Bottom Emitting VCSELs for High cw Optical Output Power

Martin Grabherr and Michael Miller

Bottom emitting VCSELs operating in the 980 nm wavelength regime have been designed for high cw optical output power. Devices of 200 μm active diameter and optimized performance reach 350 mW maximum output power when mounted on heat sink. 50 μm size lasers produce 100 mW at 25 % electrical to optical power conversion efficiency. Thermal properties and size dependent basic characteristics are investigated in detail.

1. Introduction

VCSELs have become highly efficient laser sources for optical data transmission, mainly due to reduced series resistances in Bragg reflectors and optimized current confinement. Current apertures formed by selective oxidation [1] have shown to be indispensable to achieve power conversion efficiencies above 50 % [2], [P-10]. The output power range of oxidized devices typically ranges from about 1 mW up to a few 10 mW. Higher output powers of 113 mW [4] and 180 mW [5] have already been reported for larger diameter devices, ultimately aiming at applications like solid-state laser pumping, printing, or material treatment. In this paper, investigations on size dependent electro-optical as well as thermal characteristics of bottom emitting devices are presented, clearly demonstrating the capability of VCSELs to achieve high optical output powers at still reasonably high conversion efficiencies.

2. Device Structure and Processing

A schematic cross-section of the investigated VCSEL structures is displayed in Fig. 1. The highly reflective p-type Bragg stack is built of 30 pairs of $Al_{0.9}Ga_{0.1}As$/GaAs layers, where in its first layer a single 30 nm thin AlAs sublayer is placed to form the current aperture. To reduce the series resistance of the thick multilayer stack, Carbon as p-type dopant is employed using extra modulation doping near interfaces to decrease the voltage drop without increasing absorption losses. The n-type Silicon doped Bragg reflector is composed of only 24 pairs of the same material composition. The active zone consists of 3 InGaAs quantum wells embedded in GaAs barriers and surrounded by AlGaAs claddings to build the one wavelength thick inner cavity. Growth of the entire structure is accomplished by solid source MBE. Before oxidizing the current aperture, mesas with diameters

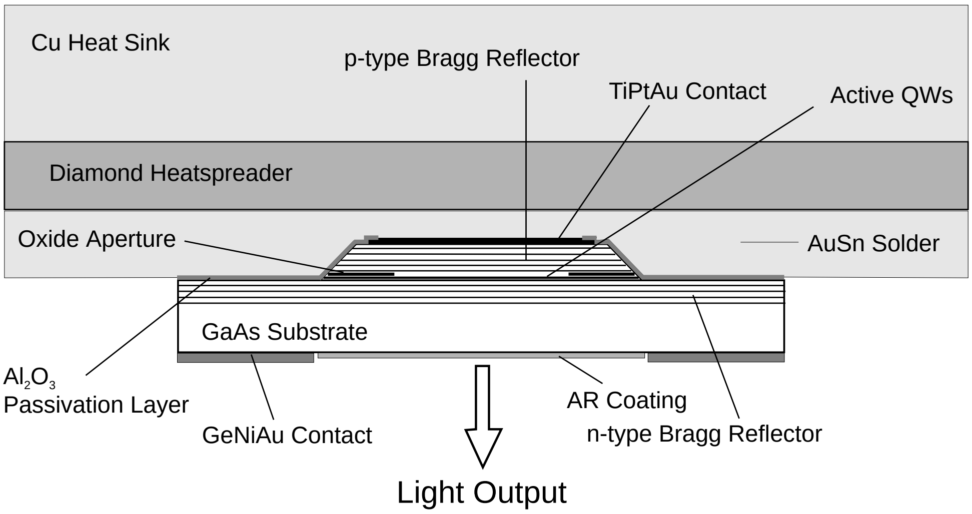

Fig. 1. Bottom emitting VCSEL soldered junction down on diamond heat spreader.

of 100 up to 250 μm are wet chemically etched down to the depth of the AlAs layer. The oxide ring of 25 μm width is formed in a water/Nitrogen atmosphere at 410 ^{o}C process temperature. After evaporating the p-type TiPtAu-contact on top of the mesa, a Si_3N_4 passivation layer is deposited on the upper side to avoid short circuits when soldering the devices on heat sinks. After polishing the substrate to a thickness of 180 μm in order to reduce absorption losses, an anti-reflection (AR) coating of $Si_xO_yN_z$ is deposited. Transmission lithography is used to define the n-type GeNiAu substrate contacts. Single devices are separated by cleaving and then soldered with AuSn on metallized diamond heat sinks, providing thermal conductivities of larger than 1100 W/(K m) for effective heat spreading. Using 5 μm thick solder, the attachment is mechanically stable and good thermal and electrical conductivity is obtained. The diamond size is 2×2 mm^2 and the chip size $300\times300\,\mu$m^2. For heat sinking the diamond is attached with silver paste on a copper submount.

