Standing Wave Engineering for Mode Control in Single-Mode Oxide-Confined Vertical-Cavity Surface-Emitting Lasers

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Keywords: Vertical-cavity surface-emitting lasers, single fundamental mode, anti-phase optical coating

Single transverse mode operation in vertical-cavity surface-emitting lasers (VCSELs) is desired over multimode operation in a number of applications. This work presents a method of achieving single-mode operation by depositing an annulus-shaped semiconductor coating atop an 850 nm oxide-confined VCSEL to modify the standing wave of the optical field in the laser cavity. The devices are benchmarked for single-mode performance as well as optical output power via optical spectra and light-current-voltage (L-I-V) measurements respectively.

INTRODUCTION

Due to the inherent properties of vertical-cavity surface-emitting lasers such as a circular beam shape, small footprint, and low manufacturing cost, VCSELs are becoming ubiquitous across several applications. This includes laser printing and optical mice to new and emerging applications in 3-D facial recognition, light detection and ranging (LIDAR), and short-haul optical communication systems utilizing pulse amplitude modulation (PAM-4). These emerging systems are also pushing existing VCSELs to their performance limits in terms of optical power and emission range over which single-mode operation is achieved. This necessitates the development of methods for ensuring single fundamental mode operation while maximizing power output. Standard methods of mode-control in VCSELs include surface-etch relief [1] and photonic crystals [2] which reduce the power reflectance of the top distributed Bragg-reflector (DBR) and in turn raise the threshold modal gain of the device, making it more difficult to lase. However, these methods face several challenges as they require extensive control over the dry etch process. Even with in-situ monitoring, etch uniformity can vary greatly over the surface of a wafer that makes etch depth difficult to control. Furthermore, any etch induced roughness can significantly degrade the reflectivity of the top DBR. To alleviate these issues, a semiconductor anti-phase coating is proposed. The finer control of deposition thickness and uniformity from modern PVD sputtering systems over dry etching techniques makes the semiconductor anti-phase coating more manufacturable and easier to implement for optical mode-control in VCSELs.

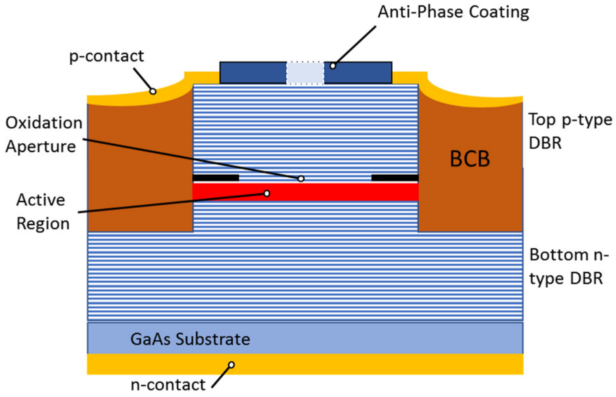

Fig. 1 VCSEL cross-sectional schematic with anti-phase coating and oxide-confined active region. Anti-phase coating is in the shape of an annulus (hollow center, lighter blue).

ANTI-PHASE COATING

The cross-section of a VCSEL with the anti-phase coating is shown in Fig. 1. The mechanism behind the effectiveness of the anti-phase coating is the spatial controllability of the threshold modal gain (g_{th} in Eq. 1)

$$\Gamma g_{th} = \alpha_i - \frac{1}{2L}\ln(R_1 R_2) \qquad \text{(Eq. 1)}$$

across the top plane of the VCSEL. In Eq.1, α_i is the total intrinsic absorption loss in the material, L is the length of the optical cavity, and R_1 and R_2 are the power reflectivities of the top and bottom DBR mirrors, respectively. The transverse mode profile of VCSEL consists of the fundamental mode (the desired lasing mode) lying in the center of the device while higher-order modes lie radially further away. By

