IMPROVING THE EFFICIENCY AND THRESHOLD CURRENT OF PHOTONIC CRYSTAL VERTICAL-CAVITY SURFACE-EMITTING LASERS

BY

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THESIS

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This work focuses on how to achieve high power, low threshold, and high efficiency single mode VCSELs. Various mechanisms that affect the differential quantum efficiency and threshold current of the proton-implanted and oxide-confined photonic crystal vertical-cavity surface-emitting lasers (VCSELs) are studied. Three degrees of freedom in designing the photonic crystal VCSELs to maximize the laser performance in terms of efficiency and threshold current are considered: the epitaxial structure, the relative size of the current aperture and the transverse optical mode, and the photonic crystal design. The theoretical background regarding the differential quantum efficiency and threshold current of the photonic crystal VCSELs is presented. Proton-implanted 850 nm VCSELs intended for high efficiency single mode lasing are fabricated and characterized, and then the experimental results are compared with the theories. It is found that spectral and spatial mode-gain overlap, optical loss, and thermal effects affect the laser efficiency and threshold current. The thermal effects also affect the dynamical change of differential quantum efficiency with the injected current. The epitaxial structure determines the spectral mode-gain overlap and the modal properties of the VCSELs, while the relative size of the current aperture and the optical mode sets the spatial mode-gain overlap factor. The photonic crystal air hole fill-factor has an impact on all the mechanisms mentioned above. By etching the photonic crystal into proton-implanted VCSELs, stronger index guiding is introduced and consequently the wide distribution of efficiency and threshold current between devices and the discontinuity in measured output power versus current are eliminated, and the threshold current is reduced. Single mode power of 2.5 mW is obtained from proton-implanted photonic crystal VCSELs.
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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

The concept of the vertical-cavity surface-emitting laser (VCSEL) was first proposed by Iga in 1977 [1], and the first working devices were subsequently reported later by the same group [2]. The VCSEL has its light output emitted perpendicular to the surface of the wafer in which the laser is fabricated, as opposed to optical power emanating from the edge of the wafer as in edge-emitting lasers. The VCSEL contains a Fabry-Perot cavity with two distributed Bragg reflector (DBR) mirrors above and below the active (gain) region. The DBRs are formed of multiple periods of high-and-low-refractive index layers, each period being half a wavelength of light in the material. Light is partially reflected at each interface of different refractive indices, and the reflectivity is proportional to the difference between the refractive indices as well as the number of DBR periods. Such mirror structure produces reflectivity of greater than 99% from multiple constructive interferences, and this is essential for VCSELs which have relatively short cavity length to achieve lasing. The laser diode, which consists of a p-i-n junction, is forward biased such that carriers are injected into the intrinsic active region through the doped DBRs. In Chapter 3, several sketches and pictures of VCSELs will be shown.

The surface-emitting characteristic of VCSELs enables mass production of VCSELs using standard silicon electronic device processing techniques at relatively low
cost per laser [3]. For the same reason, on-wafer testing is also possible because no facet formation is needed before packaging. The symmetrical transverse optical confinement of VCSELs guarantees a circular light beam, and this increases the coupling efficiency of VCSEL light output into optical fiber. The relatively short cavity of VCSELs ensures single longitudinal mode lasing, and the small active volume results in low threshold current, hence low operating power. Because of these advantages, VCSELs have in the last two decades emerged as an important light source for various optical data communication, sensing and imaging applications. Lasing in multiple transverse modes is, however, one disadvantage of VCSELs, although such an emission characteristic is natural to VCSELs due to their relatively large lasing aperture cross section. Nonetheless, operating in single transverse mode is very much desired, as high beam quality or high spectral purity is required in most applications mentioned above.

For many applications, single mode VCSELs are desired. Apart from the capability to be mass produced with low cost, VCSELs are ideal for short distance optical interconnects such as in local area networks (LANs), rack-to-rack or board-to-board interconnects, or possibly even inter-chip data links because of their low power consumption, compatibility with CMOS electronics, and manufacturability of two-dimensional arrays for parallel transmissions [4]. In optical communication, it is essential to avoid chromatic dispersion of light by eliminating all optical modes but one, such that higher data bit rate can be achieved. By allowing only the fundamental mode, which is of Gaussian profile and has the lowest far-field divergence, the coupling efficiency of light output from VCSELs into optical fibers can be enhanced. For the position sensing technology employed in laser mice, lasers with a high degree of coherence (i.e. single mode) are needed in surface illumination to produce a sharper laser speckle pattern to be detected by the sensors [5]. In optical data storage, the lasers employed must have high spatial coherence and single transverse (fundamental) mode as the laser beams are typically focused down to the diffraction limit [6]. Laser printing does not just require the capability to build monolithic arrays of lasers with robustness and high yield, but also single mode lasers with a circular beam to achieve higher resolution of images [7].
Atomic clocks using Cs or Rb cells require single frequency operation to exactly match the specified atomic transition, and single mode lasers with sub-miliAmps threshold current for low power operation (< 1 mW) are needed [8]. In short, to maximize their performance in many applications, VCSELs with stable single mode lasing, high efficiency and low threshold current are needed for the aforementioned applications.

1.2 Previous Research

Lateral oxidation [9] and proton implantation [10] can be used for transverse carrier confinement in VCSELs. These two types of confinement are also accompanied by optical wave-guiding. Index guiding in the proton-implanted VCSELs relies on the effect of thermal lensing [11], which induces a transverse index difference on the order of $10^{-3}$. The refractive index change is proportional to temperature change which depends on the current injection level, and more optical modes appear as the injected current is increased. On the other hand, the oxide-confined VCSELs have a relatively large index contrast between the lateral oxide and the semiconductor region, typically on the order of $10^{-2}$ [12]. For a cylindrical waveguide with step-like transverse index profile, it is necessary to have the normalized wavelength $V_{\text{eff}}$ given as

$$V_{\text{eff}} = \frac{\pi D}{\lambda} \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}$$

(1.1)

to be smaller than 2.405 to satisfy the single mode requirement [13]. In Equation (1.1), $D$ is the core region diameter, $\lambda$ is the wavelength, $n_{\text{core}}$ is the core refractive index, and $n_{\text{clad}}$ is the cladding refractive index. Due to the inherently large index step, a small oxide aperture of about 3 µm is needed to yield single mode operation for oxide-confined VCSELs. Such devices with small diameter suffer from poor manufacturability and reproducibility, increased threshold current, low output power, and high series resistance which entails shorter lifetime due to excessive heating and current density. Only through a proper placement of the oxide layer at the node of the longitudinal standing wave
profile, can the highest single mode power of 4.8 mW be achieved in 850 nm oxide VCSELS with 3.5-μm oxide aperture diameter [14].

Over the years, efforts have been made to obtain fundamental mode lasing in VCSELS. Nevertheless, not all of these methods produce high side-mode suppression ratio (SMSR) or maintain single mode lasing throughout the whole operating current range. Most of the methods listed below involve separating the electrical (carrier) and the optical confinement, and this provides the freedom of designing the current aperture to either minimize the series resistance or maximize the laser efficiency (see Chapter 4). The approaches to achieve single mode lasing include: (1) creating a waveguide that only supports the fundamental mode such as having a small lasing aperture or low index contrast between the core and the cladding, (2) providing more gain to the fundamental mode, and (3) introducing greater losses to the higher order modes. For lasers without external components, transverse spatial structuring has proven to be the most effective way to achieve such purposes, owing to the different spatial extent of the different transverse modes. An exception to this is utilizing a long monolithic cavity that contains a thick (few microns) cavity spacer to increase diffraction loss to the higher order modes [15]. A coupled-resonator configuration also results in high power (6.1 mW) single mode operation [16]. However, there is a risk that the second longitudinal mode will appear in these devices due to the extended cavity length.

One successful example of gain selectivity for single mode emission is by implantation disordering around the active region to create a gain area smaller than the waveguide (oxide aperture) such that the fundamental mode is preferentially pumped [17]. Young et al. reported a type of hybrid proton implanted/selectively oxidized VCSEL with single mode operation (SMSR > 45 dB) for the entire operating current range [18]. It uses proton implant to confine the carrier flow and lateral oxide to confine the optical mode. With the implant aperture smaller than the oxide aperture, single mode operation is ensured as the fundamental mode is favored in terms of spatial mode-gain overlap. Maximum single mode power of greater than 4.5 mW is achieved, and broad area single
mode lasing can be obtained. However, the relative size of the oxide and the implant aperture is important as the modes are either influenced by thermal lensing for large oxide aperture or the large oxide index step for small oxide aperture [19].

There have also been efforts to create antiguided structures instead of index-guided approaches. This can be done by either having a cladding region with higher refractive index to create modal loss discrimination [20]-[22], or utilizing the one-dimensional photonic crystal effect such that the low-radiation loss leaky fundamental mode is selected by the low index core region that is provided with gain [23]. All these methods require regrowth of laser materials, which adds complexity to the device fabrication.

Loss selectivity to induce single mode emission can be done by increasing the mirror loss (through modification of the mirror reflectivity), scattering loss or absorptive loss to the higher order modes. Unfortunately, the fundamental mode usually suffers from these losses as well, albeit at a lower level. To introduce scattering loss, modified oxide structure can be employed. For example, multiple oxide layers [24] and tapered thick oxide layer [17] have been utilized for such purpose. Nonetheless, these methods rely on very tight control of lateral oxide extent, hence manufacturability is still an issue. On the other hand, using Zn diffusion to disorder a DBR region that encompasses an area smaller than the current aperture [25] increases both mirror loss and free carrier absorption for the higher order modes [26], and recently single mode VCSELs with low threshold (0.5 mA), high differential efficiency (80%), high output power (7.3 mW) and low series resistance (78 Ω) have been obtained [27].

There are a few examples of single mode VCSELs which use increased mirror loss to the higher order modes. Mirror reflectivity can be decreased by inducing a phase-mismatch through the gold-semiconductor interface. Using metal as the spatial filter (by having a metal opening smaller than the current aperture) to modify the transverse reflectivity and to introduce scattering loss to the higher order modes has been reported in implant [28] and oxide-confined [29] VCSELs, and also VCSELs with regrown dielectric
mirror [30]. Etching a shallow surface-relief can also help to engineer the transverse reflectivity profile [31]. The mirror loss has a strong periodic variation with etch depth, and by etching away the topmost epi-layer by a quarter-wavelength to induce anti-phase reflections, the threshold gain difference between the etched and unetched area could be up to ten times [32]. However, the etch depth precision has to be within a few nanometers even for devices grown to antiresonance thickness to relax the etch depth precision requirement [33]. Nonetheless, high single mode power (6 mW) and sub-milliamp threshold current is achieved for optimized lasers [34]. Self-alignment of the surface-relief (optical aperture) and the oxide (current) aperture can also be done [35]. Another method of creating higher mirror loss to the higher order modes is by etching away a few DBR pairs at the periphery while leaving the center intact as reported by Lehman et al. [36].

