**Manufacutable Photonic Crystal Single-Mode and Fluidic Vertical-Cavity Surface-Emitting Lasers**

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**Abstract**—We describe a robust manufacturing process for single-mode photonic crystal (PhC) vertical-cavity surface-emitting lasers (VCSELs). Various PhC designs are investigated to determine endlessly single-mode designs, whereby the same PhC design yields single-mode operation for three different wavelengths (780, 850, and 980 nm). The fabrication of the PhC pattern is based on a self-aligned optical lithography process. The fabrication process results in VCSELs with a maximum output power greater than 1 mW under continuous-wave (CW) operation with side-mode suppression ratio greater than 35 dB. We also show microfluidic laser structures that are enabled by our fabrication process, which integrate fluid channels into VCSELs. Optical and electrical properties of these microfluidic VCSELs are investigated with and without fluids present under CW and pulsed operation. A shift of the lasing wavelength is found with fluid insertion.

**Index Terms**—Microfluidic laser, photonic crystal (PhC) laser, single-transverse-mode operation, vertical-cavity surface-emitting laser (VCSEL).

I. INTRODUCTION

VERTICAL-CAVITY surface-emitting lasers (VCSELs) are excellent candidates for short-haul optical data communication and sensing applications due to their high-volume manufacture, on-wafer testing, and ease of fabrication in dense 2-D arrays [1]. In particular, single-mode laser sources are desired for high-speed optical data communication, position sensing, and atomic clocks. Standard VCSEL designs normally lead to operation in multiple transverse modes because the transverse dimensions of a VCSEL (typically multiple micrometers) are much larger than the effective cavity length in the longitudinal direction (typically hundreds of nanometers).

Previously, a variety of methods have been explored to achieve single-transverse-mode operation in VCSELs. These methods include the incorporation of small diameter (<3 μm) oxide apertures [2], proton-implanted apertures [3], oxide/implant hybrid structures [4], and surface relief etching [5], [6]. Small-diameter oxide and proton-implanted apertures inherently result in laser operation at high current densities. As a result, the reliability of these devices degrades with time due to heat and photon-mediated damage [7]. Additionally, to achieve high-power single-mode operation in a reproducible and reliable manner with these methods requires the fabrication procedures to be stringently controlled. For example, the approach of surface relief etching is sensitive to the etch depth and requires a controllable etch process. Mediation of this limitation requires custom epitaxial structures, for example, with etch stop layers or out-of-phase matching layers for the fabrication of shallow surface relief VCSELs [6]. Other lithographic approaches for controlling the modal properties of VCSELs include etching periodic photonic crystal (PhC) hole patterns [8]–[13] and symmetric holey structures [14], [15]. In this paper, we describe a fabrication procedure that relies only on standard manufacturing processes for oxide-confined PhC VCSELs that can be used with any conventional VCSEL epitaxial structure. Moreover, endlessly single-mode designs, which are PhC designs that yield single-fundamental-mode operation over a wide range of wavelengths, are presented.

The term “endlessly single mode” was first described by Birks et al. [16], where the concept of incorporating 2-D arrays of air holes into an optical fiber led to single-mode operation over a wide range of wavelengths. Similarly to the situation in PhC fibers, single-mode operation in PhC VCSELs is also created by a step-like refractive index profile produced by the PhC. However, in contrast to fiber studies, the etch depth of the air holes in PhC VCSELs is an important design parameter and cannot be assumed to be infinite [17]. The introduction of the PhC hole pattern into the top VCSEL mirror also leads to optical loss that can discriminate against higher order modes [9], [18]. Taking into account design parameters such as etch depth, pattern pitch, and diameter of the PhC air holes, various designs are investigated for endlessly single-mode operation. Oxide-confined PhC VCSELs are fabricated for three different wavelength regimes (780, 850, and 980 nm). The device characteristics of the single-mode VCSELs are compared to unetched control lasers to determine the effectiveness of the PhC in supporting single-transverse-mode operation.
As described previously, VCSELs are also excellent candidates for sensing applications due to their low operation power, high device reliability, and demonstrated high-volume manufacture. Attempts have been made to integrate microfluidic channels with a VCSEL to enable ultrasensitive detection of fluid, cells, and particles [19]–[21]. Here, we describe the fabrication and characterization of a new device structure for a microfluidic VCSEL that facilitates the distribution and flow of fluids through a monolithic VCSEL. The device structure is based on the PhC VCSEL, and incorporates both horizontal and vertical fluidic channels. Optical and electrical properties of fabricated microfluidic VCSELs are investigated with and without fluid inserted into the lasers.

