# Improvement of Oxide-Confined VCSELs for High Frequency Applications

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*We report on top-emitting vertical-cavity surface-emitting laser (VCSEL) in the 850 nm wavelength regime with small mesa diameters produced by chemically assisted ion beam etching in combination with a wet-chemical etching step. Low threshold currents of 200 μA and modulation bandwidths up to 8.5 GHz are demonstrated. In addition, we also investigate three different methods of passivation and introduce a stable bondpad process.*

## 1. Introduction

Dramatic improvements in the performance of selectively-oxidized VCSELs have been achieved in the last year. High conversion efficiencies of 57 % [P-54] and continous wave optical output powers of 180 mW [P-17] have been demonstrated. Investigations in the field of single-mode devices using a weak index guiding are also pressed ahead [P-17]. High intrinsic modulation bandwidths of VCSELs are promising for excellent high frequency behavior, therefore suggesting applications in optical data links and Gbit/s transmission systems. The highest 3 dB modulation frequency of 16.3 GHz for oxide based VCSELs has been demonstrated in [1]. The active region of this structure consists of three 8 nm InGaAs quantum wells designed for emission wavelengths around 850 nm. The device was formed with two aligned oxide apertures in square mesas by selective oxidation. To reduce the pad capacitance a 5 μm thick polyimide planarization was used and the VCSEL was bonded using 100 μm wide bonding ribbon to minimize the bondwire inductance. In this article we describe our first attempts and results in processing high-speed VCSELs with small mesa diameters. We also study the RF modulation characteristics of these devices.

## 2. Fabrication of High-Speed VCSELs

There are two methods available for etching a mesa device. Wet-chemical etches are usual, but tend to undercut the etch mask by a distance similar to the etch depth. This is not ideal for producing small devices, with 20 μm diameter or less at an etching depth of 3.5 μm. Therefore it is absolutely necessary to prepare the VCSELs using dry-etching techniques. The layer structure we use is very well described in [P-59]. We start the process by cleaning the sample with organic solvents to dissolve unwanted contaminant. Then we spin on a positive resist which is a convenient etch mask to pattern our devices, followed by soft-baking, exposure and development. Chemically assisted ion beam etching (CAIBE) using $Cl_2$ can easily produce etch depths of a few μm through AlAs/GaAs multilayers while maintaining smooth vertical sidewalls [2]. A Meißner-trap is applied in order to reduce water vapor pressure in the chamber, which is important for etching Al-containing layers. The etch depth can be determined by the etching time knowing the exact etch rate and is controlled with a scanning electron microscope (SEM). Fig. 1 shows the scanning electron micrograph of a VCSEL with 20 $\mu$m diameter and etched to a depth of 3.5 $\mu$m.

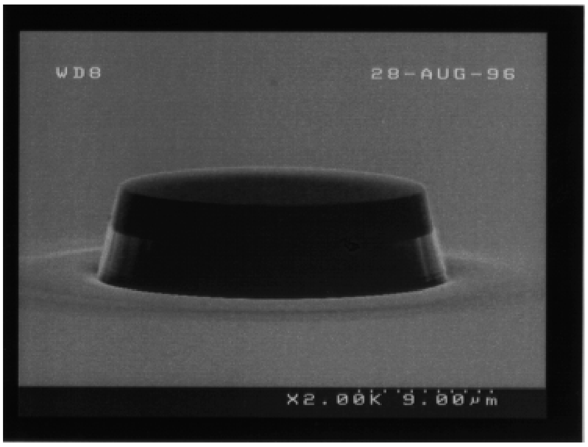


Fig. 1. Scanning electron micrograph of a dry-etched VCSEL showing smooth vertical sidewalls.

The final step in the lithographic process is resist stripping. After selective oxidation a Ti/Pt/Au ring contact for the top-emitting devices is deposited on top of the mesa and a Ge/Ni/Au broad area contact is evaporated on the backside of the substrate.