In this work, we focus on the photonic crystal (PhC) structure in the form of periodic air holes etched onto the output DBR mirror and one or more air holes removed to form the lasing defect, a method that utilizes the concepts of both single mode waveguide and loss selectivity to achieve single mode emission. Similar to most of the schemes mentioned above, the PhC method involves creating transverse variation of refractive index and loss in the lasers. It has been found to be an excellent way to produce single mode lasing in VCSELs [37], [38], [39]. The PhC VCSELs have waveguides with transverse step-index profile which is stable with respect to the carrier injection level as well as temperature. Note also that the PhC structure does not provide carrier confinement, hence lateral oxide or proton implantation is still needed for such purpose in PhC VCSELs. Note that the transverse refractive index profile has to be dominated by the PhC structure, which is possible provided that the lasing defect is smaller than the current aperture and the air holes are etched deep enough [40].

Utilizing the PhC structure, the index guiding, losses and lasing aperture size are all lithographically defined, and this provides robustness of fabrication and reproducibility. The VCSELs are monolithic and lithographically controlled, so they can
be made into two-dimensional arrays and are also readily integrated with other optical components for purposes such as wavelength-division multiplexing (WDM) and laser-detector integration. There is no stringent requirement imposed on the epitaxial design of the VCSELs in order to achieve single mode operation. Instead, the device structure is carefully considered in regard to the relative size of the lasing and the current aperture. Furthermore, PhC modal characteristics can easily be calculated because of the periodicity of the air holes, and the standard step-index fiber analysis can be applied to the PhC waveguides (see Chapter 4). In regard to performance, the PhC VCSELs have the potential to provide single fundamental mode lasing for the entire operating range of current from threshold to roll-over. Due to the small index difference on the order of $10^{-3}$ between the core and the cladding, the $V_{\text{eff}} < 2.405$ condition can be satisfied without the need to scale down the lasing aperture size; therefore, smaller divergence angle can be obtained. It has been reported that the PhC implant-confined VCSELs have higher modulation bandwidth than both oxide and implant-confined VCSELs [41].

Similar to the PhC, triangular holey structure [42] can be etched to produce single mode oxide-confined VCSELs. Single mode power as high as 7 mW can be achieved, but the near and far fields have a floral pattern, which decreases the coupling efficiency of light into single mode fiber. Using proton implant as current confinement, it is shown that the threshold current and the slope efficiency of the holey VCSELs can be improved compared to the unetched VCSELs apart from achieving single mode operation [43], and the same is achieved for PhC implant-confined VCSELs [44]. This issue will be explored further in this thesis in Chapter 4. Optical power > 1 mW, threshold current < 2 mA and SMSR > 30 dB are obtained for implant-confined PhC VCSELs [44], [45], and as will be shown in Chapter 4, further performance improvements can be achieved with optimized epitaxial and PhC designs of the VCSELs.

It was previously shown that there are PhC VCSELs that lase in single mode even though their calculated $V_{\text{eff}}$ is greater than 2.405 and some that lase in multi-mode even though they have $V_{\text{eff}}$ less than 2.405 [46]. This is due to the fact that, as will be explained
in the next chapter, the optical loss from the photonic crystal structure [47], [48] is also crucial in determining whether single mode lasing can be achieved in PhC VCSELs based on loss selectivity.

1.3 Scope of Work

The focus of this work is how to achieve high power, low threshold, and high efficiency single mode VCSELs. The epitaxial structure, the PhC designs, and the relative size of the current and the lasing aperture will be considered in producing high performance VCSELs.

Chapter 2 will present the theoretical background for both the threshold current and the slope efficiency of the PhC VCSELs. A derivation of the light output power versus current (L-I) relationship will be shown, and various loss mechanisms as well as thermal issues will be discussed. The schemes of numerical calculations for the refractive index and the optical loss of the PhC waveguides will also be presented. Chapter 3 will address the device fabrication of the PhC VCSELs. First the epitaxial structure and the design of the PhC structure will be shown and tabulated, and the fabrication steps as well as manufacturing issues associated with the oxide and the implant-confined PhC VCSELs will follow. In Chapter 4, the experimental setup will be presented, along with the results of (1) the general impact of PhC on laser performance, (2) how various PhC parameters affect the laser performance, and (3) high power PhC VCSELs. Finally, the thesis will be summarized and possible future work will be brought forth in Chapter 5.

1.4 References


CHAPTER 2

THEORY OF PHOTONIC CRYSTAL VCSEL EFFICIENCY

2.1 Introduction

In this chapter, the theoretical background regarding the differential quantum efficiency and threshold current of single mode lasers will be presented. First, the output power versus current relation will be derived from the carrier and photon rate equation in Section 2.2. The derivation shows that in contrast to the multimode lasers, single mode lasers such as the PhC VCSELs can have differential quantum efficiency and threshold current that are more sensitive to several factors such as the spatial and spectral mode-gain overlap as well as heating problems. The following sections will address the issues of thermal effects (Section 2.3) and optical loss (Section 2.4) due to etching PhC on VCSELs, and how these two factors affect both the differential quantum efficiency and the threshold current of the VCSELs. The numerical schemes to calculate the refractive index and the optical loss of the PhC waveguides will also be presented in Section 2.4. The various factors that contribute to the variation of the differential quantum efficiency and the threshold current will then be verified by experiments as discussed in Chapter 4. Through recognizing and understanding these contributions, we will be able to design PhC VCSELs with optimized differential quantum efficiency and threshold current such that high power single mode laser sources can be obtained. The temperature dependence of the differential quantum efficiency results in its variation with respect to the injected current, and this implies that maximum efficiency can be designed to coincide with the
desired operating current level if we have a better understanding of the thermal properties of the VCSELs.

2.2 Rate Equations and Laser Efficiency

To study the efficiency of lasers, it is imperative to learn the relation between the optical power and the injected current of lasers through the carrier and photon number rate equations. The two rate equations linking the carriers and the photons are given as [1]

\[
V \frac{dn}{dt} = \eta_i \frac{I}{q} + D \frac{d^2 n}{dx^2} V - \frac{nV}{\tau} - v_g g N_p V
\]

(2.1)

and

\[
V_m \frac{dN_p}{dt} = v_g g N_p V + \beta \frac{nV}{\tau_{sp}} - \frac{N_p V_m}{\tau_p}
\]

(2.2)

where \( n \) is the carrier concentration, \( N_p \) is the photon density, \( V \) is the active volume, \( V_m \) is the mode volume, \( q \) is the electron charge, \( V \) is the volume of the active region, \( \eta_i \) is the efficiency of carrier injection into the active region, \( D \) is the ambipolar diffusion coefficient, \( v_g \) is the group velocity of the photons, \( g \) is the laser gain, \( \beta \) is the spontaneous emission factor, \( \tau \) is the carrier lifetime (which in general depends on \( n \)), \( \tau_p \) is the photon lifetime, and \( \tau_{sp} \) is the spontaneous emission lifetime (the average time before carriers are lost through spontaneous emission). An implicit assumption is that the electron concentration is equal to the hole concentration, which is justified because the active region is usually very lightly doped; therefore, most carriers come from external injection. Then, strictly speaking, the second diffusion term on the right-hand side of Equation (2.1) should account for electrons and holes as they have different diffusion coefficients. Dividing Equation (2.1) by \( V \) and Equation (2.2) by \( V_m \), we arrive at

\[
\frac{dn}{dt} = \eta_i \frac{I}{qV} + D \frac{d^2 n}{dx^2} - \frac{n}{\tau} - v_g g N_p
\]

(2.3)
and

\[
\frac{dN_p}{dt} = \Gamma V g N_p + \Gamma \beta \frac{n}{\tau_{sp}} - \frac{N_p}{\tau_p}
\]  

(2.4)

where \( \Gamma = \frac{V}{V_m} \) is defined as the confinement factor.

The two rate equations describe the rate of change of carriers and photons (of the lasing mode) in the carrier and photon reservoirs, or how the reservoirs gain and lose the particles. In Equation (2.3), the first two terms on the right correspond to two carrier sources, one from the injected current that provides carriers to the active region, and another from the diffusion of carriers due to nonuniform carrier distribution in the transverse direction. The last two terms represent carrier loss: one corresponds to spontaneous emission and nonradiative recombination, and the other corresponds to stimulated emission which provides photons for the lasing mode. The third term can further be separated into two terms by acknowledging that

\[
\frac{1}{\tau} = \frac{1}{\tau_{nr}} + \frac{1}{\tau_{sp}}
\]  

(2.5)

where \( \tau_{nr} \) is the nonradiative recombination lifetime, the average time before carriers are lost through processes such as Shockley-Read-Hall recombination, Auger recombination, and surface recombination. Heat rather than light is produced if the carriers recombine through nonradiative recombination events. This causes heating of lasers and rise in temperature, which can affect the laser efficiency especially when the lasers are operated continuous-wave (CW). In Equation (2.4), the first two terms dictate that both stimulated emission as well as spontaneous emission that couples into the lasing mode should contribute to increasing photon density in that particular mode. Note that the two terms are multiplied by the confinement factor \( \Gamma \), which indicates that the contributions are proportional to the spatial overlap of active volume and mode volume. The laser gain, \( g \), is given as
\[ g = g'(n - n_{tr}) \] (2.6)

where \( g' \) is the differential gain and \( n_{tr} \) is the transparency carrier concentration. Equation (2.6) is only valid for a limited range of \( n \) because the peak gain eventually saturates for large \( n \), and the resultant gain-carrier relation becomes a logarithmic relation.

In order for the electric field to reproduce itself after a round-trip in the cavity, the modal gain has to be equal to the cavity loss such that the lasing threshold is reached. This condition is described by the equation

\[ \Gamma g_{th} = \alpha_i + \frac{1}{L} \ln\left(\frac{1}{R_1 R_2}\right) \] (2.7)

where \( g_{th} \) is the threshold gain, \( \alpha_i \) is the intrinsic loss, \( L \) is the cavity length, \( R_1 \) and \( R_2 \) are the mirror power reflectivity. The intrinsic loss is photon loss through processes such as scattering, free carrier absorption, band-to-band absorption, and diffraction. The second term is also known as the mirror loss because its magnitude determines how much light output can be extracted out of the laser cavity. The higher the mirror loss, the higher the photon escape rate for the cavity.