In the following, we first describe the fabrication process used for the fabrication of PhC VCSELs and microfluidic VCSELs. Next, optical and electrical properties of the fabricated VCSELs are investigated. We characterize the modal properties of the PhC VCSELs and the emission wavelength of the microfluidic VCSELs. The paper ends with a discussion and summary of the results.

II. FABRICATION

A. PhC VCSELs

Three different epitaxial wafers are used for the fabrication of oxide-confined PhC VCSELs corresponding to three different emission wavelength regimes (780, 850, and 980 nm). All three wafers are generic VCSEL structures, differing only in the details of the material composition and thickness of the layers, the number of periods in the mirrors, and the quantum well active regions. All three epitaxial materials have a p-doped top distributed Bragg reflector (DBR) mirror, a one-wavelength-thick cavity, and an n-type bottom DBR, all grown by metal organic vapor phase epitaxy. The 780 nm epitaxial structure consists of a bottom 47-period DBR mirror, an undoped active region with three $\text{Al}_{0.11}\text{Ga}_{0.89}\text{As}$ quantum wells, and a top 30-period DBR mirror. The DBR mirrors are formed of repeating layers of $\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}$–$\text{Al}_{0.90}\text{Ga}_{0.10}\text{As}$. The incorporation of a high aluminum content layer ($\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$) in two DBR periods above the active region allows for selective oxidation [22]. The 850 and 980 nm epitaxial structures consist of a bottom n-type 34-period DBR and a bottom n-type 36-period DBR, respectively. The 850 nm epitaxial structure contains an active region with two GaAs quantum wells whereas the active region of the 980 nm epitaxial structure contains three $\text{In}_{0.18}\text{Ga}_{0.82}\text{As}$ quantum wells. Both epitaxial structures have a top DBR mirror with 22 periods. The DBR of the 850 nm epitaxial structure is formed of repeating layers of $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$–$\text{Al}_{0.90}\text{Ga}_{0.10}\text{As}$ and the DBR of the 980 nm epitaxial structure is formed of repeating layers of $\text{Al}_{0.16}\text{Ga}_{0.84}\text{As}$–$\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$. In both epitaxial structures, the high aluminum content layer (oxidation layer) is placed one DBR period above the active region.

A cross-sectional schematic showing the fabrication process for the PhC VCSELs is depicted in Fig. 1. First, a backside contact (AuGe–Ni–Au) is deposited on the bottom n-type substrate to form an ohmic contact. Top ring contacts (Ti–Au) are then lithographically patterned and formed by liftoff after the metal deposition. Photore sist pillars covering each top ring contact are used to protect the VCSEL apertures during a proton implantation step to electrically isolate neighboring lasers. Next,
a thin layer of SiO$_2$ is deposited, and PhC hole and trench patterns are defined simultaneously using optical lithography, as shown in Fig. 1(a). The use of optical lithography for the formation of the PhC patterns allows for low-cost, high-volume manufacture. Since the trench and the PhC pattern are defined in one single step, accurate mask alignment is not critical. The photore sist patterns are transferred into the SiO$_2$ layer using a Freon (CF$_3$) reactive ion etch (RIE). In order to create the trench independently from the PhC holes, the latter are coated with a thick layer of photore sist, followed by a SiCl$_4$–Ar inductively coupled plasma (ICP) RIE [see Fig. 1(b)]. The remaining photore sist mask is removed and the samples are put into a hot steam environment at 410 °C for selective oxidation of the high aluminum content layer to form oxide apertures [22], as depicted in Fig. 1(c). A second ICP-RIE is employed to transfer the PhC pattern into the top VCSEL facet, as shown in Fig. 1(d). Various PhC patterns with a hole diameter (b) to lattice constant (a) ratio b/a = 0.4, 0.5, 0.6, and 0.7 are considered in this paper. Etch depths of the PhC holes vary from 40% to over 100% of the top DBR thickness. Finally, large metal pads and contact runners (Ti–Au) leading to the top ring contacts are lithographically defined and formed by metal deposition liftoff. An optical image and a scanning electron micrograph (SEM) image of a fabricated PhC VCSEL are shown in Fig. 2. The inset in Fig. 2 shows a closeup image of a PhC hole. The individual layers of the DBR are evident in this image, and counting these layers is how the etch depth is determined.

