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Comparative Study of Nano-Cylindrical Waveguide and Buried-SiO_2 Apertures in Blue InGaN VCSELs

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***Abstract*—We study transverse mode control in InGaN-based blue vertical-cavity surface-emitting lasers (VCSELs) by investigating the most common index-guiding structure which is an etched nano-cylinder with and without a refill of SiO_2. Using 2–8 μm wide aperture diameters, we evaluate key performance metrics—threshold material gain (g_{th}) and modal discrimination. The etched aperture with a 5 nm etch depth exhibited the lowest threshold material gain among the designs studied. Notably, this configuration showed the smallest increase in threshold material gain when the aperture diameter was reduced from 8 μm to 2 μm. Furthermore, when decreasing the aperture from 8 μm to 4 μm, the g_{th} for the fundamental LP_{01} mode increased by just 95 cm^{-1}, while still achieving a high modal discrimination of 395 cm^{-1}. These results highlight the ability of the etched aperture to maintain low loss and strong mode selectivity over a practical range of aperture sizes.**

I. Introduction

A truly single-mode VCSEL operates only in the fundamental mode, producing a near-Gaussian beam with superior spectral purity, and low divergence. These properties are critical for various applications such as underwater optical wireless communication, smart glasses, adaptive laser headlights, and atomic clocks.

Lateral optical and current confinement have been achieved through various aperture design approaches in InGaN VCSELs. Such as silicon diffusion [1], air-gap aperture formed by photoelectrochemical etching [2], buried SiO_2 layer [3], and etched-passivated nano-cylindrical aperture [4].

Kuramoto et al. [4] and Terao et al. [5] have experimentally demonstrated single-mode operation in blue-emitting VCSELs using nano-cylindrical apertures with diameters of 3.3 μm and 4 μm, respectively. These results underscore the effectiveness of the nano-cylindrical design in promoting single-mode operation while maintaining a relatively simple and fabrication-friendly structure.

In this paper, we simulated the threshold material gain and modal discrimination of blue InGaN VCSELs having two aperture designs for lateral index guiding; an etched nano-cylinder with and without a refill of SiO_2 . The etched aperture had an etch depth of 5 or 10 nm and the SiO_2 refilled had an etch depth of 20 nm that was filled up with 20 nm of SiO_2.

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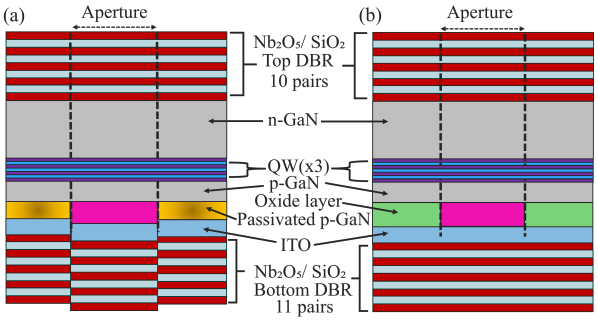

Fig. 1. Schematic of the the simulated VCSEL structure (a) with a passivated nano-cylindrical waveguide aperture and (b) with a buried SiO_2 aperture.

The studied aperture diameters were 2 μm, 4 μm, 6 μm, and 8 μm.

II. Device Simulation Design And Parameters

The VCSEL structure was simulated in Comsol multiphysics, using the finite element eigenfrequency solver. The schematic of the two aperture designs is shown in Figure 1. The VCSEL structure consists of a 10 λ cavity sandwiched in between 10 top and 11 bottom distributed Bragg reflectors (DBRs) of SiO_2 and Nb_2O_5. The DBR pairs were assumed to have zero absorption loss whereas the absorption coefficient for the quantum well barrier was 3 cm^{-1} , GaN 1 cm^{-1}, p-GaN 75 cm^{-1} and ITO 1000 cm^{-1}.

III. Results and Discussion

The modal discrimination was calculated as the difference in the threshold material gain (g_{th}) for the fundamental mode (LP_{01}) and the next higher order modes (LP_{11} or LP_{02}). Figure 2 shows the variation in g_{th} for LP_{01} as a function of the aperture diameter. As expected, g_{th} increases with decreasing aperture size due to increased diffraction loss, especially for aperture diameters below 4 μm. The effective index difference [6] (Δn_{eff}) between the central aperture region and the periphery region as shown in Figure 1 is 6.11 x 10^{-3} for a 5 nm etch, 12.27 x 10^{-3} for 10 nm etch and 8.16 x 10^{-3} for a 20 nm etched structure filled up with SiO_2. A larger Δn_{eff} leads to an enhancement in the mode confinement, but at the expense of an increase in the diffraction losses. The 5 nm

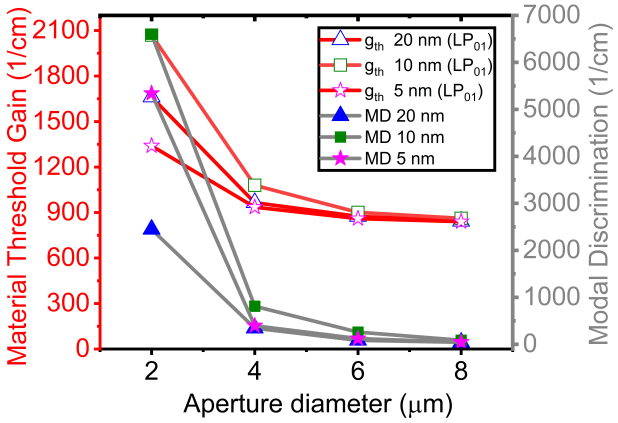

Fig. 2. Simulated impact of the aperture diameter on threshold material gain (g_{th}) for LP_{01} in red and modal discrimination in gray for 20 nm buried SiO_2 aperture and nano-cylindrical aperture with 10 nm and 5 nm etch depth.

