Polarization Control in Vertical-Cavity Surface-Emitting Lasers via Elliptical Aperture Definition in Optical Coatings

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Elliptical apertures of varying eccentricity are defined in a silicon anti-phase optical coating deposited atop circular-aperture oxide-confined 850 nm VCSELs to enable preferential lasing in a single-polarization state. The introduction of an asymmetrical coating aperture induces dichroism into the VCSEL, suppressing the polarization state aligned to the longer, major axis of the elliptical aperture. A circular oxide aperture is retained to maintain the spatial symmetry of the optical transverse modes. The VCSELs are characterized for output power and polarization state suppression via polarization-resolved light-current-voltage (PR-LIV) curves and optical spectra measurements.

INTRODUCTION

The field of vertical-cavity surface-emitting lasers (VCSELs) has experienced a resurgence after their incorporation into 3D scanning applications including facial recognition in consumer smartphones and light detection and ranging (LiDAR) for autonomous systems. This is made possible due to their energy-efficient operation, small footprint with the capability of on-wafer probing, and a circularly-symmetric emission beam. The oxidation aperture, the process first discovered by Dallesasse and Holonyak [1] and applied to VCSELs by Huffaker et al. [2], is used to define the active region and confine optical/electrical carriers resulting in linearly polarized (LP) transverse modes. VCSELs, however, typically operate with 2 perpendicular polarization states aligned to the [110] and $[1\bar{1}0]$ crystal axis, operating at 2 different wavelengths as a result of the polarization-independent distributed-Bragg reflector (DBR) mirrors, an isotropic gain medium, and a circularly-symmetric cavity. Having multiple polarization states leads to polarization switching, a higher relative noise intensity (RIN), and a lower optical signal to noise ratio (SNR). Many sensing applications implement wavelength-dependent components, motivating the need to suppress one of the polarization states to maintain spectral purity and coherence.

The suppression of polarization states can be accomplished by introducing dichroism into the VCSEL, where the threshold gain is asymmetric across the device such that one polarization state is suppressed. By patterning an elliptical aperture into an optical coating on the top of the device, the polarization state along the longer, major axis of the VCSEL is suppressed leading to lasing in the polarization state aligned to the minor axis. Previous attempts have included elliptical surface relief [3] and elliptically-shaped mesas [4], where device performance and spatial transverse mode symmetry were negatively affected. This work resolves these issues by introducing elliptically-shaped anti-phase coating (APC) apertures building off of previous multilayer anti-phase coatings [5] and circular-aperture anti-phase coatings [6]. By defining elliptical apertures into single-layer anti-phase coatings, preferential lasing of the polarization state aligned to the minor axis of the elliptical aperture occurs. The circular symmetry of the fundamental mode, provided by the index contrast created by the circular oxide aperture, is maintained. This is one of the main advantages of the anti-phase coating compared to other methods mentioned; retaining the circular symmetry of the optical beam is vital for optical transceivers and other applications necessitating a smooth gaussian beam to achieve high optical SNR.

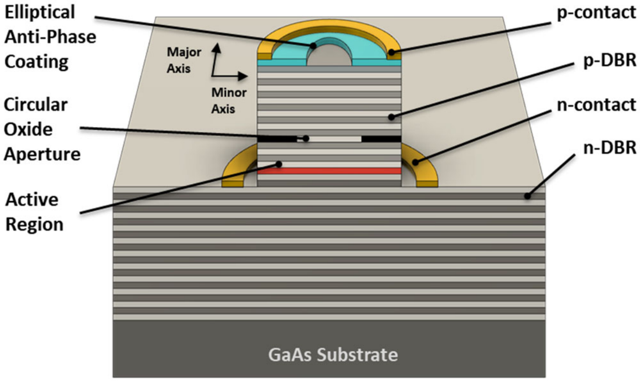

Fig. 1 Cross-sectional schematic of an oxide-confined VCSEL with an elliptical anti-phase coating aperture for preferential operation in a single-polarization state.

ANTI-PHASE COATING DESIGN

The basics of the anti-phase coating as a mode-control [5, 6] and polarization-control method relies on disrupting the fine-tuned electric-field standing-wave pattern of the structure. By depositing an additional layer atop the VCSEL, destructive interference between the outgoing wave and reflected wave from the surface of the VCSEL creates an out-of-phase (anti-phase) standing-wave pattern, increasing the local threshold gain. By selectively patterning an elliptical aperture into the layer to form the anti-phase coating, a higher threshold gain can be imparted onto the major axis polarization state, suppressing its ability to lase. The thickness and refractive index of the coating needs to be precisely controlled to ensure proper performance. The thickness of the anti-phase coating is λ/4n, the same thickness as a half-DBR pair and leads to maximum disruption of the standing-wave pattern. Additionally, a material with a large refractive index such as silicon (n = 3.8) produces more destructive interference than materials with low index such as SiO_2 (n = 1.45) or TiO_2 (n = 2.3), leading to a larger threshold modal gain and enhanced capability to suppress the undesired polarization state.