Under CW operation, lasers achieve a steady state after a short time (determined by thermal time constant), and the left-hand side of both Equation (2.3) and (2.4) can be set to zero. It is also safe to assume that stimulated emission is absent below laser threshold (before gain overcomes cavity loss), so the last term in Equation (2.3) can be dropped. Under subthreshold condition, the second term on the right of Equation (2.3) is negligible due to uniform recombination and effective current spreading along the transverse direction. At threshold, Equation (2.3) becomes

\[ n_{th} = \tau_{th} \eta_t \frac{I_{th}}{qV} \] (2.8)

where \( \tau_{th} \) is defined as \( \tau(n_{th}) \).
Above threshold, it is usually assumed that gain, the carrier concentration and the carrier recombination rate are clamped to the value of $g_{th}$, $n_{th}$ and $\tau_{th}$ regardless of current injection level. However, due to the different diameter of the current and optical aperture in PhC VCSELs (with current aperture larger than optical aperture), the field intensity does not fully overlap the electrically pumped area; therefore, spatial hole burning is expected to occur. This means that the gain and the carrier concentration are pinned at threshold gain and threshold carrier concentration in the region where the lasing field intensity is present, but will increase with injected current outside of such region. Therefore $n$ should really be written as

$$n = n_{th} + \Delta n(I, x)$$  \hspace{1cm} (2.9)

with the first term corresponding to the clamped carrier concentration at the center of the laser and the second term corresponding to the unclamped peripheral carrier concentration, which is proportional to the current injection level. The unclamped carrier concentration leads to enhanced recombination rate at the periphery, and increases the number of photons produced due to spontaneous emission, which should be accounted for in the photon rate equation. At the same time, the increase in spontaneous emission suppresses the stimulated emission (see Equation (2.4)), and this effectively reduces the differential quantum efficiency [2]. Even though the diffusion of carriers to the device center from the periphery due to a built-up transverse gradient of carrier concentration tends to counteract the spatial hole burning effect [3], we should still observe background light coming from spontaneous emission in the area bounded by a smaller optical aperture with a larger current aperture. Ignoring the transverse variation of recombination rate and diffusion current (since the variations are not captured by the broad area photodetector used in measuring the optical power of the lasers), we consider only the first, third (without $\Delta n(x)$) and last terms on the right of Equation (2.3) when we derive the relation between the photon density and the carrier concentration, even above threshold.

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Above threshold, stimulated emission dominates the generation of photons, and Equation (2.3) gives

\[ N_p = \frac{\eta_i \left( \frac{I}{qV} - n_{th} \left( \frac{1}{\tau_{nr}} + \frac{1}{\tau_{sp}} \right) \right)}{v_g g} \]  

\[ (2.10) \]

Solving for \( g \) from Equation (2.4) (setting the left hand side to zero) and substituting it into Equation (2.9), and after some algebraic manipulation, we obtain

\[ N_p = \Gamma \tau_p \left[ \eta_i \left( \frac{I}{qV} - n_{th} \left( \frac{1}{\tau_{nr}} + \frac{1 - \beta}{\tau_{sp}} (n_{th}) \right) \right) \right] \]  

\[ (2.11) \]

To derive Equation (2.10), two assumptions are made: (1) Auger recombination is less important in the GaAs-AlGaAs laser system, so \( \frac{1}{\tau_{nr}} \) only includes the rate of SRH and surface recombination, both of which have no dependence on \( n \), and (2) \( \frac{1}{\tau_{sp}} \) is linearly proportional to \( n \).

To obtain the power-current or light-current (LI) relation, it is typical (in the case of edge-emitting lasers) that we multiply the photon density by the mode volume, the photon energy, and the photon escape rate, which is the photon group velocity multiplied by the mirror loss \( (\alpha_m) \). By doing so, \( \Gamma \) and \( V \) (which appears in the denominator) of Equation (2.10) are cancelled. The definition of \( \Gamma = \frac{V}{V_m} \) is made by separating the confinement factor into two factors, one corresponding to the longitudinal (propagation) direction and another for the transverse (perpendicular) plane, given as

\[ \Gamma = \frac{d \cdot w \cdot L_s}{d_{eff} \cdot w_{eff} \cdot L} \]  

\[ (2.12) \]
where \( w \) is the electrically pumped width, \( L_a \) is the length of the active region, \( d_{\text{eff}} \) and \( w_{\text{eff}} \) are the effective widths of the (Gaussian) mode in the transverse directions, and \( L \) is the total length of the cavity. This definition, however, might not be applicable to microcavity lasers such as PhC VCSELs due to the size difference between the optical and the electrical apertures. It has been observed experimentally that the optical power is limited by the ratio of the mode area to the active area [4]. For VCSELs, the longitudinal confinement factor \( \Gamma_z \) is a product of the active length fill factor and the enhancement factor \( \Gamma_{\text{enh}} \) [1] due to the quantum wells being placed at the standing wave field antinode, and is typically close to two [5]. For confinement factor in the transverse directions, we need to go back to the fundamental definition of \( \Gamma_t \), given by

\[
\Gamma_t = \frac{\int_{\text{active}} |u(r, \varphi)|^2 dA}{\int_{\text{all}} |u(r, \varphi)|^2 dA}
\]  

(2.13)

in which the numerator is an integration of the transverse field intensity profile over the active region (where gain is present) and the denominator an integration of the transverse field intensity profile over all space. For PhC VCSELs in which the optical aperture diameter is smaller than the current aperture diameter, \( \Gamma_t \) approaches unity because most of the intensity is confined within the lasing defect and decays rapidly in the region with PhC. To correct for the effect of optical and electrical aperture separation, we multiply Equation (2.10) by \( V_m \cdot \frac{\Gamma_z \Gamma_t}{\Gamma} \) instead of just \( V_m \). Taking the mode volume \( V_m \) to be

\[
V_m = \pi \left( \frac{D_{\text{eff}}}{2} \right)^2 L
\]

(2.14)

where \( D_{\text{eff}} \) is the mode size defined as the \( 1/e \) point of the maximum field intensity (typically greater than the optical aperture diameter) and \( L \) is the cavity length taking into account penetration of field into the DBRs, and the active volume

\[
V = \pi \left( \frac{C_{\text{current}}}{2} \right)^2 L_a
\]

(2.15)
where \( C_{\text{current}} \) is the current aperture diameter defined by the lateral oxide or proton implant, then the optical power \( P \) is given by

\[
P = \eta_i \frac{\alpha_m}{\alpha_i + \alpha_m} \frac{\hbar \omega}{q} \Gamma_{\text{enh}} \frac{D_{\text{eff}}^2}{C_{\text{current}}} [I - I_{th}(1 - \beta \eta_r)]
\]

(2.16)

where a new quantity, radiative efficiency \( \eta_r = \frac{1}{\tau_{sp}} \) is introduced. Note that to arrive at Equation (2.16), the photon lifetime \( \tau_p \) is related to the cavity loss through

\[
\frac{1}{\tau_p} = v_g g_{\text{th}} = v_g (\alpha_i + \alpha_m)
\]

(2.17)

\( \beta \) represents the fraction of energy going into the lasing mode, and is proportional to \( \frac{\Gamma}{V} \) [1]. The term \( \beta \eta_r \) is typically ignored because \( \beta \) is usually much smaller than unity (on the order of \( 10^{-3} \)) in VCSELs due to their large transverse active area, while the value of \( \eta_r \) is always bounded by unity. If \( \beta \) or \( \eta_r \) is increased (for example, smaller cavity volume or shorter recombination lifetime), the effective threshold current becomes smaller because then spontaneous emission contributes more significantly to the number of photons in the lasing mode.

In lasers with single longitudinal mode, the spectral overlap of gain and cavity resonance has a tremendous impact on laser efficiency and threshold [6]. If the cavity resonance, which has a narrow distribution in wavelength (less than 1 nm), overlaps the gain (with bandwidth on the order of few tens of nanometers) at its peak value, the lasers can be pumped less than if the cavity resonance overlaps the tails of the gain profile. For the sake of simplicity, a unitless phenomenological gain-resonance overlap factor, \( \kappa \), is introduced in Equation (2.16), giving
\[ P = \kappa \eta_i \frac{\alpha_m}{\alpha_i + \alpha_m} \frac{\hbar \omega}{q} \Gamma_{\text{enh}} \frac{D_{\text{eff}}^2}{C_{\text{current}}} \left[ I - I_{\text{th}} (1 - \beta \eta_i) \right] \]  

(2.18)

Note that \( \kappa \) ranges from zero (when the gain at the cavity resonance wavelength, \( g(\tilde{\lambda}_m) \) is lower than the cavity loss) to one (when the gain peak coincides spectrally with the cavity resonance). If the peak gain does not spectrally coincide with the cavity resonance, part of the injected current is used up to satisfy the condition that \( \Gamma g(\tilde{\lambda}_m) \) is equal to the cavity loss, hence the laser effectively sees a lower efficiency compared to when the gain peak spectrally aligns with the cavity resonance.

For the conditions (1) \( \kappa \) is equal to one, (2) gain is a multiple of half wavelength (no gain enhancement), (3) the lasing defect diameter is about the same as or equal to the current aperture diameter (as in oxide or implant-confined VCSELs where oxide or implant provides both optical and electrical confinement), and (4) \( \beta \) is negligibly small, the L-I relation reduces to

\[ P = \eta_i \frac{\alpha_m}{\alpha_i + \alpha_m} \frac{\hbar \omega}{q} (I - I_{\text{th}}) \]  

(2.19)

as found in reference [1]. Hence the slope of L-I is a constant which is determined by the cold cavity condition. However, Equation (2.18) reveals that \( P \) can never be a linear function of \( I \) due to Joule heating of lasers as current injection is increased. The main contributors to this nonlinearity are \( \kappa \) and \( \eta_i \). Both the peak gain and the cavity resonance change in wavelength with respect to temperature; therefore, \( \kappa \) also varies with temperature. \( \eta_i \) is related to the number of carriers that do not recombine in the active region and is an exponentially decaying function of the temperature [1], so it has a strong dependence on injected current. The effect of temperature on L-I will be addressed in more detail in Section 2.3. Taking the derivative of \( P \) from Equation (2.18) with respect to \( I \), we get

\[ \frac{dP}{dI} = \frac{\alpha_m}{\alpha_i + \alpha_m} \frac{\hbar \omega}{q} \Gamma_{\text{enh}} \frac{D_{\text{eff}}^2}{C_{\text{current}}} \left[ \kappa \eta_i + I \left( \kappa \frac{d\eta_i}{dI} + \frac{d\kappa}{dI} \eta_i \right) \right] \]  

(2.20)
From this, we can see that the differential quantum efficiency \( \frac{dP}{dl} \) is a product of two factors, one from the cold cavity condition and one that is dependent on the magnitude of the injected current (temperature). Even though \( \frac{dP}{dl} \) seems to scale with current, the \( \kappa \frac{d\eta_i}{dl} + \frac{d\kappa}{dl} \eta_i \) term decreases with increasing temperature, and will eventually become negative in the high temperature regime (as \( \kappa \) and \( \eta_i \) goes to zero and \( \frac{d\eta_i}{dl} \) and \( \frac{d\kappa}{dl} \) become negative); therefore, the slope efficiency can be a negative number as well.

