Growth and fabrication of 850 nm AlGaAs/GaAs vertical cavity surface emitting laser structure

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Abstract. In this work, we demonstrate the NIP's all in-house development of a vertical cavity surface emitting laser structure. The VCSEL structure grown via MBE consists of an AlAs/AlGaAs distributed Bragg reflector and an AlGaAs/GaAs quantum well designed to issue at the 850 nm region. Reflectance spectroscopy showed that the stop band is centered around the designed wavelength. The electroluminescence spectra displayed that the maximum light emission corresponded to its design. This is a crucial step in the NIP's development of semiconductor lasers, leading towards future high-speed and highly-tunable VCSEL devices.

1. Introduction
Semiconductor lasers have been at the forefront of high-speed interconnects, thanks to the development of lasers capable of operating at gigahertz speeds [1]. Expansion to other applications such as proximity sensing [2] and light detection and ranging (LIDAR) [3] have driven further research on this field. For high-speed devices, switching speeds at the gigahertz range are desired [1], while high tuning speeds and increased tunability are sought for wavelength-tunable devices [4]. With its molecular beam epitaxy (MBE) and device fabrication facilities, the National Institute of Physics (NIP) has recently renewed its research thrust in this field, most notably on vertical cavity surface emitting lasers (VCSELs).

The VCSEL is a type of semiconductor laser with light emission orthogonal to the wafer plane. Its main advantages over other conventional semiconductor lasers such as edge-emitting lasers are the ease of coupling to optical fibers, direct wafer scale probing and low threshold operation [5]. A standard VCSEL design is composed of an optical cavity with an active region in the center, which is usually a quantum well (QW). The optical cavity is then sandwiched between two distributed Bragg reflectors (DBRs), which are highly reflecting mirrors composed of alternating high and low refractive index medium materials. The stop band of the DBR, which is the wavelength region with the highest reflectance, should coincide with the QW emission wavelength. Oxidation apertures, usually situated near the active region, are also employed for optical and current confinement [6].

In this paper, we report on the all in-house development of an AlGaAs/GaAs-based DBR VCSEL structure at the chip level. The whole process entails the whole production processes: the growth of the layers, device fabrication, and characterization of both as-grown and device-fabricated layers. Oxidation was also performed to explore the possibility of current and optical confinement effects [6].

2. Experimental Details
The VCSEL layers were grown using a Riber 32P molecular beam epitaxy chamber and are detailed in Figure 1. The layers were grown on an GaAs substrate, starting with 24.5 DBR pairs of Si-doped AlAs/Al$_{0.29}$Ga$_{0.71}$As layers. The λ-cavity was composed of 248 nm Al$_{0.29}$Ga$_{0.71}$As spacer, at the middle of which is the active region composed of three 90 Å GaAs QWs with 80 Å of Al$_{0.29}$Ga$_{0.71}$As barriers in between the wells. On top of the cavity is another 25 pairs of Be-doped Al$_{0.29}$Ga$_{0.71}$As/AlAs layers, which was terminated by a 20 nm Be-doped GaAs cap. To confirm the presence of the DBR, the wafer was subjected to normal incidence reflectance spectroscopy, in which light from a tungsten-halogen lamp dispersed by a Spex 500M monochromator was used as excitation, and a Si photodiode was used for detection. Scanning electron microscopy (SEM) using a Hitachi SU8230 was used to observe the morphology and measure the thickness of the grown layers.

![Figure 1. MBE layer details of the VCSEL structure.](image)

The wafer was then cleaved to 1cm×1cm chips, which were then degreased using acetone, methanol and deionized H$_2$O. Mesas with 250 μm diameter were patterned onto the chips using a Karl Suss MJB3 mask aligner. The mesas were etched in piranha solution until the first few bottom DBR pairs below the active region were accessed. One of the chips was then oxidized for one hr at 430°C in a tube furnace with ambient H$_2$O vapor and N$_2$ carrier gas. The extent of oxidation along the mesa was measured using a Wyko interferometer. Top metal contacts were then patterned onto both unoxidized and oxidized samples using the MJB3, and 147 nm of indium were deposited onto on both front and backside using resistive evaporation. The current-voltage (IV) curves of the fabricated devices were taken using a Tektronix 370A curve tracer and electroluminescence (EL) spectroscopy was performed using a 10× objective to collect the EL signal, which was fiber-fed to an Andor Shamrock 303i spectrometer equipped with a CCD detector.

3. Results and Discussion

The SEM images of the as-grown layers are shown in Figure 2. While the DBR layers are mostly consistent regarding thicknesses, there are two outlier AlGaAs layers present at the bottom DBR, which were at the 11th and 15th layers.
Figure 2. (a) SEM image of the whole VCSEL structure. The green and yellow arrows label the 11th and 15th bottom DBR AlGaAs layers, respectively, which were the outlier layers. (b) Higher magnification SEM image in the region of the 15th bottom DBR AlGaAs layer, which is labeled by the yellow arrow.

The thicknesses of the layers are summarized in Table 1. The cause of the outlier layers in the 11th and 15th AlGaAs layers is possibly due to sudden overflux of gallium during growth of the bottom DBR. The top DBRs were close to their nominal thicknesses, which is confirmed by the high reflectance at the 850 nm region as shown in its reflectance spectrum in Figure 3. The nominal emission wavelength of the 90 Å quantum well at 850 nm was within the stop band, and the stop band’s width was measured to be 127.5 nm.

| Layer                    | Measured Thickness (nm) | Nominal Thickness (nm) | % Error |
|--------------------------|-------------------------|------------------------|---------|
| AlGaAs DBR layers        | 54.3 ± 4.4              | 62                     | 12.4    |
| AlGaAs outlier DBR Layers| 180.6 ± 2.7             | 62                     | 191.3   |
| AlAs DBR layers          | 73.0 ± 9.1              | 71                     | 2.8     |

Table 1. Measured DBR layer thicknesses.

