Oxide Confined 2D VCSEL Arrays for High-Density Inter/Intra-Chip Interconnects

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We have designed and fabricated vertical-cavity surface-emitting laser (VCSEL) arrays with 4 × 8 elements intended to be used as transmitters in short-distance parallel optical interconnects. In order to meet the requirements of two-dimensional (2D), high-speed optical links, each of the 32 laser diodes is supplied with two individual top contacts. The metalization scheme allows flip-chip mounting of the array modules junction-side down on silicon complementary metal oxide semiconductor (CMOS) chips. The driving characteristics of all arrays are fully compatible to advanced 3.3 V CMOS technology. Using these arrays, we have measured small-signal modulation bandwidths exceeding 10 GHz and transmitted pseudo random data at 8 Gbit/s per channel over 500 m graded index multimode fiber. This corresponds to a data transmission rate of 256 Gbit/s per array of 1 × 2 mm^2 footprint area.

1. Introduction

Due to continuous progress in very-large-scale integrated circuit (VLSI) technology in terms of integration density and clock rate, enormous computing bandwidths will be available to electronic microchip and multichip systems. This development creates a great demand for high-bandwidth, high-density interconnects which conventional electrical interconnection technologies are expected not to be able to fulfill [1], neither on system-to-system, nor chip-to-chip or chip level. In order to overcome the interconnection bottleneck, new interconnection technologies have to be developed, where optoelectronic interconnects may offer attractive solutions.

The requirements of future integrated circuits (ICs) and multichip modules can only be fulfilled using optical interconnects if the optics fit into the chip architecture. This means that overall I/O rates in the Tbit/s range should be made available by using massively parallel interconnects, each operating in the Gbit/s range, rather than using a small number of channels. The 2D array approach avoids multiplexing the electrical signals to a high bandwidth on few channels and therefore such parallel optical interconnects should be competitive with advanced electrical interconnect schemes in terms of performance and cost. Designing optical interconnections around 2D input and 2D output arrays does also open up new possibilities for designing faster parallel computing algorithms and systems.

The inherent possibility of forming 2D arrays, high-speed modulation [2], and high-speed data transmission capabilities [P-24] even under bias-free operating conditions [P-32] make the VCSEL the transmitter of choice for parallel optical interconnects. Due to high efficiency operation at low driving currents [P-35], VCSEL transmitters can significantly reduce thermal problems when using optical interconnections combined with today's high speed ICs.

2. Design and Fabrication

The top view of a whole array is shown in Fig. 1. Mounting the arrays junction-side down is done straightforward as all electrical contacts are on the top-side, whereas the light is emitted through the substrate. Each unit cell of 250×250 μm^2 size contains the VCSEL with its p-contact as well as an n-contact going down to the n^+-GaAs substrate through a plated via hole. Both contacts are connected by tracks to remote solder bump pads.

Fig. 2 shows a schematic cross section through the VCSEL and its remote p-contact pad. The epitaxial layers are grown on n^+-GaAs substrate with a solid-source molecular beam epitaxy (MBE) system. Three $In_{0.2}Ga_{0.8}As$/GaAs quantum wells for emission wavelengths of around 980 nm are surrounded by quarter-wave AlGaAs spacer layers to form the one-wavelength long inner cavity. This optical cavity is sandwiched between an upper p-doped and a lower n-doped distributed Bragg reflector. A 30 nm thin AlAs layer is incorporated in the first $\lambda/4$ layer above the inner cavity for selective lateral oxidation [P-35].

Mesas are etched in the epitaxial material and the surface is planarized by polyimide. Current is supplied through a full p-contact and is confined by a dielectric aperture, obtained by selective wet oxidation of the AlAs layer. The n-contact is brought to the surface by a plated gold via in the polyimide, shown in Fig. 3. Both, the VCSEL as well as the plated via are connected with tracks to remote bond pads. A non-wettable dielectric layer serves to restrict the solder flow during a subsequent flip-chip bond process.