The spectral misalignment of the peak gain and the cavity resonance can be represented by a phenomenological method using an analytic expression for the gain as a function of the difference between the peak gain and the cavity resonance wavelength, \( \Delta \lambda \), as well as the active region temperature, giving the threshold current as a function of \( \Delta \lambda \) and temperature [6]. The variation of the differential quantum efficiency with temperature can then be lumped into the threshold current [2]. In fact, by separating the threshold current into two terms

\[
I_{th} = I_{th'} + I_{th''}(I)
\]

where the first term is due to the cold cavity condition and the second term is due to the variation in temperature, we have

\[
\frac{dP}{dl} = \eta_c [\eta_i (1 - \frac{dI_{th''}(I)}{dl}) + \frac{d\eta_i}{dl} (I - I_{th'} - I_{th''}(I))]
\]

where \( \eta_c = \frac{\alpha_m}{\alpha_i + \alpha_m} \frac{\hbar \omega}{q} \Gamma_{enh} \frac{D^2}{C_{current}} \). In Equation (2.18), we already eliminated the dependence of threshold current on temperature such that \( I_{th} = I_{th'} \). Modifying Equation (2.20) we have
\[
\frac{dP}{dl} = \eta_i [\kappa (I - I_{th}^\prime) \frac{d\kappa}{dl} + \frac{d\eta_i}{dl} \kappa (I - I_{th}^\prime)]
\]  \hspace{1cm} (2.23)

Comparing (2.22) and (2.23), we see that
\[
\kappa (I - I_{th}^\prime) = I - (I_{th}^\prime + I_{th}^{\prime\prime}(I))
\]  \hspace{1cm} (2.24)

hence \( \kappa \) is inversely proportional to \( \Delta \lambda \).

Setting Equation (2.20) to be zero, we obtain the expression for the roll-over current \( I_{ro} \) as
\[
I_{ro} = \left. -\frac{\kappa \eta_i}{\kappa \frac{d\eta_i}{dl} + \frac{d\kappa}{dl} \eta_i} \right|_{l = I_{ro}}
\]  \hspace{1cm} (2.25)

The roll-over current is difficult to solve analytically as \( \kappa \) and \( \eta_i \) are functions of injected current. If we substitute Equation (2.25) into Equation (2.18), we can easily obtain the expression for the maximum output power. It is obvious that the roll-over current and the maximum output power are closely related to the thermal properties of the lasers.

Finally, we modify Equation (2.8) such that
\[
I_{th} - I_{tr} = qV \left( \frac{n_{th} - n_r}{\eta_i \tau_{th}} \right)
\]  \hspace{1cm} (2.26)

where \( I_{tr} \) is the transparency current. Then using the gain expression given in Equation (2.6), we arrive at
\[
I_{th} = \frac{qV}{\eta_i \tau_{th}} \frac{g_{th}}{g} + I_{tr}
\]  \hspace{1cm} (2.27)

This equation dictates that the threshold current is proportional to the active volume and the cavity loss, and is inversely proportional to the injection efficiency, the carrier lifetime and the differential gain coefficient.
2.3 Thermal Effect on Laser Efficiency and Threshold Current

As stated in the previous section, heating of lasers is the primary source of nonlinearity of the L-I curve. In PhC VCSELs, Joule heating and nonradiative recombination are the two heating mechanisms that are altered significantly by introducing photonic crystal structure into the lasers. Due to removal of heat conducting material in the top DBR, it is expected that the lasers will suffer higher thermal impedance (lower thermal conductance) and hence Joule heating will be aggravated. A trend to be anticipated is that the higher the total volume of the air holes, the greater the thermal impedance.

Nonradiative recombination is another source of heating, which can be exacerbated if the photonic crystal penetrates the active region. Air holes that are either etched to or through the active region introduce exposed surfaces, and atoms that are immediately next to the exposed surfaces have dangling bonds that can capture carriers and facilitate nonradiative recombination. This effectively creates surface states in the middle of the gain material bandgap, and carriers can be trapped in these states before they recombine to produce heat. It is known that surface recombination rate is proportional to the surface recombination velocity, and larger surface area results in higher surface recombination velocity [1].

The carrier injection efficiency $\eta_i$ can be affected by thermal effects profoundly. As temperature increases around the active region, leakage current increases due to the increase of Fermi level producing a Fermi distribution with a high energy tail, which causes some of the carriers to have sufficient energy to overcome the quantum well barrier [1]. This reduces the number of carriers that actually recombine inside the active region, and deteriorates the carrier injection efficiency of the lasers as carriers can recombine or be reabsorbed in the barrier layers.

The gain-resonance overlap factor $\kappa$ has a strong dependence on temperature as well. An increase in carrier concentration and/or temperature causes a narrowing of the electronic bandgap, and also increases the quasi-Fermi energy separation of holes and
electrons. The net effect is the shifting of gain peak towards a longer wavelength and a wider gain bandwidth. On the other hand, rise in temperature affects the cavity resonance through increase in dielectric constant of materials that compose the lasers, and this increases the optical path length \((nL, \text{ where } n \text{ is the refractive index and } L \text{ is the cavity length})\) and shifts the cavity resonance to a longer wavelength, albeit at a slower rate of change with respect to temperature compared to the shift of gain peak. It has been established experimentally that VCSELs with a GaAs-AlGaAs quantum well system have a resonance wavelength shift rate of about 0.06 nm/K [6], and gain peak shift rate of about 2.9 nm/K [6], [7].

As the active region temperature increases, the threshold current increases due to a lower injection efficiency and differential gain coefficient as well as higher transparency current (see Equation (2.27)). If the surface recombination rate is enhanced due to etching the air holes through the active region, both heating and shorter carrier lifetime contribute to the increase in threshold current.

### 2.4 Optical Loss Induced by Photonic Crystal

By etching holes partially into the top DBR, optical loss is also introduced into the lasers. The optical loss is in the form of scattering due to (1) index discontinuity along the transverse direction, which is on the order of \(10^{-4}\) to \(10^{-2}\) from core to cladding region, (2) surface roughness of the air holes, which is caused by the dry etching process, is random in terms of shape, size and location, and is different from one hole to another, and (3) index mismatch at the surface where the holes end. All of these scattering loss mechanisms contribute to the intrinsic loss \(\alpha_i\), and decreases the slope efficiency according to Equation (2.19). Figure 2.1 shows two air holes under scanning electron microscope (SEM), one with smooth side wall and another with rough side wall. It is expected that PhC VCSELs with air holes shown in Figure 2.1 (b) will suffer higher scattering loss compared to those that contain air holes like in Figure 2.1 (a) due to irregularity in refractive index variation. Besides scattering and diffraction loss, the
mirror loss of the cladding region can also be changed due to the PhC structure [8]. It will be shown experimentally in Chapter 4 that the higher order modes suffer higher optical loss than the fundamental mode due to their greater spatial overlap with the photonic crystal lossy region, hence they are suppressed [8], [9]. This is analogous to the mode-selective loss schemes mentioned in Chapter 1.

It is also apparent that different photonic crystal designs have different scattering loss magnitude because the refractive index of the cladding region depends on the parameters (size and pitch) of the air holes. If the modes are more strongly guided in the core region, they will diffract less and have a smaller mode size [8], hence they will see a lower scattering loss from the lossy PhC region. Therefore we can infer that the photonic crystal designs that yield higher index contrast between the core and the cladding region will introduce lower optical loss to the lasers.

From Equation (2.20) and (2.27), it is obvious that the differential quantum efficiency is inversely proportional to the optical loss while the threshold current is an increasing function of the optical loss. Therefore etching PhC modifies both the differential quantum efficiency and the threshold current due to the higher optical loss.

**Fig. 2.1**: SEM image of two different air holes. Type (a) has smooth side wall, while type (b) has much rougher side wall. They introduce different scattering loss to the PhC VCSELs, with (a) lower than (b).
introduced by the PhC. In gain-guided VCSELs, etching PhC causes a reduction in
diffraction which results in lower optical loss, but the PhC also increases the scattering
loss. It is possible to increase the differential quantum efficiency and decrease the
threshold current by etching PhC on gain-guided VCSELs if the reduction in diffraction
dominates over the higher scattering loss introduced [10].

To determine if a certain photonic crystal waveguide design yields single mode
operation, both the effective index and the optical loss of the cladding region need to be
calculated. The modified index of the materials perforated by the air holes of photonic
crystal can be obtained from the band structure of the lowest out-of-plane propagation
mode calculated from the plane wave expansion method [11]. This method treats the
inverse of the dielectric constant and the field profile as a Fourier series, which is valid
due to their periodicity in the two-dimensional space (x-y plane) perpendicular to the
direction of light propagation (z-direction). Then, an eigenvalue problem derived from
the Maxwell’s equations can be set up to find the eigenvalues corresponding to the
wavelengths and the eigenfunctions corresponding to the field profiles. The refractive
index change in both the high and low refractive index layers in the DBR can be
calculated separately, and the modified indices that are homogenous in the x-y plane can
be obtained from the slope of the band diagram given as $k_z/k_o$, where $k_z$ is the propagation
constant in the material and $k_o$ is defined as $2\pi/\lambda$ with $\lambda$ as the freespace wavelength. Due
the finite etch depth of the air holes in PhC VCSELs, only layers perforated by the air
holes experience cladding index change. The modified cavity with perforated DBR pairs
in the cladding region has different resonance wavelength compared to the core (original)
cavity due to the index change, as calculated from the transfer matrix method. The
cladding effective index can then be calculated from the difference in resonance
wavelength between the modified and the original cavity according to [12]

$$\frac{n_{core} - n_{clad}}{n_{core}} \approx \frac{\lambda_{original} - \lambda_{modified}}{\lambda_{original}}$$

(2.28)
where \( n_{\text{core}} \) is the overall effective index of the core region, \( n_{\text{clad}} \) is the overall effective index of the cladding (PhC) region, \( \lambda_{\text{original}} \) is the resonance wavelength of the original (core) cavity, and \( \lambda_{\text{modified}} \) is the resonance wavelength of the modified (cladding) cavity. Note that this calculation is different from that of the previous works in which an etch depth dependence parameter proportional to the longitudinal standing wave intensity is used to calculate \( n_{\text{clad}} \) [1]. Here, the etch depth dependence is accounted for during the transfer matrix calculation of the cladding index [9], [13].