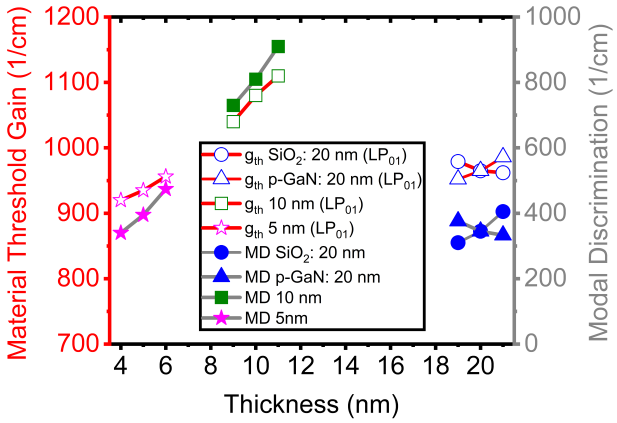

Fig. 3. Thickness vs. threshold material gain (g_{th}: left Y-axis) and modal discrimination (right Y-axis) for 4 μm aperture structures, highlighting tolerance to fabrication variations. Etch depth variations of $\pm$1 nm were applied to the nano-cylindrical aperture with 5 nm and 10 nm etched p-GaN. For the buried-SiO_2 structure two cases were considered: (1) variation of the deposited SiO_2 thickness by $\pm$1 nm with a fixed 20 nm p-GaN etch depth, and (2) variation of the p-GaN etch depth by $\pm$1 nm while keeping the SiO_2 thickness constant at 20 nm.

nano-cylindrical waveguide, with the smallest Δn_{eff}, shows the lowest g_{th}, while the 10 nm design, with the largest Δn_{eff}, exhibits the highest g_{th} across all aperture sizes. Figure 2 also presents the corresponding modal discrimination values for each structure as a function of the aperture diameter. The 5 nm etched nano-cylindrical waveguide design exhibited superior modal discrimination, particularly for smaller aperture diameters. For an aperture diameter of 2 μm, the 5 nm nano-cylindrical waveguide structure showed a modal discrimination of 5340 cm^{-1} and g_{th} of 1340 cm^{-1}, while the 20 nm SiO_2 buried structure showed values of 2448 cm^{-1} and 1661 cm^{-1}. The high modal discrimination reflects strong lateral confinement, which suppresses higher-order modes but also increases diffraction losses, raising the threshold gain. A 4 μm aperture diameter device with 5 nm etch shows a good trade-off between high modal discrimination (395 cm^{-1}) and low threshold material gain (935 cm^{-1}). The 20 nm SiO_2 configuration was equally good in terms of single-mode performance with a threshold material gain of 965 cm^{-1} and modal discrimination of 345 cm^{-1}.

Figure 3 presents a tolerance analysis for the 4 μm aperture case reflecting realistic fabrication deviations. The calculated g_{th} remained relatively stable, with values of 920 cm^{-1} for a 4 nm etch depth and 956 cm^{-1} for 6 nm. The corresponding modal discrimination values were 339 cm^{-1} for a 4 nm etch depth and 473 cm^{-1} for 6 nm - sufficient to favor LP_{01} over higher order modes and maintain single mode operation.

The g_{th} values for the constant 20 nm p-GaN etch with deposited SiO_2 thickness equal to 19 nm is 952 cm^{-1} and for 21 nm is 986 cm^{-1}. The corresponding modal discrimination values were 376 cm^{-1} for a 19 nm SiO_2 deposition and 333 cm^{-1} for 21 nm. Whereas for the constant 20 nm SiO_2 deposition the calculated g_{th} values were 979 cm^{-1} for 19 nm nm p-GaN etch and 962 cm^{-1} for 21 nm. The modal discrimination for this case was 310 cm^{-1} for 19 nm p-GaN etch and 405 cm^{-1} for 21 nm. For the nano-cylindrical apertures, varying the p-GaN etch depth results in centrally elevated structures in all cases. And both g_{th} and the modal discrimination increase with increasing height of this central elevation. However, for the buried-SiO_2 structure, changing either the etched p-GaN or deposited SiO_2 thickness while keeping the other constant leads to both centrally elevated and peripherally elevated structures. We saw that the centrally elevated structure has the lower g_{th} values of the two. Thus, both the 5 nm nano-cylindrical design and the centrally elevated buried-SiO_2 design demonstrates strong modal selectivity, but the latter requires an additional fabrication step.

Conclusion

In summary, we performed simulations of InGaN-based blue VCSELs with varying aperture diameters, investigating two transverse index guiding schemes. Our results, together with those from [4, 5] suggest that a modal discrimination value in the range of 300-350 cm^{-1} is a practical benchmark for effective suppression of higher-order transverse modes. This guideline is useful for the design of mode-filtering structures such as surface reliefs, metasurfaces, or tapered oxide apertures. It is important to note that our study is based solely on optical simulations of a cold cavity. For a complete evaluation of VCSEL performance, future work should incorporate coupled optical, electrical, and thermal modeling to account for the full complexity of the device behavior.

References

[1] Yeh et al., Appl. Phys. Lett, 109, 241103 (2016).
[2] Leonard et al., Appl. Phys. Lett, 108, 031111 (2016).
[3] Kuramoto et al., Appl. Phys. Express, 12, 091004 (2019).
[4] Kuramoto et al., Appl. Phys. Express, 13, 082005 (2020).
[5] Terao et al., Proc. Of SPIE Vol. 11686 (2021).
[6] G. R. Hadley, Opt. Lett. 20, 1483 (1995).