A Fabrication Approach for Hybrid-Integrated Electrically Pumped VECSELs

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We report on a fabrication approach for hybrid-integrated electrically pumped vertical-extended-cavity surface-emitting lasers (VECSELs). The fabrication involves parallel processing steps while maintaining reasonable alignment tolerances. An output power of more than 0.4 mW is achieved for an output coupler with a transmission of 5 %.

1. Introduction

Unlike a vertical-cavity surface-emitting laser (VCSEL), which comprises two highly reflecting distributed Bragg reflectors (DBRs), the extended cavity in VECSELs employs a third mirror. The fabrication of such a device requires a long process chain, including the patterning of the VCSEL structures, definition of the extended optical resonator, mirror coating and die bonding. While VCSELs have matured to be used in commonplace applications like optical computer mice necessitating volume production [1], products incorporating VECSELs are still rare.

Laborious and delicate steps like substrate removal reduce the process yield [2]. Wafer-scale approaches lack an economic utilization of the epitaxial material [3], because the electrical connections occupy valuable wafer area, whereas the demand for mass production prohibits any non-wafer-scale processing steps. The method presented here features a compromise between producibility and area efficiency.

2. Fabrication Steps

The cross-section of the complete device is depicted in Fig. 1. The extended plano-concave resonator consists of the VCSEL DBR, an air gap, the glass substrate and the curved surface of the microlens with a second DBR mirror. The fabrication of the VECSELs includes four steps, which are in the proper order: (i) fabrication of top-emitting VCSELs with solder bumps, (ii) patterning of fanout tracks and microlenses on the anti-reflection coated glass substrate, (iii) flip-chip solder connection of the latter with the VCSEL, and (iv) coating of the microlenses with the DBR.

The available GaAs/AlGaAs-based top-emitting VCSELs have a dominant emission wavelength which ranges from 785 to 830 nm due to a layer thickness gradient within the wafer sample. The VCSELs employ optical and carrier confinement by a thin AlAs layer which is selectively oxidized in water vapor. The resulting apertures range from 6 to 20 µm.

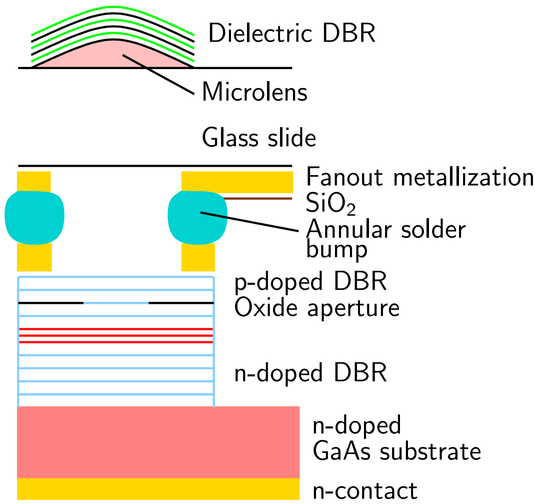

Fig. 1: Schematic cross-sectional view of the VECSEL.

The top mirror is thick enough to support laser emission without any extended resonator. On each annular p-contact on top of the mesas, a 4 µm thick ring-shaped indium solder bump is deposited. The indium facilitates both electrical connection and mechanical self-alignment during the soldering process. The extended cavity consists of a 100 µm thick boron-doped glass slide which is anti-reflection coated on one side. As illustrated in Fig. 2 (left), the measured reflectivity of this surface is less than 0.1 % in the wavelength range from 780 to 840 nm. The coated side is metallized with the fanout tracks and 180 nm thick SiO_2 is selectively deposited on the areas where wetting of the solder is undesired. The neccessary radii of curvature r_c were calculated by the transfer-matrix method [4]. Assuming no volume loss during reflow, the lens diameter D can be calculated from

$$D = \sqrt{(6t + r_c)\sqrt{9r_c^2 - 6tr_c + 9t^2} - 6r_c^2 - 18t^2}$$

with t being the photoresist thickness. Too small apertures of the microlens or the annular ring contact would result in beam aberrations due to beam cutoff. For this reason, the aperture diameter was chosen at least 3.4 times the beam diameter. Under this condition, the aperture loss is expected to be less than 1 %, assuming a circular Gaussian beam. The microlenses are made from Microchem PMGI SF17 photoresist which is reflown at 360 °C, resulting in radii of curvature between 100 and 2800 µm. The high transparency of the glass substrate allows checking the alignment under a light-optical microscope. The measurement with an atomic force microscope reveals a smooth surface of the lens, as shown in Fig. 2 (right). The surface can be fitted to a general sphere according to $(x/\varrho_x)^2 + (y/\varrho_y)^2 + (z/\varrho_z)^2 = 1$ with radii of curvature $\varrho_x = 102.9\,\mu m$, $\varrho_y = 103.3\,\mu m$, and $\varrho_z = 103.1\,\mu m$.

After a coarse pre-alignment using a silicon CCD camera, the VCSEL and extended cavity parts are solder-joined in a formic acid saturated atmosphere. The peak temperature in this step is critical and is approximately 170 °C in order to suppress the formation of indium whiskers and diffusion of indium into the fanout. In a final step, 3.5 pairs of TiO_2/SiO_2 are deposited on the microlenses by ion beam sputter deposition using 1 keV energy argon ions. The DBR transmits about 5 % of the incident light at the operation wavelength.