Siegman has shown in [14] that gain or loss guiding can also become important if the imaginary index difference is comparable to the real index difference between the core and the cladding, which is on the order of \( 10^{-4} \) to \( 10^{-2} \) for the PhC designs utilized in this work. The paper also describes the cutoff conditions for waveguides with gain or loss, and suggests that waveguides with low \( V_{\text{eff}} \) can lose their mode confinement capability and become multi-mode if gain is present. This explains the observation in [15] where it is shown that PhC VCSELs with \( V_{\text{eff}} < 0.6 \) typically lase in multi-mode. Recently, the approach by Siegman has been adapted for PhC VCSEL analysis, and a technique for determination of optical loss has been demonstrated [9]. To account for the optical loss induced by the PhC structure, the refractive index takes the form of a complex number with the imaginary part representing the loss. The complex refractive index can then be substituted into the Helmholtz equation [16]

\[
\frac{d^2 u}{dr^2} + \frac{1}{r} \frac{du}{dr} + (n^2 k_o^2 - \beta^2 - \frac{l^2}{r^2})u = 0 \tag{2.29}
\]

where \( r \) is the radial direction, \( z \) is the propagation direction, \( u \) is the field profile transverse to \( z \) (only a function of \( r \)), \( n \) is the radial refractive index, \( k_o \) is the vacuum propagation constant, \( \beta \) is the propagation constant in the waveguide, and \( l \) is an integer that characterizes the azimuthal distribution of the field. Discretizing the equation in the \( r \)-direction using the finite difference method and forming a matrix eigenvalue problem, the equation can be solved numerically [9]. The eigenvalues (complex wavenumber \( k_o \)) yield the lasing wavelength and the optical loss of the modes, while the eigenfunctions
$u(r)$ give the modes’ field profile. A fit to the measured fundamental and first higher order mode splitting obtained from sub-threshold (about 0.9 times threshold current) optical spectrum is used to determine the imaginary part of the cladding index, and then the wavelengths and losses of the subsequent higher order (second and up) modes can be extracted from the numerical calculation. The purpose of inspecting the sub-threshold spectrum is to rule out any disturbances to the cladding index, eliminate the effects of loss that come from thermal or carrier effects, and avoid mode competition effects from laser operation.

2.5 References


30


CHAPTER 3

DEVICE FABRICATION

3.1 Epitaxial Structure

VCSELs fabricated from wafers with three different epitaxial structures are examined. The epitaxial layers are grown on 3-inch-diameter $n$-type GaAs substrates by metalorganic chemical vapor deposition (MOCVD). In general, the VCSELs consist of a $p$-type top DBR mirror, an $n$-type bottom DBR mirror, and a single-wavelength-long cavity which contains an undoped active region. In this work, the active region of the VCSELs consists of three GaAs quantum wells. The top mirror typically has fewer DBR pairs than the bottom mirror to facilitate light extraction. Table 3.1 describes the top DBR mirrors of the three different epitaxial structures utilized in this work.

<table>
<thead>
<tr>
<th>Table 3.1:</th>
<th>Wafers of different epitaxial structure utilized in this work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer</td>
<td>DBR Materials</td>
</tr>
<tr>
<td>IQE 688B</td>
<td>Al$<em>{0.12}$Ga$</em>{0.88}$As-Al$<em>{0.9}$Ga$</em>{0.1}$As</td>
</tr>
<tr>
<td>IQE 727</td>
<td>(linearly graded)</td>
</tr>
<tr>
<td>F1122</td>
<td>GaAs-AlAs</td>
</tr>
</tbody>
</table>
| # Top DBR Pairs | Current Confinement
| 22           | Oxide                                                    |
| 20           | Implant                                                  |
| 21           | Implant                                                  |

Wafers labeled IQE 688B and IQE 727 are intended for producing VCSELs with oxide current confinement; therefore, the aluminum (Al) composition of the low
refractive index layer in the DBR pair is capped at 0.9. The major difference between the two IQE wafers is the number of top DBR pairs, which affects the LIV of the VCSELs. In these two epitaxial structures, there is a high-Al-content layer (with Al composition of 0.98) placed right above the active region for lateral oxide formation. Such a high-Al layer is absent in the F1122 wafer, which is designed to produce VCSELs with proton implantation current confinement. Moreover, in the F1122 sample, the top mirror consists of GaAs-AlAs DBR pairs, giving a higher refractive index contrast compared to that of the IQE wafers, hence higher mirror reflectivity given the same number of DBR pairs [1]. Nevertheless, VCSELs fabricated in the IQE 727 wafer are actually proton-implanted in this work. A comparison of performance between the VCSELs fabricated in the IQE 727 wafer and the F1122 wafer will be made in Chapter 4.

3.2 Photonic Crystal Designs

The hexagonal-lattice photonic crystal structure has two lithographically controlled parameters: hole diameter, $b$, and hole pitch, $a$. In the sample with oxide-confined PhC VCSELs, there are four $b/a$ values: 0.4, 0.5, 0.6, and 0.7. Variation of $a$ is from 2 to 9 µm, with a step of 0.5 µm. Six different photonic crystal etch depths, which depend on reactive ion etching (RIE) time, are produced to enable studies of etch depth dependence of modal characteristic and laser efficiency of the VCSELs. Three different mesa sizes (43, 48 and 53 µm) are present on the samples, hence three different current aperture diameters (approximately 8, 13 and 18 µm) for each photonic crystal design are formed. The lasing defect diameter is given as

$$D = 2a - b$$  \hspace{1cm} (3.1)

These designs were utilized for the endlessly single mode PhC VCSELs experiment [2], [3].
For the efficiency study of proton-implanted PhC VCSELs, only nine photonic crystal designs are considered as shown in Table 3.2. These designs yield single mode lasing for a wide range of etch depth in the oxide-confined PhC VCSELs [3], [4], and correspond to a hole diameter-to-depth ratio of approximately unity, which is conducive for the manufacturability of dry etching. Furthermore, these photonic crystal designs produce relatively broad area single mode lasing with the lasing defect diameters in the range of 4 to 7 µm. The current aperture diameter corresponding to each design is also lithographically defined by the implantation mask diameter, and only depends on $b$ and $a$, given as

$$C = 2a + b$$  \hspace{1cm} (3.2)

and thus is always $2b$ larger than the lasing aperture diameter of each design. However, the actual current aperture sizes are typically smaller than the nominal sizes due to unavoidable overdevelopment of the photoresist masks that cover the unimplanted area. The actual current aperture sizes can be determined from the control VCSELs that are not patterned with photonic crystal and etched with air holes, by measuring the size of the illuminated area in each control VCSEL at a current level slightly below lasing threshold. Several etch depths are produced to study the etch depth dependence of slope efficiency of the implant-confined PhC VCSELs.

**Table 3.2:** Nine photonic crystal designs for proton-implanted PhC VCSELs

<table>
<thead>
<tr>
<th>$b/a$</th>
<th>$a$ ($\mu$m)</th>
<th>$b$ ($\mu$m)</th>
<th>$D$ ($\mu$m)</th>
<th>$C$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>3</td>
<td>1.8</td>
<td>4.2</td>
<td>7.8</td>
</tr>
<tr>
<td>0.6</td>
<td>3.5</td>
<td>2.1</td>
<td>4.9</td>
<td>9.1</td>
</tr>
<tr>
<td>0.7</td>
<td>3</td>
<td>2.1</td>
<td>3.9</td>
<td>8.1</td>
</tr>
<tr>
<td>0.6</td>
<td>4</td>
<td>2.4</td>
<td>5.6</td>
<td>10.4</td>
</tr>
<tr>
<td>0.7</td>
<td>3.5</td>
<td>2.45</td>
<td>4.55</td>
<td>9.45</td>
</tr>
<tr>
<td>0.6</td>
<td>4.5</td>
<td>2.7</td>
<td>6.3</td>
<td>11.7</td>
</tr>
<tr>
<td>0.7</td>
<td>4</td>
<td>2.8</td>
<td>5.2</td>
<td>10.8</td>
</tr>
<tr>
<td>0.6</td>
<td>5</td>
<td>3</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>0.7</td>
<td>4.5</td>
<td>3.15</td>
<td>5.85</td>
<td>12.15</td>
</tr>
</tbody>
</table>
3.3 Device Fabrication of Proton-Implanted Photonic Crystal VCSELs

Fabrication starts with deposition of broad area bottom-side contact of $n$-type metal with 40 nm Au$_{0.4}$Ge$_{0.6}$, 20 nm of Ni, and 150 nm of Au by thermal and electron-beam evaporation on the substrate side of the wafers. Then the top ring contacts are formed by coating AZ4330 positive photoresist (PR) on the top surface of the wafers, patterning by standard photolithography process (softbake, mask-sample alignment, UV exposure, and development), depositing $p$-type metal with 15 nm Ti and 160 nm Au, and metal liftoff in acetone solvent.

The next step is the formation of current apertures. First, hexamethyldisilazane (HMDS) is coated on the wafer surface for better adhesion of PR to the wafer surface. Then AZ 9260 PR is spun onto the wafer surface with a spin speed of 3000 rpm, resulting in a PR coating that is 8 µm thick. This spin speed is designed to produce a PR coating thick enough to stop high-energy proton implant; but such slow spin speed also causes non-uniformity in coating thickness across the wafers, and therefore edgebead removal is extremely critical for intimate contact between the PR and the mask during exposure. Both edgebead removal and formation of PR masks that cover unimplanted area are done by standard photolithography process. To stabilize (harden) the PR pillars, the wafers are subject to a deep UV flood exposure followed by a 1 min, 125 °C hardbake. The wafers are then sent out for proton implantation at 340 keV energy and a dose of $5 \times 10^{14}$ cm$^{-2}$, with the wafers being tilted 7° to prevent ion channeling [5]. After the proton implantation, the PR is removed using an O$_2$ plasma asher (with 600 W O$_2$ plasma) and an acetone stream repeatedly until the wafer surface is completely rid of PR. It is found from measuring the size of the illuminated area under subthreshold condition in the control VCSELs that the actual implant aperture diameters are 3 to 4 µm smaller than the nominal values, and some PhC VCSELs with small $b$ have implant aperture smaller than the optical aperture.

