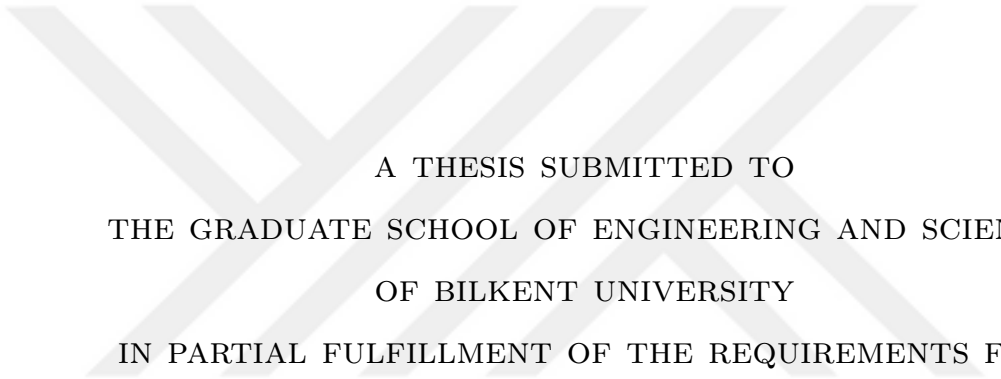


WAVELENGTH-SCALE LITHOGRAPHIC VERTICAL-CAVITY SURFACE-EMITTING LASER (LI-VCSEL)

Design, fabrication and optical characterization



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May 2021

Wavelength-scale Lithographic Vertical-Cavity Surface-Emitting Laser
(Li-VCSEL)

Design, fabrication and optical characterization

By Abdulmalik Abdulkadir Madigawa

May 2021

We certify that we have read this thesis and that in our opinion it is fully adequate,
in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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M.S. in Material Science and Nanotechnology
Advisor: Abdullah Demir
May 2021

Vertical-cavity surface-emitting lasers (VCSEL) are the ideal light sources for optical data communication and 3D sensing due to their small size, low power consumption, high-speed modulation, and low cost. The key to meeting the ever-increasing demand for higher efficiency and modulation devices is scaling down the cavities to near- or sub-wavelength sizes. The current state-of-the-art commercial oxide-VCSEL technology has been very successful for micro-scale cavity diameters ($> 3 \mu\text{m}$), but its processing approach is not appropriate for further miniaturization. Improvement in the performance of oxide-VCSELs can be achieved with smaller oxide aperture diameters. However, the high thermal resistance induced by the oxide layer significantly degrades the device performance, especially for the smaller sizes, making this method unreliable for scaling. In this work, we investigated a lithographically defined VCSEL (Li-VCSEL) method in which the transverse photonic and electrical confinement can be enabled by epitaxial growth and lithography. Transverse optical confinement is achieved by introducing an intracavity phase-shifting mesa that provides the confinement by index guiding. Numerical simulation results show high-quality factors even for submicron sizes, which is promising for the realization of submicron size single emitter and high-density array lasers. The fabrication steps include the epitaxial growth of the bottom semiconductor DBR and the cavity, defining the phase-shifting mesa using optical lithographic processes, and the deposition of the top dielectric DBR using thin film deposition techniques. We demonstrated room-temperature lasing around 980 nm from Li-VCSELs with mesa diameters ranging from $0.75 \mu\text{m}$ to $2.0 \mu\text{m}$ under continuous-wave optical pumping and presented detailed characterization of these devices. The results represent a significant step towards the realization of electrically pumped small-size lasers for practical optoelectronics applications.

Keywords: VCSEL, Lithographic VCSEL, Mode confinement, High quality factor, microlaser, nanolaser.



ÖZET

TÜRKÇE BAŞLIK

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Dikey-kovuklu yüzey-ışımalı lazerler (VCSEL), küçük boyutları, düşük güç tüketimleri, yüksek modülasyon hızları ve düşük maliyetleri nedeniyle optik veri iletişimi ve üç boyutlu algılama için ideal ışık kaynaklarıdır. Daha verimli ve modülasyon hızları yüksek cihazlara karşı sürekli artan talebi karşılamanın anahtarı, kovuk boyutunu dalga boyuna yakın veya daha küçük olacak şekilde ölçeklendirmektir. Mevcut son teknoloji olan ticari oksit-VCSEL teknolojisi, mikro ölçekli kovuk çapları ($> 3 \mu\text{m}$) için çok başarılı olmuştur, ancak üretim yöntemi daha fazla küçültmek için uygun değildir. Oksit-VCSEL'lerin performansında iyileşme, daha küçük oksit açıklık çapları ile sağlanabilir. Bununla birlikte, oksit tabakasının neden olduğu yüksek termal direnç, özellikle daha küçük boyutlar için cihaz performansını önemli ölçüde düşürür ve bu yöntemi küçültme için güvenilir hale getirir. Bu çalışmada, enine fotonik ve elektriksel sınırlamanın epitaksiyel büyüme ve litografi ile etkinleştirilebildiği litografik olarak tanımlanmış VCSEL (Li-VCSEL) yöntemini tanıttık ve araştırdık. Enine optik hapsetme, indeks kılavuzluğuyla hapsetmeyi sağlayan kovuk-içi faz-kaydırmalı bir mesa eklenerek elde edildi. Nümerik simülasyon sonuçları, mikron altı boyutlar için bile yüksek kalite faktörleri göstermektedir. Bu boyutlarda tek ve yüksek yoğunluklu dizin lazerlerin gerçekleştirilmesi için ümit vericidir. Üretim aşamaları, alt yarı iletken ayna (DBR) ve kovuk epitaksiyal yapısının büyüttürülmesini, optik litografik süreçler kullanılarak faz-kaydırıcı mesanın tanımlanmasını ve ince film biriktirme teknikleri kullanılarak üst dielektrik aymanın (DBR) biriktirilmesini içerir. Sürekli dalga optik pompalama altında 0,75 ila $2,0 \mu\text{m}$ arasında değişen mesa çaplarındaki Li-VCSEL'lerden oda sıcaklığında 980 nm civarında lazer ışıması elde ettik ve detaylı karakterizasyonlarını sunduk. Sonuçlar, pratik optoelektronik uygulamalar için elektrikle pompalanan küçük boyutlu lazerlerin gerçekleştirilmesine yönelik önemli bir adım olmuştur.

Anahtar sözcükler: VCSEL, Litografik VCSEL, Mod sınırlaması, Yüksek kalite faktörü, mikrolazer, nanolazer.

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To My Family



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Chapter 1

INTRODUCTION

1.1 Laser principle

Laser is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Lasers are devices that generate light through the process of optical amplification by stimulated emission of photons. Three components are required to generate a laser light: An active medium, a pumping mechanism, and an optical feedback mechanism. The active medium, also known as the lasing medium, is the optical gain's source within the laser. The pump source acts as the source of energy to excite electrons in the gain medium. The pump energy can be provided in the form of light or electric current. The feedback mechanism is provided by two highly reflective mirrors placed on opposite sides of the active medium to form an optical cavity or resonator. This configuration allows for the continuous passage of photons through the gain medium for light amplification. One mirror has lower reflectance to out-couple the light. Three processes enable the laser operation;

1. Absorption: The gain medium absorbs the pump energy and excites electrons from their ground state to excited states.
2. Spontaneous emission: The excited electrons return to a lower energy state and lose their energy by emitting a photon each.
3. Stimulated emission: Instead of electrons spontaneously dropping to a lower state, the electronic transitions are enabled by stimulating the electrons by

a photon. This process leads to the emission of a photon that is identical in phase and frequency to the actual photon. This process is sustained by the continuous round trip of photons in the resonator, leading to light amplification.

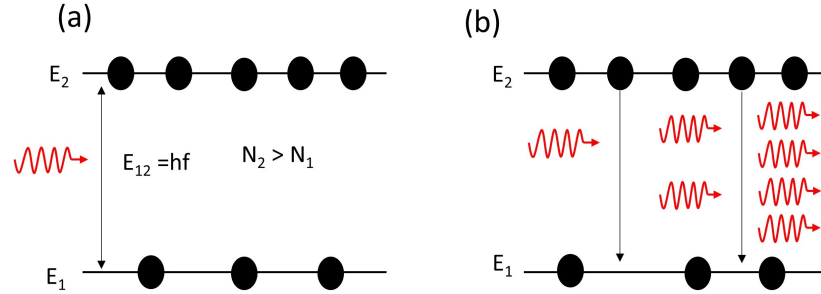


Figure 1.1: (a) *Electrons excitation to achieve population inversion* (b) *Light amplification by stimulated emission*

For light amplification or lasing to occur, the population of electrons in the excited states should be higher than electrons in the ground state. This condition is known as population inversion. Population inversion is achieved by the continuous pumping of the electrons to higher energy levels by the pump source. Another prerequisite for lasing to occur is that the gain must overcome all losses in the resonator. The minimum gain required to reach this condition is known as the threshold gain g_{th} and is given by:

$$g_{th} = \gamma + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right) \quad (1.1)$$

Where L is the cavity length, R_1 and R_2 are the power reflectance of the mirrors, and γ is the effective loss coefficient which includes all losses. For a net amplification to occur, g_{th} must be greater than γ . The second term of the equation represents the useful laser output, which depends on the mirror reflectivities. The generated laser light has three main properties that make it different from other light sources such as fluorescent lamps :

1. Near-monochromaticity: it emits light with a very narrow range of wavelengths or a single color.
2. The emitted light is coherent, i.e., all the individual waves of light move in phase with each other.

3. The emitted light beam is directional, i.e., it is well collimated and has low divergence compared to other light sources.

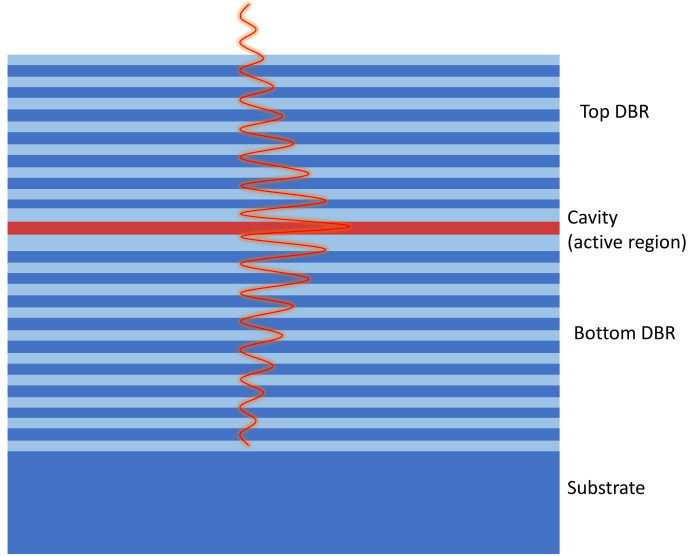
These qualities of a laser make it a good light source for many applications, including information technology, medicine, industry, military, e.t.c.

1.2 Vertical-cavity surface-emitting lasers

As the name implies, vertical-cavity surface-emitting lasers (VCSEL) are semiconductor lasers that emit light perpendicular to the wafer surface. This configuration enables several exciting and unique properties as compared to edge-emitting lasers. Its high beam quality with low divergence makes it an excellent choice for coupling to optical fibers. Its small cavity volume compared to edge-emitting lasers leads to low threshold current, high quantum efficiency, and high-speed modulation. It also enables the fabrication of large-scale high-density two-dimensional (2D) arrays for high-power and low-cost devices. Due to these unique properties, VCSELs have been used as ideal light sources in short-distance data communication [1], 3D sensing [2], optical interconnects [3], laser printing [4], laser mouse [5], light detection and ranging (LIDAR) [6] to mention a few. A standard VCSEL consist of an active medium (QWs) sandwiched between two highly reflective mirrors ($> 99\%$) to form a vertical resonance cavity, with one mirror having slightly lower reflectivity to couple the light out. The mirror acts as a feedback mechanism to confine the light to the cavity. The reflective mirrors consist of alternating quarter-wave thick layers of high and low refractive index material known as the Distributed Bragg Reflectors (DBRs). The DBR is a vital component that provides optical feedback for light amplification. It is designed so that the reflectivity band is centered to the cavity mode and emits in the resonance wavelength. The QWs are positioned in the center of the cavity to align the antinode of the cavity standing wave for efficient light amplification.

1.3 Developments and state-of-the-art VCSELs

VCSELs have been developed for over 40 years since their invention in 1978. The first pn-junction based electrically pumped VCSEL was demonstrated in 1979 [7].

Figure 1.2: *Basic VCSEL structure*

The device consists of a double heterostructure of InGaAsP/InP with a $1.8\ \mu\text{m}$ thick InGaAsP active layer, and metal reflectors were used to form the cavity. The device was driven under pulse current injection at 77 K with a threshold current density of $11\ \text{kA}/\text{cm}^2$. The high threshold of this device resulted in a short life-time of the devices. The reduction of the cavity volume and metal reflector losses was deemed necessary in order to reduce this high threshold. A series of methods, such as employing a short cavity [8], changing the active media to a broader bandgap material, and increasing the reflectivity of the metal reflectors [9], was employed to reduce the threshold current density. However, the metal reflectors were limiting the efficiency due to their high optical absorption losses. The use of dielectric materials as mirrors was introduced to tackle this problem, as they have very low absorption losses. Multilayers of dielectric materials were used to achieve high reflective mirrors (Bragg reflectors). Distributed Bragg reflectors (DBR) is a quarter-wave multilayer stack consisting of alternating layers of high and low refractive index material (dielectric or semiconductor), in which the multiple reflections from the interfaces add up in phase to form high reflective mirrors ($> 99\%$). The use of DBRs in VCSELs led to the realization of low threshold devices [10] [11]. The first room-temperature continuous wave (CW) GaAs VCSEL was demonstrated in 1988 [12] using a combination of metal reflector and AlGaAs/AlAs DBR. AlGaAs/GaAs DBRs are mostly used in VCSELs because of the lattice matching and high index contrast between the AlGaAs and GaAs layers, which result in mirrors with high quality and high reflectivity with low

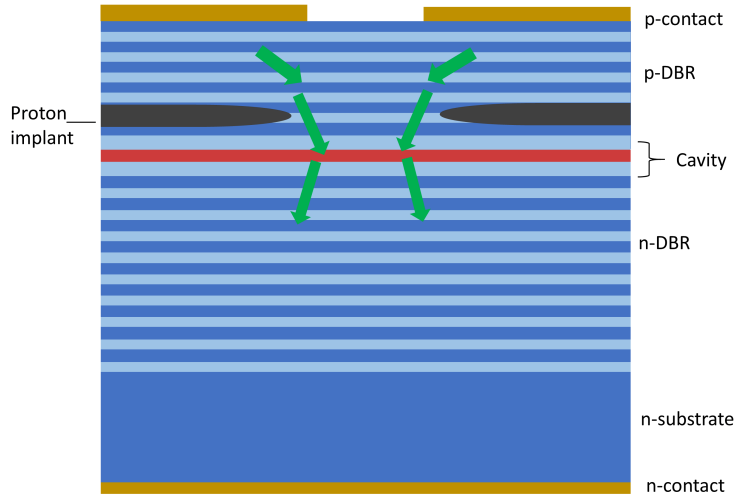
loss [13] [14]. Significant improvements were made by incorporating semiconductor DBRs as top and bottom mirrors, and VCSELs were employed for practical applications starting in the mid-1990s.

In order to obtain low threshold and high-performance VCSELs, three essential points should be considered in the design:

1. High-quality mirrors: High reflectivity of $> 99\%$ and low absorption losses.
2. Optical/photon confinement to a small volume in the structure.
3. Good electrical/current confinement.

