High-Efficiency Selectively-Oxidized MBE-Grown Vertical-Cavitiy Surface-Emitting Lasers

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Performance of Vertical-Cavity Surface-Emitting Laser Diodes (VCSELs) has drastically improved using selective oxidation [1] instead of proton implantation for lateral current confinement. The modified layer structure, the laser processing, and the output characteristics of the new devices are presented. A maximum output power of 47 mW and a maximum power conversion efficiency of 47 % have been achieved for devices with an active diameter of 25 µm and 20 µm in a non heatsinked configuration.

1. Layer Structure

A schematic cross-section of the VCSEL structure under investigation is shown in Fig.1. Growth is done by solid source MBE. The active region contains 3 strained $\mathrm{In}_{0.2}\mathrm{Ga}_{0.8}\mathrm{As}$ quantum wells with GaAs barriers surrounded by $\mathrm{Al}_{0.33}\mathrm{Ga}_{0.67}\mathrm{As}$ layers for efficient carrier confinement. The bottom Bragg reflector consists of 32 n-type Si doped AlAs/GaAs quarter wavelength layer pairs. The 26 pair $\mathrm{Al}_{0.67}\mathrm{Ga}_{0.33}\mathrm{As}$/GaAs p-type Be doped top reflector has an optimized doping profile [2] to reduce the electrical series resistance. A single 30-nm-thick AlAs layer is introduced as the lowest layer in the p-type mirror next to the active region to be used for selective oxidation.

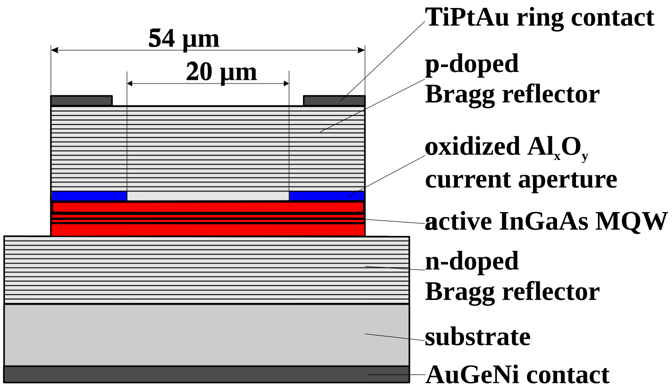

Fig. 1: Schematic drawing of a selectively oxidized InGaAs/AlGaAs VCSEL

Mesas with diameters from 38 to 59 µm have been structured by wet chemical etching using a positive resist mask. Etching has to be stopped immediately after removing the p-doped AlAs layer outside the mesa within an accuracy of ± 100 nm. This can be achieved using in situ optical monitoring of the etching depth. Subsequent lateral selective oxidation is of the AlAs layer is performed in an N_2/H_2O atmosphere at a temperature of 400 °C [3]. With an oxidation rate of 1.2 µm/min, an oxidation depth of 17 µm is achieved within 15 min of processing time.

This current aperture reduces the active diameters of the devices to 4-25 μm. TiPtAu p-type ring contacts and n-type GeNiAu are deposited to complete the structure.

2. Devices and Measurements

The thin Al_xO_y layer formed by selective oxidation is found to provide excellent current confinement for the injected carriers. Losses caused by nonradiative recombinations, absorption and defraction at the perimeter of the aperture are considerably smaller than in proton implanted devices allowing even small-single mode lasers and enhancing the efficiency of broad-area devices. The refractive index of the oxide is $n = 1.6$ and therefore much smaller than in the semiconductor material. The resonator is detuned in the partially oxidized areas inducing an optical wave guiding that can be described by an effective index method [4]. Theoretical analysis [5] gives an index reduction of $\Delta n_{eff} = 6.5 \cdot 10^{-2}$ for the outer regions. In contrast to proton implanted lasers, optical guiding is well defined and can be adjusted to the device characteristics desired.

Fig.3 shows top side output power, driving voltage, and wallplug efficiency as a function of injection current for a 20 μm active diameter VCSEL. Threshold current and threshold voltage are 3 mA and 1.65 V, respectively. Due to the differential resistance of less than 40 Ω under lasing conditions, driving voltage remains below 3.5 V up to the maximum output power of 40 mW which is limited by thermal rollover in the non heat sinked device. Optical output power is measured using a Newport 835 optical power meter with calibrated wavelength selective detector. Maximum wallplug efficiency of 47 % is observed for a driving current of 10 mA at an output power of 10.2 mW. The high power conversion efficiency is mainly due to high optical gain represented by a top side differential quantum efficiency of about 90 %. Losses are estimated to be caused by series resistance and leakage current (41 %), bottom emission (5 %) as well as residual non-radiative recombination and internal absorption in mirrors and active region (7 %).

