Fabrication and Characterization of the Oxidation Process for 940 nm VCSEL Wafers

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Abstract: The oxidation process is critical in fabricating 940 nm vertical-cavity surface-emitting lasers (VCSELs), directly affecting device efficiency, beam quality, and production yield. This study investigates the design and control of oxidation apertures using simplified epitaxial structures and aluminum composition tuning. IR microscopy, SEM, and XRD were applied to evaluate aperture size, oxidation rate, and uniformity. A strong linear correlation was observed between Al content and oxidation distance, identifying an optimal range of 98.2–98.4% Al. These findings provide a predictive model for oxidation control and a practical strategy for scalable VCSEL manufacturing.

Key Words: VCSEL; wet oxidation; aluminum composition; characterization

1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) are compact and efficient semiconductor lasers that emit light vertically from the wafer surface. A typical VCSEL structure consists of a pair of distributed Bragg reflectors (DBRs), a multiple quantum well (MQW) active region, and a current confinement aperture formed through selective oxidation (Iga, 2000; Choquette & Lear, 1997).

The DBRs, composed of alternating high- and low-index materials, act as highly reflective mirrors to form an optical cavity. Light generated in the active region undergoes multiple reflections between the DBRs, enabling vertical resonance. The MQW region, located at the center of the cavity, is designed with alternating thin layers of lower bandgap materials (wells) and higher bandgap barriers. Due to quantum confinement, charge carriers (electrons and holes) are confined in discrete energy states, which enhances radiative recombination and improves threshold and efficiency (Coldren, Corzine, & Mashanovitch, 2012). This makes MQW structures ideal for achieving stable, wavelength-specific emission with low threshold current.

The emission wavelength of a VCSEL is determined by the interplay between quantum confinement in the MQW region and optical resonance in the vertical cavity. Quantum wells confine electrons and holes in discrete energy levels, leading to efficient radiative recombination at a narrow spectral range. This gain peak must align with the cavity's optical resonance, defined by the condition $2nL = m\lambda$, where L is the cavity length and n is the effective refractive index (Choquette & Lear, 1997; Piprek, 2003). For 940 nm emission, both the MQW band structure and the optical cavity must be precisely engineered to ensure spectral overlap, which is essential for minimizing threshold current and ensuring single-mode stability.

A crucial component of VCSEL performance is the oxide aperture, formed by wet thermal oxidation of high-Al-content AlGaAs layers. The oxide layer serves to restrict current injection and lateral optical modes, improving efficiency, mode control, and power stability. However, the oxidation process is highly sensitive to Al composition, temperature, and oxidation time — making process repeatability a major challenge (Chung, Lee, & Shieh, 2015; Lee & Lin, 2019; Park, Lee, & Kim, 2014).

This study aims to optimize the oxidation process for 940 nm VCSELs using simplified epitaxial structures to model and predict oxidation behavior. The effects of aluminum composition on oxidation rate and aperture uniformity are evaluated through a combination of microscopy and material analysis techniques. The resulting findings provide practical guidelines for process tuning and scalable VCSEL fabrication.

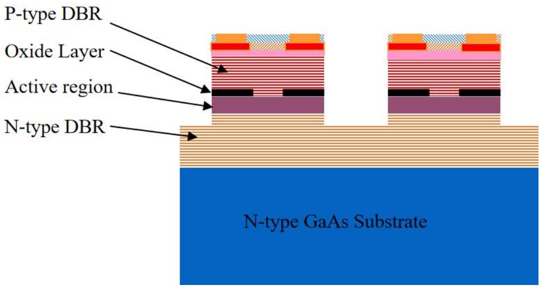

Figure 1. Schematic cross-section of a typical VCSEL structure. The laser cavity is formed by the top and bottom DBRs. The MQW active region lies in the center, and a selectively oxidized AlGaAs layer forms a current-confining aperture. Current injection and optical emission occur vertically.

2. METHODOLOGY

2.1 Sample Preparation

Epitaxial wafers with simplified VCSEL structures were grown using metal-organic chemical vapor deposition (MOCVD) by the EPI team. These wafers were designed to exclude the top and bottom distributed Bragg reflectors (DBRs) to focus the experiment on oxidation behavior. Variants of aluminum (Al) composition were included in the oxidation layer to study its impact on oxidation characteristics (Kim et al., 2014; Park et al., 2014).

2.2 Wet Oxidation Process

Prior to oxidation, wafers were cleaned using a standard solvent sequence and immediately loaded into the oxidation chamber within 10 minutes to prevent surface degradation. Oxidation was carried out in a vertical multi-wafer furnace. The process temperature was held constant while oxidation time was varied across experiments (5–10 minutes). After oxidation, a SiN_x layer was deposited via PECVD to prevent further exposure to moisture and thermal diffusion (Chung et al., 2015; Tsai et al., 2018).