## 3. Mesa Passivation

Direct bonding or probing might be difficult for devices smaller than 20 $\mu$m in diameter. Thus it is often desirable to put larger contact pads over the device mesas to allow for easier contacting. This requires an insulating layer to prevent the pad from short cutting to the substrate. The next sections describe in more detail three different options for passivation.

### A) Oxide Passivation with $Al_2O_3$

First attempts for passivation are done using a thin sputtered isolation layer. Contacting the devices requires windows on the top-sides of the mesas. This can be realized with a lithographcal step followed by wet-chemical etching. To form the contact pads we apply an image reversal process. The negative resist walls and the nearly 2.5 $\mu$m thick resist layer provides a reliable lift-off technique. The high relative permittivity $\epsilon_r = 10$ of $Al_2O_3$ and the thin oxide layer are limiting factors for high frequency applications due to the large parasitic capacitance caused by the bondpad. A bondpad size of $120{\times}120\,\mu m^2$ yields a pad capacitance of approximately 13 pF. According to the differential resistance of the VCSEL, we observed RC lowpass behavior limiting the 3 dB modulation response to nearly 700 MHz.

### B) Ion Implantation for Passivation

Ion implantation is well-known as a very effective tool to create highly resistive regions in semiconductors. While in more conventional VCSELs a proton implantation step is necessary to define the active region, it is used hre only for passivation.

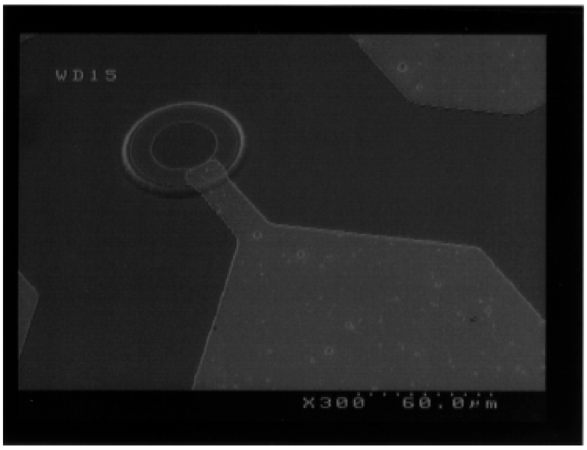


Fig. 2. SEM picture showing a bondpad on a proton implantation passivated area.

First a thick positive resist is put on top of the mesa. The implantation is carried out using protons with an energy of 80 keV and an ion dose of $10^{15}$ cm$^{-2}$ leading to an implantation depth of approximately 1 $\mu$m. To ensure implantation of the mesa sides the sample is rotated during the process. After removing the resist with an oxygen plasma step and cleaning with organic solvents, the Ti/Au bondpads are deposited. Fig. 2 shows a scanning electron micrograph of a bondpad over an implantation passivated area. The bondpad metallization is about 400 nm thick. The advantage of proton implantation passivated oxide confined VCSELs is obviously the much easier bonding on a semiconductor surface.

### C) Planarization and Passivation Using Polyimide

In this section we describe the attempt to passivate a VCSEL using a photosensitive polyimide. Polyimide is a polymer coating especially developed to provide a smooth planar coating of surface relief features. Fig. 3 illustrates the steps involved in passivating VCSELs in this way. First polyimide is spun (a) to planarize the surface. For contacting the devices a window has then to be opened into the polyimide (b). After exposing and developing a bake is performed