1.3.1 Ion-implanted VCSEL

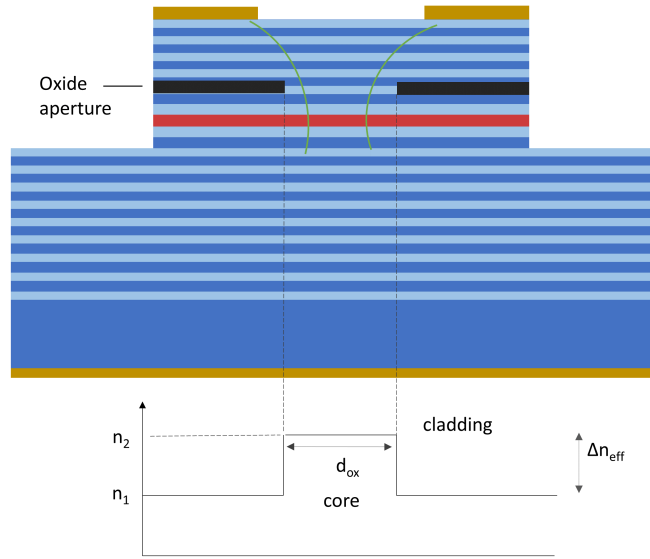
The keys to obtaining low threshold and high-performance VCSELs after high reflective low loss mirrors are the effective transverse confinement of the current and photon to a small volume in the cavity. One of the methods applied to GaAs VCSEL design uses ion/proton implantation to provide transverse current confinement as illustrated in Figure 1.3. Current confinement is achieved in the structure by ion implantation within the top DBR layers to form a high resistive region around a low resistive aperture. During implantation, the ions knock atoms off their lattice sites and create a semi-insulating region around the aperture. This insulating region restricts the current flow to the aperture area, thereby preventing the current from spreading to a larger area in the structure. The ions can be implanted in different areas around the structure to form apertures of different diameters. Ion-implanted VCSELs were demonstrated to exhibit high power single-mode emission, low threshold, and high efficiency [15]. However, since the implantation does not introduce lateral optical confinement, there are high optical losses caused by the field penetration into the lossy regions below the implant. Although the thermal lensing effects have been shown to introduce a thermally induced guiding that decreases the diffraction losses in small implant devices [16], its dependence on other parameters results in increased threshold current, nonlinear light-current characteristics, and unstable beam profile [17]. Incorporating a built-in optical guiding mechanism was a subject of research towards addressing this problem.


 Figure 1.3: *Proton-implanted VCSEL*

1.3.2 Oxide-aperture VCSEL

Although ion-implanted VCSEL has been shown to provide excellent current confinement, it suffers from high optical loss due to a lack of effective transverse optical confinement. The development of oxide-aperture VCSEL was inspired by the discovery of the III-V oxidation process by Dallesasse and Holonyak in 1989 [18]. In this discovery, selective lateral oxidation of AlAs buried in a multi-layer structure of GaAs was observed. This was observed after the hydrolyzation oxidation of the sample at a temperature of 400 °C in an ambient atmosphere in the presence of water vapor and nitrogen. The oxide formed from this process was found to be uniform and mechanically stable. This invention opened up the possibility for the integration of this process in optical devices. The first oxide-confined VCSEL was demonstrated by Deppe's group [19], utilizing the lateral oxidation of AlAs in the top DBR to improve the performance of VCSELs by increasing the optical overlap of the optical field with the gain region. The insulating oxide layer has the advantage of providing both transverse current and optical confinement. The oxidized layer has a lower refractive index than the surrounding medium. This produces a local blue shift of the resonance wavelength ($\Delta\lambda_o$) and a change of the effective refractive index (Δn_{eff}) between the inner and outer region, thus forming a waveguide for the optical modes [20].

The oxide VCSEL design is as shown in Figure 1.4. A mesa is created by etching from the top DBR to some part of the bottom DBR to make room for the


 Figure 1.4: *Oxide-aperture VCSEL*

oxidation process. The AlGaAs layer with high Al-content in the top DBR is oxidized by a wet chemical oxidation process to create an insulating aperture that confines both the current and optical mode to the center of the cavity [21]. The use of oxide-aperture has significantly increased the performance of VCSEL by effectively reducing the optical losses, and threshold current and enhancing the device power conversion efficiency [22] [23]. These oxide-aperture VCSEL characteristics have made it an ideal light source for use in data communication, high-end printing, and computer mice [21] [24].

1.3.3 Lithographic VCSEL Motivation

The drawback of oxide-confined VCSELs is that the oxide creates stress in the structure due to the difference in the thermal expansion coefficient between the oxide and the surrounding layers. This degrades the device's performance, and reliability, especially for small aperture diameter [25] [26]. Another issue is that smaller devices suffer from poor uniformity because the oxidation process is difficult to control. The ever-increasing application demand for higher efficiency and modulation bandwidth devices has opened the way to the development of better approaches to achieve high optical confinement with high scalability and reliability. Instead of relying on oxide apertures to develop better performance devices, a new method was introduced to provide similar transverse current and

optical mode confinement as the oxide aperture by only epitaxy and lithographic techniques. The optical mode confinement was achieved by introducing an intra-cavity phase shifting layer that provides optical confinement by index guiding as shown in Figure 1.5. Previous studies showed that this method has good mode confinement with lower loss than the oxide-VCSEL for $7\ \mu\text{m}$ aperture diameter devices [27].

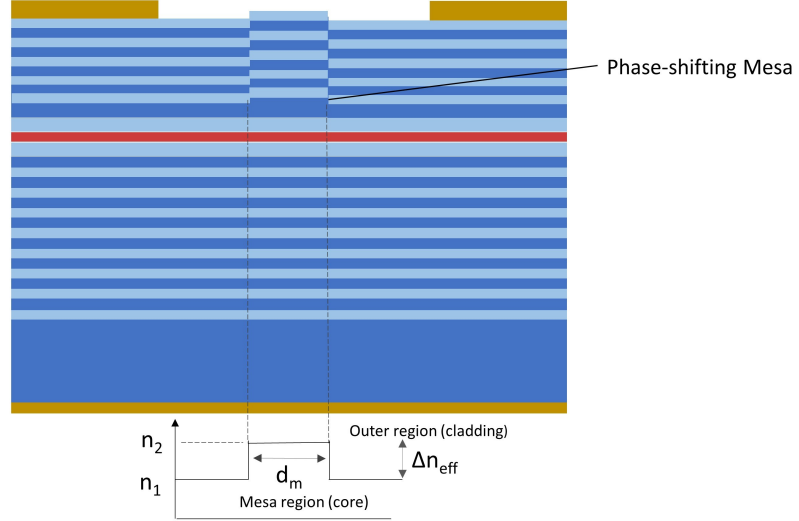


Figure 1.5: *Lithographic VCSEL*

Some of the advantages that this method has compared to other methods is that:

1. It is fabricated using scalable optical or e-beam lithographic techniques, allowing for good control of the device size.
2. Compared to oxide-confined VCSELs, it offers better heat dissipation and uniformity leading to higher device performance [28] and reliability [29].
3. High quality submicron and micron-scale cavity with wavelength tuning capability can be obtained [30].
4. With its high scalability, high-density 2D VCSEL arrays can be easily fabricated to achieve high output power and brightness for 3D sensing applications.
5. Current confinement can be incorporated by proper junction design [31].

In this work, we introduced and investigated the lithographically defined VCSEL method (Li-VCSEL) for micron and sub-micron mesa diameters.

1.4 Outline

Chapter 1 gives a brief background of VCSELs and the state-of-the-art technologies of VCSELs. Moreover, the motivations of the lithographic-VCSEL approach were discussed.

In Chapter 2, the mechanism by which mode confinement is achieved in lithographic VCSEL is presented. Investigation and optimization of the design using numerical FDTD simulations were also presented.

Chapter 3 explains the design and fabrication steps of the Li-VCSEL. The optimization approach and results of the various fabrication parameters were presented.

Chapter 4 presents and discusses the optical characterization results of the fabricated device.

In Chapter 5, the conclusion and future works were presented.

Chapter 2

LITHOGRAPHIC VCSEL (Li-VCSEL)

2.1 Optical mode confinement in Li-VCSEL

In this approach, the transverse optical confinement is enabled by lithographically defining an intra-cavity mesa to form two regions of different effective refractive index, forming a waveguide for light propagation in the longitudinal direction. This mechanism can be understood by applying the effective index model [20], which shows that any change in a VCSEL resonator that leads to a difference in the resonance wavelength ($\Delta\lambda_o$) between different lateral position in the device produces a corresponding change in the effective refractive index between the regions (Δn_{eff}).

$$\frac{\Delta n_{eff}}{n_{eff}} \approx \frac{\Delta\lambda_o}{\lambda_o} \quad (2.1)$$

This change can either be positive for redshift or negative for the blue shift, which results in guiding or anti-guiding of the light, respectively. This means that the cavity mode's optical confinement/guiding can be controlled by designing the VCSEL resonator with two regions having different effective refractive index. The controllability of this method allows for flexible design parameter choice to optimize and obtain high-performance devices.

2.1.1 Mesa Li-VCSEL

In this design, the transverse optical and electrical confinement is enabled by introducing a phase-shifting mesa, which is lithographically defined in the cavity as shown in Figure 2.1. The introduction of this phase-shifting mesa increases the effective refractive index in the mesa region, which creates a positive refractive index contrast (Δn_{eff}) between the mesa (core) and the outer region (cladding). This (Δn) value can be obtained by determining the resonance wavelength of the two regions and then measuring the amount of shift ($\Delta\lambda_o$) between them. The resonance wavelength shift can be controlled by adjusting the height and the diameter of the mesa(d_m).

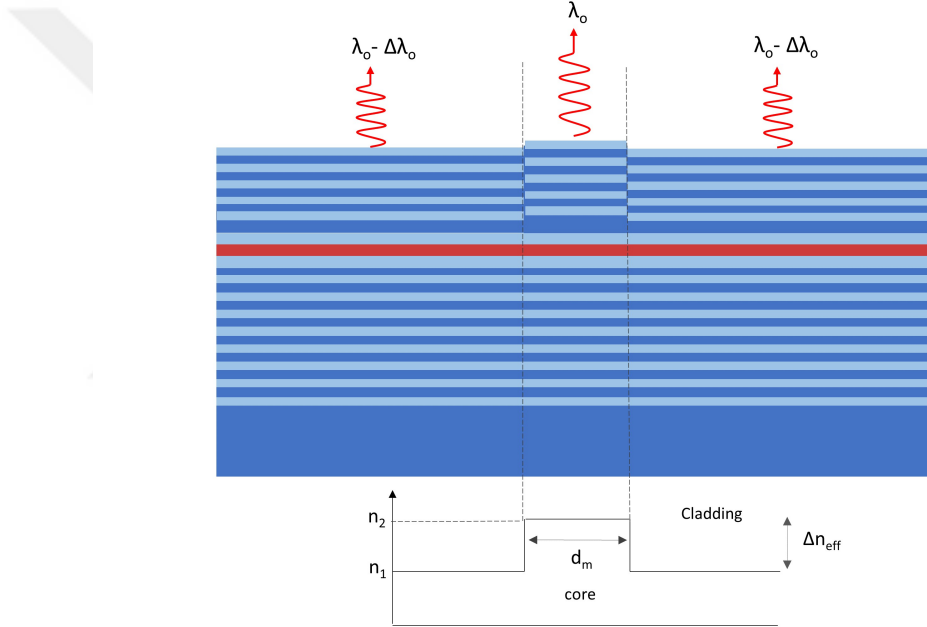


Figure 2.1: *Schematic view of mesa-type Li-VCSEL structure*

2.2 Simulations: Lithographic Cavity

A numerical simulation study was carried out to investigate and analyze the Li-cavity's behavior using a commercial finite-difference time-domain (FDTD) software package (Lumerical Inc.) [32]. Our aim is to obtain the optimum design parameters to achieve a high-quality cavity. We simulated this approach with a simplified structure for both the 980 nm and 970 nm resonance wavelength designs, as shown in Figure 2.2. The structure comprised of 35.5 pairs of quarter wavelength-thick GaAs/AlAs bottom DBRs on GaAs substrate, a cavity

consisting of a wavelength-thick GaAs layer in between two quarter-wave AlAs spacer layers, a 10 nm thick GaAs as the mesa layer, and an 11-pair quarter-wave SiO₂/HfO₂ top DBR. The materials refractive indices used for GaAs, AlAs, SiO₂ and HfO₂ are 3.493, 2.951, 1.46, and 1.97, respectively. The first DBR layer of SiO₂ is employed as wavelength-tuning film to adjust the cavity resonance to the desired wavelength. We investigated the film thicknesses using the Simulase Designer simulation software package [33], which shows the electric field profile in each layer of the structure. The right thickness was determined so that the node of the electric field profile is at the interface of each layer. The SiO₂ wavelength-tuning layer thickness of 322 nm and 307 nm was chosen to obtain 980 nm and 972 nm as the cavity resonance, respectively, which are in agreement with the planar cavity resonance wavelength values shown in Figure 2.5.

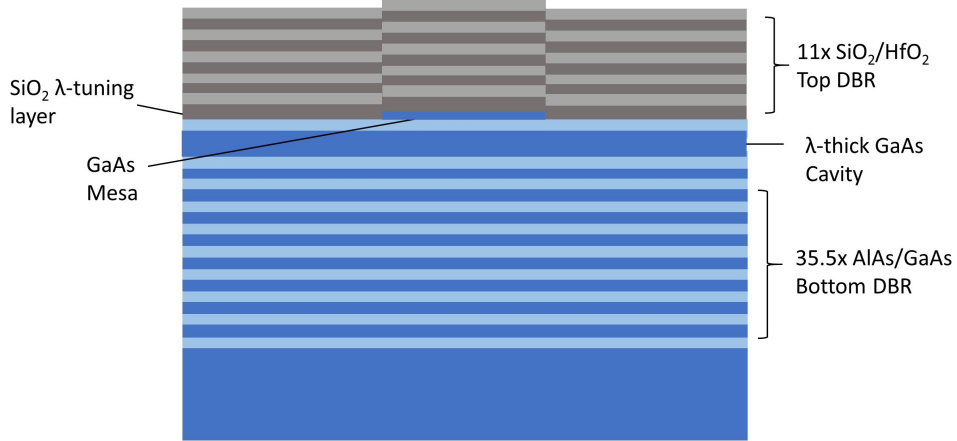


Figure 2.2: *Simplified Li-VCSEL structure using GaAs/AlAs bottom and SiO₂/HfO₂ top DBRs*

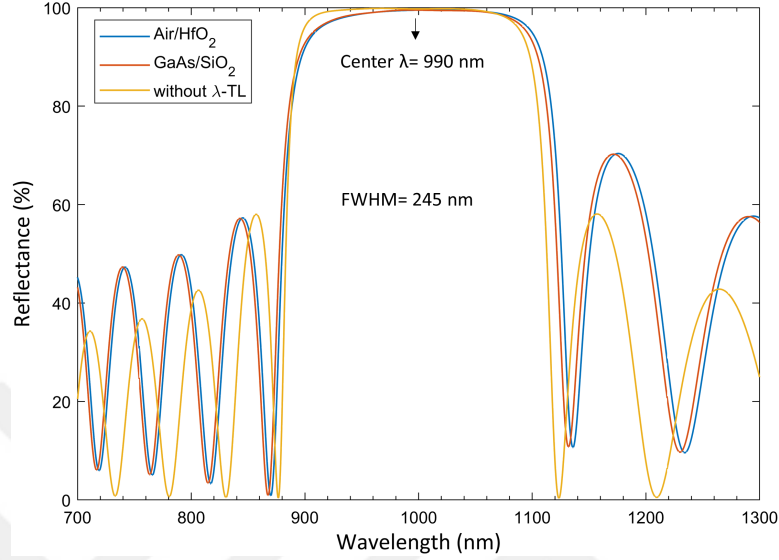
DBR simulation

Since a DBR with reflectance $> 99\%$ is required for lasing in VCSEL, we first simulated the DBR to determine the number of pairs required to reach this reflectance range. For this simulation, a plane wave source incident from the top of the DBR was used in the wavelength range of 700-1200 nm. The boundary condition was set to be periodic in both x- and y-axis, and a non-uniform meshing was employed, with a maximum mesh step of 100 nm x 100 nm x 10 nm ($\delta x \times \delta y \times \delta z$). The reflectance result was obtained from a power monitor place above the plane wave source.

We started the simulation with 10-pairs of quarter-wave SiO₂/HfO₂ on GaAs

Table 2.1: R for different number of pairs and configuration @980 nm

	Air/HfO ₂	GaAs/SiO ₂
$R_{10pair}(\%)$	98.90	98.93
$R_{11pair}(\%)$	99.37	99.44


 Figure 2.3: Simulated Reflectance spectrum with 11-pairs of SiO₂/HfO₂ on GaAs

substrate with the first SiO₂ being the 322 nm λ -tuning layer. 10-pairs gives a reflectance of 98.9 %, which is short of our target value. We added 1-pair to make it 11-pairs, which increases the reflectance to 99.37%. Since the light will be incident from inside of the cavity (GaAs/SiO₂ in this case) in the real VCSEL, we obtained the reflectance of this configuration using the same number of pairs as summarized in Table 2.1. The result shows not much of a change in the reflectance between the Air/HfO₂ and GaAs/SiO₂ incidence. Figure 2.3 shows the reflectance spectrum of the 11-pairs of SiO₂/HfO₂ for Air/HfO₂ and GaAs/SiO₂ incidence. GaAs/SiO₂ incidence without the wavelength-tuning layer ($\lambda - TL$) was also simulated to see its effect on the reflectance. The result shows that the introduction of the λ -tuning layer results in a slight shift in the spectrum and an increased reflectance outside the stopband, which will not have much of an effect in the VCSEL performance.

