Optimization of VCSEL Structure for High-Speed Operation

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***Abstract*—The optimization of our tapered-oxide-apertured VCSEL structure for high-speed operation is presented. Using a new aperture design and *p*-doping recipe in the top mirror, bandwidths $>$ 20 GHz and 35 Gb/s error-free operation has been demonstrated.**

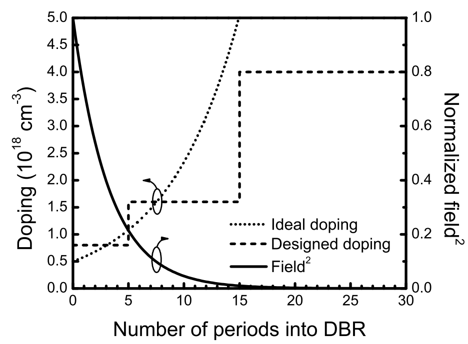
I. Introduction

In the past several years, vertical-cavity surface-emitting lasers (VCSELs) have received renewed interest for their potential applications in optical interconnects. Compared with edge emitters, VCSELs are preferable due to their small footprint, ease of fabrication in arrays, on-wafer testing, high-speed operation at lower power dissipation, and cost effectiveness. Last year, we first demonstrated 35 Gb/s error-free operation on 3 μm diameter high-speed VCSELs [1]. This achievement was enabled by the optimization of several key components of our VCSEL structure, especially tapered oxide aperture and *p*-doping in the top mirror, in order to minimize cavity loss and mode volume.

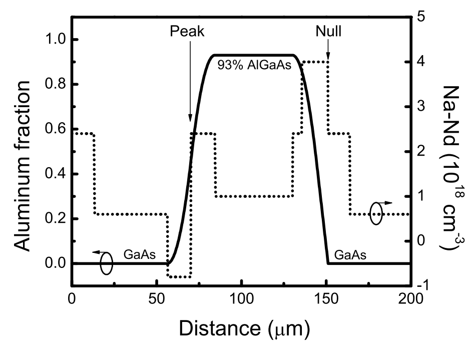
II. Device Design

We use *n*-intracavity, bottom-emitting, tapered-oxide-apertured VCSEL structure emitting at 980 nm wavelength. Details of the device structure and fabrication can be found in [1], [2]. The design of the structure involves many trade-offs and one of them is the electrical resistance and optical loss by doping concentration. Bandgap-engineering is commonly used to simultaneously achieve low resistance and low loss. Due to higher free carrier absorption loss and lower mobility of holes, we mainly focused on the optimization of the *p*-mirror. Fig. 1(a) plots the average doping concentration for each DBR period. Three different doping levels are used to approximate the calculated ideal doping profile. The doping is the lowest near the active region for low optical loss and increases as moving towards the top contact layer. Fig. 1(b) shows the low-doped DBR design within the period. At the standing-wave peaks, bi-parabolic grade and modulation doping is used to flatten the valence band [3]. On the other hand, uni-parabolic scheme is used at the standing-wave nulls so that holes are accumulated at the interfaces to reduce the resistance without adding extra losses [4].

Another trade-off is the mode confinement and optical scattering loss by aperture design. Fig. 2(a) shows two tapered oxide aperture designs. The top one is our original design which yields negligible optical scattering loss down to 1.5 μm diameter devices. However, it does not provide enough



(a) Average doping profile



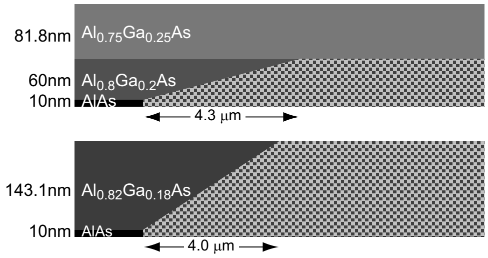
(b) Doping/grading within one period

Fig. 1: Optimization of the doping in the *p*-mirror.

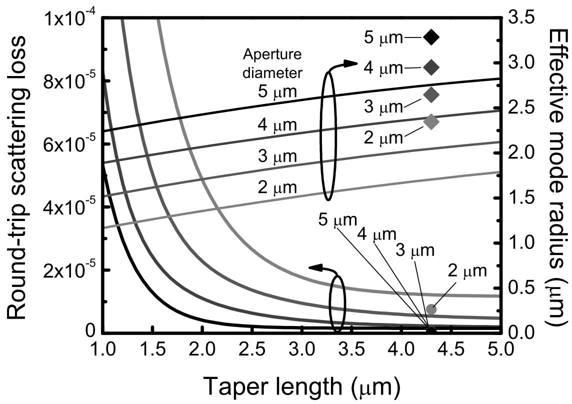
mode confinement for efficiently achieving high bandwidth. To optimize the aperture design, we simulated round-trip scattering loss and effective mode radius as a function of the taper length for a $\lambda/2$ thick aperture based on the model in [5]. The results are plotted in Fig. 2(b). Taper length of 4 μm was chosen and the final design is shown in the bottom of Fig. 2(a). Compared with our original design for 3 μm diameter devices, the effective mode radii reduced from 2.64 to 2.01 μm, corresponding to a 1.73 time mode volume reduction, which should give a 31% increase in relaxation resonance frequency and bandwidth. At the same time, the optical scattering loss does not increase noticeably.