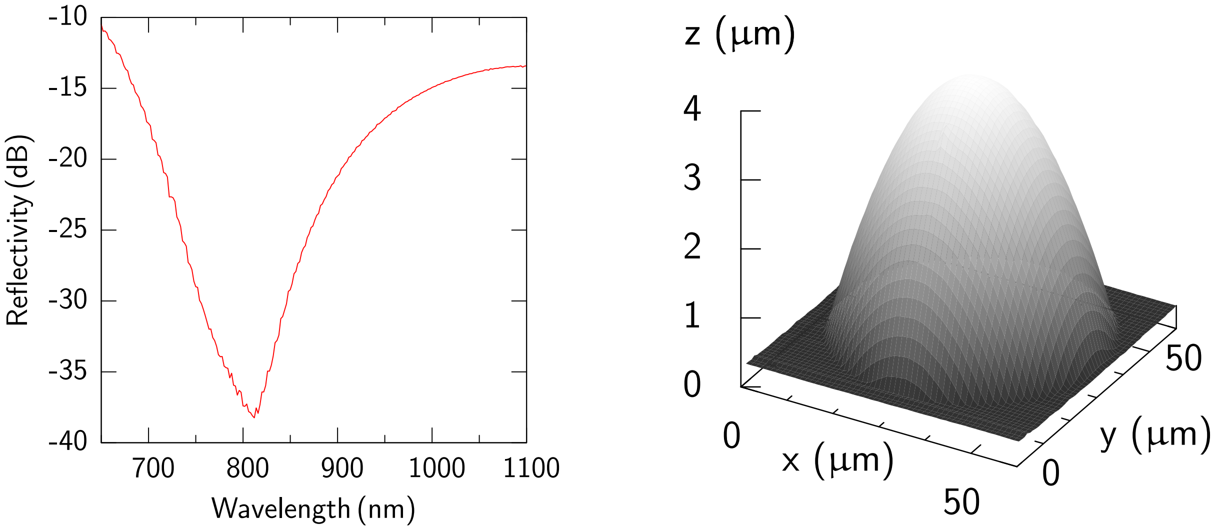

Fig. 2: Measured reflectivity spectrum of a four-layer anti-reflection coated glass slide (left) and surface topology of a microlens aquired by atomic force microscopy (right).

3. Characterization of the VECSELs

The processed VCSELs show smooth light–current–voltage (LIV) characteristics. As depicted in Fig. 3, the threshold current I_{th} of a reference device with 10 µm active diameter is 6.8 mA, whereas the threshold currents of all fabricated VECSELs (Fig. 4) are lower by 10 to 20 %. The LI characteristics of the VECSELs show multiple kinks, which can be attributed to transverse or longitudinal mode hops. The maximum output power of more than 400 µW corresponds to an incident power of 8 mW on the output coupler, which is much more than in the VCSEL. This is a clear indication that light is oscillating in the extended resonator, however, the quality factor of this resonator is lower than expected. A possible reason could be an improper alignment of the extended cavity or losses induced by the GaAs cap layer on the VCSEL surface. The differential electrical resistance R_{d} of the VCSELs and VECSELs is less than 150 Ω.

4. Conclusion

We have successfully introduced a fabrication approach for electrically pumped VECSELs. It supports wafer-scale processing while making efficient use of the wafer surface. A process yield of 75 % was achieved. The function of the extended cavity was demonstrated, but the quality of the external resonance is still to be improved. A possible way to minimize the losses in the extended cavity could be a shift in emission wavelength above 850 nm which would result in a suppression of fundamental absorption in the GaAs cap layer. In future work, the loss mechanism could be studied in lasers with a thinner p-doped DBR which allows better coupling of the generated light into the extended cavity.

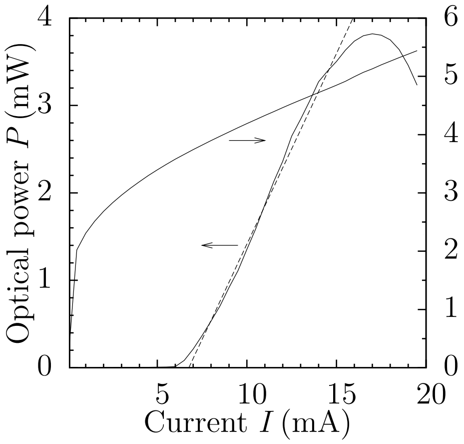

Fig. 3: LIV characteristics of a 10 µm active diameter reference VCSEL.

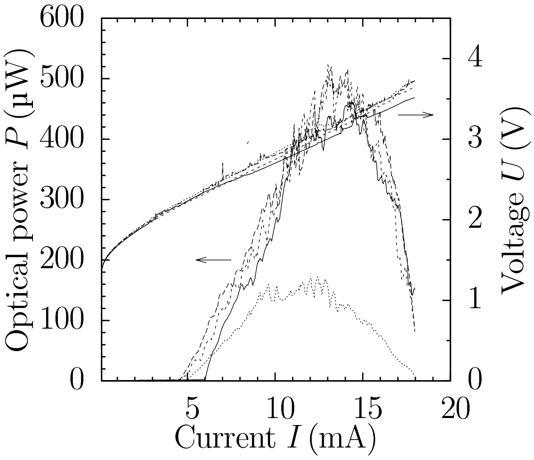

Fig. 4: LIV characteristics of several VECSELs with 10 µm active diameter. The devices differ in the radius of curvature of the microlens.

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