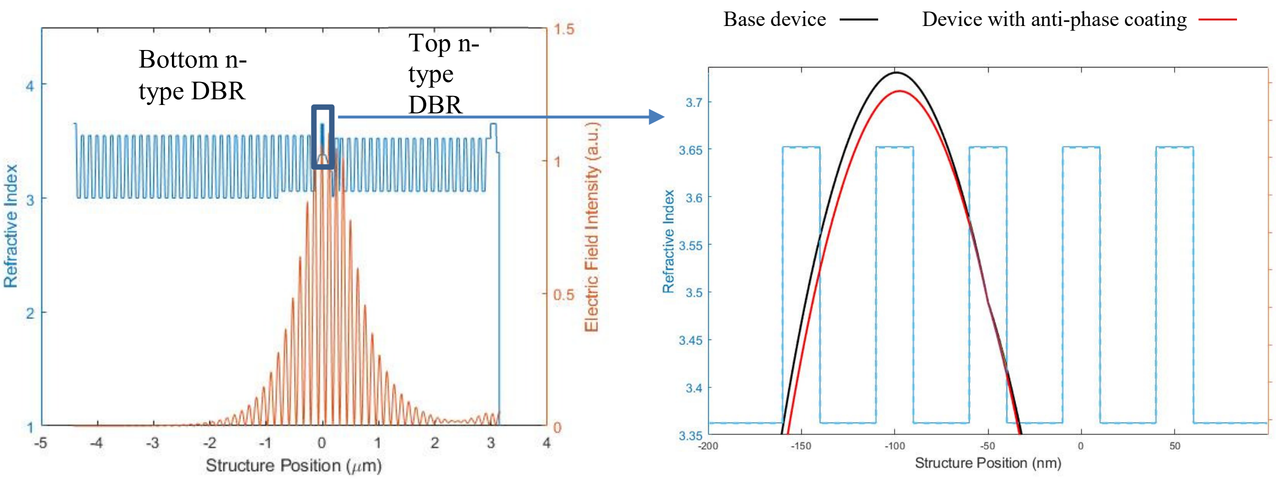

Fig. 2 Standing wave pattern in a VCSEL superimposed with the refractive index of the structure. The wave pattern in the mode-controlled device (left) contains ripples near the surface and a shift in the wave pattern in the active region (right).

depositing a silicon thin film atop of the device, a phase mismatch is introduced into the electric field standing wave pattern. This shift misaligns the peak electric field with the quantum-wells in the gain region and leads to a reduced confinement factor and consequently increased threshold modal gain. If this is done only on the outer region of the device by depositing the silicon anti-phase coating in the shape of an annulus, fundamental mode operation can be ensured by suppressing the higher order modes and without significantly impacting the threshold modal gain of the fundamental mode. Previous work on VCSEL filters [4,5] were designed for VCSEL structures with incomplete top mirrors intended for inverted surface relief devices. This required a multilayered dielectric coating to account for and correct the incomplete mirror design. It was found that utilizing an epitaxial structure with a complete mirror allowed the design of a single layer rather than multiple that moreover achieves superior results. It was determined through threshold modal gain calculations that if a higher refractive index material, such as silicon, is used rather than a dielectric material, the phase mismatch in the top DBR can be maximized and create the greatest threshold modal gain difference between the center and the outer regions.

The electric field standing wave pattern of this VCSEL structure can be seen in Fig. 2, where the wave pattern is in orange and the index of refraction of the structure is in blue (surface of VCSEL is at 3 μm mark). When the anti-phase coating is added to the device (Fig. 2, left), the standing wave is shifted such that destructive interference occurs at the surface of the device and manifests as ripples due to the phase mismatch. This destructive interference reduces the field amplitude in the quantum well active region from 1.066 to 1.061 (Fig. 2, right), lowering the confinement factor and raising the threshold modal gain from 26 cm^{-1} to 245 cm^{-1}. This effect can be seen in Fig. 3 (left), where the blue curve represents the GaAs cap layer that minimizes the threshold gain of the device (100 nm mark) and the red curve represents the Si layer that is maximized at the 150 nm mark. This determined the thickness of the Si annulus to be 50 nm in order to maximize the threshold gain for the higher order modes of the VCSEL. As mentioned earlier, Si was used over a dielectric material such as TiO_2 because of its higher refractive index and the advantages can be seen by comparing the graphs in Figure 3. The peak threshold modal gain achieved via a TiO_2 coating is 120 cm^{-1} at a thickness of 80 nm, whereas the peak modal gain achieved via a Si coating increases in value by 104% to 245 cm^{-1} at a thickness of 50 nm. By increasing this peak threshold modal gain value and designing the coating in the shape of an annulus, greater higher-order mode suppression can be obtained.