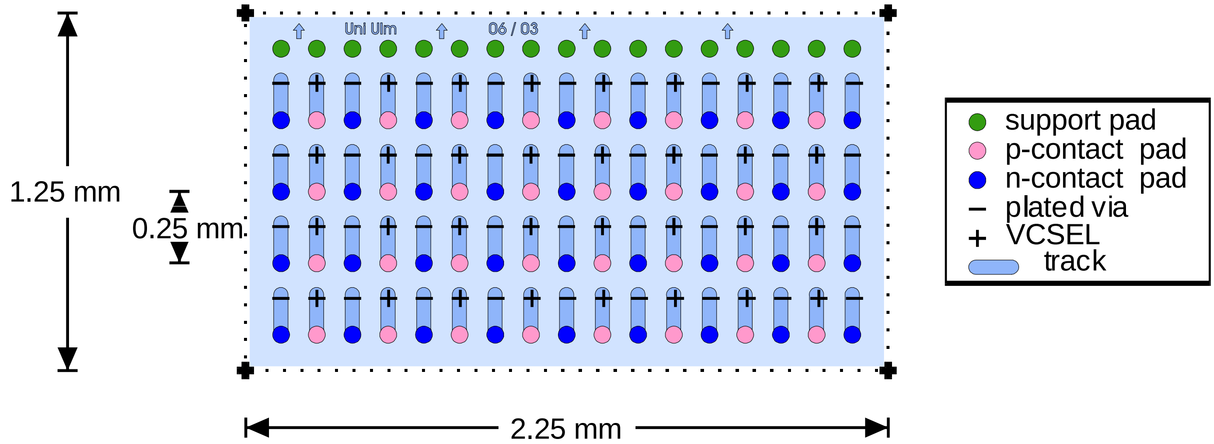

Fig. 1. Top view of the 4×8 VCSEL array with a device pitch of 250 μm. All electrical contacts are located on the top-side, whereas light is emitted through the transparent GaAs substrate.

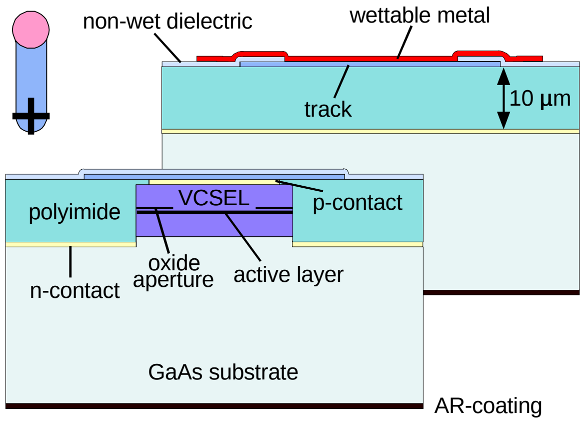

Fig. 2. Cross-sectional view through a VCSEL and the corresponding remote bond pad.

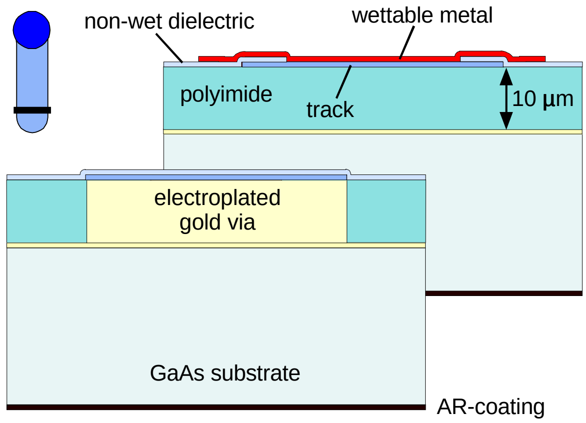

Fig. 3. Cross-sectional view of a ground contact.

3. Continuous Wave Characteristics

Bottom emitting VCSEL arrays with active diameters of 3 μm and 6 μm have been characterized. As Fig. 4 shows, all devices of the arrays do work and have maximum conversion efficiencies from electrical to optical power better than 20 %.

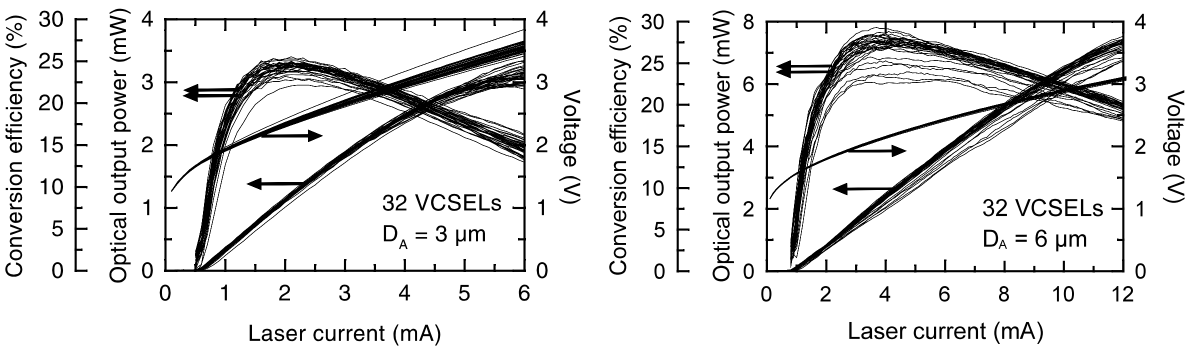

Fig. 4. Optical and electrical characteristics of 4×8 VCSEL arrays with 3 μm and 6 μm diameter oxide apertures.

Optical and electrical characteristics across the arrays are rather homogeneous. Because of their small active diameters the 3 μm VCSELs emit a single mode whereas the 6 μm devices emit several transverse modes. The emission wavelength is around 1000 nm. In multimode fiber systems it is preferable to use multi-transverse-mode VCSELs in order to avoid high bit error rate (BER) floors caused by modal noise [3]. BER floors are found if the electrical noise in the receiver is dominated by detected optical noise, such that increasing the emitted optical power does not result in better BER.