B. Microfluidic VCSELS

The same fabrication process that is used for the fabrication of PhC VCSELS enables the creation of microfluidic VCSEL structures [21]. For the microfluidic VCSELS, the oxide aperture is formed such that the oxide extends under the PhC holes. The subsequent ICP-RIE hole etch will then stop on this oxide layer. As the final step, a wet etch using a 1:12 KOH (45% w/w):H$_2$O solution is performed to dissolve the oxide layer and form horizontal channels that interconnect with the vertical PhC holes [23]. The horizontal channels can be accessed from an etched reservoir beside the laser that allows for confinement of fluids close to the VCSEL. The fluid reservoir is formed by employing another ICP-RIE etch. Fluids in the reservoir can flow through the horizontal channel to the vertical holes in the VCSEL. This allows for a controlled distribution of fluids as well as avoiding liquid coverage on the top VCSEL facet. The metal pad connecting to the top contact ring of the microfluidic VCSEL allows for electrical probing without damaging the undercut structure. Fig. 3 shows a cross-sectional schematic and a SEM cross section of a microfluidic VCSEL. The VCSEL cross section is made using a focused ion beam (FIB) process [24] to expose the buried vertical and horizontal channels.

A closeup of the interconnection between a horizontal and a vertical channel is depicted in Fig. 3(b). For this particular VCSEL, the oxide layer extends only to the outer row of PhC holes so that the undercut horizontal channel only intersects with the outer vertical PhC holes. The wet etch rate for the oxide layer (~2.5 μm/min) is approximately 100 times faster than the wet etch rate for unoxidized high aluminum content AlGaAs layers.

Fig. 2. Optical image and SEM image of a fabricated oxide-confined PhC VCSEL.

Even though the etch rate for unoxidized layers is relatively slow, high aluminum content DBR layers (Al$_{0.90}$Ga$_{0.10}$As) experience slight undercut in the KOH solution, as depicted in the inset in Fig. 3(b).

III. RESULTS AND ANALYSIS

A. PhC VCSEL Design

A PhC is a periodic variation in the index of refraction of a material. The DBR of a VCSEL is a 1-D PhC, while a period pattern of air holes is an example of a 2-D PhC. Perpendicular to a triangular lattice of holes, there exist frequencies that are unable to propagate, which is the concept of the photonic bandgap formally proposed by Yablonovitch in 1987 [25]. Based on the lattice spacing, hole diameter, index of refraction of the medium, and index of refraction of the holes, a photonic band diagram can be calculated to determine the in-plane and out-of-plane dispersion properties of the PhC structure.

Fig. 4 is the 2-D photonic band diagram for a perfect (no defect) 2-D triangular lattice PhC [9]. In-plane, a bandgap is formed at frequencies where there are no allowed modes. However, the in-plane bandgap is not utilized for confinement within the VCSEL, similar to the case of PhC fiber [16]. For emission
out-of-plane, the PhC provides a means of lithographically controlling the effective index of refraction. The out-of-plane band diagram can be used to calculate effective index of the perfect 2-D PhC. This is done by taking the inverse slope of a straight line that intersects the origin and the operating point corresponding to the lowest out-of-plane propagating mode, as shown in Fig. 4. It is noteworthy that this effective index differs from that which would be obtained by using a geometric fill-factor approach [17].