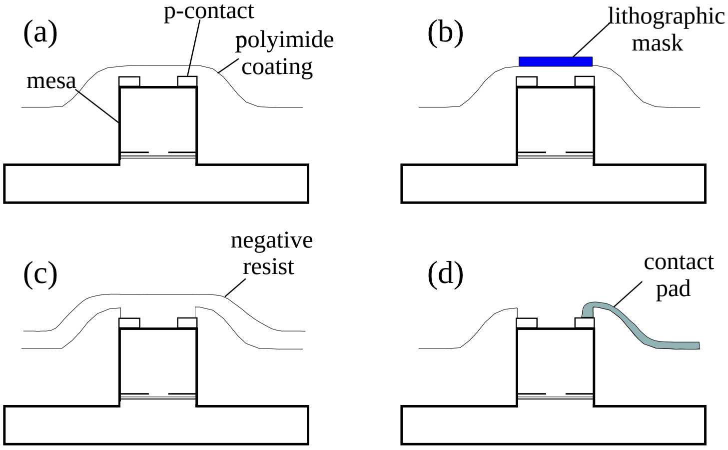


Fig. 3. Process steps to passivate VCSEL mesas using polyimide for applying bondpads.

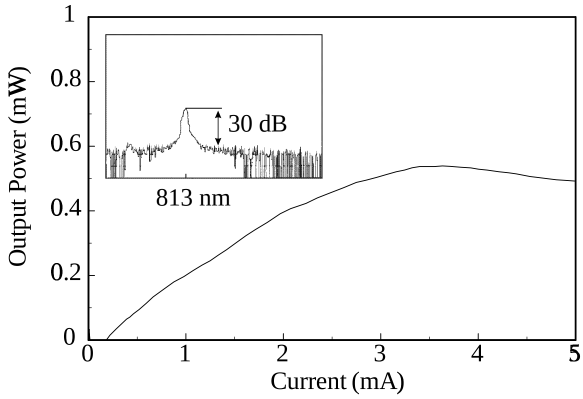


Fig. 4. Optical power against current characteristic of a 2 $\mu$m active diameter GaAs VCSEL. The inset depicts the corresponding emission spectrum at 2 mA current in a logarithmic scale with 10 dB/div. The laser oscillates at a wavelength of 813 nm and is single-mode up to 3 mA with a side mode suppression of about 30 dB.

to complete the imidization process. A pattern of contact pads is formed in the negative resist process (c) and finally p-type contact metals are evaporated (d).

Polyimide as passivating insulator around the mesa prevents AlAs layers from erosion in a moist atmosphere. Another advantage of thick polyimide layers is the very small relative permittivity of $\epsilon_r = 3.3$ predicting a better high frequency behavior compared to the oxide layer passivation using $Al_2O_3$. On the other hand bonding on the polyimide surface is much more difficult and requires a lot of experience.

## 4. Measurements

Fig. 4 depicts the continuous wave output characteristics of a selectively oxidized GaAs VCSEL with an active diameter of 2 $\mu$m. Threshold current and maximum output power are 200 $\mu$A and 0.5 mW, respectively. The inset illustrates the oscillation of the VCSEL on the fundamental mode ($\lambda = 813$ nm) up to 15 times threshold current with a side mode suppression of more than 30 dB.

For RF measurements VCSELs with larger current apertures are desirable due to the smaller differential resistance and higher optical output power. Output characteristics of a polyimide planarized dry-etched 8 $\mu$m VCSEL are shown in Fig. 5.

This laser diode exhibits a threshold current of 2.4 mA at a voltage of 1.8 V. The maximum optical output power is 5 mW, limited by thermal roll over. The emission wavelength of 810 nm reveals laser oscillation on the short wavelength side of the gain peak. Differential quantum efficiency and series resistance can be estimated to 51 % and 100 $\Omega$, respectively. An approximately 2.2 $\mu$m thick polyimide layer is used to planarize the surface. Therefore, we expect a pad capacitance of 0.09 pF for the 80×80 $\mu m^2$ large bondpad. For small signal modulation measurements the VCSELs are mounted on a SMA socket and short bonded to avoid large bondwire inductance. The laser emission is detected with a 25 GHz Si photodetector, fed to a 10 dB broadband amplifier and recorded with an HP scalar network analyzer. Typical modulation responses at various currents are shown in Fig. 6. The measurements indicate a maximum 3 dB modulation bandwidth of 8. 5 GHz at a bias of 9.0 mA. At higher currents, further increased bandwidths cannot be observed due to damping of the relaxation resonance and reduced differential gain due to heating. Size dependent investigations reveal that VCSELs of smaller active diameter but the same pad capacitance exhibit a smaller electrical 3 dB modulation bandwidth due to