Figure 3. Reflectance spectra of the as-grown VCSEL structure. The dotted line indicates the nominal emission wavelength of the QWs.
The optical and Wyko image of the oxidized sample depicting the oxidation fronts is shown in Figure 4. There is an observable band at the outer edge of the mesa structure from both optical and Wyko image. This corresponds to the oxidized parts of the AlAs layers exposed along the sidewall of the mesa having been oxidized to Al$_2$O$_3$. From Figure 4b, the unoxidized aperture was measured to be 172.33 μm, which is the remaining conducting region within the mesa.

**Figure 3.** (a) Optical and (b) Wyko images of the oxidized mesa structures. Scale bar in (a) is 50 μm.

The IV curves for both oxidized and unoxidized fabricated devices are shown in Figure 4a. For the unoxidized sample, the turn-on voltage was 2.8 V, and the forward bias resistance was at 7.66 kΩ. For the oxidized sample, the turn-on voltage was 6.0 V, and the forward bias resistance was at 9.43 kΩ. The high forward bias resistance for both devices was due to the use of AlAs instead of high Al mole fraction AlGaAs for the DBR layers. The increased resistance in the oxidized sample was due to a conversion of the exposed AlAs DBR layers to Al$_2$O$_3$, which has higher resistivity than AlAs [7,8]. Performing grading between AlGaAs and AlAs could lower the forward bias resistance [9].

**Figure 4.** (a) I-V curves and (b) EL spectra of the unoxidized and oxidized VCSEL structure. The EL spectra were taken with each of devices driven at 20 mA.

The devices were then driven to 20 mA, and the resulting EL spectra are shown in Figure 6. Both unoxidized and oxidized sample display EL emission at around 850 nm and FWHM of roughly 2.4 nm, which corresponds to the QW emission wavelength and the λ-cavity wavelength. There is a marked 2.8× increase in the EL intensity from the unoxidized sample to the oxidized sample. This is due to the increased current confinement in the oxidized sample resulting from the reduced conducting region in the mesa [6,10]. However, the EL intensities for both samples are too low to be indicative of
lasing. The samples did not lase possibly due to the imperfect bottom DBR mirror. Table 2 summarizes the fabricated laser structures’ optoelectronic properties.

**Table 2.** Optoelectronic properties of fabricated laser structures. Peak emission wavelength, FWHM, and EL intensity were taken at 20mA source current.

| Sample          | Turn-on Voltage (V) | Forward Bias Resistance (kΩ) | Peak EL Wavelength (nm) | Peak EL FWHM (nm) | Peak EL Intensity (counts) |
|-----------------|---------------------|-------------------------------|-------------------------|-------------------|---------------------------|
| Unoxidized      | 2.8                 | 7.66                          | 850.8                   | 2.4               | 369                       |
| 1 hr Oxidized   | 6.0                 | 9.43                          | 850.1                   | 2.5               | 1050                      |

4. Conclusion
An all in-house 850 nm AlGaAs/GaAs VCSEL structure was successfully fabricated. The high forward bias resistance attributed to the use of AlAs instead of high mole fraction AlGaAs in the DBRs. Increased forward bias resistance from unoxidized to oxidized samples was due to oxidation of AlAs to Al₂O₃. EL emission centered at 850 nm resulted from effective top DBR, cavity and an active region. However, lasing was not achieved in both samples due to imperfections in the bottom DBR. The increase in the EL intensity in the oxidized samples was due to current confinement resulting from the reduced conducting region within the mesa.

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References
[1] Ou Y, Gustavsson J S, Westbergh P, Haglund A, Larsson A, and Joel A 2009 IEEE Photon. Tech. Lett. 21 (24) 1840-1842
[2] Marciniak M, Piskorski L, Gębski M, Dems M, Wasiak M, Panajotov K, Lott J A, and Czyszpanowski T 2018 J. Lightw. Technol. 36 (16) 3185-3192
[3] Warren M E, Podva D, Dacha P, Block M K, Helms C J, Maynard J, Carson R F 2018 Proc. SPIE 10552, Vertical-Cavity Surface-Emitting Lasers XXII, 105520E
[4] Li K, Chase C, Qiao P, and Chang-Hasnain C J 2017 Opt. Exp. 25 (10) 11844-11854
[5] Chuang S L 2009 Physics of Photonic Devices (Hoboken: John Wiley & Sons, Inc.)
[6] Grabherr M, Jäger R, Michalzik R, Weigl B, Reiner G, and Ebeling K J 1997 IEEE Photon. Tech. Lett. 9 (10) 1304-1306
[7] Madelung O 1991 Semiconductors Group IV Elements and III - V Compounds (Berlin: Springer – Verlag)
[8] Shackelford J F, Alexander W 2001 CRC Materials Science and Engineering Handbook (Boca Raton: CRC Press LLC)
[9] Hong M, Mannaeits, J P, Hong, J M, Fischer R J, Tai K, Kwo J, Vandenberg J M, Wang Y H, Gamelin J 1991 J. Cryst. Growth 111 (1) 1071-1075
[10] Choquette K D, Lear K L, Schneider R P, and Geib K M 1995 Appl. Phys. Lett. 66 (25) 3413-3415