Device simulation

For the device simulations, the FDTD region boundary condition was set to symmetric/antisymmetric in the x and y-axis and a perfectly matched layer (PML) in the z-axis to reduce the memory requirements. A dipole source was added to the center of the cavity, which acts as a point source to simulate the QWs

emission. Gain and absorption losses were not taken into consideration. The source's wavelength was set in the range of 970-985 nm for 980 nm resonance and 960-975 nm for 970 nm to cover the resonances of all mesa diameters. The source represents the emission of the quantum wells in active region centered in the λ -thick cavity. Two frequency-domain and power monitors were used to measure the emission/transmission spectrum and mode profile. One monitor was placed on top of the structure for the spectrum measurement and the other one was placed across the structure for cross-sectional mode profile. A non-uniform meshing was employed, with a maximum mesh step of (100 nm) x (100 nm) x (10 nm) for $(\delta x) \times (\delta y) \times (\delta z)$. An override mesh step of (50 nm) x (50 nm) x (5 nm) for $(\delta x) \times (\delta y) \times (\delta z)$ was used in the mesa region for more accurate results. The lateral dimension of the structure was adjusted for the different mesa diameters and separation. For accurate quality factor (Q-factor) calculations, 10000 points were recorded from the monitor in the wavelength range, leading to a maximum resolution of around 0.003 nm.

Simulations were carried out to obtain;

1. The quality factor of the cavity and its spectral behavior for different mesa diameters.
2. The effect of the first SiO₂ layer thickness on the resonance wavelength and Q-factor for different mesa diameters.
3. Mesa diameter range for single-mode operation.
4. Mode profile for different mesa diameters.

2.2.1 Quality factor

An optical cavity's quality factor describes how long the cavity sustains an optical field/energy after several oscillations before the maximum amplitude falls off to around $1/e$ (37%) of its initial value. It is often defined as the ratio of the energy stored to the energy dissipated per oscillation cycle. Alternatively, the Q-factor is defined in terms of the resonance bandwidth, as the ratio of the resonance frequency f_o to the full width at half-maximum (FWHM) Δf of the resonance.

$$Q = \frac{f_o}{\Delta f} \quad (2.2)$$

The quality factor is a crucial parameter in laser cavities for obtaining high-performance devices. A high-Q laser cavity can sustain the cavity modes with low loss, leading to more efficient light amplification and, subsequently, low threshold devices. On the other hand, a low-Q cavity has high optical losses that result in broadband emission, low output power, and low efficient devices. To investigate this design, we did a detailed numerical study of the Q factor of the mesa Li-cavity for different diameters between $0.6 \mu\text{m}$ and $3 \mu\text{m}$ employing a mesa height of 10 nm ($\Delta n_{eff} \approx 0.024$). We chose this diameter range in order to show the trend between the sub-micron and microscale sizes.

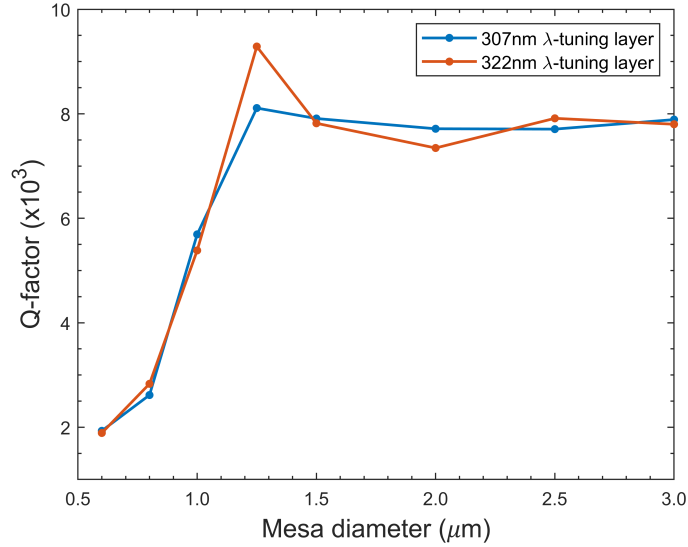


Figure 2.4: *Quality factor change with mesa diameter and λ -tuning film thickness using $11x$ ($\text{SiO}_2/\text{HfO}_2$) top DBR.*

All sizes were simulated with a $1 \mu\text{m}$ separation between the mesa region and the symmetric/antisymmetric boundary region. We obtained the resonance spectrum of five different sizes, including planar geometry for the two designs with different SiO_2 λ -tuning layers. Using the spectrum data and Equation 2.2, we obtained the Q-factor for the diameter range, as shown in Figure 2.4. It can be seen that the Q-factor decreases for diameters smaller than $1.25 \mu\text{m}$. This is partially due to the blue shift of the fundamental mode with a decrease in diameter, as shown in Figure 2.5. As the mesa diameter decreases, the mode volume also decreases, and the mode is confined more to the cavity, which in turn shifts the resonance wavelength [34] [35] [36]. This wavelength change leads to a change in the effective

refractive index and a mismatch between the DBR designed wavelength and the resonance, which results in mirror losses. However, it is important to note that the Q-factors are still very high (> 2000) even for the smallest mesa diameter of $0.6 \mu\text{m}$. The λ -tuning layer does not seem to affect the Q-factor values. Another cause of the Q-factor degradation is the diffraction losses that result from the small mesa diameters. Since the two regions have different resonances, the mesa region acts as an aperture for the resonance wavelength. Moreover, by decreasing the diameter, the cavity mode is more tightly confined, leading to the beam's spreading as shown in Figure 2.6. This effect is more detrimental for higher-order modes than the fundamental modes. This is one reason why there is a single-mode operation for smaller mesa diameters ($< 5 \mu\text{m}$). With this design, it is also possible to tune the resonance wavelength without affecting the Q-factor by just changing the SiO_2 λ -tuning film thickness, as shown in Figure 2.7.

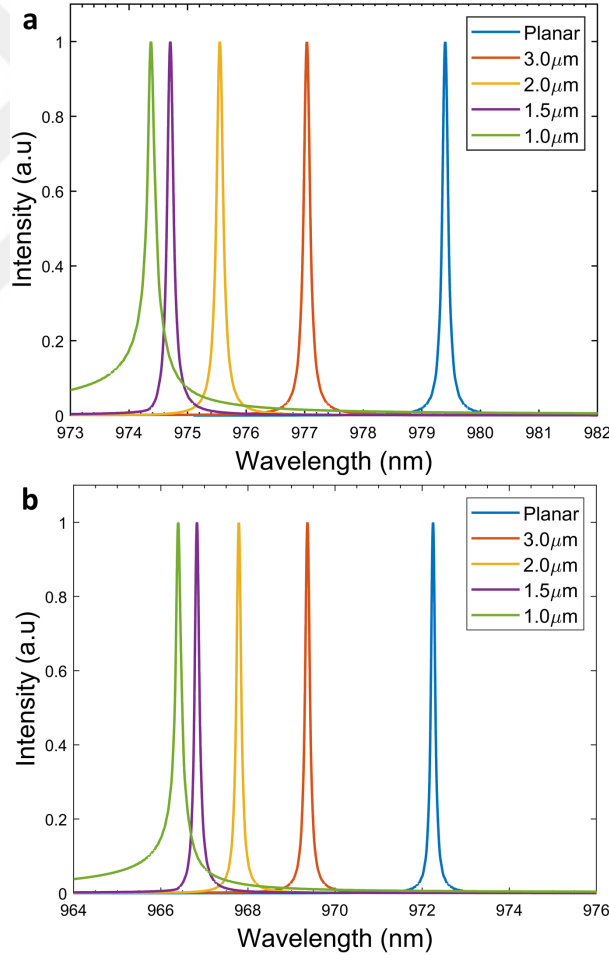


Figure 2.5: *Li-VCSEL resonance spectrum a) 322 nm b) 307 nm SiO_2 λ -tuning film*

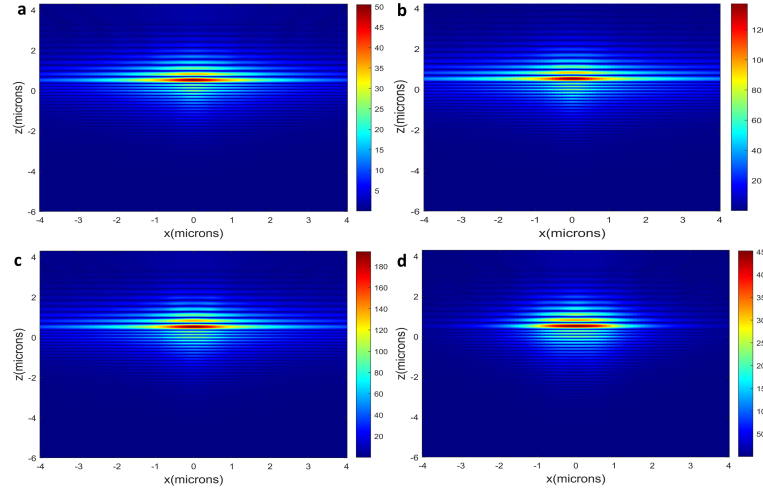


Figure 2.6: *E*-field profiles for mesa diameter of a) $0.8 \mu\text{m}$ b) $1.0 \mu\text{m}$ c) $1.25 \mu\text{m}$ d) $2 \mu\text{m}$ using λ -tuning film thickness of 322 nm .

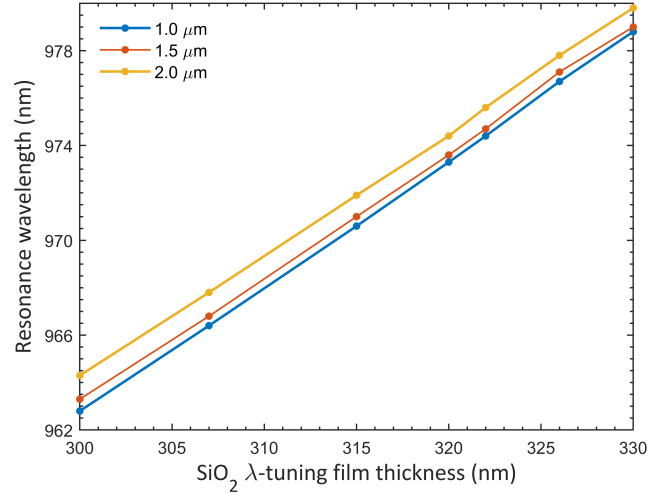


Figure 2.7: *The resonance wavelength versus the SiO_2 λ -tuning film thickness for various cavity diameters.*

2.2.2 Purcell factor

Another figure of merit of a microcavity that is worth looking into is the Purcell effect. As the size of an optical cavity is reduced to subwavelength scale (compared to the free space emission wavelength), interesting quantum electrodynamics (QED) effects emerge. These effects are a result of the strong interaction of light with matter in these small cavities. The Purcell effect is the enhancement of the spontaneous emission of atoms or emitters in a cavity [37]. This effect is highly desirable in optical microcavities and lasers, as it lowers the lasing threshold by enhancing the cavity mode's emission. The magnitude of this enhancement

is given by the Purcell factor F_p ;

$$F_p = \frac{3}{4\pi^2} \left(\frac{Q}{V_a} \right) \left(\frac{\lambda_o}{n} \right)^3 \quad (2.3)$$

Where Q and V_a are the quality factor and mode volume of the cavity, λ_o is the free-space resonance wavelength, and n is the refractive index of the cavity material. Since the F_p is proportional to Q/V , we can increase the enhancement by increasing the Q -factor and decreasing the mode volume. The Purcell factor can also be defined as the ratio of the power emitted in the cavity medium by the power emitted in a homogeneous (bulk) medium. We calculated the Purcell factor using Equation 2.4 by the ratio of the dipole source power emitted in the cavity by the power emitted to the dipole source in a homogeneous medium (bulk material).

$$F_p = \frac{P_{cavity}}{P_{bulk}} \quad (2.4)$$

A F_p less than unity means that the cavity inhibits the spontaneous emission compared to the emission in free space. In contrast, a F_p greater than unity means the cavity enhances the spontaneous emission. Figure 2.8 shows the Purcell factor obtained for the 322 nm λ -tuning layer design. The maximum F_p was expected to be at the size with the maximum Q -factor (i.e., 1.25 μm), however as observed in Figure 2.6, the mode volume increases with a decrease in mesa diameter, leading to an overall decrease in F_p . The maximum F_p at 2.5 μm shows that the effective mode volume is smaller for the bigger sizes, and it has more impact on the F_p than the Q -factor. The F_p for the sub-micron sizes can be improved by increasing the number of DBR pairs to increase the Q -factor or increase the optical confinement to decrease the mode volume. The optical confinement can be increased by adjusting the mesa height to an optimal value.

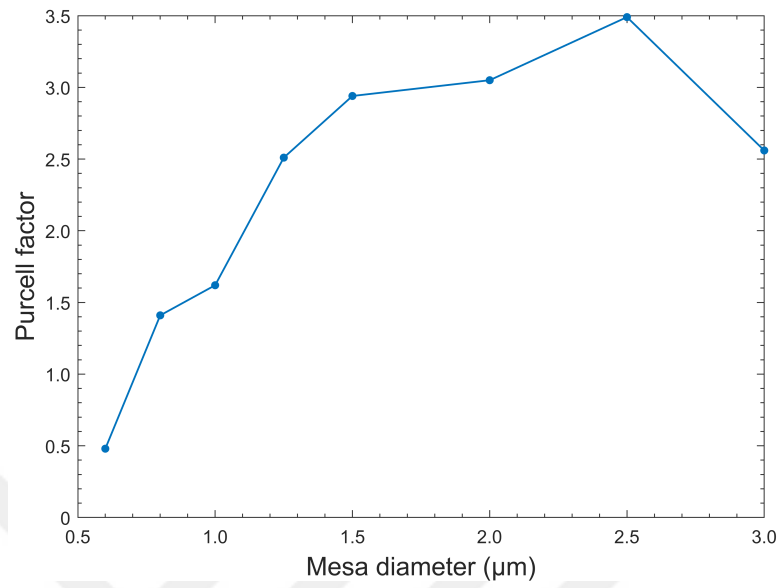


Figure 2.8: *Purcell factor vs Li-cavity diameter for 322 nm λ -tuning design using 11x ($\text{SiO}_2/\text{HfO}_2$) top DBR*

Chapter 3

DESIGN AND FABRICATION OF Li-VCSEL

3.1 Li-VCSEL Design

The Li-VCSEL cavity can be divided into four different segments: Bottom DBR, cavity, mesa region, and the top DBR. The bottom DBR consists of 30-pair quarter-wave thick AlAs/GaAs layers on GaAs substrate. The λ -cavity consists of 3 InGaAs Quantum wells (QWs) in between two AlGaAs cavity spacers. The cavity was designed to emit at a wavelength of 980 nm. The mesa region consists of layers of InGaP/GaAs/InGaP/GaAs of thicknesses 10 nm/120 nm/10 nm/20 nm, respectively. The GaAs in-between act as an etch stop layer to provide a good etching selectivity. The mesa is defined from the second layer of InGaP. The last section contains dielectric materials of SiO₂ λ -tuning layer and 11-pairs of a quarter-wave thick SiO₂/HfO₂ DBR. Details are shown in Table 3.1.

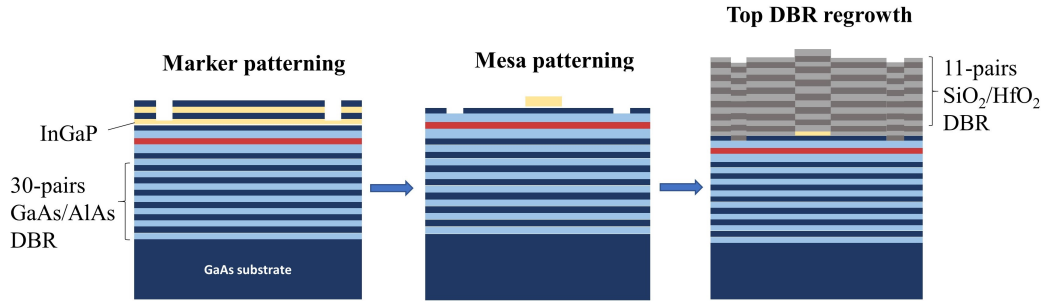
3.2 Fabrication steps

The sample's fabrication is classified into three main steps: Firstly, an alignment marker is patterned on the epitaxially grown structure containing the GaAs/AlAs

Table 3.1: *Structure of Li-VCSEL*

	Material
11-pairs DBR	SiO ₂ HfO ₂ SiO ₂ λ -tuning film
Mesa region	InGaP
λ -cavity region	AlGaAs Spacer 3x InGaAs QWs AlGaAs Spacer
30-pairs GaAs/AlAs DBR	AlAs GaAs
	AlAs
Substrate	GaAs

bottom semiconductor DBR and active region, using optical lithographic processes. The alignment marker is for recognizing the samples during optical characterization. Secondly, the mesa pattern is defined using optical or e-beam lithographic processes. Finally, the top Dielectric DBR is deposited on the patterned wafer using thin film deposition techniques. An illustration of the process flow is shown in Figure 3.1. I developed recipes and optimized all the various fabrication parameters, which is a crucial approach to successful device fabrication.