Tuning of the physical thickness during the fabrication process has been accomplished multiple ways, with the most reliable and manufacturing-friendly method consisting of deliberate over deposition of the target thickness (t=44 nm) and etch back in a reactive ion etching (RIE) system. Various gas chemistries have been utilized to achieve a low etch rate and an anisotropic etch profile in the optical coating. This has resulted in a 20 nm/min etch rate, requiring short etches of ~20 s to realize the incremental etches down towards the target thickness. Optimization into achieving a high refractive index coating was accomplished via altering the electron-beam current during the electron-beam evaporation process. By increasing the e-beam current and thus the deposition rate, higher energy silicon atoms bombard the structure, reducing pillaring of the existing atoms and densifying the coating [7]. Additionally, the use of a high-quality tantalum crucible is preferred due to the enhanced thermal environment, resulting in more runs-per-crucible and a more controllable evaporation. A high e-beam current of 110 mA was used to realize a deposition rate of ~25Å/s, resulting in a refractive index of ~3.8, as verified via a witness sample composed of a quartz microscope slide covered in deposited silicon and characterized in a spectroscopic ellipsometer.

As shown in Fig. 2, the baseline structure without the coating has a minimized threshold modal gain at a value of 24 cm^{-1} with an unetched 100 nm GaAs cap layer. With an anti-phase coating fabricated with a low refractive index (n=2.2) silicon, a peak threshold modal gain of 126 cm^{-1} can be realized at a coating thickness of 78 nm. As mentioned, with a higher refractive index coating, an even larger threshold modal gain can be achieved. By fabricating a coating with high quality silicon (n=3.8), a peak threshold modal gain of 296 cm^{-1} can be realized at a coating thickness of 44 nm. With this higher threshold modal gain, enhanced suppression of transverse modes and polarization states can be achieved, as will be shown later in this work.

DEVICE FABRICATION AND CHARACTERIZATION

Fabrication of the VCSELs begins with the growth of the epitaxial material via MOCVD and follows a standard oxide-confined VCSEL process flow (the epitaxial structure is described elsewhere [6]). The process begins with the definition of the VCSEL mesas in an inductively-coupled plasma (ICP)-RIE etcher using a SiN_x hard mask. The mesas are etched deep enough to expose the high aluminum content oxide layer, and wet oxidation is done to form the 4μm circular oxide aperture. Afterwards, the devices are planarized using benzocyclobutene (BCB) to provide electrical insulation. The BCB is then etched back in an RIE system to expose the top cap layer of the VCSEL where the Ti/Pt/Au p-contact is deposited and annealed to form ohmic contacts. Finally, the substrate is thinned via chemical-mechanical polishing (CMP) and the bottom AuGe/Ni/Au n-contact is deposited and annealed. Elliptical apertures of varying eccentricity are patterned via a photolithographic liftoff process. The optimal size and eccentricity of the elliptical aperture coatings has been found to be slightly less than the oxide aperture size while maintaining only a slight elliptical shape. It was found that a coating aperture with too much eccentricity disrupted the transverse modes and desired polarization state too much, leading to lower output powers and lower OPSR, as will be shown later.

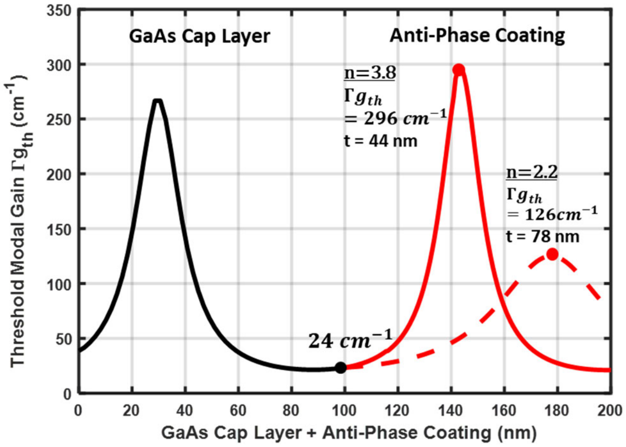

Fig. 2 Threshold modal gain of 850 nm VCSEL minimized for the base structure (24 cm^{-1}), maximized with n=3.8 coating (296 cm^{-1}) and n=2.2 coating (126 cm^{-1}).