DEVICE FABRICATION & CHARACTERIZATION

The epitaxial design of the VCSEL presented in this work was specifically designed for high power operation. The structure from top to bottom is follows: a 100 nm GaAs cap layer, 20 top p-type $Al_xGa_{1-x}As$ DBR pairs, 5 $In_xGa_{1-x}As$ quantum wells, 32 bottom n-type $Al_xGa_{1-x}As/AlAs$ DBR pairs and an n-type GaAs substrate. A single high-aluminum content AlGaAs layer is inserted above the active region for selective oxidation during the fabrication process. The choice of InGaAs quantum-wells is designed to provide increased differential gain, dg/dn, compared to traditional AlGaAs quantum-wells. The insertion of binary AlAs into the bottom DBR allows for a higher thermal conductivity from the active region to the substrate. Fabrication of the VCSEL begins with depositing a PECVD SiN_x film that is lithographically patterned to serve as a dielectric hard mask. The VCSEL mesas are then formed by using a $BCl_3/Cl_2/Ar$ ICP-RIE dry etch monitored in-situ by a laser interferometer. The devices are then loaded into a wet furnace at 430°C to form the oxidation aperture. The diameter of the oxidation aperture is

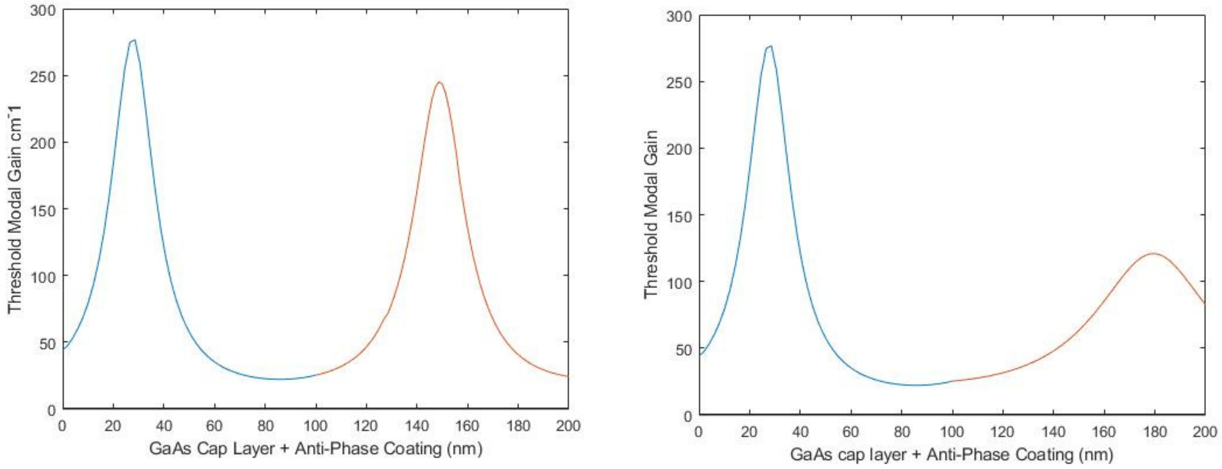

Fig. 3 Threshold modal gain of VCSEL. Modal gain with GaAs cap layer (blue curve) is minimized at 100 nm and maximized with a Si coating at 50 nm (left graph, red curve) and with a TiO_2 coating at 80 nm (right graph, red curve).

verified through infrared imaging. Next, the devices are planarized and electrically isolated using spin-on curable polymer, benzocyclobutene (BCB). The BCB is then etched back to expose the VCSEL mesas and a BCB via etch is done to expose the bottom DBR. Afterwards a n-type ohmic metal stack consisting of AuGe/Ni/Au can be deposited via electron beam evaporation and patterned via a liftoff process. Following this a Ti/Pt/Au top side ohmic p-contact is formed using a similar process. Next, preliminary characterization data is taken to measure the threshold current, optical power, and spectra. Following this, the anti-phase coating is created by Si deposition via e-beam evaporation and photolithographic patterning. Finally, the VCSELs are recharacterized to measure single-mode operation and improvements in fundamental mode output power and optical spectra.

CONCLUSION

Mode-control in oxide-confined VCSELs via an anti-phase filter enables single-mode operation, allowing for enhanced performance for emerging applications well-suited to VCSELs and their inherent properties over other lasers. By manipulating the shape of an anti-phase filter, this can be achieved by selectively lasing the fundamental mode while suppressing higher-order modes.

ACKNOWLEDGEMENTS

This work is sponsored in part by the II-VI Foundation under the Block-Gift program.

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ACRONYMS

VCSEL: Vertical-Cavity Surface-Emitting Laser
DBR: Distributed Bragg Reflector