 Figure 3.1: *Li-VCSEL fabrication process flow*

3.2.1 Mask Design

For the optical lithography processes, two 4-inch masks were designed using the L-edit software package [38]. The first mask is the alignment marker mask. This mask was designed to align the wafer patterns and recognize the different sizes employed in the patterned arrays during characterization. It comprises alignment markers and frames around each array for easy recognition. The second mask is the mesa mask. This mask was designed with hexagonal arrays of mesa circles

of different diameters and separation. Hexagonal geometry is employed to have denser 2D arrays. For a detailed study, arrays of eight different diameters were employed with three different individual emitter's separation as outlined in Table 3.2. Single emitters with 12 different diameters were also employed in the mask. This leads to a 3 x 8 array size having a dimension of (1.2 mm) x (3.2 mm), with each cell containing emitters in a (300 μm) x (300 μm) area. Multiple of these array sets were incorporated to cover the 3-inch wafer.

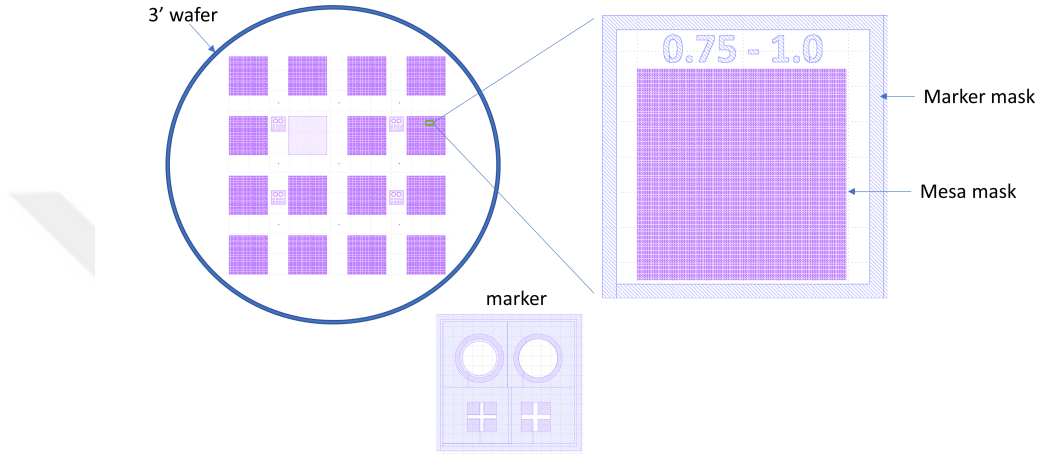


Figure 3.2: *Mask layout view*

Table 3.2: *Mesa mask pattern matrix*

	Diameter (μm)	Spacing (μm)
Arrays	0.75, 1.0, 1.25, 1.5, 2.0, 2.5, 3.0	1.0, 2.0, 25
Single emitters	0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7	-

3.2.2 Patterning

Firstly, the epitaxially grown 3-inch wafer is cleaned with acetone and IPA for the marker mask features patterning. The wafer is then spin-coated with AZ1505 photoresist at 4000 rpm for 1 min, forming a ≈ 600 nm thick resist film. The wafer is then soft-baked at 90 $^{\circ}\text{C}$ for 2 minutes in an oven to remove solvents in the photoresist. The sample is then exposed using EVG 620 UV-lithography machine for a dose of 20 mJ/cm² in vacuum hard contact mode. The sample is then developed in (AZ726MIF:DI) (3:1) developer for 2 minutes followed by hard bake at 110 $^{\circ}\text{C}$ for 6 minutes. Oxygen plasma cleaning of the sample is done using a reactive-ion etching (RIE) machine for 1 minute to remove the photoresist

leftover and any organic residue on the developed areas. A wet etching process is used in order to have a smooth and isotropic etching profile, as opposed to dry etching that leads to rough walls and thereby inducing scattering losses in the device. The first GaAs layer is etched in a solution of $\text{H}_3\text{PO}_4\text{:H}_2\text{O}_2\text{:DI}$ (1:1:64) for 1 minute to remove the 20 nm GaAs which was deposited for wafer protection after the epitaxial growth. The next step is etching the first layer of InGaP etch stop in an etching solution of $\text{H}_3\text{PO}_4\text{:HCl}$ (3:1) for 1 minute to remove the 10 nm InGaP layer. The same process is done for the subsequent 120 nm GaAs using the same GaAs etch recipe for 3 minutes. Lastly, the photoresist is removed with acetone and IPA followed by an oxygen plasma cleaning to remove the photoresist residues. Secondly, before the mesa patterning, the first three layers of 20 nm GaAs, 10 nm InGaP and 120 nm GaAs are removed by selective wet etch process using the same etching recipe as the marker process. These layers are removed to provide room for defining the mesa from the second 10 nm InGaP layer. The marker-patterned wafer is then spin-coated with AZ1505 photoresist at 6000 rpm for 1 minute, forming an ≈ 450 nm resist film. Thin resist film is used for higher resolution patterning due to the sub-micron features in the mask. The sample is exposed using the Karlsuss MJB3 UV-lithography machine with the mesa mask. This machine resolves sub-micron features as opposed to the machine used in patterning the alignment markers. Exposure is done for 36 seconds in contact mode, followed by post-exposure bake (100 °C for 1 minute in an oven). The sample is then developed in AZ726MIF:DI (4:1) developer for 2 minutes and 30 seconds, followed by a hard bake at 120 °C for 3 minutes in an oven. The wafer is then treated with oxygen plasma for 40 seconds to remove the photoresist leftovers on the developed areas. The mesa pattern is then formed by etching the 10 nm InGaP layer for 1 min in the InGaP etching solution. The photoresist is removed using acetone and IPA, followed by oxygen plasma cleaning. Inspection of each step was done with an optical microscope and profilometer to confirm the etching profile and depth, respectively. For detailed flow, refer to Appendix A.

3.2.3 Top Dielectric DBR

Due to the good optical and electrical properties of compound semiconductors and their compatibility with photonic devices, they are generally the materials of choice for DBRs in standard VCSELs. However, there are many challenges in selecting materials, film growth requirements, and performance limitations in

incorporating semiconductor DBRs to VCSELs. Firstly, since compound semiconductors are grown using epitaxial growth, the deposited film has to have a close or same lattice structure and orientation as the substrate to avoid crystalline defects that significantly degrade device performance. This puts a constraint in the choice of materials. Secondly, high refractive index contrast materials are required in achieving high reflective DBRs ($> 99\%$) with low penetration depth and broader stopband [39]. The limitation on the choice of materials for semiconductor DBRs makes it challenging to achieve this high contrast, leading to narrow stopband, high penetration depth, and the requirement for more DBR pairs to achieve $> 99\%$ reflectance. Moreover, since semiconductor DBR are conductive, the generated light is absorbed by the electrically excited carriers, also known as free-carrier absorption, leading to optical losses that result in low device performance [40]. Dielectric materials, on the other hand, are not crystalline and therefore have no materials choice limitations. As a result, high refractive index contrast materials can be easily chosen to achieve high reflective DBRs with good performance. Also, since they are electrical insulators and transparent, they do not suffer from optical losses due to free-carrier absorption. Thus, with the high-quality deposition of these DBRs, high-performance VCSEL devices can be developed [41].

Although the main reason for the use of dielectric DBR in this study is because we are pumping our devices optically for proof-of-concept, dielectric DBRs can still be incorporated with electrically pumped devices at the expense of defining contacts from the side of the device [42].

Materials choice

For the dielectric DBR, two materials are needed: One with a low refractive index and the other with a high refractive index for a high contrast mirror. The most common choice for the low index material is SiO_2 because, among available dielectric materials, it has the lowest index ($n=1.45$) and zero absorption ($k=0$) at our design wavelength of 980 nm [43]. For the high refractive index material, the commonly used dielectrics for DBR are a-Si, Si_3N_4 , TiO_2 , and HfO_2 [44] [45] [46]. Among these options, we choose to use HfO_2 due to the availability and limitation of the materials we have.

3.2.3.1 DBR Deposition

The DBRs are deposited using two different thin-film deposition techniques; Plasma Enhanced Chemical Vapor Deposition (PECVD) for SiO_2 layer and Atomic Layer Deposition (ALD) for the HfO_2 layer. Before the DBR deposition, I developed and optimized a recipe for each material. I did this by depositing each layer on GaAs substrate, and by measuring the optical constants (n, k) and thickness of each layer, I obtained the deposition rate. These parameters were obtained by spectroscopic ellipsometry using the Woollam M-2000 ellipsometer (J.A. Woollam Co., Inc.) at an angle of incident of 65° , 70° , and 75° in the spectral range of 700-1200 nm. Data analysis was done with the V-vase software using the Cauchy fitting model. From the optical constant results, I determined the design target thickness using the formula:

$$t = \frac{\lambda_o}{4n} \quad (3.1)$$

where λ_o is the free space resonance wavelength (980 nm), and n is the refractive index of the material at 980 nm resonance.

SiO_2

Silicon dioxide was deposited using the Advance Vacuum Vision 310 Plasma Enhanced Chemical Vapor Deposition (PECVD) machine. This deposition is achieved by introducing reactant gases into the chamber, which are excited to a plasma state with RF power. The sample is placed on the grounded electrode, which is heated to a temperature ranging from 200°C to 350°C . The reactant gasses used for the deposition are silane diluted in nitrogen (2% SiH_4 in nitrogen) and Nitrous oxide (N_2O). The recipe parameters are summarized in Table 3.3.

Table 3.3: SiO_2 deposition recipe by PECVD

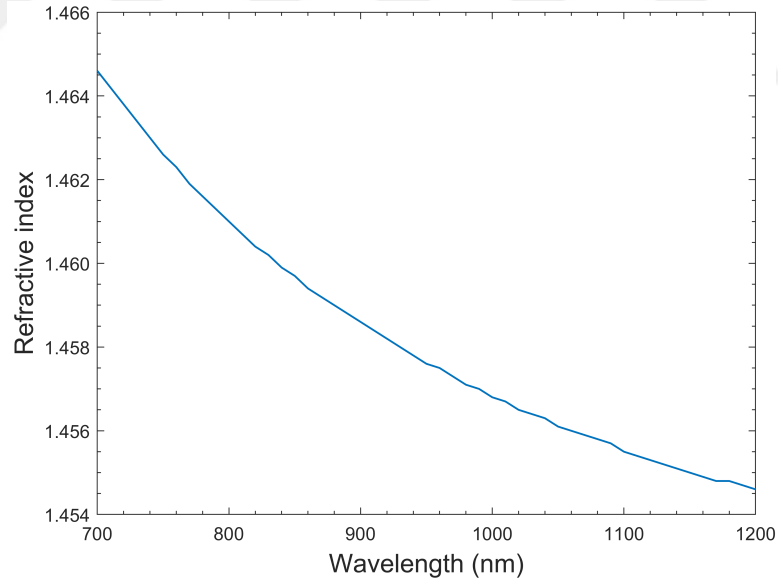
Parameter	Value
RF power	70 W
Pressure	700 mTorr
Temperature	250°C
$\text{Si}_4(\text{N})$ flow	180 sccm
N_2O flow	720 sccm

The time required to deposit a quarter-wave thick SiO_2 is approximately 400 seconds, corresponding to 167 nm. I did a series of trials to determine the repeatability of the tool. Using the ellipsometer, I measured the optical constants

(n and k) and the film thickness, from which I obtained the deposition rate for each run as summarized in Table 3.4. The extinction coefficient k was zero across the wavelength range for all samples. For the second and third trials, the samples were placed at different positions in the chamber to check for the deposition uniformity across the chamber. The results showed a good uniformity of the deposition with high repeatability. Figure 3.3 shows the refractive index of the SiO_2 layers that comprised the DBR which was obtained with an ex-situ spectroscopic ellipsometer. The SiO_2 shows a clear dielectric behavior with refractive index values similar to previous studies [46] [47].

 Table 3.4: *Ellipsometer data of SiO_2*

Trial	time (sec)	thickness (nm)	$n(@ 980 \text{ nm})$	depos. rate (nm/sec)
1	300	124.30	1.457	0.413
2	350	143.16	1.457	0.409
3	350	142.70	1.456	0.408
4	400	167.40	1.457	0.419
5	770	325.80	1.456	0.423
Mean	-	-	1.466 ± 0.0002	0.4144 ± 0.0029
Error	-	-	0.01%	0.7%


 Figure 3.3: *Refractive index vs wavelength from the ellipsometry measurement of PECVD deposited SiO_2 film*

HfO₂

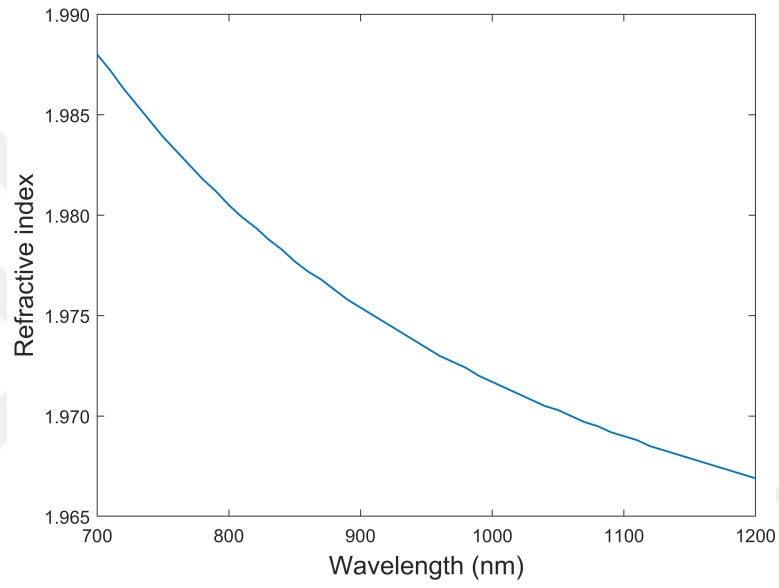
Hafnium dioxide (HfO₂) was deposited using the commercial Savannah S100 thermal ALD system (Ultratech/Cambridge NanoTech). The film is grown atomic layer-by-layer by the reaction between a metal precursor and water. Tetrakis(dimethylamido)hafnium (TDMAHf) was used as the precursor for hafnium (Hf) and deionized H₂O as the oxygen (O₂) source. Pulses of each material are release to the sample surface for a particular time duration for the surface reaction to occur, and with a continuous flow of N₂ carrier gas into the chamber, the unreacted by-products are purged/evacuated from the chamber. The chamber and substrate can be heated in the temperature range of 80 °C up to 350 °C to allow for temperature-controlled surface reaction. The ALD system consists of an inner and outer heater. Both heaters were set to the same temperature for our deposition. The metal precursor is also heated to evaporate the source. Figure 3.4 shows the process flow and instructions for the HfO₂ deposition. I used the standard recipe of the company's ALD machine as the starting recipe for optimization. I deposited a couple of samples on GaAs to optimize the number of cycles required to reach the target thickness(124 nm). I measured each sample's optical constants and thickness using the spectroscopic ellipsometer to obtain the deposition rate. The results are summarized in Table 3.5. The results show that around 830 cycles are required to reach the target thickness. Figure 3.5 shows the refractive index of the HfO₂ layers that comprised the DBR which was obtained with an ex-situ spectroscopic ellipsometer. The HfO₂ shows a clear dielectric behavior with refractive index values similar to previous studies [48] [49] [46].