The PhC VCSEL makes use of this effective index by modeling the region within the defect as bulk semiconductor with index of refraction $n_{\text{core}}$ and the region outside the defect as bulk PhC with index of refraction $n_{\text{clad}}$, which is obtained from the out-of-plane photonic band diagram (see Fig. 4). The resulting optical confinement structure is a circularly symmetric step-index transverse index profile, similar to that of step-index optical fiber. Because of this, the normalized $V$ parameter [26] can be used in conjunction with the theoretical model of modes in an optical fiber to predict the modal properties of the PhC VCSELs [9], [12], [17], [27], [28]. The $V$ parameter of the waveguide can be calculated from [26]

$$V_{\text{eff}} = \frac{2\pi D}{\lambda} \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}$$
where $D$ is the defect diameter, $\lambda$ is the operating wavelength, $n_{\text{core}}$ is the average refractive index of the material, and $n_{\text{clad}}$ is the effective out-of-plane index of refraction for the PhC.

The defect diameter is given by twice the lattice spacing ($a$) minus the hole diameter ($b$). When $V < 2.405$, it is found that only a single mode is supported [26]. Therefore, PhC VCSELs that are designed with $V_{\text{eff}} < 2.4$ are predicted to operate single mode.

Unless the PhC holes are etched completely through the VCSEL structure, the finite hole etch depth must be taken into account [17]. This can be performed using a layer-by-layer effective index approach [17], [27]. In this computation, the index of the cladding region is computed for each etched DBR layer by using the index obtained from a perfect 2-D out-of-plane band diagram; the remaining unetched layers of the DBR possess their bulk refractive index. The DBR mirror reflectivity is then calculated and the cavity resonance shift (relative to the unetched case) is used to compute the effective index [29].

Fig. 5 illustrates the calculated $V_{\text{eff}}$ for a PhC VCSEL [15]. In this example, the PhC has $b/a = 0.5$ etched into a SiO$_2$-SiN$_x$ top dielectric DBR to three different etch depths (corresponding to 20%, 40%, and 60% into the top DBR) [15]. By calculating the normalized frequency $a/\lambda$, this plot can be used to predict whether a specific design etched to a specific depth will operate single mode. In this case, a VCSEL operating with $a/\lambda = 2.9$ would yield single-mode emission for the three etch depths shown, but would lase multimode if etched deeper. Fig. 5 also depicts the endlessly single-mode condition: as $a/\lambda$ increases, $V_{\text{eff}}$ approaches an asymptotic limit. This is because as $a$ or $\lambda$ is scaled, the change in the effective index in the PhC ($n_{\text{clad}}$) exactly compensates for the normalized diameter of the core ($D/\lambda$). This property is well known in PhC optical fibers [16] and can be exploited to allow scaling of either $a$ (which, in turn, scales the defect aperture and allows for greater single-mode output power) or $\lambda$ (which allows a single design to maintain its single-mode property regardless of lasing wavelength). The manufacturability of a PhC VCSEL can be enhanced by using designs that are single mode for a wide range of wavelengths and are relatively insensitive to etch depth.

### B. Endlessly Single-Mode VCSELs

The light output versus current and voltage characteristics of a 980 nm PhC VCSEL and of an unpatterned but otherwise identical control device are illustrated in Fig. 6. The higher threshold voltage of the PhC VCSEL is a result of the increase in series resistance due to etching in the top DBR, while the increase in threshold current and decreased slope efficiency for the PhC VCSEL arises from optical loss introduced by the PhC. Optical loss introduced by the PhC predominantly discriminates higher order modes that overlap the PhC region [10], [18]. As a result, the differential quantum efficiency of the single-mode PhC VCSEL (22%) is much lower compared to the multimode VCSEL without holes with a differential quantum efficiency of 53%. Higher efficiency has been previously obtained from single-mode VCSELs using other approaches [2], [6], so similar improvements for the endlessly single-mode designs are under study.