After the current apertures are formed, the VCSELs are isolated electrically using a second ion implantation. First HMDS is coated on the wafer surface, but for this step
two layers of PR are spun on, both with a spin speed of 5000 rpm. This results in a PR coating of more than 10 µm thick. Edgebead removal, PR masks formation, and PR stabilization follow as discussed previously. Note that the PR stabilization step results in a considerable reflow of PR due to internal heating of the UV exposure system. A scanning electron microscopy (SEM) image of one reflowed PR mask is shown in Figure 3.1. In spite of the reflow, the PR masks are still rigorous enough for the purpose of blocking the implanted ions in the area covered. For electrical isolation, multiple ion implantations with different ion species, energy and dose are utilized [5] as summarized in Table 3.3. After the ion implantation (with PR masks still on the wafer surface), the samples are subjected to a short inductively coupled reactive ion etching (ICP-RIE) to remove the heavily doped top contact layer. The PR is then removed again with an O₂ plasma ash and an acetone stream until no trace of PR is found on the wafer surface. Following this, thermal annealing of metal contact is done in a furnace at 410 °C for 10 min. At this point, the VCSELs (without PhC) can be tested before further processing to confirm the formation of current apertures and electrical isolation. Some light-current-voltage (LIV) plots of proton-implanted VCSELs will be shown in Chapter 4.

The following sequence is used to produce the photonic crystal structures. First a silicon oxide (SiO₂) layer of about 300 nm is deposited on the wafer surface by plasma-enhanced chemical vapor deposition (PECVD) to act as an etch mask. This is followed by PR patterning of the photonic crystal to be etched, which is done with coating of AZ5214 and standard photolithography process. Then the area of SiO₂ layer not covered by PR (where the air holes are) is over-etched with Freon 14 (CF₄) RIE down to the semiconductor wafer surface. The PR is then stripped off with acetone, and the samples are subjected to ICP-RIE with SiH₄ (providing the chemical component to etch the semiconductors) and Ar (providing the kinetic component of sputtering ions onto the wafer surface) to etch the photonic crystal air holes. The etch time is varied to render different etch depths of photonic crystal.
Fig. 3.1: SEM image of one reflowed PR pillar intended for blocking stacked ion implantation.

Table 3.3: Implant species, energy and dose for stacked isolation implantation

<table>
<thead>
<tr>
<th>Implant Species</th>
<th>Energy (keV)</th>
<th>Dose (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td>340</td>
<td>$5 \times 10^{14}$</td>
</tr>
<tr>
<td>protons</td>
<td>300</td>
<td>$5 \times 10^{14}$</td>
</tr>
<tr>
<td>protons</td>
<td>260</td>
<td>$5 \times 10^{14}$</td>
</tr>
<tr>
<td>protons</td>
<td>210</td>
<td>$5 \times 10^{14}$</td>
</tr>
<tr>
<td>protons</td>
<td>160</td>
<td>$5 \times 10^{14}$</td>
</tr>
<tr>
<td>protons</td>
<td>100</td>
<td>$5 \times 10^{14}$</td>
</tr>
<tr>
<td>oxygen</td>
<td>300</td>
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Unfortunately, a fixed etch time results in different etch depth for holes of different sizes, due to the aspect ratio scaling of etch rate (slower etch rate for larger depth to hole size ratio), and possibly microlading effects as well [6]. For example, the time required to etch 90% of the top DBR mirror for the biggest hole diameter ($b = 3.15$
µm) only results in 65% of the top DBR mirror etched for the smallest holes (b = 1.8 µm). The etch rate as a function of hole diameter has logarithmic functionality [6], [7]. ICP-RIE of air holes also results in tapered etch depth (concaved bottom) due to nonparallel directionality of the energetic ions bombarding the wafer surface [8], and thus the depth range can span two DBR periods or so (about 250 nm) as shown in Figure 3.2. The deepest etch depth is at the center of the air hole. This depth variation causes difficulty in exact determination of etch depth. In this work, the number of DBR periods etched is taken to be the middle point of the range of etch depth from the center to the edge of the bottom of the air holes.

Another processing issue arises from the dependence of PhC hole size on the development time of PR used in the photolithography step that forms the PhC structures. For example, a development time of 35 s results in b/a ratio of 0.4 and 0.6 respectively for the smallest and the biggest holes (with nominal b/a of 0.6 and 0.7 on the mask), but a development time of 40 s produces smallest and biggest holes with b/a of 0.5 and 0.7. A
few seconds of overdevelopment seems to give better results in terms of actual hole size produced compared to the intended one, and is extremely critical if we want to get the right $b/a$ ratio for the smaller air holes. Moreover, the resultant $b/a$ ratio of the air holes is highly dependent on the hole diameter. This is illustrated in Figure 3.3 where the actual $b/a$ is plotted against the nominal hole diameter for the nine PhC designs. In short, the bigger the holes are, the closer the $b/a$ ratio is to the nominal mask value.

![Graph](image_url)

**Fig. 3.3:** Actual $b/a$ ratio as a function of nominal hole diameter for the nine PhC designs. Clearly, the bigger the holes are, the closer the $b/a$ ratio is to the nominal mask value.

An optional step of depositing thick fan and pad metal of 2 µm Au for the top contact could be carried out if the VCSELs were to be packaged. Otherwise, the VCSELs are ready to be tested after the SiO2 layer is removed with care such that the top laser facet is not damaged [9]. A cross-sectional sketch and an optical microscope image of one completed device (without fan and pad metal) are shown in Figure 3.4 (a) and (b), respectively. The implant-confined PhC VCSELs are nearly planar with a topological
difference between the VCSEL mesa and the wafer surface of less than 1 µm; therefore, no further planarization step is required before fan and pad metal are deposited. This is apparent in Figure 3.4 (c), which is an SEM image (taken at 45° from the wafer surface) of an implant-confined PhC VCSEL.

![Cross-sectional sketch and optical microscope images of a completed implant-confined PhC VCSELs](image)

**Fig. 3.4:** (a) Cross-sectional sketch and (b) optical microscope of a completed implant-confined PhC VCSELs (without fan and pad metal). (c) SEM image of an implant-confined PhC VCSEL, taken at 45° from the wafer surface, showing planarity of such device.
3.4 Device Fabrication of Oxide-Confined Photonic Crystal VCSELs

The main differences between the proton-implanted and the oxide-confined VCSELs are their scheme of current confinement and electrical isolation. The oxide-confined PhC VCSELs have the advantage of self-alignment of current and lasing aperture [3], but trenches as deep as about 3 µm reaching the high Al layer will need to be etched for lateral oxidation. The fabrication of oxide-confined VCSELs follows the same procedure as implanted devices up to the cavity definition.

The electrical isolation of the VCSELs is done by etching ring-like trenches surrounding the devices. In fact, patterning of PR that defines the trenches and the photonic crystal structures is done in one photolithography step, using the same type of PR for photonic crystal formation as depicted in the previous section. A single SiO$_2$ layer serves as the mask for ICP-RIE etching of both the trenches and the photonic crystal structures. The area where photonic crystal structures are present is covered with a layer of PR before the trenches are etched. After etching of trenches, the PR covering the photonic crystal structures is removed, and lateral oxidation is done at 410 °C for about 20 to 30 min in an oxidation furnace. Finally, the photonic crystal structures are etched by ICP-RIE, followed by removal of the SiO$_2$ layer. A cross-sectional sketch of the final device structure is shown in Figure 3.5 (a), and an optical microscope and a SEM image of one such VCSEL are shown in Figure 3.5 (b) and (c), respectively [3].
Fig. 3.5: (a) Cross-sectional sketch of the final device structure of oxide-confined PhC VCSELs. (b) Optical microscope and (c) SEM image of one such device.

3.5 References


4.1 Experimental Setup for Device Characterization

The VCSELs are characterized on a probe station equipped with a single pin probe and a backside contact which serve to provide bias to the lasers. An optical microscope which is coupled to a multimode fiber is attached to the probe station and the images captured by the microscope are projected onto the computer monitor screen. A Keithley 236 voltage/current source is used to excite the VCSELs for spectral measurements in continuous-wave (CW) fashion. Light output from the VCSELs is collected through the multimode fiber by an Agilent 86141B optical spectrum analyzer (OSA), which then displays the optical spectra of the lasers. In this work, a maximum spectral resolution of 0.06 nm and a sensitivity of -70 dBm are employed for typical spectral measurements. However, when the optical spectra of low light intensity such as those of subthreshold operation are needed, the sensitivity is increased to -80 dBm. To perform light-current-voltage (LIV) measurements, the VCSELs are biased by an Agilent 4156C semiconductor parameter analyzer (SPA) which collects light output through a calibrated broad area infrared detector and then displays the LIV plots. Data acquisition, measurement settings adjustment and conversion of detector current to optical power are carried out on a Microsoft Windows XP workstation running National Instruments LabVIEW 6.1. To eliminate the effects of heating on laser efficiency, pulsed LI measurements are performed using the ILX pulsed current source. Light output is
collected by the broad area photodetector, and the Keithley voltage/current source is used to reversely bias the photodetector and also to measure the photocurrent.

To determine whether a VCSEL lases in single mode, a side mode suppression ratio (SMSR) of 30 dB between the fundamental and the first higher order mode for the entire operating current range (from slightly above threshold to roll-over of power) is the criterion applied. The differential quantum efficiency of the lasers is measured at the linear portion of the LI curves slightly above threshold where nonlinearity due to thermal effects is still negligible.

To quantify the thermal properties of the VCSELs, lasing wavelength versus bias current is measured. The temperature of the active region has a quadratic dependence on the injected current [1], while the change in lasing wavelength is linear with respect to the temperature as mentioned in Section 2.2. Together they dictate that the lasing wavelength is also a quadratic function of the injected current. Hence by measuring the change of lasing wavelength with respect to injected current, the temperature of the active region as a function of injected current can be obtained.

4.2 Influence of Photonic Crystal on Efficiency and Threshold Current

It has previously been found [2], [3] that introducing PhC or holey structure to the proton-implanted VCSELs can decrease the threshold current and increase the differential quantum efficiency. This can be explained by the introduction of index guiding to the inherently gain-guided lasers and hence lower diffraction loss to the fundamental mode, which affects both the threshold current and the differential quantum efficiency. Furthermore, the higher order modes are absent at threshold in gain-guided VCSELs, so the increase in threshold current due to greater loss to the higher order modes can be minimized. In this work, we fabricated proton-implanted VCSELs with and without PhC on IQE 727 and F1122 wafers with two different epitaxial structures for comparison. For the wafer IQE 727, comparisons of threshold current and differential quantum efficiency are made between proton-implanted control and PhC VCSELs. For the wafer F1122, we
compare the VCSELs before and after the air holes are etched to eliminate the impact of wafer nonuniformity on laser performance.