	Instruction	#	Value	Units	
0	heater	9	100		Sets the inner heater to 100C
1	heater	8	100		Sets the outer heater to 100C
2	heater	15	75		Sets the precursor gas cylinder heater to 75C
3	stabilize	9			Stabilizes the temperature of the heaters
4	stabilize	8			
5	stabilize	15			
6	flow		20		Sets the N2 gas flow to 20sccm
7	wait		600		Wait 600s for the chamber pressure to stabilize
8	pulse	0	0,015		Pulse the precursor 0 (H ₂ O) for 0.015sec
9	wait		20		Wait 20sec for exposure and purging
10	pulse	1	0,4		Pulse the precursor 1 (TDMAHf) for 0.4sec
11	wait		10		Wait 10sec for exposure and purging
12	goto	8	830		Repeat the cycle 830 times

Figure 3.4: *ALD deposition process flow for HfO₂*

Table 3.5: *Ellipsometer data of HfO_2*

Trial	No. of cycles	thickness (nm)	$n(@ 980 \text{ nm})$	depos. rate (nm/cycle)
1	500	74.800	1.9635	0.1496
2	860	127.08	1.9785	0.1478
3	830	122.70	1.9718	0.1478
4	830	122.65	1.9722	0.1478
5	830	123.89	1.9724	0.1493
Mean	-	-	1.9717 ± 0.0024	0.1485 ± 0.0004
Error	-	-	0.12%	0.3%

Figure 3.5: *Refractive index vs wavelength from the ellipsometry measurement of ALD deposited HfO_2 film*

Chapter 4

RESULTS AND DISCUSSION

4.1 Fabrication results

4.1.1 Mesa

After the mesa patterning, as described in Chapter 3, a small sample was cleaved to check for the fabricated mesa patterns' profile. I used a scanning electron microscope (SEM) to verify the mesa diameter and image the topological structure of these patterns. It is crucial to have a smooth circular profile to avoid scattering losses in the device. As shown in Figure 4.1, the mesa diameters are 0.75, 1.1, 1.6 and 2.0 μm . The sizes were smaller than expected as summarized in Table 4.1. Since the dose optimization and etching were done on a GaAs substrate, this difference is attributed to the unexpected change of the required dose and etching in the real VCSEL wafer. Although the real sizes are not as expected, we still have the size range we need for our study. Also, as seen from the SEM image, there is ellipticity in the profile, measured to be $\approx 90\%$. The effect of this asymmetry is analyzed in the measurements section. It is critical to check the surface morphology after the lithographic processes to ensure a smooth surface before the DBR deposition. Having a smooth surface is essential in avoiding roughness build-up at the interface of the DBR layers. For this purpose, I measured the roughness of the VCSEL sample after forming the mesa using an Atomic force microscope (AFM) as shown in Figure 4.2. The measured Root Mean Square (RMS) roughness is 1.3 nm, indicating an increase in roughness compared to the roughness of the VCSEL wafer (RMS=0.71 nm) before patterning. The source

of this roughness could be a result of incomplete etching of the etched layers or related to the growth quality of GaAs/InGaP transition.

Table 4.1: *Measured mesa diameters*

Expected diameter (μm)	Measured diameter (μm)
0.75	Unpatterned
1.00	0.48
1.25	0.55
1.50	0.75
2.00	1.10
2.50	1.60
3.00	2.00

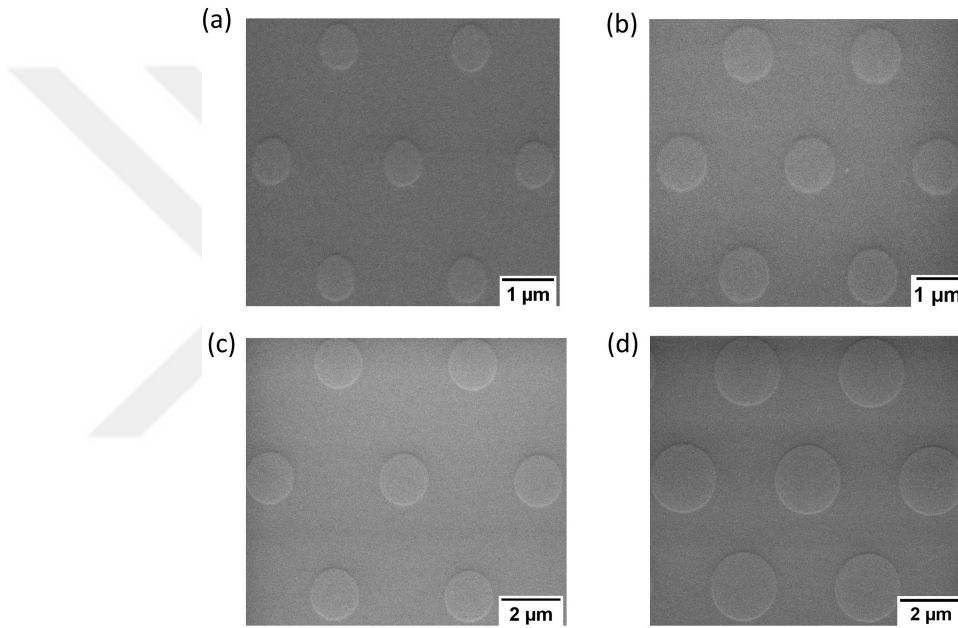


Figure 4.1: *SEM image of fabricated mesas with diameter of (a) 0.75 μm (b) 1.1 μm (c) 1.6 μm (d) 2.0 μm*

4.1.2 DBR

The morphological characterization of the DBR was done using AFM measurements by calculating the RMS surface roughness of the individual DBR layers and the 11-pair DBR after the deposition. As shown in Figure 4.3, the RMS roughness of the SiO_2 layer is around 1.5 nm while that of the HfO_2 is measured to be 1.1 nm. A scanning area of $(3 \mu\text{m}) \times (3 \mu\text{m})$, which is in the dimension of the mesas, was chosen for all the measurements. The higher roughness of the SiO_2 layer is likely to be due to the high substrate temperature of the PECVD process [50].

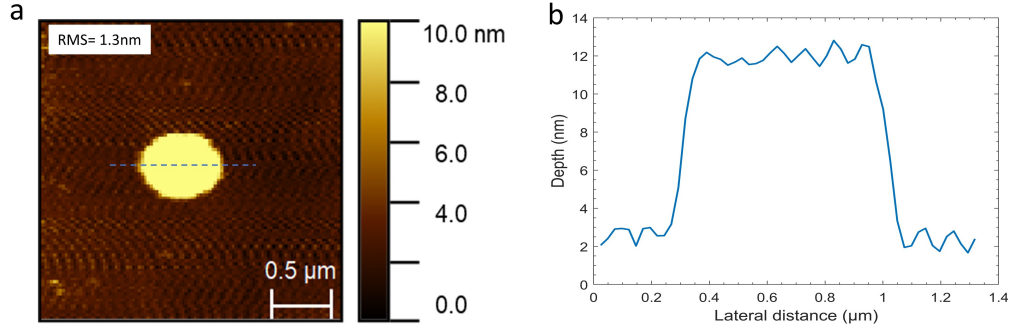


Figure 4.2: (a) AFM image of mesa before DBR deposition. (b) Mesa AFM cross section of figure a) as shown by dashed blue line.

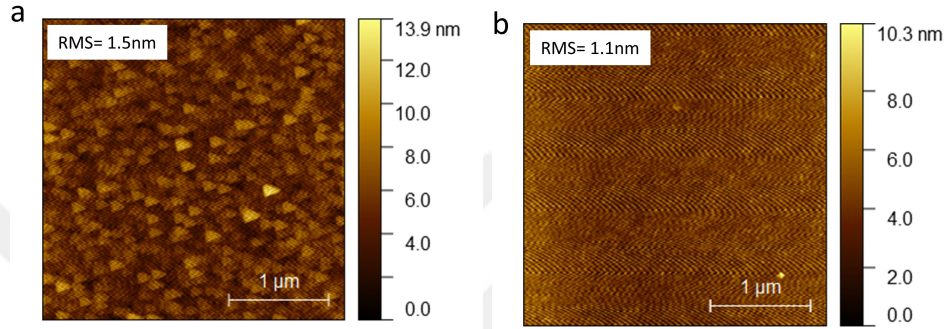


Figure 4.3: AFM image of the surface topology for (a) SiO_2 layer b) HfO_2 layer.

The RMS surface roughness of the 11-pair DBR stack was also determined. Figure 4.4 (b) shows the AFM image of the surface of the 11-pair $\text{SiO}_2/\text{HfO}_2$ DBR with an RMS value of 4.7 nm. This high roughness value is correlated to the interface roughness build-up from the patterned sample and the DBR layers during deposition. The rough interfaces can be seen in the SEM image of Figure 4.4 (a). The interface roughness is observed more in the SiO_2 layer, indicating that most of the roughness is coming from the PECVD SiO_2 layer.

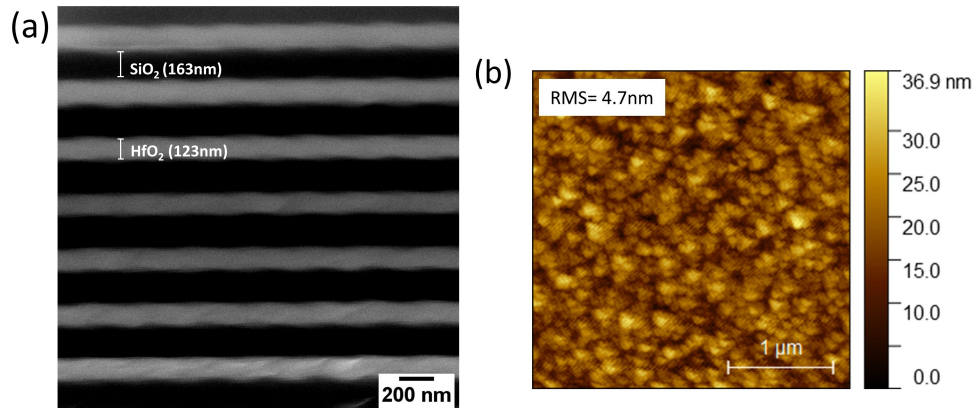


Figure 4.4: (a) SEM image of the fabricated 11-pairs $\text{SiO}_2/\text{HfO}_2$ DBR b) AFM image of the 11-pair $\text{SiO}_2/\text{HfO}_2$ DBR surface

Figure 4.5 shows the cross-sectional transmission electron microscope (TEM) image of the final fabricated device and a zoomed view of the mesa step. As seen in the image, the mesa step has good conformity with the deposited DBR films.

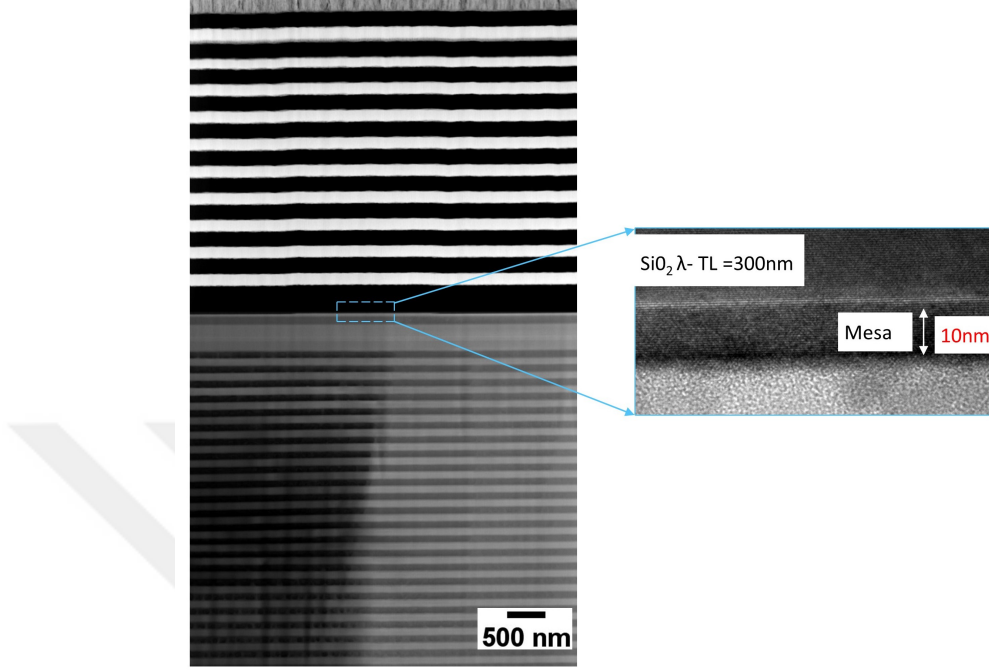


Figure 4.5: *TEM image of final structure of Li-VCSEL*

Spectral reflectance

For the transmission measurement, the DBR was also deposited on a quartz substrate simultaneously. The transmission was determined using a UV-VIS-NIR spectrophotometer, from which the reflectance ($100-T\%$) was obtained as displayed in Figure 4.6. For each layer deposited, the thickness and refractive index were measured using a spectroscopic ellipsometer; Results show a thickness deviation (5 nm less) of some of the SiO_2 layers from the target thickness. This deviation results in a blue shift of the spectrum compared to the simulation of the DBRs with the targeted thickness, leading to around 30 nm shift of the central design wavelength (970 nm). The reflectance at the stop band's center is 99.56% and 99.11% for the simulation and measurement, respectively. If we consider the resonance wavelength shift for the different mesa diameters, our range of interest is between 970 nm and 980 nm. Therefore the reflectance will be in the range of 98.82% to 98.71% in this wavelength range. Since the fit data obtained with the ellipsometer shows no sign of absorption in the DBR layers, the reduced reflectivity from the simulation can be attributed to the scattering losses that result from the interface roughness of the DBR and measurement accuracy of the

spectrophotometer. The same point can be made for the decrease in transmission for the wavelength range outside the stopband.

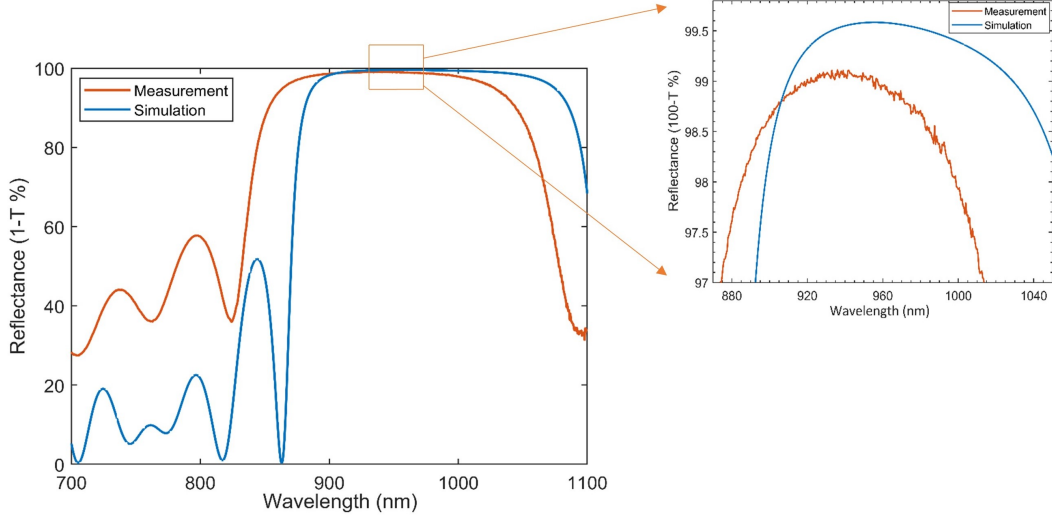


Figure 4.6: *Spectral reflectance measurement and simulation results of the 11-pair $\text{SiO}_2/\text{HfO}_2$ DBR*

4.2 Optical characterization

The device characterization aims to determine the laser's static properties, such as the spectrum, lasing threshold, emitted power, and mode profile. Furthermore, using the spectral data, we can verify the cavity design's behavior by determining the quality factor. The reason behind optical pumping is to investigate and confirm the performance of the design without dealing with the losses that come with electrical pumping. By doing this, we can also predict which sizes have a good chance of lasing with electrical pumping when all loss mechanisms are taken into consideration.

4.2.1 Micro-photoluminescence setup

The sample was characterized using a home-built micro-photoluminescence (μ -PL) setup, as illustrated in Figure 4.7 and Figure 4.8. The sample is fixed to an X-Y-Z stage which provides motion in all 3-axis for focusing and sample positioning. Utilizing the basic principle of confocal microscopy, an objective lens ($M=40\times$, $\text{NA}=0.75$) is used to focus the pump source on the sample and simultaneously

collect the sample's emitted light. The setup consists of two light sources: A 970 nm LED and a 780 nm laser source. The LED is used for sample imaging, while the laser is used as the excitation source to pump the VCSEL sample. The pump source was chosen to be outside the stopband of the DBR to allow for maximum transmission. The long pass dichroic mirror (LP DM) reflects 99% of the pump source towards the objective lens while allowing all reflected and emitted wavelength > 805 nm to pass through. The long-pass filter (LPF) allows all wavelength > 900 nm to pass through and ensures that all light sources outside the emission bandwidth, including the pump source, are blocked. This allows for collecting and imaging of only the emission source in the camera. The 10/90 (reflection/transmission) beam splitter at the LED's path reflects 10% of the LED source to the sample and transmits 90% of all other wavelengths. The 90/10 beam splitter is used to split the emitted light towards the camera and the spectroscopic measurement path. The 10% of the light that is transmitted is focused to the CMOS camera using a tube lens. 90% of the reflected light is split into the path of an Optical Power Meter (OPM) and optical fiber coupler using a 50/50 beam splitter. The coupled light is then passed through an Optical Spectrum Analyzer (OSA) for spectral measurements.