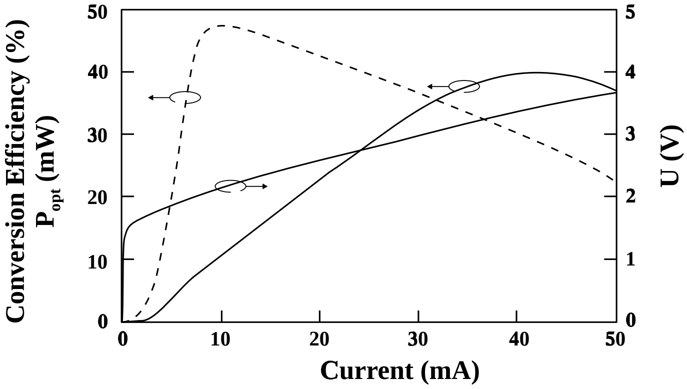

Fig. 2: Output power P_{opt}, conversion efficiency (dashed), and voltage U as function of driving current for a VCSEL of 20 μm diameter

The emission spectrum in Fig. 3 recorded at 15 mA driving current centered at 983 nm wavelength is relatively broad. The appearance of several transverse modes oscillating simultaneously is typical for an index guided VCSELs.

We believe that the high conversion efficiency observed in 20 μm diameter devices is due to very efficient optimum index guiding provided by the 30-nm-thick oxidized layer. VCSELs

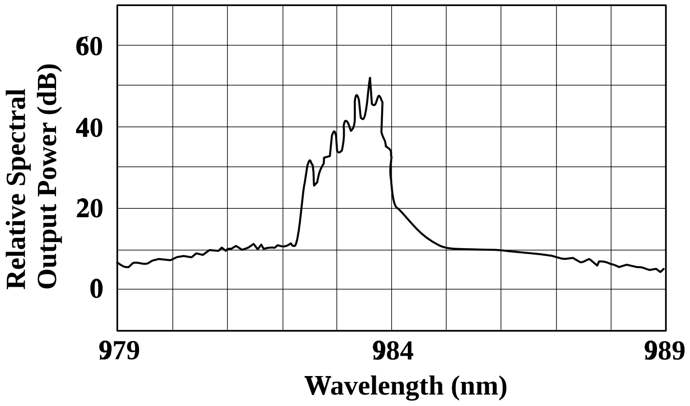

Fig. 3: Emission spectrum of 20 μm VCSEL at 15 mA driving current

of larger active sizes of 25 μm show larger maximum output powers of 50 mW with slightly reduced conversion efficiencies due to current crowding effects at the edges. Generally it is found that selectively-oxidized devices are about three times as efficient as proton implanted devices produced from the very same wafer.

3. Conclusion

We have demonstrated that extremely efficient VCSELs can be fabricated using conventional solid source MBE with Be *p*-type dopant for wafer growth,a simple wet etching and subsequent lateral AlAs single layer oxidation. The maximum wallplug efficiency is as high as 47 % at 10 mW output power while maximum output power is above 40 mW in devices with an aperture diameter of 20 μm. High efficiency combined with high output power is favorable for producing high-power densely-packed two-dimensional arrays.

References

[1] K.L. Lear, K.D. Choquette, R.P. Schneider, Jr., S.P. Kilcoyne, K.M. Geib, "Selectively oxidized vertical cavity surface emitting lasers with 50 % power conversion efficiency," *Electron. Lett.*, vol. 31, no. 24, pp. 208-209, 1995.

[2] G. Reiner, E. Zeeb, B. Möller, M. Ries, K.J. Ebeling, "Optimization of Planar Be-Doped InGaAs VCSELs with Two-Sided Output," *Photon. Technol. Lett.*, vol. 7, pp. 730-732, 1995.

[3] M. Grabherr, B. Weigl, "Selective Oxidation of AlGaAs Layers," *Annual report*, Department of Optoelectronics, University of Ulm, 1995.

[4] G.R. Hadley, "Effective index model for vertical-cavity surface-emitting lasers," *Optic Letters*, vol. 20, no. 13, pp. 1483-1485, 1995.

[5] R. Michalzik, "Simple Understanding of Waveguiding in Oxidized VCSELs," *Annual report*, Department of Optoelectronics, University of Ulm, 1995.

Ph.D. Theses

1. E. Zeeb, *Planar Vertical Cavity Laser Diodes and Two-Dimensional Laser Diode Arrays for Optical Interconnects*, Ph.D. Thesis, Dept of Optoelectronics, University of Ulm, 1995.
2. B. Möller, *Emission Properties and High Frequency Behavior of Vertical Cavity Laser Diodes for Optical Interconnects*, Ph.D. Thesis, Dept of Optoelectronics, University of Ulm, 1995.
3. A. Fricke, *Waveguide Integrated-Metal-Semiconductor-Metal Photodiodes and Modulators in InAlGaAs on InP Substrate for Optical Communications*, Ph.D. Thesis, Dept of Optoelectronics, University of Ulm, 1995.
4. C. Rompf, *Optoelectronic Devices Based on Organic Semiconductors*, Ph.D. Thesis, Dept of Optoelectronics, University of Ulm, 1995.