Large-Area Single-Mode GaSb-based VCSELs using an Inverted Surface Relief

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Abstract: *Large-area GaSb-based BTJ VCSELs at ~ 2.35 µm were fabricated using an inverted surface relief technique to support the single transverse mode operation. The devices operate in continuous-wave and are (electro-)thermally tunable over 6 nm.*

Keywords: surface relief, VCSEL, single-mode.

1. INTRODUCTION

Trace gas sensing in the mid-infrared (IR) above 2 µm requires low-cost laser devices operating in single-mode with excellent optical beam quality and sufficiently broad wavelength tunability. These goals can ideally be fulfilled by GaSb-based vertical-cavity surface-emitting lasers (VCSELs) as light sources. Because of material limitations, InP-based devices are not expected to reach more than 2.3 µm [1]. In contrast, the GaSb-based material system allows covering a large part of the mid-IR (2 - 3.5 µm) wavelength regime.

In this paper, electrically-pumped (EP) continuous-wave (CW) operating GaSb-based VCSELs utilizing large current apertures defined by Buried Tunnel Junction (BTJ) are demonstrated. Devices with relatively large BTJ-defined apertures exhibit stable single transverse mode operation with a side mode suppression ratio of at least 25 dB over the entire operating current range. Usually, large-aperture devices promise low differential series resistance, long lifetime and high output power through a reduced self-heating. This is advantageous for any type of spectroscopic applications since a reasonable amount of output power can be obtained from large-aperture devices but they excite many transverse modes. The so-called inverted surface relief (ISR) technique [2] has been successfully applied to the devices in order to select only the single fundamental mode and suppress higher order modes. In this method, an annular deposition of additional quarter-wave thick antiphase a-Si layer on top of the dielectric Bragg mirror will lower the reflectivity for higher order modes. The resulting differences in threshold gain then strongly favor the fundamental mode. Compared to other mode filtering methods, the ISR technique involves a minor modification to the VCSEL processing since it offers a relatively less fabrication complexity with respect to the requirement of less precise deposited layer thickness.

Fig. 1 schematically displays the design of the BTJ-defined GaSb-based top emitting VCSELs with an inverted surface relief in the top mirror.

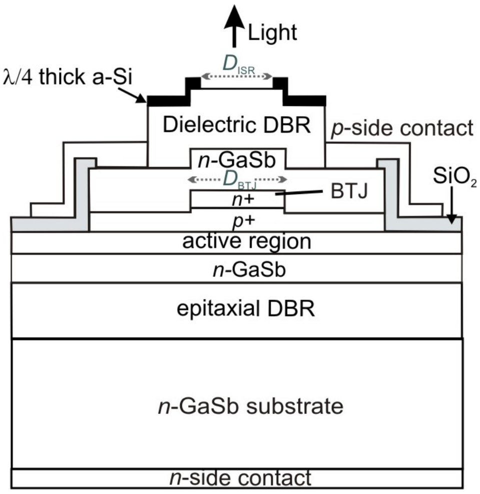

Fig. 1: Schematic cross-sectional view of the GaSb-based VCSEL structure with inverted surface relief in the top mirror.

2. DEVICE FABRICATION AND SIMULATION

The VCSEL structure was grown in two growth steps by a Varian Gen-II solid-source molecular beam epitaxy (MBE) system. Details of the device design and all fabrication steps required to realize the device without inverted surface relief are given in [3]. A circular ring-shaped relief, intended for fundamental mode operation, was precisely defined using a standard photolithography and an extra λ/4 thick e-beam-evaporated a-Si was selectively added to the top dielectric mirror to provide an anti-phase reflection from the semiconductor-air interface. It results in lowering the mirror reflectivity to 93.2% @ 2.35 µm outside the device centre compared to the reflectivity, 99.5% @ 2.35 µm at the device centre. Thus we spatially change the modal threshold gain of the device by selective deposition of this antireflection coating.

According to the optical cold-cavity calculations, the optimum diameter of the surface relief, D_{ISR} should be about 60% of the diameter of the BTJ, D_{BTJ}. Using an electro-thermal optical model, we have also simulated the modally-resolved output power versus current characteristics for the VCSEL with and without a surface relief for single fundamental mode control. The results show that the relatively large diffraction loss in these devices (particularly for higher order modes) gives rise to strong fundamental mode selection, indicating that a surface relief is redundant in this aspect for devices with a BTJ diameter smaller than 8 µm. However, the results show that the surface relief can be used to efficiently boost the maximum output power.