2.3 Characterization and Analysis

The oxidation behavior was characterized through a combination of optical microscopy (OM), infrared microscopy (IR) and scanning electron microscopy (SEM). OM was used to inspect surface morphology and measure aperture dimensions, while IR microscopy provided non-destructive imaging of lateral oxidation depth and uniformity. The SEM and FIB offered cross-sectional views of the oxide interface and mesa structure, confirming boundary sharpness and structural integrity. During epitaxial growth, X-ray diffraction (XRD) was employed to quantify the aluminum composition in the AlGaAs layers. Subsequent wafer processing, including oxidation, enabled the correlation of Al content with oxidation rate. Together, these techniques provided comprehensive insights into the oxidation process and its dependence on material parameters(Zhou et al., 2016; Lin et al., 2020).

2.4 Experimental Logic and DOE Flow

Initial tests were performed on wafer fragments to rapidly screen oxidation rates at various durations. Once an approximate oxidation rate was obtained, full wafer experiments were conducted using optimized time intervals. The oxidation rate, aperture uniformity, and resulting structure were recorded and analyzed for each wafer. Results were iteratively fed back to the EPI laboratory for aluminum composition adjustments in the next growth batch (Tsai et al., 2018; Lee & Lin, 2019).

3. RESULTS AND DISCUSSION

3.1Oxide Aperture Visualization Using Infrared Microscopy

Infrared (IR) microscopy was used to examine the lateral oxidation profile of the VCSEL mesa. As shown in Figure 2, a distinct circular oxide aperture was formed around the central unoxidized region. The high contrast between oxidized and unoxidized AlGaAs layers allows for direct visualization of the aperture boundary. This result confirms that the oxidation process proceeded uniformly and predictably under the chosen process conditions (Zhou, Lin, & Zhang, 2016).

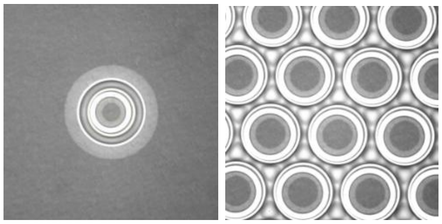

Figure 2. Infrared microscopy image of a VCSEL mesa after wet oxidation.

3.2 Cross-Sectional Structural Analysis by SEM

To evaluate the structural integrity and oxidation depth, scanning electron microscopy (SEM) was conducted. The cross-sectional image in Figure 3 shows a well-preserved multilayer epitaxial structure, with clear horizontal striations corresponding to DBR layers. The lateral oxidation distance reached approximately 8.55 µm, and the DBR oxide distance was measured at approximately 305 nm. The oxidation interface is smooth and continuous, with no signs of delamination, void formation, or thermal stress damage. These observations validate the reliability of the oxidation process and its compatibility with VCSEL vertical structures (Lin, Wu, & Kuo, 2020).

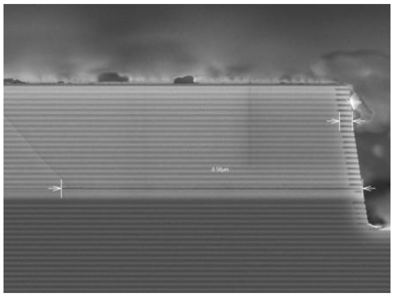

Figure 3. SEM cross-section of an oxidized VCSEL mesa.

3.3 Influence of Aluminum Composition on Oxidation Behavior

To investigate the effect of aluminum content on oxidation behavior, epitaxial wafers with varying Al mole fractions were oxidized under identical conditions. The resulting oxide aperture sizes were measured and plotted in Figure 4. A clear positive correlation was observed between the aluminum composition and oxidation distance, consistent with findings in prior literature (Chung et al., 2015; Park et al., 2014).

The oxidation distance increased from 7.10 µm (Sample C, 98.185% Al) to 12.55 µm (Sample A, 99.1% Al). Notably, Sample D (98.30% Al) achieved an oxidation distance of 7.76 µm, closely matching the target value. This composition window (98.2 – 98.4%) provides both a predictable oxidation rate and high uniformity, making it optimal for volume production.

A linear regression yielded the following relation: Oxidation Distance (µm) =
5.958×Al Composition (%) – 577.883
with a coefficient of determination of R^2=0.9998, confirming a strong linear dependency.

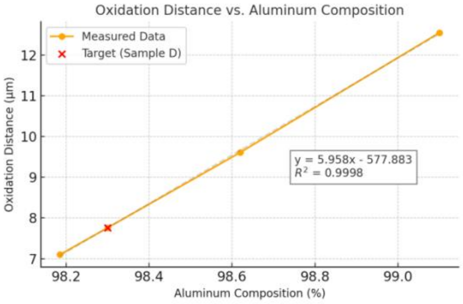

Figure 4. Measured oxidation distances at different aluminum compositions. The linear fit shows an excellent correlation (R^2=0.9998), with Sample D marked as the design target.

4. CONCLUSIONS

This study demonstrated that oxidation aperture size in 940 nm VCSELs can be accurately predicted and controlled via aluminum composition. Simplified structures effectively simulate full-device oxidation behavior. With Al content between 98.2%–98.4%, reproducible and stable oxidation was achieved. These results offer a practical guide for VCSEL process tuning and scale-up.

5. ACKNOWLEDGMENTS

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