3. Measurements and Results

Fig. 2 shows light output power characteristics and conversion efficiencies for VCSELs of various diameters from 20 to 200 μm. Solid lines correspond to devices mounted on not actively cooled heat sinks, whereas dashed lines describe unmounted lasers. Output power increases linearly above threshold and rolls over for higher driving currents due to self-heating. VCSELs of 20 μm size exhibit similar behavior for mounted and unmounted operation, since small devices benefit from low electrical power consumption and high conversion efficiency. Reduced thermal resistances of heat sinked devices lead to higher output power of mounted compared to unmounted devices of 50 μm and 100 μm active diameter, where unmounted VCSELs show saturation of maximum output power, as observed before for bottom emitting VCSELs [6]. Due to strong internal heating, even

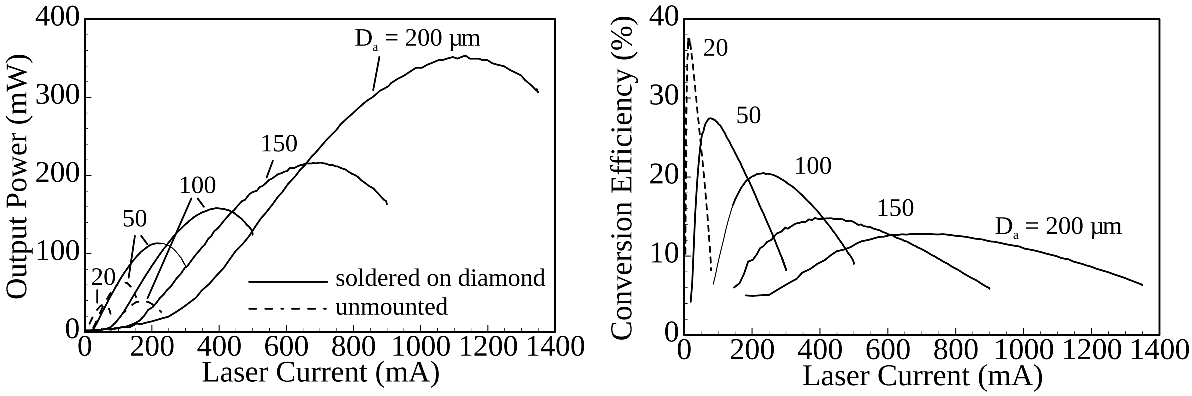

Fig. 2. CW output powers (left) and conversion efficiencies (right) of bottom emitting single devices with active diameters from 20 to 200 μm at room temperature. Solid and dashed lines correspond to mounted and unmounted devices, respectively.

suppression of cw laser emission is found for unmounted devices of 150 μm and 200 μm diameter, whereas soldered devices still show further increased maximum output power and no saturation is anticipated for even larger active areas. With diameters increasing from 20 to 200 μm near threshold, differential quantum efficiencies decrease from 80 % to 44 %. Similarly, as seen in the right hand part of Fig. 2, conversion efficiency decreases with increasing active diameter, which is additionally caused by the differential resistance. Maximum conversion efficiency of 20 μm lasers is 37 % but just 13 % for 200 μm diameter devices. Reduced efficiencies are mainly caused by increased heating but may also partly be due to amplified spontaneous emission (ASE) of laterally guided in-plane modes. Compared to VCSELs with bulk active material [7] the influence of ASE in the quantum well devices investigated is much weaker due to the smaller confinement factors.The maximum output power of 350 mW obtained for the 200 μm diameter device is the highest cw output power for an electrically pumped solitary VCSEL reported so far. The power is measured using a calibrated power meter (Newport 1830 C) with broad area photodetector. Maximum power is observed at 1100 mA driving current and 3.2 V driving voltage where an extra voltage drop of 0.2 V is included which is due to non-perfect soldering on the submount. Nevertheless the conversion efficiency at maximum power is still 10 %. Higher conversion efficiency combined with moderate output power is observed for smaller devices. It is worth to note that VCSELs of 50 μm diameter emit 100 mW at 25 % conversion efficiency. Radiation patterns and spectra are rather similar for the device sizes studied. An optical spetrum is shown in Fig. 3 for a 200 μm diameter device driven at 700 mA laser current. Transverse multimode emssion is centered at 980 nm wavelength with a spectral width of about 2 nm. Far field radiation patterns plotted in Fig. 4 for a VCSEL of 150 μm diameter typically show FWHM angles of less than 20°. Fig. 5 presents a detailed study of threshold current, differential resistance, and thermal resistance dependencies on active diameter. Maximum output powers and maximum conversion efficiencies extracted from Fig. 2 are also included. Differential resistances decrease proportionally to $D^{1.7}$ indicating residual inhomogeneities in current supply from outer contact regions. Threshold currents