3. Device Results

Devices were tested on-wafer under CW operation on a temperature controlled heat sink. Fig. 2 illustrates the emitted optical power and voltage drop for VCSELs with and without ISR as a function of drive current. Threshold current, threshold voltage and differential quantum efficiency for the device without ISR are 4.15 mA, 0.8V and 7.4%, respectively. Corresponding values for the device with ISR are 5.31 mA, 0.856 V and 14.5%, respectively. The higher threshold current/voltage and the higher differential quantum efficiency of the device with ISR can be explained by a somewhat lower top mirror reflectivity for the fundamental mode (since it has a certain overlap with the ring-shaped surface relief). The maximum optical output power of the device with and without ISR are 613 µW @ 16.7 mA and 560 µW @ 21.4 mA, respectively where it is seen that the thermal rollover occurs earlier in the device with ISR than without ISR. The reason is not fully understood yet. The smaller kinks in the multimodal device without ISR (as shown in Fig. 2) can be explained by changes in intensity distribution among all excited modes or the change of the mode pattern with the change of driving current.

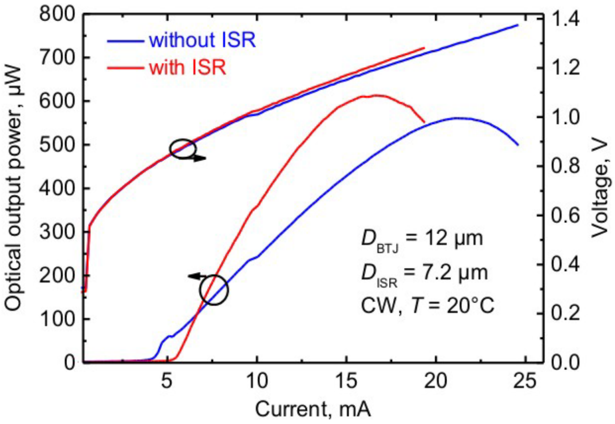

Fig. 2: *L-I-V* characteristics of a standard BTJ VCSEL with and without inverted surface relief.

Fig. 3 shows emission spectra for both devices with and without ISR measured at 6, 12 and 18 mA. Here we can see that the original device without ISR is highly multimode whereas the device with ISR becomes single-mode even at thermal rollover current. The SMSR is over 25 dB. Note that, the transverse mode spacing in BTJ VCSELs is a bit higher than in GaAs or InP-based VCSELs because of larger emission wavelength. Measured values are in the range of 7 - 9 nm as shown in Fig. 3. By (electro-)thermal tuning, one achieves a tunability of 0.5 nm/mA at a constant heat-sink temperature of $T = 20°\mathrm{C}$, making the devices well-suited as light sources for spectroscopic photonic sensors.

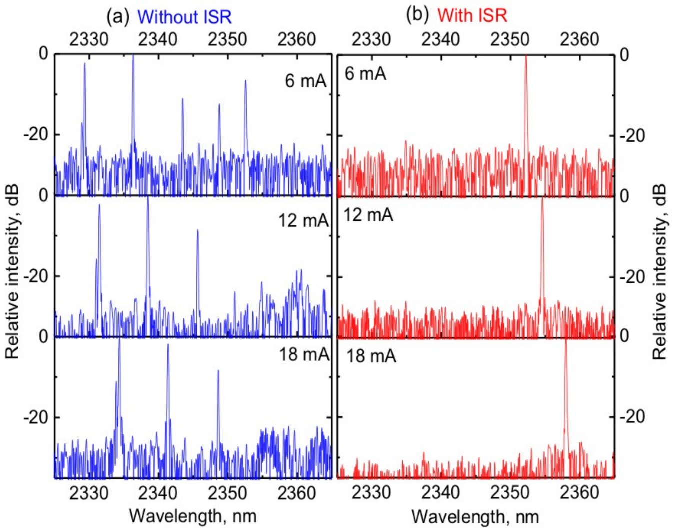

Fig. 3: Emission spectra of the VCSEL at different driving currents. device (a) before and (b) after applying an ISR

4. Conclusion

We have introduced single fundamental mode selection and stabilization in a large-area BTJ-VCSEL by structuring a circular ring-shaped inverted surface relief on top of the dielectric Bragg mirror. Single-mode lasing over the entire operating range is obtained for devices with aperture diameters as large as $D_{\mathrm{BTJ}} = 12$ µm in this way. These results strongly confirm the suitability of the ISR technique for single-mode enhancement, since it is effective and reliable as well as relatively simple in fabrication.

5. Acknowledgments

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