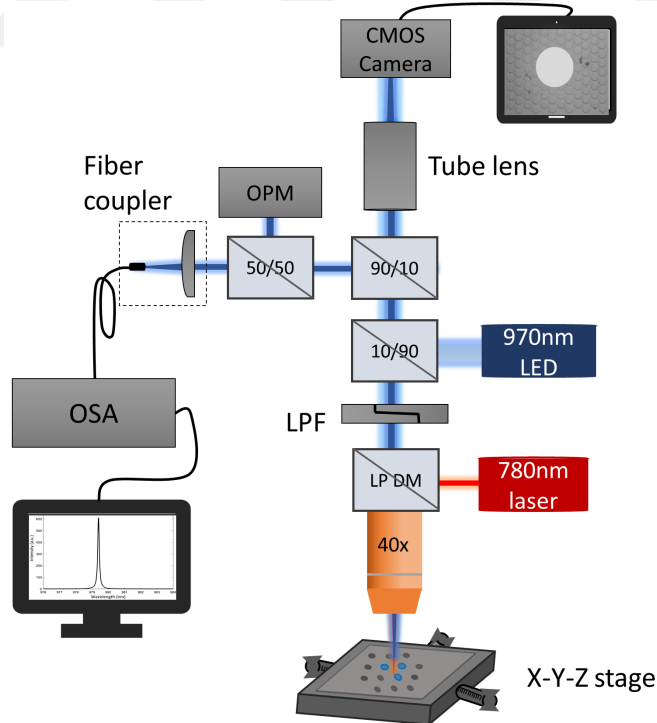


Figure 4.7: *Schematic of the microphotoluminescence setup*

The whole system was built in a cage to develop a compact system for easier beam alignment. The setup was calibrated by first aligning the beam to the cage

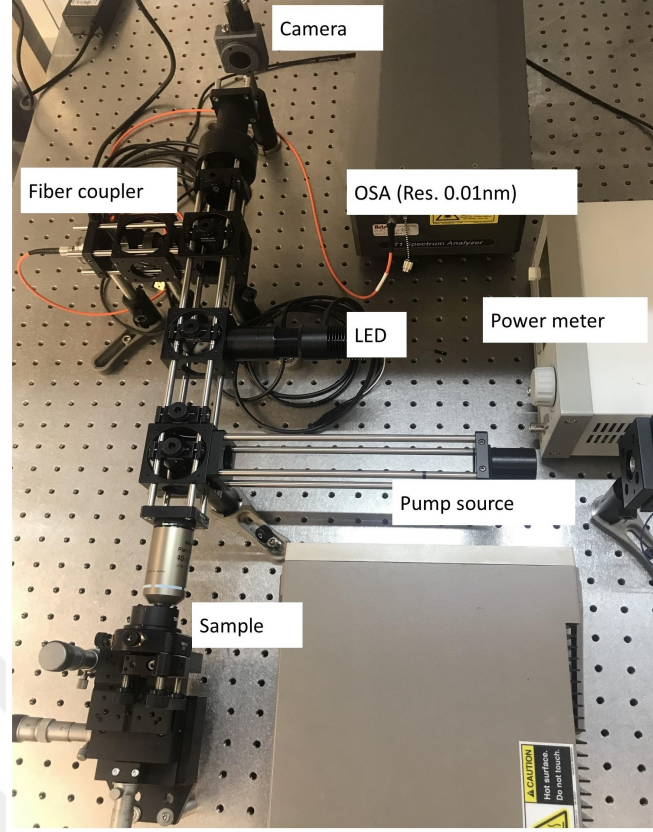


Figure 4.8: *View of the microphotoluminescence setup*

system's center using the pump source. The power is then measured across each optical component to confirm the specifications and determine the total losses across the setup. 20% of the optical power is lost across the objective lens while other components have minimal losses. Measurement was also done to measure the coupling efficiency of the single-mode fiber coupler. A maximum efficiency of 90% and 70% was achieved using a 905 nm and 785 nm diode laser, respectively.

4.3 L-L characteristics

To determine the LD source's pumping intensity, the beam was focused on a mirror sample, and the reflected beam was collected by the objective and focused to the camera. The pump spot size was then calculated from the camera spot image size, which results in a beam size of around $4.9 \mu\text{m}$ by $4.5 \mu\text{m}$. The beam area is enough to cover the mesa for the whole range of diameters. By taking out all the losses across the setup and the DBR pump wavelength reflection loss, the input pump power variation was calculated to be in the range between 0.5 mW to 18.8 mW in continuous-wave (CW) operation. The light-in-light-out (L-L) curve

was measured for the single emitters of both VCSEL samples (with λ -tuning film thickness of 295 nm and 275 nm) as shown in Figure 4.9. The difference between the two samples is the resonance wavelength and a negligible difference in the Q-factor for the same sizes as outlined in chapter 2.

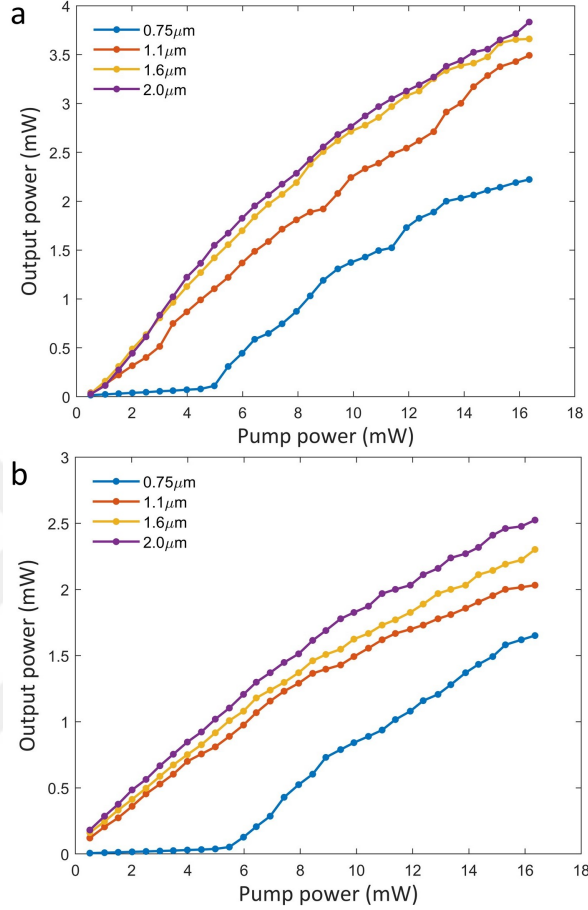


Figure 4.9: *L-L curve for different mesa sizes with λ -tuning layer thickness of (a) 295 nm and b) 275 nm.*

Lasing was observed even for the submicron size, reflecting a good lateral optical confinement and high quality of the cavity. The lasing threshold occurs at around 5 mW for the sub-micron size while the other sizes have threshold of less than 1 mW. The threshold of the micron-scale sizes is not within range due to the limit of our pump source. As investigated in the FDTD simulations, there is a significant reduction of the quality factor for the sub-micron sizes due to the increase in diffraction losses. This accounts for the high threshold of the 0.75 μm mesa as compared to the micron-scale sizes. Both samples showed similar behavior with a slight shift in the threshold and an increased output power. This is attributed to the difference in the cavity mode alignment to the QWs emission, resulting in one device more aligned to the emission than the other. As seen, the threshold of the VCSEL with 295 nm λ -tuning layer is slightly lower than

that of the VCSEL with 275 nm λ -tuning layer, this is likely due to the pump beam alignment or the Q-factor difference between the two samples. Also, the output power and slope efficiency in a) is higher than in b), the reason for this is because of the change in the top DBR reflectivity with change in the resonance wavelength as illustrated in Figure 4.6. This results in more out-coupled power in a) than in b). Another reason could be due to Q-factor variation which will require experimental Q-factor analysis to find out. The estimated optical-optical power conversion efficiency (PCE) is $\approx 30\%$.

4.4 Emission spectrum

The laser emission spectrum was observed using the 771 series Bristol Laser spectrum analyzer with a spectral resolution of 4 GHz (≈ 0.01 nm). Figure 4.10 is the lasing spectrum of all VCSEL samples measured at 11 mW pumping power. The result is consistent with the simulation results regarding the wavelength shift as the mesa diameter changes. The wavelength difference compared with the simulation is due to the shift caused by the thicker λ -tuning layer. Figure 4.11 and Figure 4.12 show the spectral emission above the threshold ($\approx 2 P_{th}$) and how it behaves with increasing pump power. The emission is observed only in the mesa region, which is evidence of the mesa's optical confinement. All sizes are lasing in single mode with no sign of the emergence of sides modes up to the maximum power. The observed side peak in the spectrum can be attributed to the elliptical symmetry in the mesa shape, as illustrated in the fabrication results. The redshift of the spectrum with increasing pump power is due to the thermal effects under high pump intensities.

4.5 Near field profile

The near field profile of the VCSEL samples was obtained using a WinCamD-LCM laser beam profiler. The sample imaging CMOS camera is removed and replaced by the beam profiling camera. The laser beam is then focused on the image plane using the tube lens. Neutral density filters of different optical densities were placed on the profiler aperture according to the laser power to avoid the camera's saturation. The real-time beam profile is viewed using the camera's

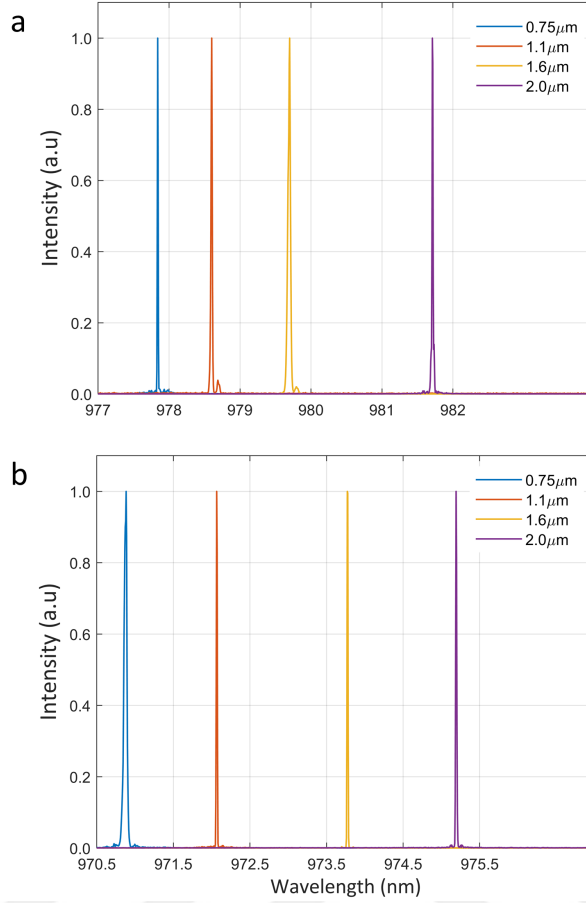


Figure 4.10: *Normalized laser spectrum of different mesa sizes at 11 mW pump power for VCSELs with λ -tuning layer thickness of , (a) 295 nm and b) 275 nm.*

software (DataRay). Figure 4.13 and Figure 4.14 show the spatial intensity distribution of the VCSEL samples above the threshold, observed along the y-axis of the beam. There is a 90-95% ellipticity in the beam, which results from the elliptical symmetry of the mesa. The result shows a good beam quality with a smooth Gaussian profile, which also shows the mesa's excellent optical confinement and confirms the laser's single-mode operation. The insets show the near field image at two different points above the threshold (1.1 and $2 P_{th}$). The images show a single peak gaussian profile that spread over the mesa pattern with full width at $1/e^2$ beam size ($2w$). A minimum beam diameter of around $3 \mu\text{m}$ is observed for $2 \mu\text{m}$ mesa. The bigger beam diameter compared to the mesa diameter indicates the beam spreading around the edge of the mesa as observed in the simulations. The beam spreading increases with a decrease in the mesa diameter. This can be explained by the diffraction property of the beam as it is confined to a smaller aperture. The variation in the λ -tuning layer thickness is observed to not affect the beam profile as seen in the figures.

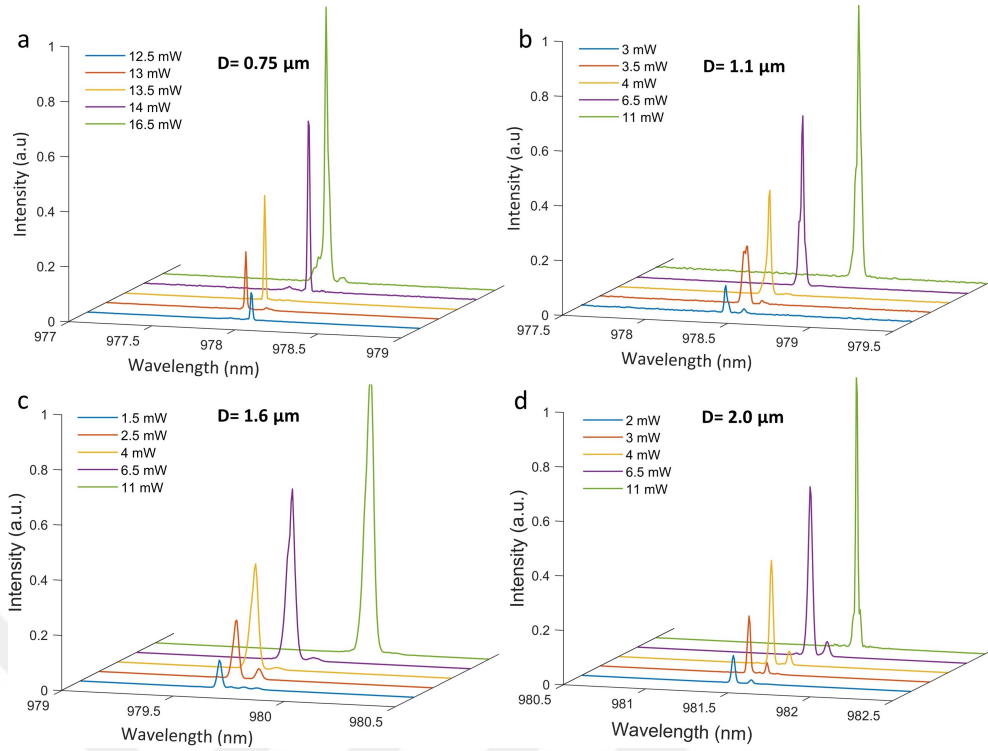


Figure 4.11: *Laser spectrum above threshold at different pump powers for VCSELs with λ -tuning layer thickness of 295 nm : (a) 0.75 μm b) 1.1 μm c) 1.6 μm d) 2.0 μm .*

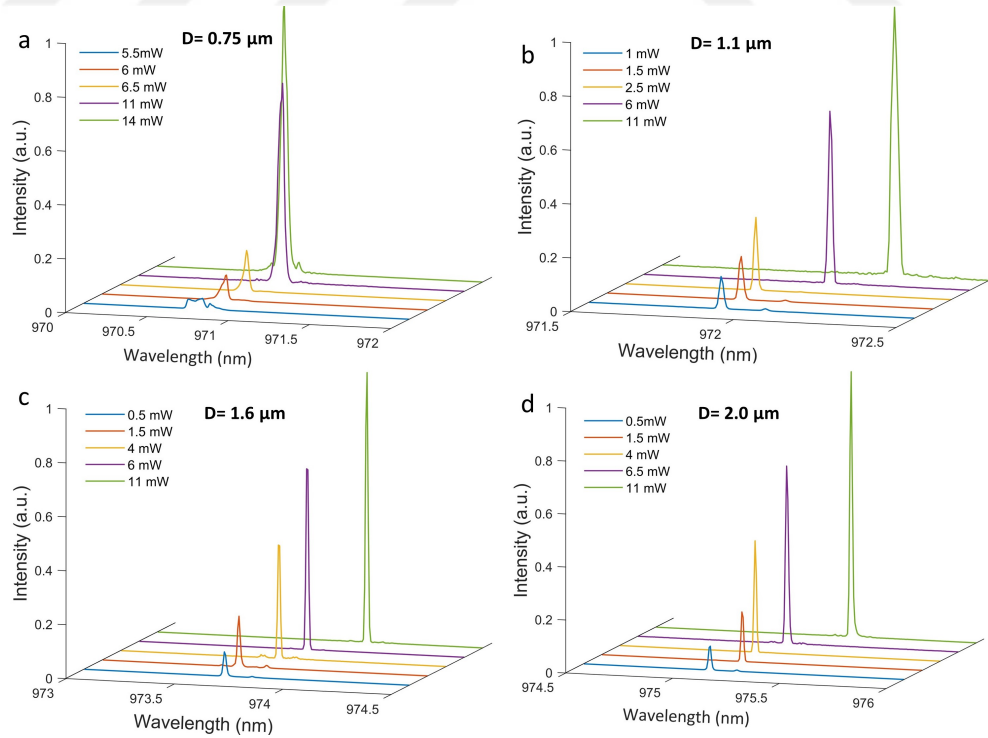


Figure 4.12: *Laser spectrum above threshold at different pump powers for VCSELs with λ -tuning layer thickness of 275 nm : (a) 0.75 μm b) 1.1 μm c) 1.6 μm d) 2.0 μm .*

