Ultra-compact intra-cavity contacts for multi-terminal VCSEL power enhancement

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Abstract – We demonstrate ultra-compact intra-cavity contacts fabricated with an embedded Al_2O_3 etch-stop, which effectively shorten the cavity length and enhance the output power of a multi-terminal VCSEL.

I. Introduction

As the conventional diode vertical-cavity surface-emitting lasers (VCSELs) gained huge process in the communication and sensing area [1], multi-terminal VCSELs have also become very intriguing due to their novel functionalities [2]-[4]. These complex devices normally incorporate lengthened cavity designs and extra intra-cavity contacts. A lengthened cavity and the insertion of extra highly-doped layers inevitably lead to a smaller confinement factor Γ, a higher internal loss α_i, and thus a higher threshold current I_{th}. The differential quantum efficiency (DQE) η_d, determined by the injection efficiency η_i, the internal loss α_i, and the mirror loss α_m according to (1), will also be reduced as a result.

$$\eta_d = \eta_i \frac{\alpha_m}{\alpha_m + \alpha_i} \tag{1}$$

The combined effect of a higher I_{th} and a lower DQE is a reduction in the output power. Moreover, a higher I_{th} also means a lower differential gain and a lower modulation speed. To address these issues that multi-terminal VCSELs commonly share, a way to make compact intra-cavity contacts is very desirable.

II. Wet thermal oxide as the embedded etch-stop

To compress the cavity length and enhance device yield, we developed an etch-stop process by tailoring the composition of the first AlGaAs DBR layer that is directly adjacent to the quantum wells (QWs), so an elongated Al_2O_3 layer will form after the wet thermal oxidation together with the oxide aperture. This wet thermal Al_2O_3 is impervious to Cl_2-based dry-etch and can be easily removed with a selective wet-etch, making an embedded etch-stop feasible.

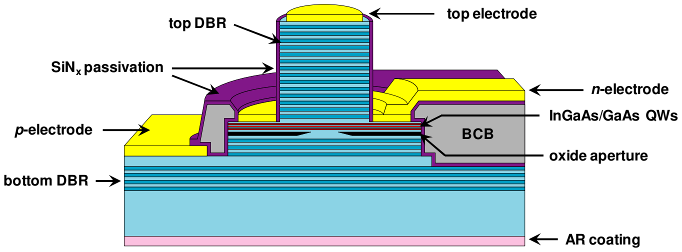

Fig. 1. Schematic of a compact cavity three-terminal VCSEL.

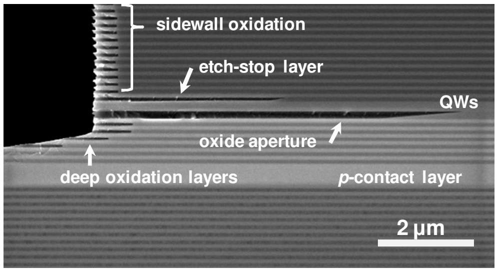

Fig. 2. Cross-sectional SEM image of various oxide structures.

To demonstrate this process, we designed a compact cavity three-terminal VCSEL with the embedded Al_2O_3 etch-stop, with schematic is shown in Fig. 1. The SEM image of various oxide structures (after wet thermal oxidation) is shown in Fig. 2. It is crucial to design the layer structure carefully so the etch-stop extends long enough to protect the quantum well layer completely, but also short enough so the optical mode will only be confined by the oxide aperture, otherwise extra loss will be induced. The InGaAs/GaAs quantum wells, sandwiched by the oxide aperture and the etch-stop layer, are grown with delta-doped silicon in the barriers to provide two-dimensional electron gas (2DEG) carrier injection from the ring contact. As a result, no extra etch buffer layer is required, the cavity length is kept minimal, and the doping within the cavity is minimized.

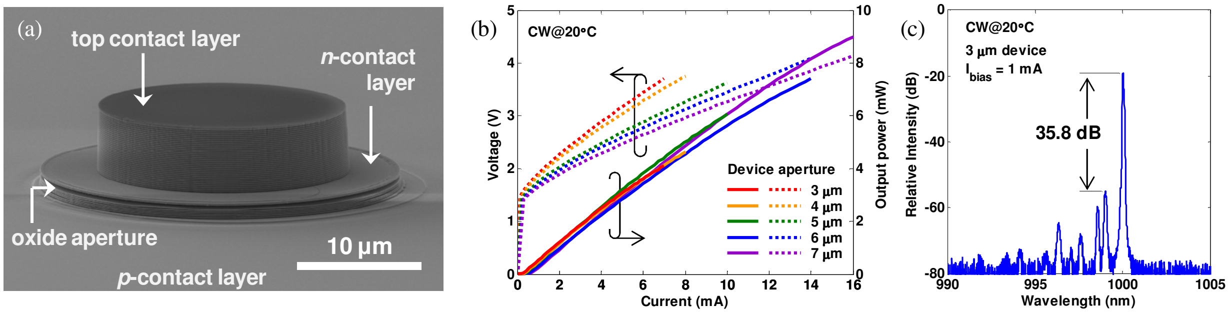

Fig. 3. (a) SEM image of the double mesa, after etch-stop removal . (b) L-I-V curves. (c) lasing spectrum of a 3μm devie with I_{bias} = 1 mA.

III. Device Fabrication

The base structure was grown on semi-insulating GaAs (100) substrate with a bottom emission configuration. First dry-etching down to the *p*-contact layer was used to define the outer mesa. Afterwards, wet thermal oxidation simultaneously created the oxide aperture and the etch-stop layer, which endured the second inner mesa dry-etch and allowed over-etching for good uniformity. The Al_2O_3 etch-stop and the residual Al_2O_3/GaAs sidewall were removed with AZ400K developer, exposing the smooth intra-cavity *n*-contact layer, as shown in Fig. 3(a). A vertical silicon nitride sidewall was created through a semi self-aligned process [5] to isolate the ring *n*-contact and the top DBRs. The ring *n*-contact, *p*-contact and top *n*-contact metals were deposited separately, followed by annealing, BCB planarization, electrode pads deposition, and backside anti-reflection (AR) coating.

IV. Experimental Results

The fabricated devices were tested with a dc setup. Fig. 3(b) shows the voltage and output power versus current (L-I-V) curves for devices with apertures ranging from 3 μm to 7μm in diameter. The lasing wavelength is around 1000 nm. All of these devices have a sub-mA threshold current, with a differential quantum efficiency around 54%, and a threshold voltage around 1.54 V, just slightly above the bandgap. The series resistance decreases as the aperture scales up, from 298 Ω for the 3 μm device, to 156 Ω for the 7 μm device. Due to the nature of dual intra-cavity carrier injection, larger devices support multiple higher order modes. The 3 μm device supports single-mode operation up to 1.6 mA of bias current (Fig. 3(c)).

V. Conclusion

We have demonstrated the novel method of fabricating ultra-compact intra-cavity contact layers for VCSELs with the assist of an embedded Al_2O_3 etch-stop layer. Compact cavity three-terminal VCSELs were fabricated, and threshold currents and output powers were on par with those of state-of-the-art diode VCSELs. The series resistance can be further reduced by increasing the delta-doping in the quantum well barriers, or by introducing modulation doping at the optical nodes in the *p*-contact layer.

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