Gain-guided VCSELs have a few drawbacks compared to the index-guided VCSELs due to the lack of strong index guiding. For instance, there is a wide range of threshold current and differential quantum efficiency in proton-implanted VCSELs with the same implant aperture diameter due to the weak, unstable (with respect to current) and random (in radial direction) index guiding. Furthermore, a quarter of a 3-inch wafer is processed up to the patterning of the SiO$_2$ mask in this work, so nonuniformities such as uneven thickness of PR across the wafer during photolithography steps and nonuniform thickness of the epilayers can become an issue. The same problem also affects the LI of the implant VCSELs; i.e. random discontinuities in LI are observed in the control devices due to the asymmetrical index guiding that results in sudden change of far-field pointing direction and beam divergence when bias current increases, as reported earlier [4]. Figure 4.1 shows the LI of a proton-implanted VCSEL and its optical microscope image at various bias currents. It is obvious that the maximum intensity is off-center even right above threshold, and the power changes abruptly when current is varied from 6.5 to 6.6 mA and the light intensity maximum moves away from the laser center. Note that the discontinuity is not due to turning on of a second mode as observed from the lasing spectra (not shown) before and after the discontinuity. As will be illustrated in Section 4.5, this kind of LI discontinuity of the proton-implanted VCSELs is almost completely eliminated once they are etched with a PhC and index guiding is introduced.
Fig. 4.1: LI of a proton-implanted VCSEL indicating discrete “jump” of optical power as current is varied above 6.5 mA. Optical images at various current levels (2.9 mA, right above threshold, 6.5 mA, before the jump, and 6.6 mA, after the jump) are taken to illustrate the discontinuity in LI due to the abrupt change of the lasing center.

Etching air holes onto the top DBR provides stronger, more stable and more uniform index guiding, thereby greatly reducing the distribution of differential quantum efficiency and threshold current. Figure 4.2 shows the variation of differential quantum efficiency and threshold current as a function of the air hole fill-factor of the proton-implanted control and PhC VCSELs using the IQE 727 sample. The air hole fill factor is defined as $b/a$ multiplied by the etch depth normalized to the total top DBR thickness. Note that due to the small implant aperture and the epitaxial structure design, most of the unetched devices have minimal change in modal properties compared to the PhC VCSELs (i.e. multi-mode control VCSELs do not become single mode with PhC). Nevertheless, inspecting the slope of the LI right above threshold helps us to understand how the PhC affects the optical loss and the thermal properties of the VCSELs. In general,
Fig. 4.2: Differential quantum efficiency for (a) $a = 4.0 \, \mu m$ and (b) $a = 4.5 \, \mu m$, and (c) threshold current for $a = 4.5 \, \mu m$ as a function of air hole fill-factor of proton-implanted control and PhC VCSELs fabricated on wafer IQE727. The labels indicate the PhC etch depth.
for deeper etch depth or higher fill factor of the holes, the distributions of the differential quantum efficiency and threshold current are reduced, indicating the effects of stronger index guiding. For $a = 4.5$ µm, the differential quantum efficiency generally increases with etch depth due to the reduction of diffraction loss (see Figure 4.2 (a)). For $a = 4.0$ µm, there is an opposing trend of slightly decreasing differential quantum efficiency with etch depth as shown in Figure 4.2 (b), and this is due to the lower spatial mode-gain overlap for deeper etch depth as will be explained in more detail in the next section. Whether the spatial mode-gain overlap or the optical loss has a stronger impact on the differential quantum efficiency can be dependent on the PhC hole pitch. The threshold current generally decreases with deeper etch as evident in Figure 4.2 (c), also due to the reduced optical loss, except when the holes are etched to or through the active region. The same trend is observed for both $a = 4.0$ (not shown) and $4.5$ µm due to the fact that the threshold current is not affected by the spatial mode-gain overlap factor. When the air holes stop in the active region resulting in the highest surface recombination rate from the exposed area of the bottom of the air holes and hence reduced internal quantum efficiency due to excessive heating, the PhC VCSELs have the highest threshold current and the lowest differential quantum efficiency. When the holes are etched through and beyond the active region, the efficiency increases and the threshold current drops back down as the total exposed surface area in the active region is reduced (hence lower surface recombination rate). Note also that the differential quantum efficiency and the threshold current distributions become wider once the PhC is etched to the active region due to random perturbations from heating of the devices.

On the other hand, the PhC always causes higher threshold current and lower differential quantum efficiency in the oxide-confined VCSELs, even for oxide aperture diameter as small as 8 µm (the size of the smallest implant aperture studied) as evident in Figure 4.3 where the LI of the oxide-confined control and PhC VCSEL ($b/a = 0.6$, $a = 3.0$ µm) are compared. The PhC VCSEL has an etch depth of 92% of the top DBR thickness, and it has the highest differential quantum efficiency and the lowest threshold current among all the oxide-confined PhC VCSELs with the same $b/a$ and $a$. Note that the oxide-
confined VCSEL in Figure 4.3 operates multi-mode from threshold, whereas the PhC VCSEL remains single mode.

**Fig. 4.3**: LI of the oxide-confined control and PhC VCSEL ($b/a = 0.6, a = 3.0 \ \mu m$). The PhC VCSEL has an etch depth of 92% of the top DBR thickness. This shows that the oxide-confined PhC VCSEL has lower efficiency and higher threshold current compared to the control VCSEL.

Etching the PhC causes the series resistance of the VCSELs to increase. This is illustrated in Figure 4.4, in which the series resistance of the proton-implanted VCSELs on wafer F1122 before and after etching of PhC is plotted as a function of the actual implant aperture diameter determined from the size of the illuminated area below threshold. The red squares represent the PhC VCSELs and the blue diamonds represent the proton-implanted VCSELs. The data points correspond to VCSELs from different areas of the wafer. For the PhC VCSELs with the smallest implant aperture ($\approx 4 \ \mu m$, not shown in Figure 4.4), the heating problem is so severe that the lasers degrade very quickly and they fail with only a few repeated LI measurements.
Fig. 4.4: Series resistance as a function of the actual implant aperture diameter for proton-implanted VCSELs before and after PhC etching, on wafer F1122. The red squares represent the PhC VCSELs and the blue diamonds represent the proton-implanted VCSELs. The different data points correspond to VCSELs on different area on the wafer.

4.3 Dependence of Laser Efficiency on Photonic Crystal Design

The transverse optical confinement is found to be an increasing function of the PhC etch depth, hence reduction of both diffraction loss due to stronger mode confinement [5] and scattering loss as light sees a smaller photonic crystal cross section are expected for deeper etch depth. Figure 4.5 shows the fundamental mode optical loss of the oxide-confined PhC VCSELs as a function of etch depth normalized to the top DBR thickness for two different PhC designs ($b/a = 0.7, a = 4.0$ and $4.5$ µm) and two oxide aperture diameters (13 and 18 µm), calculated using the method described in Section 2.4. The decreasing trend of optical loss with etch depth is confirmed by the experimental trends shown in Figure 4.5. The current aperture size does not affect the optical loss, indicating the decoupling of PhC optical confinement from the lateral oxide.
Fig. 4.5: Fundamental mode optical loss of the oxide-confined PhC VCSELs as a function of etch depth normalized to the top DBR thickness, for $b/a = 0.7$, (a) $a = 4.0$ and (b) 4.5 μm. For each PhC design, optical loss versus etch depth of two different oxide aperture diameters (13 and 18 μm) are shown.

Note that the size-dependent optical loss due to lateral oxide is close to zero for oxide aperture greater than 7 μm [6], but this is not achieved even for PhC with very deep etch, possibly because of scattering from the irregular shape of the air holes. The calculations also show that the higher order modes suffer greater optical loss because they have more spatial overlap with the cladding region. For example, a PhC VCSEL with $b/a = 0.7$, $a =$
4.5 μm, etch depth = 112% and oxide aperture = 13 μm has fundamental mode optical loss of 2.6 cm⁻¹, and higher order mode loss of 7.3, 15.9, and 23.1 cm⁻¹ (in increasing mode order). Consequently, the higher order modes are greatly suppressed as compared to the fundamental mode resulting in single mode behavior.

Nonetheless, the differential quantum efficiency does not increase monotonously with etch depth even though the optical loss decreases with etch depth. Figure 4.6 shows the differential quantum efficiency of the oxide-confined PhC VCSELs as a function of etch depth for the same PhC designs as in Figure 4.5. The trend of the differential quantum efficiency in Figure 4.6 could be due to several reasons as discussed in the next two paragraphs.

As shown in Chapter 2, the ratio of the mode area to the active area (the spatial mode-gain overlap) can affect the differential quantum efficiency. Figure 4.6 indicates that the smaller the oxide aperture diameter, the higher the differential quantum efficiency, an observation that is consistent with the spatial gain-mode overlap factor [7], [8]. For shallow PhC etches, the optical modes are allowed to expand in the transverse direction due to the weaker optical confinement, hence they can extract more gain from the active region. As the higher spatial mode-gain overlap more than compensates for the greater optical loss, the VCSELs with shallow PhC etch depths end up having higher differential quantum efficiency than those with deep etches.
Fig. 4.6: Differential quantum efficiency of the oxide-confined PhC VCSELs as a function of etch depth normalized to the top DBR thickness, for $b/a = 0.7$, (a) $a = 4.0$ and (b) 4.5 µm. For each design, differential quantum efficiency versus etch depth of two different oxide aperture diameters (13 and 18 µm) are shown.
Thermal effects can also have a profound impact on both the threshold current and the differential quantum efficiency of the lasers. By etching deeper into the VCSELs, more thermally and electrically conducting materials are removed. This affects both the series resistance and the thermal conductivity of the lasers, which exacerbates ohmic heating. The heating problem can be quantified by the thermal impedance, \( R_T \), which is defined as

\[
R_T = \frac{IV - P}{T}
\]

where \( I \) is the injected current, \( V \) is the bias voltage, \( P \) is the optical power, and \( T \) is the temperature of the active region. Note that in Equation (4.1), the photon cooling effect is also taken into account such that the thermal impedance is reduced by the dissipated power, instead of scaling with the total supplied power. As mentioned above, the temperature of the active region can be measured by determining the shift of lasing wavelength with respect to the injected current, and the thermal impedance of the VCSELs can then be obtained experimentally from a combination of the \( V-I \), \( P-I \) and \( T-I \) curves. Figure 4.7 shows the measured thermal impedance as a function of injected current for oxide-confined PhC VCSELs with \( b/a = 0.7, \ a = 4.0, \) and oxide aperture diameter = 18 µm, for various etch depths (normalized to the top DBR thickness). Figure 4.7 proves that in general, the thermal impedance is higher for deeper etch depth. Note that there is a drastic increase of \( R_T \) for PhC etch that stops before (99%) and after (108%) the active region, indicating the significant contribution of non-radiative recombination to the heating of PhC VCSELs.
Fig. 4.7: Thermal impedance as a function of injected current of oxide-confined PhC VCSELs with $b/a = 0.7$, $a = 4.0$, and oxide aperture diameter $= 18 \, \mu m$, for various etch depths (normalized to the top DBR thickness).