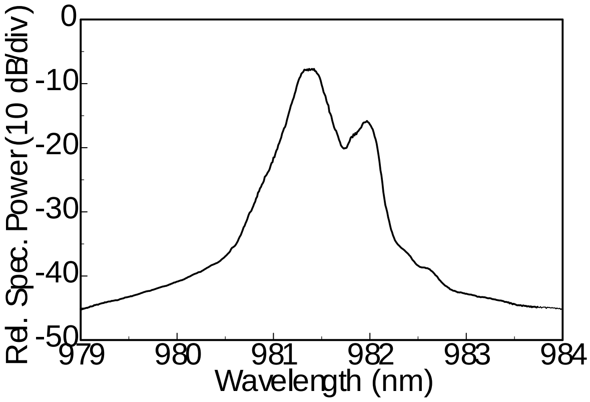

Fig. 3. Spectrum of a 200 μm diameter device at 700 mA laser current.

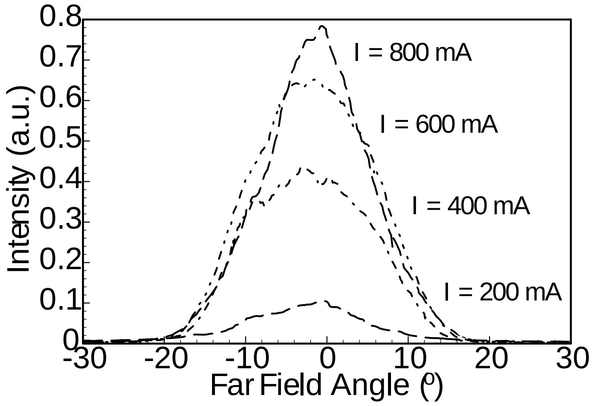

Fig. 4. Far field patterns for different laser currents of a 150 μm active diameter VCSEL.

increase linearly with active area, giving a constant threshold current density of about 850 A/cm^2 independent of device size. Thermal resistances R_{th}, determined from the mode red shift with increasing dissipated power and the red shift with growing heat sink temperature vary inversely proportional to the active diameter D in good agreement with simple analytical estimations according to [8]

$$R_{th} = (2\lambda_c D)^{-1} , \tag{4}$$

where the experimentally obtained thermal conductivity is $\lambda_c \approx 44\,\mathrm{W/(K{\cdot}m)}$ and is thus close to that of bulk material. Thermal resistance data given in Fig. 5 are measured for unmounted devices but are a factor of about 3 lower for soldered lasers.

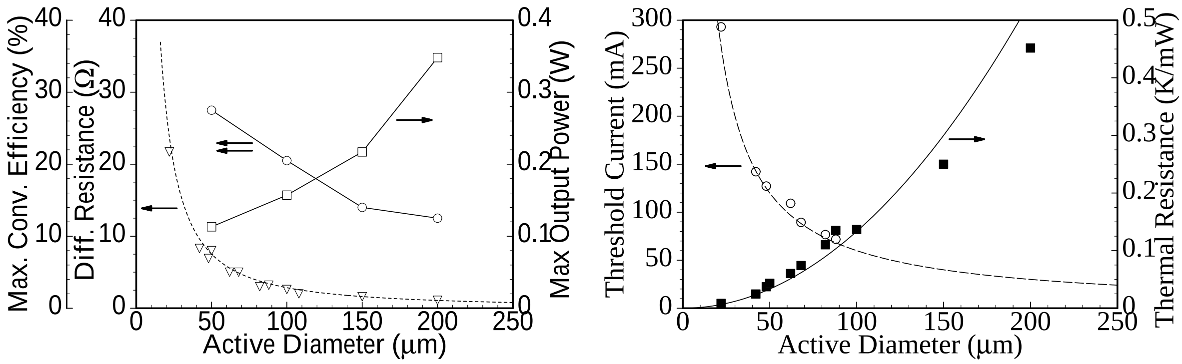

Fig. 5. Differential resistance, maximum cw output power and conversion efficiency versus active diameter of mounted bottom emitting VCSELs (left) and size dependence of threshold current and thermal resistance of unmounted devices (right).

4. Conclusion

Bottom emitting VCSELs have been fabricated that show record output powers when applying appropriate heat sinking. 350 mW for a single 200 μm device is obtained at a corresponding conversion efficiency of 10 %. An output power of 100 mW at 25 % conversion efficiency is demonstrated for a 50 μm device. Size dependent investigations show no saturation of maximum output power with increasing size, but due to further decreasing efficiencies, larger devices do not seem prospective. From the investigated scaling behavior of differential and thermal resistances it is concluded that cw output powers above 1 W at reasonably high conversion efficiencies might be attainable by using densely packed two-dimensional VCSEL arrays with small size individual devices.

References

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