Although optical receivers should operate error-free at much lower signal levels, optical links with high channel attenuation or high fan-out may require transmitters with output powers up to 1 mW. Even at this output level the driving voltages of the arrays are fully compatible with advanced 3.3 V CMOS technology. As for the array with circular oxide apertures of 3 μm we have measured threshold currents of 0.6 mA and threshold voltages of 1.7 V. The differential quantum efficiencies are 64 %. These lasers exhibit single-mode emission with better than 30 dB side mode suppression up to 5.5 mA driving current corresponding to 3 mW output power.

4. Modulation Characteristics

For large signal digital modulation experiments a $2^{11}-1$ word length pseudo-random bit sequence (PRBS) was transmitted at 8 Gbit/s over 500 m of multimode fiber. After amplification in two stages the detected electrical signal was fed to a sampling oscilloscope or a bit error detector. The results of the transmission experiments are summarized in Fig. 5, where full circles denote back-to-back testing. It also shows the eye diagram at a BER of 10^{-11}. The eye is symmetric, wide open, and without considerable relaxation oscillations. The received optical power for a BER of 10^{-11} is -8.5 dBm for fiber transmission which is similar to values observed during a 10 Gbit/s experiment with proton-implanted VCSELs [4]. In this experiment the data rate was limited to 8 Gbit/s by the available pattern generator. To measure the modulation characteristics, the laser diode was directly contacted with a microwave probe tip. Bias current and modulation signal with 0.5 V_{pp} were combined in a bias-tee and the modulated light was detected with a 10 GHz bandwidth photodiode. Using this setup, bandwidths of around 10 GHz at a bias current of 8 mA were measured with all 32 lasers.

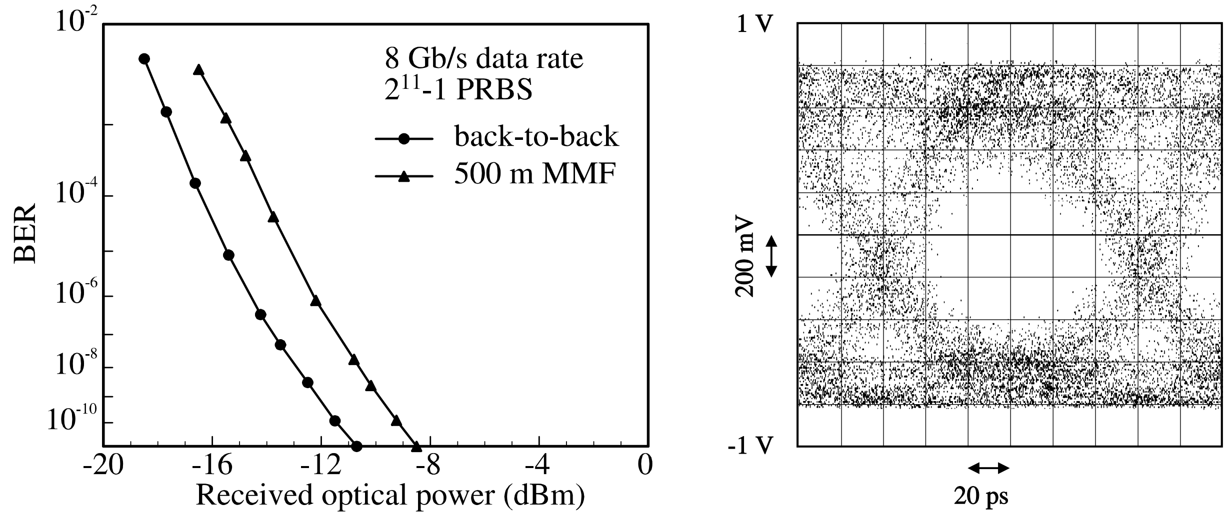

Fig. 5. BER measurement at 8 Gbit/s with $2^{11}-1$ PRBS using a 6 μm diameter VCSEL for transmission over 500 m of 50 μm core diameter graded index multimode fiber.

5. Conclusion

In summary, we have demonstrated flip-chip bondable VCSEL arrays which are ideally suited for transmitter action in parallel optical interconnects, both in terms of packaging and performance. Hybrid inter/intra-chip optoelectronic interconnects in microelectronic integrated systems may help to overcome the bottlenecks to further performance increases and miniaturization arising from conventional electrical interconnects. Measurements of top-surface contacted, bottom-surface emitting vertical cavity lasers have shown single-mode output powers as high as 3 mW, threshold currents as low as 600 μA, modulation bandwidths in excess of 10 GHz, and 8 Gbit/s data rates. The total transmission capability of a 4×8 VCSEL array with 250 μm pitch is 256 Gbit/s resulting in an information flow density of 12.8 Tbit/s/cm^2. The devices used are fully compatible with advanced 3.3 V CMOS technology.

References

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