To eliminate the thermal effects, pulsed LI measurements are also performed. Figure 4.8 shows the pulsed LI (pulse width of 100 ns, duty cycle of 5%) of the oxide-confined PhC VCSELs with different etch depths, for $b/a = 0.7$, $a = 4.0$ and oxide aperture diameter $= 18 \, \mu m$. The vertical scale is the same for all measurements. For the etch depth of 66 and 75%, the spontaneous emission has a significant contribution to the output power, probably because etching air holes allows more spontaneous emission to be coupled out of the top mirror. But assuming clamping of the carrier concentration, the slope efficiency of the spontaneous emission should vanish above lasing threshold and will not add to the slope efficiency of the stimulated emission. This figure indicates that without ohmic heating, the differential quantum efficiency of the PhC VCSEL with the shallowest etch depth is still higher than those with deep etches, proving the importance of spatial mode-gain overlap in determining the laser efficiency. Note that in the absence
of heating, the PhC VCSELs with 108 and 121% etch depth now have higher efficiency than the one with 75% etch depth, which is a different trend from that found for CW measurements (see Figure 4.6). The threshold current is still the highest for 99% etch depth as the threshold current has a strong dependence on the non-radiative recombination rate, which cannot be eliminated even with pulsed current source.

![Graph](image)

**Fig. 4.8:** Pulsed LI (pulse width of 100 ns, duty cycle of 5%) of the oxide-confined PhC VCSELs with different etch depths, for \( b/a = 0.7, a = 4.0 \) and oxide aperture diameter = 18 \( \mu \)m. The vertical scale is the same for all measurements.

### 4.4 Photonic Crystal VCSELs with Improved Efficiency

Even though increasing the spatial mode-gain overlap is crucial in obtaining higher laser efficiency, it also leads to a thermal lensing problem as the index change due to heating might become comparable to the index difference between the core and the cladding PhC region. Furthermore, by decreasing the current aperture diameter, there is a
trade-off between obtaining high differential quantum efficiency and high series resistance.

With the proper epitaxial structure, single mode PhC VCSELs with higher output power can be obtained. Figure 4.9 (a) shows the LI of a proton-implanted VCSEL before (blue, called implant VCSEL) and after (red, called PhC VCSEL) the etching of PhC ($b/a = 0.6$ and $a = 3.5$, etched through the top DBR), and Figure 4.9 (b) shows the lasing spectra of the VCSELs at their respective roll-over current. As mentioned in Section 4.3, the LI discontinuity is completely eliminated after the air holes are etched, but the roll-over current is reduced due to greater heating. The side mode suppression ratio is 32 dB in the PhC VCSEL, as opposed to the multi-mode implant VCSEL in which the first higher order mode is 14 dB higher than the fundamental mode at roll-over. As can be observed from Figure 4.9 (a), the threshold is decreased from 3.0 mA to 2.1 mA after the PhC etching. The maximum output power of the single mode PhC VCSEL is reduced from that of the multi-mode implant VCSEL. As can be observed from Figure 4.9 (b), the first higher order mode, which is the dominant lasing mode for the implant VCSEL, is suppressed by 40 dB after PhC etching, so some power reduction is to be expected. In spite of the decrease in maximum output power, the PhC VCSEL has higher measured output power than the implant VCSEL in the operating current range of 5 to 14 mA due to the stable index guiding. No sudden change of diffraction as apparent in the implant VCSEL occurs in the PhC VCSEL, hence a continuous LI curve is achieved. With the PhC structure, a higher single mode output power of the fundamental mode Gaussian beam profile can be obtained in the proton-implanted VCSEL.
Figure 4.9: (a) LI and (b) lasing spectra of proton-implanted VCSELs fabricated on wafer F1122 before (blue, called implant VCSEL) and after (red, called PhC VCSEL) etching a PhC ($b/a = 0.6$ and $a = 3.5$) pattern. The arrow in (a) denotes the nonlinear trend of the single mode slope efficiency.
For PhC designs used in wafer F1122 that do not yield SMSR > 30 dB, the higher order modes are still suppressed considerably as can be seen from Figure 4.10 in which the lasing spectra of the PhC VCSEL with $b/a = 0.6$, $a = 4.5$ (red) and the implant VCSEL (blue) at the roll-over current of the implant VCSEL are shown. With the PhC, the fundamental mode replaces the second higher order mode as the dominant lasing mode. Note that the wavelength of the PhC VCSEL is red-shifted by about 0.6 nm, consistent with a higher active region temperature. Note that for the same designs, PhC VCSELs on one area of the wafer can exhibit multi-mode behavior but PhC VCSELs on another area can be single mode. This suggests that the spectral alignment of the gain and the cavity resonance modes can also have an effect on the modal properties of the PhC VCSELs [9].

Figure 4.10: Lasing spectra of PhC VCSEL (red) ($b/a = 0.6$, $a = 4.5 \, \mu$m) and implant VCSEL (blue) fabricated on wafer F1122. The spectra are taken at the roll-over current of the implant VCSEL.
In both the oxide-confined and proton-implanted PhC VCSELs, a nonlinear LI characteristic in single mode PhC VCSELs can sometimes be observed (see the arrow in Figure 4.9 (a)). This is not the same behavior that is typically present in the multi-mode lasers in which kinks in LI appear due to the appearance of higher order modes, or in proton-implanted VCSELs that lack index guiding (e.g. see the discontinuity of the blue curve in Figure 4.9 (a)). For single mode lasers, this phenomenon can be explained by the shifting of gain peak into alignment with the lasing mode, which causes the differential quantum efficiency to be higher at higher bias point (which is maximum at the inflection point of the LI) as opposed to the typically observed highest differential quantum efficiency right above threshold. It is thus expected that higher single mode power and SMSR can be achieved for proton-implanted PhC VCSELs if the gain peak is designed such that it coincides with the fundamental mode resonance wavelength near threshold, which helps to decrease the threshold current as well as increase the differential quantum efficiency.

In Figure 4.11, the threshold current of proton-implanted VCSELs fabricated from wafer F1122 before and after the PhC etch are plotted as a function of the measured implant aperture diameter. The different data points correspond to VCSELs from different areas of the wafer. Threshold current in general decreases after the PhC is introduced except for the smallest implant apertures. This can be explained by the fact that the proton-implanted VCSELs with larger implant aperture have weaker index guiding compared to those with the smallest aperture due to reduced heating (hence weaker thermal lensing); therefore, the effect of reduced diffraction in lowering the threshold current is more pronounced in the VCSELs with larger implant aperture. Moreover, the PhC VCSELs with the smallest optical aperture have current aperture smaller than the optical aperture, so the scattering loss can become much stronger and more dominant in affecting the threshold current.
Figure 4.11: Threshold current of proton-implanted VCSELs fabricated on wafer F1122 before and after PhC etch, plotted as a function of the measured implant aperture diameter. SM stands for single mode PhC VCSELs, MM stands for multi-mode PhC VCSELs, and the controls are implant VCSELs lacking PhC.

4.5 References


CHAPTER 5

CONCLUSION

5.1 Summary

In this work, the theoretical background regarding the differential quantum efficiency and the threshold current of the PhC VCSELs is presented. Proton-implanted 850 nm VCSELs are fabricated and characterized. With lithographically defined implant aperture, the freedom to design the current aperture size can be achieved. Furthermore, the requirement to etch trenches for the purpose of lateral oxidation as well as electrical isolation is eliminated, which provides planar topology. By etching the PhC into proton-implanted VCSELs, stronger index guiding is introduced and consequently the wide distribution of threshold current and efficiency between devices and the discontinuity in LI of the VCSELs are eliminated, and the threshold current is reduced. Single mode power of 2.5 mW is obtained from proton-implanted PhC VCSELs. Oxide-confined PhC VCSELs [1] are also investigated to study their performance in terms of differential quantum efficiency and threshold current.

Various mechanisms that affect the differential quantum efficiency and the threshold current of the PhC VCSELs are studied. It is found that those mechanisms include spectral and spatial mode-gain overlap, optical loss, and thermal effects. The thermal effects also affect the dynamical change of differential quantum efficiency with the injected current. Three degrees of freedom in designing the PhC VCSELs to maximize the laser performance in terms of efficiency and threshold current are
considered: the epitaxial structure (more specifically, spectral alignment of the resonance mode and the peak gain), the relative size of the current aperture and the transverse optical mode, and the photonic crystal design (air hole fill-factor). The epitaxial structure determines the spectral mode-gain overlap and the modal properties of the VCSELs, while the relative size of the current aperture and the optical mode sets the spatial mode-gain overlap factor. The PhC air hole fill-factor has an impact on all the mechanisms mentioned above. By etching the PhC deeper, the VCSELs have lower optical loss but suffer from exacerbated heating as well as lower spatial mode-gain overlap. To achieve low threshold current and to promote single mode lasing, it is necessary to have a peak gain that aligns spectrally with the resonance mode at the lasing threshold. Depending on the application, the relative size of the current aperture and the optical mode can be designed to achieve either high efficiency or low series resistance by varying the current aperture diameter. To obtain high efficiency and low threshold current at the same time, it is recommended to etch the PhC through the top DBR but avoid penetrating the active region such that the optical loss is low while heating problem does not become too severe.

5.2 Future Work

As mentioned in Chapter 1, it is convenient to incorporate VCSELs in a wavelength-division multiplexing (WDM) system due to the two-dimensional array configurability of the VCSELs. The same applies to the PhC VCSELs due to their planarity and ease of fabrication. By altering the photonic crystal design, the resonance wavelength of the PhC VCSELs can be varied because of the change in both the real and the imaginary refractive index of the cladding PhC region [2]. However, to be able to employ single mode PhC VCSELs in WDM systems, we need to be able to determine the change in resonance wavelength with respect to the PhC design without resorting to fitting the numerical results to the experimental data for the purpose of designing the WDM system. In other words, we need to be able to perform ab initio calculations of the optical loss induced by the PhC given a certain design. While different PhC designs result
in different optical loss that affects both the threshold current and the efficiency of the VCSELs, a careful spectral placement of the gain and the resonance mode can cancel such an effect and guarantee uniform threshold current and efficiency of all the PhC VCSELs in the array.

Armed with all the knowledge obtained from this work, it is then possible to design and fabricate single mode PhC VCSELs that emit a few miliwatts with careful considerations on all the degrees of freedom in design mentioned above. As shown in Chapter 2, it is possible to design the PhC VCSELs such that maximum efficiency is obtained at the desired operating current level if we have a better understanding of the thermal properties of the laser such as how the spectral mode-gain overlap factor, $\kappa$, and the injection efficiency, $\eta$, vary with the injected current and the active region temperature.

5.3 References