III. Results

Fig. 3 shows the voltage, output power, and temperature rise against current (L-I-V-T) curves for a 3 μm diameter device. The device has a very low threshold current of 0.144 mA and a high slope efficiency of 0.67 W/A. This low threshold as well as high efficiency indicates that our short tapered



(a) Top: long taper design and bottom: short taper design.



(b) Simulated optical scattering loss and effective mode radius as a function of taper length for the devices with diameters ranging from 2 to 5 μm. Superimposed are the results for the long taper aperture: diamonds (effective mode radius) and circles (scattering loss).

Fig. 2: Optimization of tapered oxide aperture.

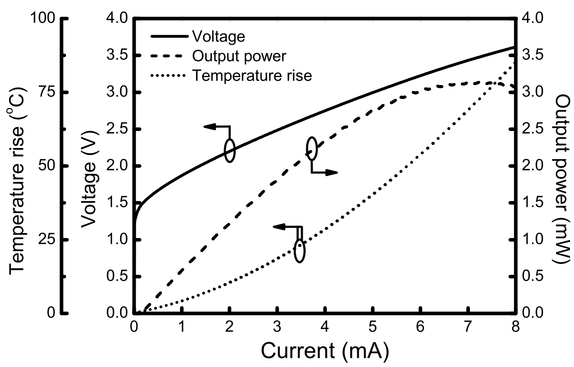
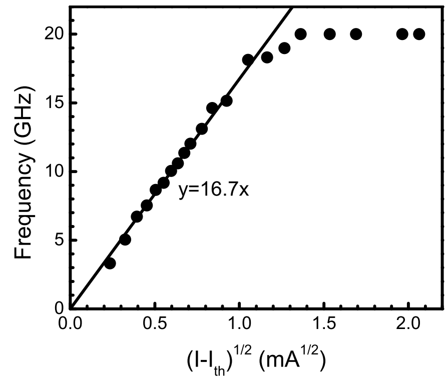


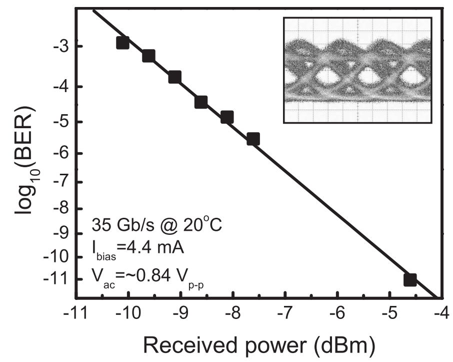
Fig. 3: L-I-V-T curves for 3 μm diameter device.

oxide aperture indeed does not introduce excess optical loss even down to 3 μm diameter range. The threshold voltage is only 1.47 V, 220 meV larger than the photon energy. This low threshold voltage is the consequence of the optimized *p*-doping scheme and the low threshold current. The series resistance is approximately 250 Ω at a bias current of 4.4 mA, where large-signal modulation experiments were performed. The peak wall-plug efficiency is 31% and the maximum output power is 3.1 mW. The thermal impedance of the devices is 3.3°C/mW.

Fig. 4(a) plots the 3-dB frequency versus $(I - I_{\text{th}})^{1/2}$. A bandwidth exceeding 20 GHz is achieved at bias currents > 2 mA. This is the highest bandwidth for 980 nm VCSELs. The modulation current efficiency factor (MCEF) of this



(a) 3-dB frequency vs. $(I - I_{\text{th}})^{1/2}$



(b) Bit-error-rate curve

Fig. 4: High-speed performance for 3 μm diameter device.

device is 16.7 GHz/mA$^{1/2}$, very close to the highest 16.8 GHz/mA$^{1/2}$ for QW-based VCSELs [6]. This high MCEF is the consequence of better lateral mode confinement from our short tapered oxide aperture. Fig. 4(b) plots the bit-error-rate curve at 35 Gb/s for a 3 μm diameter device [1]. The input was a non-retrun-to-zero signal with 2^7-1 word length. The bias current was 4.4 mA and the RF voltage swing was ~ 0.84 $V_{\text{p-p}}$. The inset shows the optical eye diagram and the eye is clearly open with an extinction ratio of 5.4 dB. The VCSEL power dissipation, excluding the RF circuitry, is only 10 mW. This corresponds to the highest data-rate/power-dissipation ratio of 3.5 Gbps/mW.

IV. Conclusion

By carefully designing the *p*-doping profile in the top mirror as well as the shape of the tapered oxide aperture, we demonstrate an improvement in our VCSELs' high-speed performance without compromising the static performance. Modulation bandwidth exceeding 20 GHz at bias currents $>$ 2 mA has been achieved. Moreover, data rate up to 35 Gb/s is demonstrated for only 10 mW power dissipation.

References

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