a short-period and high-reflective stack of dielectrics is used as the back mirror, itself embedded in an electroplated heat-sink.



(a)

(b)

Figure 2. (a) Light-current and voltage-current curve of 5µm BTJ-VCSEL. (b) Emission spectrum and far-field pattern.

Device characteristics

The strong index guiding associated with the BTJ-technique allows for the application of very small aperture sizes with superior mode behavior. Figure 2a shows the light-current and the voltage-current curve for a VCSEL with a tunnel junction of 5µm diameter under cw operation at room temperature. The threshold current for this device is as low as 700µA with a corresponding ultralow threshold voltage of 0.92V (only about 100mV above the λ=1.55µm photon energy). The differential series resistance also exhibits a very low value: around 60Ω. For these devices, cw lasing is observed up to 75°C. While the threshold current increases with increasing temperature, an even better performance is expected with an optimized matching of cavity resonance and gain curve at elevated temperatures. As can be seen from Figure 2b, the side mode suppression ratio for the 5µm devices is even beyond 50dB with a laser emission in the fundamental mode as derived from the far-field pattern in Figure 2c. Furthermore, by using elliptically-shaped apertures, it is possible to lift the polarization degeneracy and to obtain true single-mode devices with a stable polarization.[5]

The stationary characteristics of our BTJ-VCSELs represent the best performance among all other 1.55µm structures presented so far. A reduction of the parasitic capacitance along with the ultra-low series resistances promises a 10GHz modulation bandwidth making these la-

continued on p. 10

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