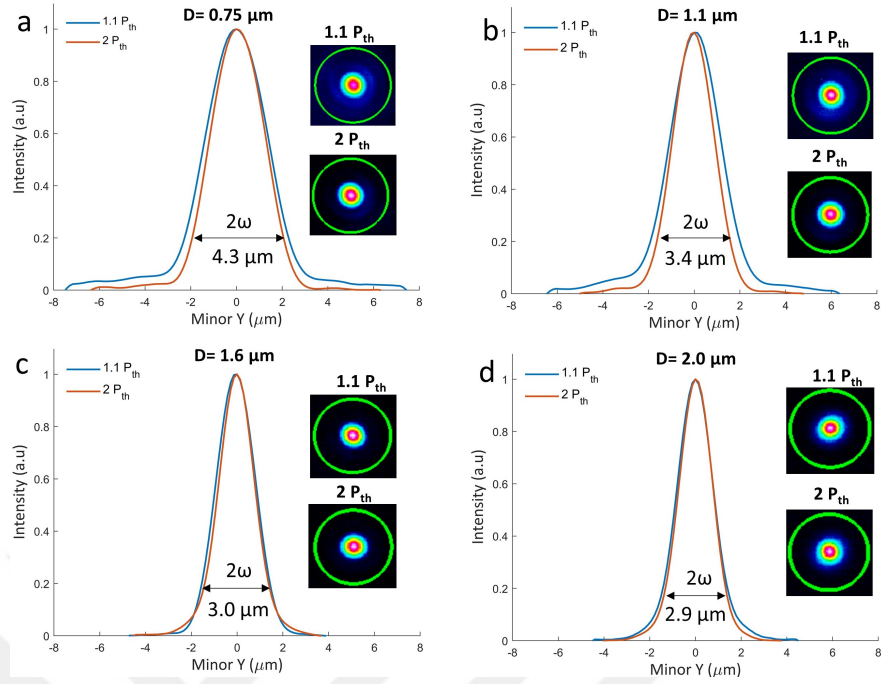


Figure 4.13: *Spatial intensity distribution of VCSELs with λ -tuning layer thickness of 295 nm at $1.1 P_{th}$ and $2 P_{th}$ for mesa diameter of a) $0.75 \mu\text{m}$. b) $1.1 \mu\text{m}$ c) $1.6 \mu\text{m}$ d) $2.0 \mu\text{m}$. Insets: Shows the 2D Gaussian beam profile of the laser*

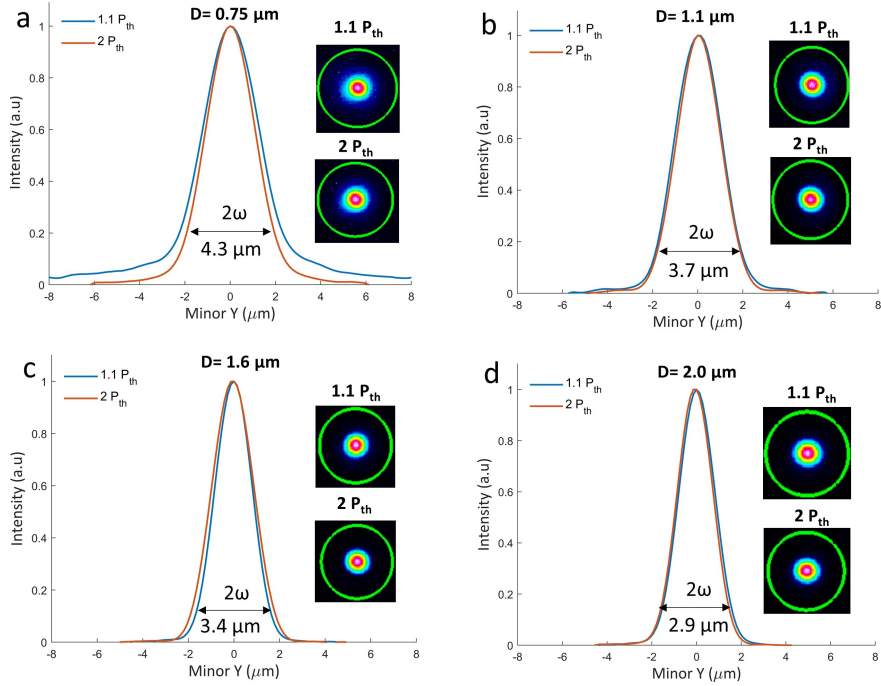


Figure 4.14: *Spatial intensity distribution of VCSELs with λ -tuning layer thickness of 275 nm at $1.1 P_{th}$ and $2 P_{th}$ for mesa diameter of a) $0.75 \mu\text{m}$. b) $1.1 \mu\text{m}$ c) $1.6 \mu\text{m}$ d) $2.0 \mu\text{m}$. Insets: Shows the 2D Gaussian beam profile of the laser*

Chapter 5

CONCLUSION AND FUTURE WORK

In this project, I have implemented the design, simulation, fabrication, and optical characterization of wavelength-scale Lithographic Vertical-Cavity Surface-Emitting Laser (Li-VCSEL). We aimed to investigate the performance of Li-VCSEL at submicron and micron-scale for use as a potential source in short distance communication and 3D sensing applications. In this approach, a phase-shifting mesa is lithographically defined on top of a λ -cavity, which provides both transverse optical and electrical confinement. This approach has the advantage of eliminating the high thermal resistance and fabrication non-uniformity of the commercial oxide VCSELs for wavelength scale devices.

To investigate the design, we carried out numerical finite-difference time-domain (FDTD) simulations. The results show a good quality factor even for submicron mesa diameters, which confirms the good optical confinement of Li-VCSELs. Wavelength tuning is also possible by adjusting the thickness of the first layer of the top DBR that acts as a λ -tuning layer thin film.

The device fabrication starts with defining the mesa on an epitaxially grown wafer (consisting of the bottom DBR, λ -cavity, and the mesa region) using optical lithographic techniques. It ends with the top DBR deposition with thin-film deposition techniques. Mesas with a diameters of 0.75, 1.1, 1.6 and 2.0 μm were obtained with good uniformity and repeatability. Two different VCSEL designs were fabricated and tested; One with a λ -tuning layer of 295 nm, for lasing around

980 nm and the other with 275 nm λ -tuning layer, for lasing around 970 nm. The designs were chosen to cover the gain bandwidth range of the active region with different mesa sizes. Thin-film deposition recipes have been developed for SiO₂ by PECVD and HfO₂ by ALD deposition. The dominant surface roughness source was found to be SiO₂ films, which have caused scattering losses in the DBR .

The device was optically pumped using a home-built microphotoluminescence setup at RT in continuous-wave (CW) operation. The L-L curve, spectrum, and near field profile were obtained for both samples for the different mesa diameters. Lasing was observed even for Li-VCSELs with diameter of 0.75 μm . The estimated optical-to-optical power conversion efficiency (PCE) is around 30%. The spectral behavior of the devices is consistent with the simulation results. Single-mode operation was observed for all the sizes. Mode profiles show an excellent beam quality with Gaussian profile for all the sizes.

The successful demonstration of lasing for the submicron size, even with all the mirror losses, is a promising sign of the design's quality and the degree of optical confinement. Improvement in the fabrication, especially the quality of the DBR, will lead to a lower threshold devices. The ability to tune the wavelength with marginal impact on the quality factor is a good advantage for tunable VCSELs, for use in sensing and coherence tomography applications. Our next step is to demonstrate lasing in electrically pumped devices by investigating the optimal design for efficient current injection and confinement.

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Appendix A

Device fabrication flow

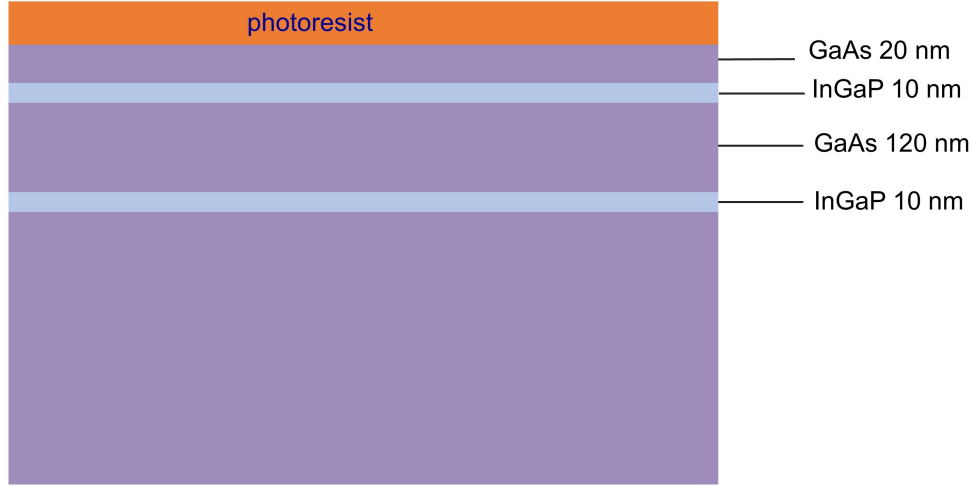
MARKER PATTERNING

1. Epitaxial structure



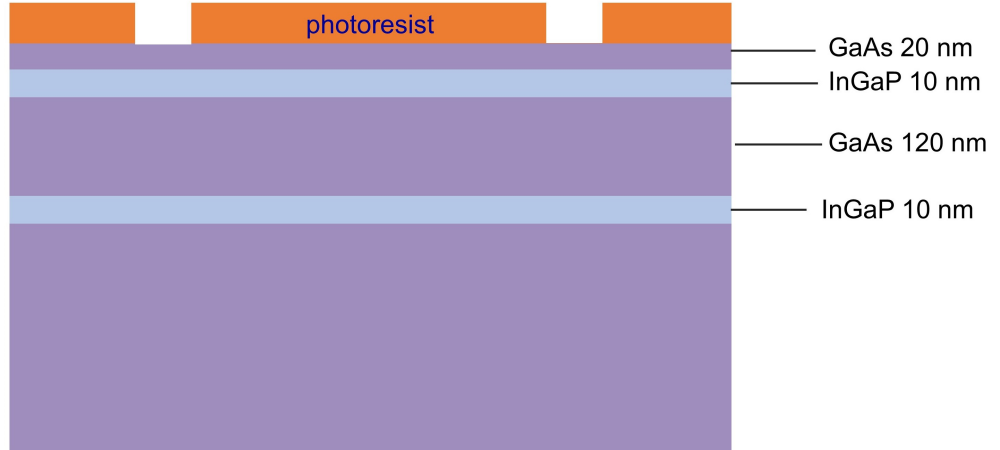
2. Photo-resist coating

- Spin-coat HMDS at 4000 rpm and 500 rpm/s for 60 s.
- Spin coat AZ1505 photoresist at 4000 rpm and 500 rpm/s for 60 s.
- Soft-bake in hotplate at 90 °C for 2 min.



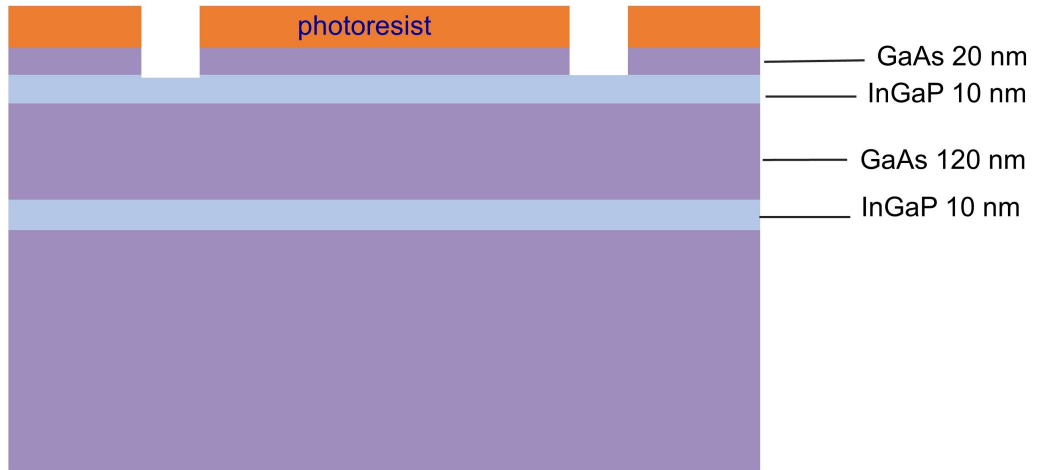
3. Photolithography

- Dose : 20 mJ/cm^2 in vacuum hard contact mode.
- Develop in AZ726MIF:DI (3:1) for 2 min.
- Post-bake in oven at 110°C for 6 min.
- Oxygen plasma cleaning for 1 min in Reactive ion etching (RIE) machine (71 W , $2 \mu\text{bar}$).



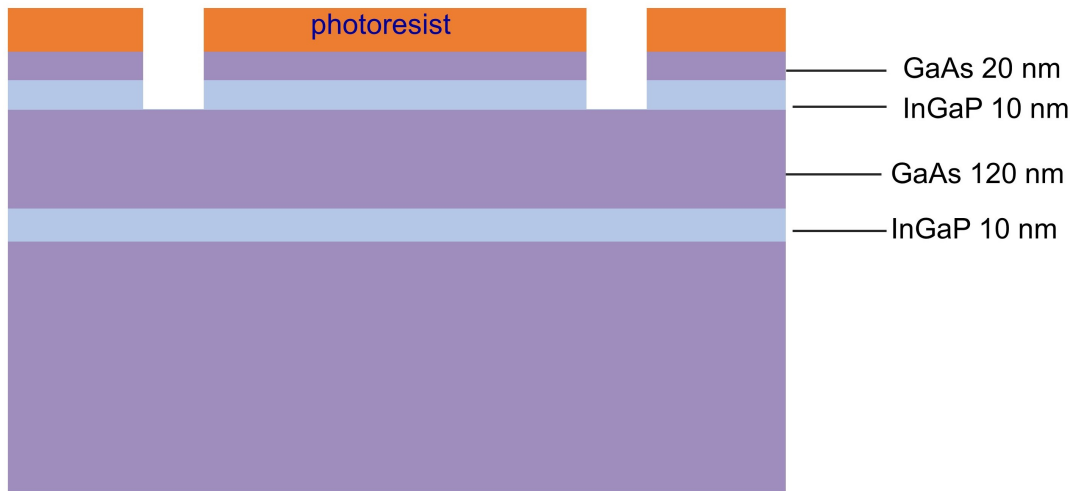
4. GaAs-1 Etch

- Etch in $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{DI}$ (1:1:64) solution for 1 min.
- Rinse in DI water and blow dry with N_2 .
- Inspection with microscope and step measurement with profilometer.