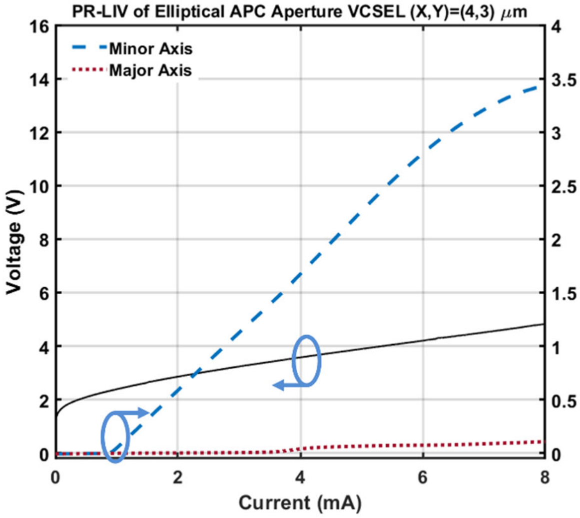

Fig. 3 Polarization-resolved light-current-voltage (PR-LIV) curve of VCSEL with a 4x3 μm elliptical aperture patterned into anti-phase coating.

The VCSELs are characterized for output power and polarization suppression via polarization-resolved light-current-voltage (PR-LIV) curves, where single-polarization operation is defined as an orthogonal polarization suppression ratio (OPSR) of 20 dB. The apparatus for characterizing the VCSELs involves an integrating sphere equipped with a linear polarizer and photodetector calibrated for operation at 850 nm. The polarization-resolved measurements are obtained by integrating the linear polarizer in the beam path and rotating it to align with the major and minor axis of the elliptical anti-phase coating aperture. Fig. 3 shows the PR-LIV curves of a slightly elliptical (4 x 3 µm) anti-phase coating aperture VCSEL that exhibits polarization suppression of the major axis polarization state until 3 mA of injection current with single-polarization output powers polarized along the minor axis up to 1.15 mW, and a maximum total output power of 3.4 mW. This single-polarization operation is confirmed in Fig. 4 where the OPSR at 3mA reaches 20 dB. Below 3 mA, the major axis polarization is suppressed such that it only emits with spontaneous emission. At 4 mA, threshold is reached and begins to emit with very low power, peaking at 0.2 mW. While this output power increase is very low, it is significant enough to reduce the OPSR below the 20 dB benchmark for single-polarization operation. This highlights one of the biggest issues faced when attempting to realize consistent polarization control in VCSELs: having sufficient suppression of the major axis polarization state while maximizing lasing in the minor axis polarization state.

As the elliptical aperture size decreases to 3.5 x 2.5 µm, the elliptical coating begins to impinge on the transverse mode profile and the minor axis polarization state, resulting in a lower OPSR of 17 dB. Further reduction of the aperture size to 3.0 x 2.5 µm further reduces the OSPR to 15 dB, and the smallest aperture of 2.5 x 2.0 µm results in the lowest OPSR of 11 dB. There is a significant increase in the threshold current for the VCSELs with the 3 smallest coating apertures due to the mirror losses induced by the elliptical coating. As for devices with a larger elliptical aperture than those mentioned above, particularly when one of the dimensions is larger than the oxide aperture, the overlap between the coating and transverse modes decreases such that the suppressive effects of the coating are mitigated.

Conclusion

Elliptical aperture optical coatings deposited atop VCSELs have been shown to produce single-polarization operation by suppressing the polarization state aligned to the major axis of the elliptical aperture. An optimal coating size and eccentricity needs to be found to adequately suppress the major axis polarization state without unwanted impingement onto the minor axis polarization state and fundamental transverse mode. Further tailoring of the aperture size is needed to extend the single-polarization operation range while simultaneously achieving single-fundamental-mode operation, desirable for emerging sensing applications.

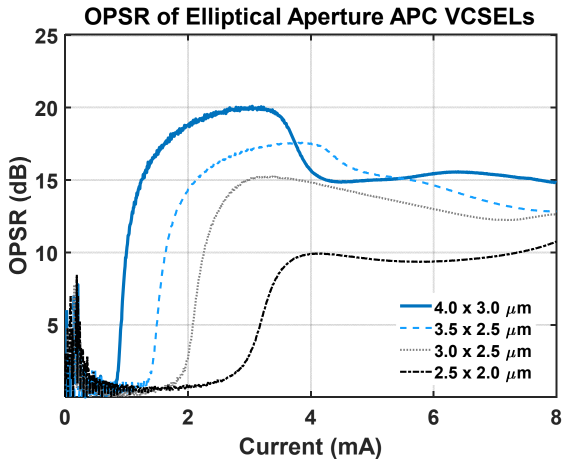

Fig. 4 Orthogonal polarization suppression ratio (OPSR) curves of VCSELs with varying elliptical aperture sizes patterned into anti-phase coatings.

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