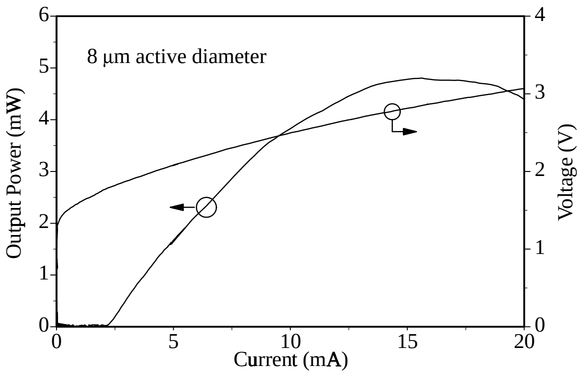


Fig. 5. Light output and voltage against current characteristic of a dry-etched VCSEL with 8 $\mu$m current aperture.

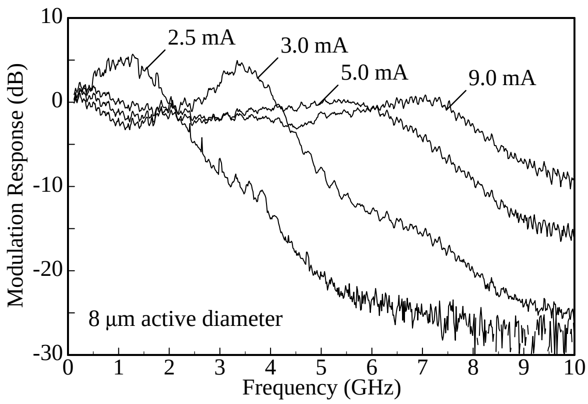


Fig. 6. Modulation response of a polyimide passivated VCSEL for different driving currents.

their higher differential resistance. Therefore the modulation response is obviously limited in bandwidth by the RC time constant of the pad capacitance and series resistance of the VCSEL.

On the other hand we also investigated the RF behavior of wet-chemically etched VCSELs with the intention to compare polyimide and proton implantation for mesa passivation. A bondpad size of $120 \times 120\,\mu\text{m}^2$ results in pad capacitance of 1.4 pF and 0.2 pF for proton implantation and polyimide passivated VCSELs, respectively. Small proton implantation passivated devices show a very strong lowpass behavior due to their large RC time constant resulting in bandwidths of only 1 GHz. Similar lasers with nearly the same series resistance using polyimide passivation exhibit 3 dB bandwidths of about 4.1 GHz.

## 5. Summary

In conclusion, VCSELs with a small mesa diameter of 20 $\mu$m using a special dry-etching method in combination with a wet-chemical etching step have been fabricated. Low threshold currents of less than 200 $\mu$A have been demonstrated. We have also discussed proton implantation and polyimide as two possible methods for passivation. The 3 dB modulation frequency of VCSELs with polyimide passivation exceeds 8.5 GHz. The modulation frequency is limited by the capacitance of the bondpad and the corresponding differential resistance of the VCSEL. For obtaining higher frequencies the capacitance of the selectively oxidized VCSEL should be minimized and the differential resistance should be lowered. Moreover, we have found inferior modulation characteristics of proton implanted as compared to polyimide planarized VCSELs.

## References

[1] K. L. Lear, V. M. Hietala, A. Mar, K. D. Choquette, H. Q. Hou, and R. P. Schneider, Jr., "High frequency modulation of oxide-confined vertical-cavity surface emitting lasers", *IEEE J. Lightwave Technol.*, vol. 32, pp. 457–458, 1996.

[2] F. Eberhard and M. Schauler "Sputter etching of GaAs and GaN", *Annual Report 1995, Dept. of Optoelectronics, University of Ulm*, pp. 96–101, 1996.