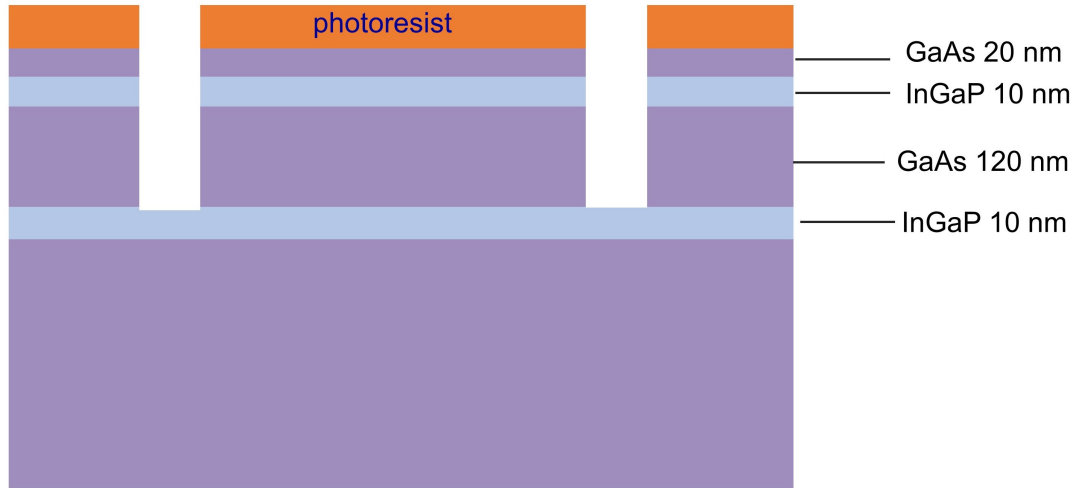
5. InGaP-1 Etch

- Etch in $\text{H}_3\text{PO}_4:\text{HCl}$ (3:1) solution for 1 min.
- Rinse in DI water and blow dry with N_2 .
- Inspection with microscope and step measurement with profilometer.



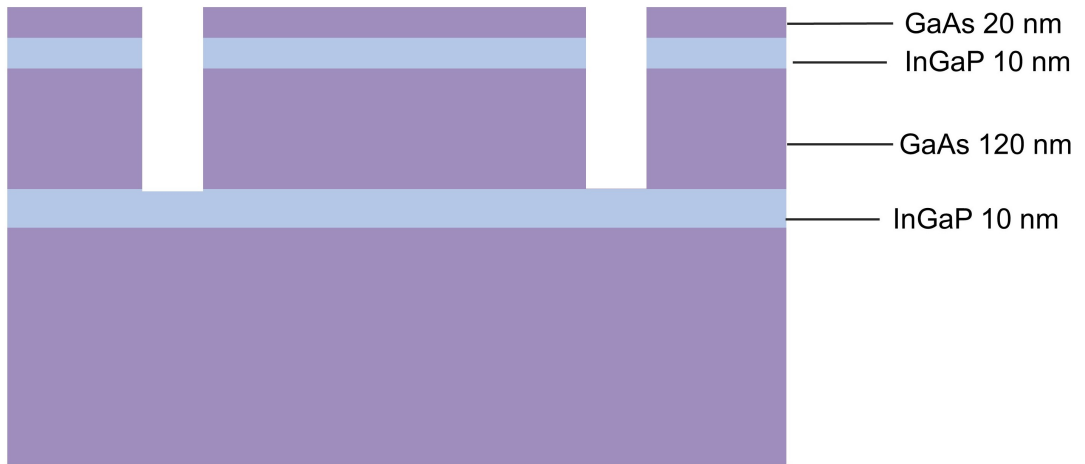
6. GaAs-2 Etch

- Etch in $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{DI}$ (1:1:64) solution for 3 min.
- Rinse in DI water and blow dry with N_2 .
- Inspection with microscope and step measurement with profilometer.

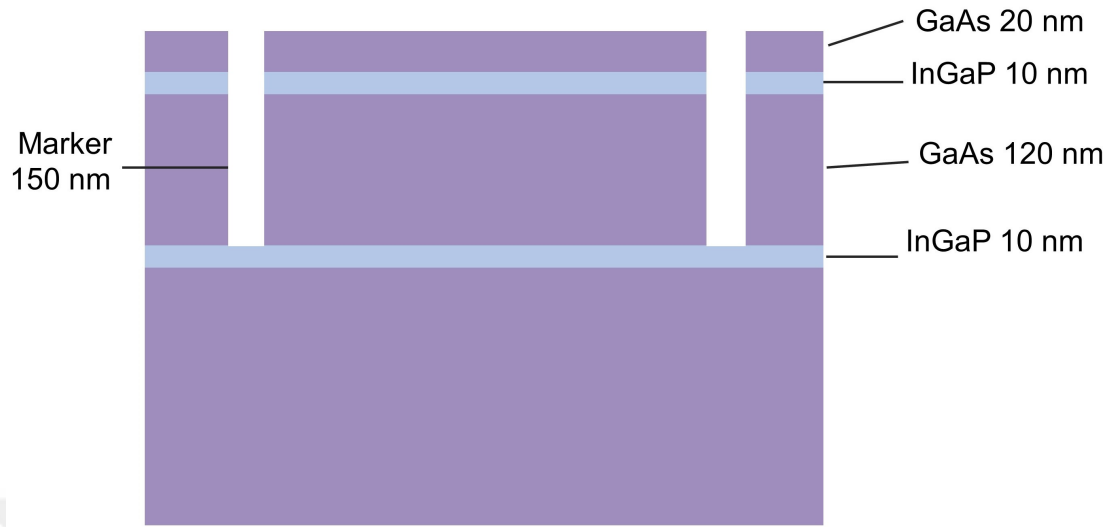


7. Photo-resist strip

- Dip in acetone for 1 min, Isopropanol (IPA) for 1 min.
- Rinse in DI water and blow dry with N_2 .
- Oxygen plasma cleaning for 1 min in reactive ion etching (RIE) machine (71 W, 2 μ bar).
- Inspection with microscope and step measurement with profilometer.

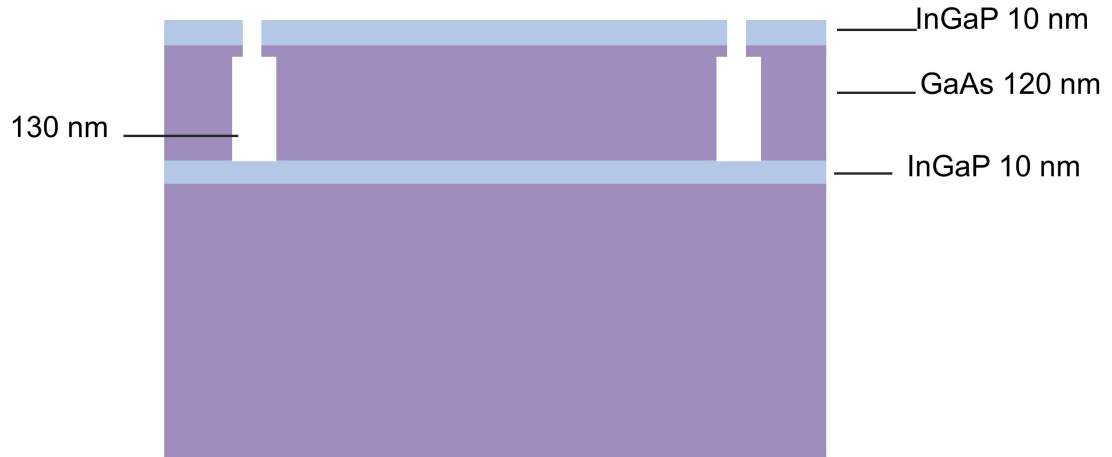


MESA PATTERNING



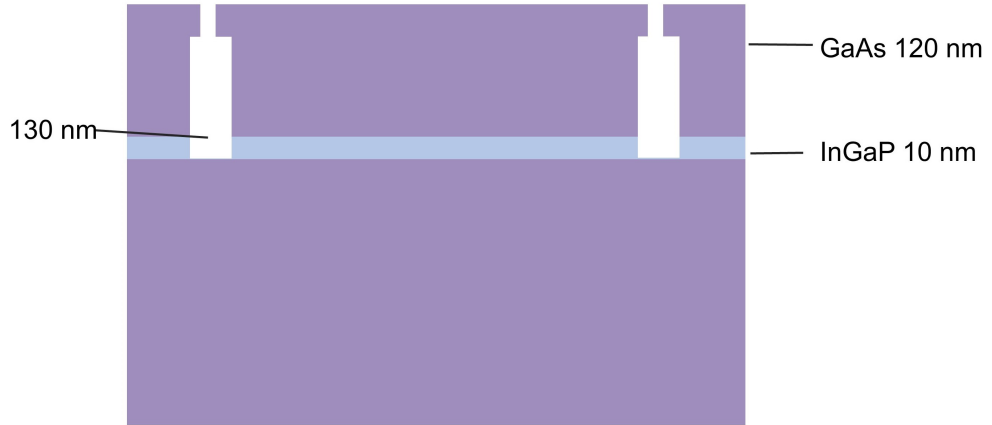
8. GaAs-1 Etch

- Etch in $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{DI}$ (1:1:64) solution for 45 s.
- Rinse in DI water and blow dry with N_2 .
- Inspection with microscope and step measurement with profilometer.



9. InGaP-1 Etch

- Etch in $\text{H}_3\text{PO}_4:\text{HCl}$ (3:1) solution for 1 min.
- Rinse in DI water and blow dry with N_2 .
- Inspection with microscope and step measurement with profilometer.



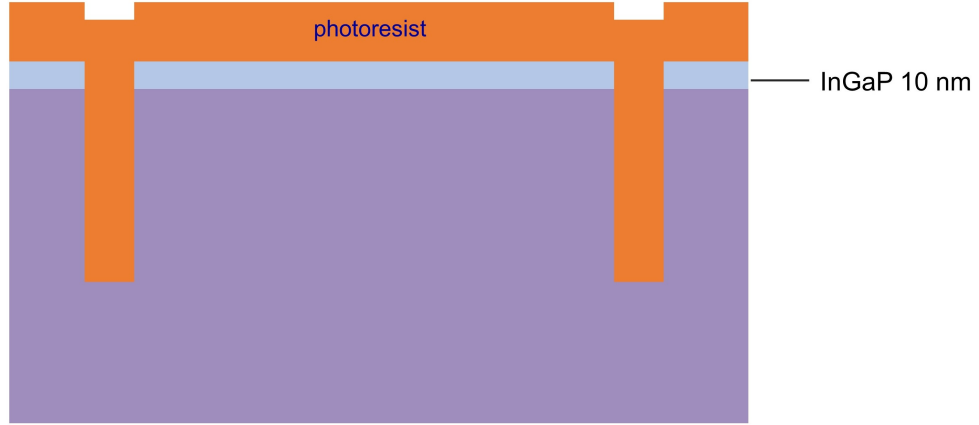
10. GaAs-2 Etch

- Etch in $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{DI}$ (1:1:64) solution for 3 min.
- Rinse in DI water and blow dry with N_2 .
- Inspection with microscope and step measurement with profilometer.



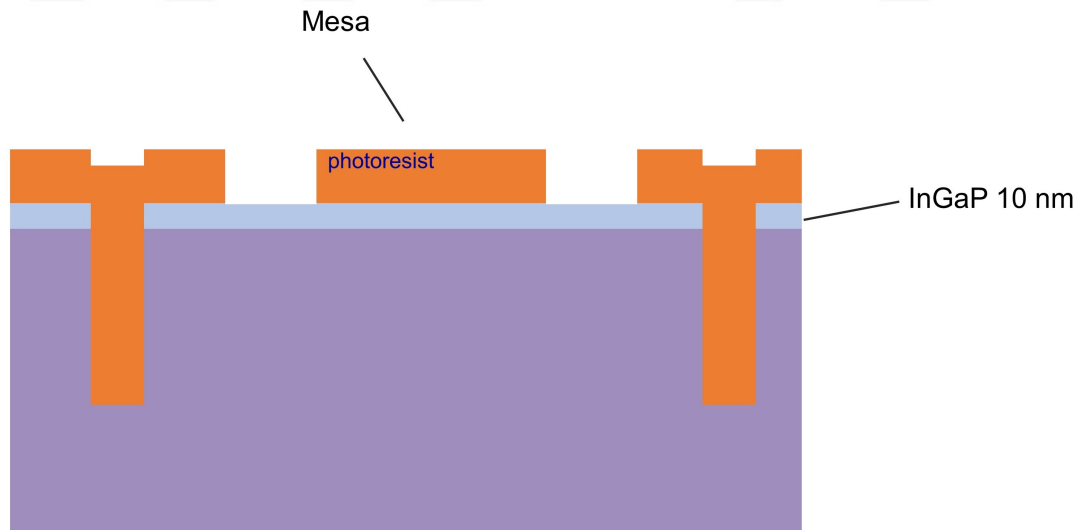
11. Photo-resist coating

- Spin-coat HMDS at 6000 rpm and 500 rpm/s for 60 s.
- Spin coat AZ1505 photoresist at 6000 rpm and 500 rpm/s for 60 s.
- Soft-bake in hotplate at 100 °C for 1 min.



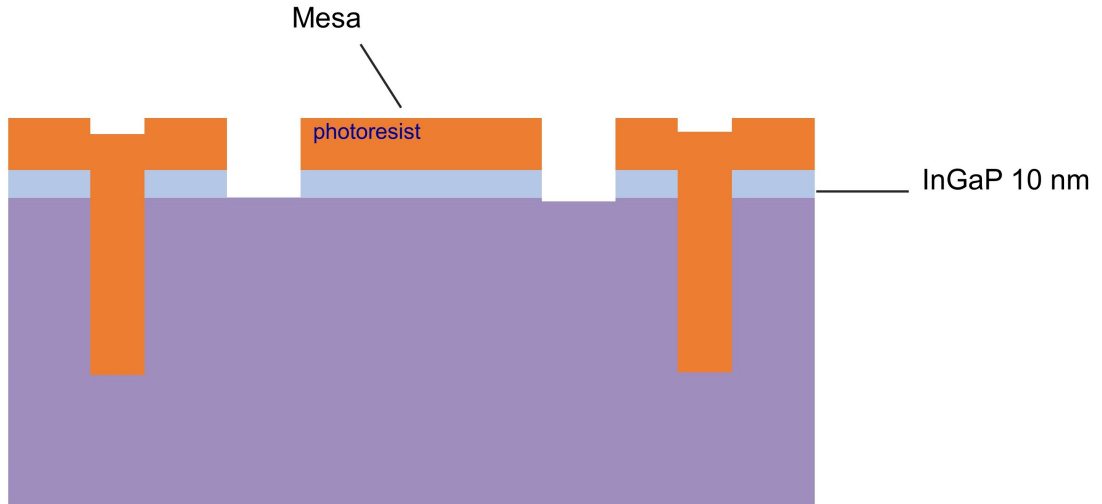
12. Mesa lithography

- Exposure for 36 s in hard-contact mode.
- Post-exposure bake at 100 °C for 1 min.
- Develop in AZ726MIF:DI (4:1) for 2 min 30 s.
- Post-bake in hotplate at 110 °C for 6 min
- Oxygen plasma cleaning for 1 min in Reactive ion etching (RIE) machine (71 W, 2 μ bar).



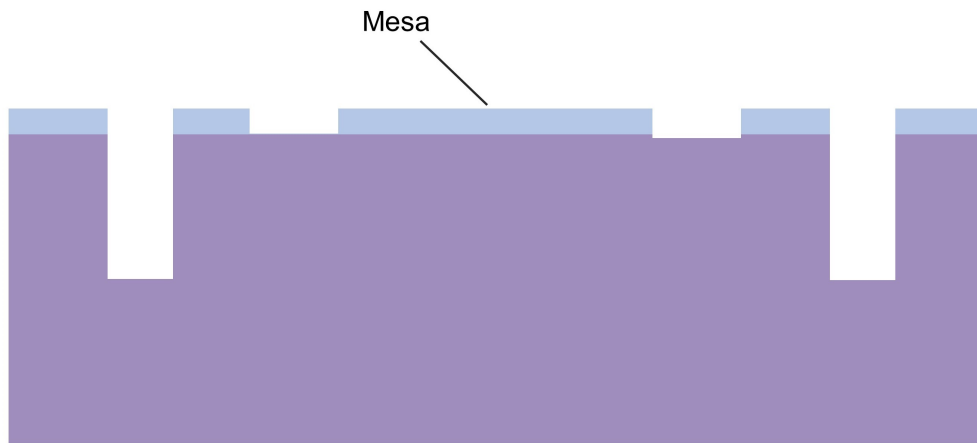
13. InGaP-2 Etch

- Etch in $\text{H}_3\text{PO}_4:\text{HCl}$ (3:1) solution for 1 min.
- Rinse in DI water and blow dry with N_2 .
- Inspection with microscope and step measurement with profilometer.



14. Photo-resist strip

- Dip in acetone for 1 min, Isopropanol (IPA) for 1 min.
- Rinse in DI water and blow dry with N_2 .
- Oxygen plasma cleaning for 1 min in reactive ion etching (RIE) machine (71 W, 2 μ bar).
- Inspection with microscope and step measurement with profilometer.



15. Top DBR deposition

- 11-pair SiO_2/HfO_2 DBR deposition with SiO_2 in PECVD and HfO_2 in ALD.
- Mesa profile check using SEM