The output spectra for various injection currents of the 980 nm PhC VCSEL with $b/a = 0.7$, $a = 5.5$ μm, oxide aperture = 11 μm, and etch depth of 77% are shown in Fig. 7(a). In this study, single-mode operation is defined as a side-mode suppression ratio (SMSR) greater than 30 dB from threshold through
rollover. To demonstrate the effectiveness of the PhC design, output spectra for the unpatterned, but otherwise identical, control VCSEL are shown in Fig. 7(b). The control device clearly operates multimode for all levels of injection current. Far-field measurements of single-mode PhC VCSELs are found to be approximately a Gaussian profile for all etch depths.

PhC VCSELs fabricated at wavelengths of 780, 850, and 980 nm are examined to find endlessly single-mode PhC VCSEL designs. A range of etch depths from 40% to over 100% of the top DBR thickness are considered. Two endlessly single-mode designs with the ratio of $b/a = 0.7$ and lattice constants $a = 4 \mu m$ and $a = 4.5 \mu m$ are shown in Fig. 8. A wide range of etch depths, indicated by the dashed circles, produce endlessly single-mode 780, 850, and 980 nm VCSELs, as depicted in Fig. 8. The invariance of the modal characteristics over a wide range of etch depths for all three wavelengths shows that hole etch depth uncertainty during fabrication will not inhibit single-mode VCSEL manufacture. PhC designs with other $b/a$ ratios are found to yield single-mode operation for a limited wavelength regime or etch hole depth.

The increase of the cavity diameter of PhC VCSELs is potentially an advantage for single-mode laser reliability. However, the impact of the introduction of holes into the top DBR should be considered. The normalized laser output of PhC VCSELs ($b/a = 0.6$, $a = 3.75 \mu m$, oxide aperture = 10 $\mu m$) are shown in Fig. 9. These lasers were operated at 4 mA constant current, 55 °C temperature, and ambient humidity, and show no significant degradation of their output power up to 5000 h. No laser “burn-in” was performed prior to the life testing [7], so the slight increase in output power for some devices is most likely due to current annealing.

C. Microfluidic VCSELs

The microfluidic VCSELs are studied by introducing fluids into the reservoir. Fig. 10 shows a lasing microfluidic VCSEL with and without deionized water. With the fluid inserted into the reservoir and surrounding trench, the fluid could also be observed emerging from the PhC holes. Room-temperature continuous-wave (CW) and pulsed measurements (50-ns pulselength with 1-$\mu s$ period) were performed to obtain output power and optical spectra for the VCSELs during operation. The threshold current of the PhC air-gap (no fluid) VCSELs with 8 $\mu m$ diameter oxide aperture is approximately 3 mA. The current versus voltage characteristic of the microfluidic VCSELs do not change with the introduction of deionized water.
Fig. 9. Normalized CW output power of 12 PhC VCSELs ($b/a = 0.6$, $a = 3.75$ µm, oxide aperture = 10 µm) operated at $55^\circ$C for 5000 h.

Fig. 10. (a) SEM picture showing the fluid reservoir and trench of a microfluidic VCSEL. (b) Near-field optical image of a lasing microfluidic VCSEL with fluid present.

Fig. 11. Optical spectrum with and without water present in microchannels. (a) Pulsed operation. (b) CW operation.

Fig. 12. Far-field angle with and without fluid present in microchannels.

Fig. 11 depicts the optical spectra of the VCSELs with and without water inserted to the fluid reservoir under both CW and pulsed current injection. The PhC pattern is designed for single-mode operation for an unetched oxide layer; when the oxide layer is removed (to form the fluid channel), the core-cladding effective index contrast increases and multimode operation can be obtained, as evident in Fig. 11(b). A decrease (blue-shift) in the lasing wavelength of about 0.3 nm is observed with the introduction of deionized water for both CW and pulsed operation. A reversal back to the original value of lasing wavelength is observed after the fluid is removed. Far-field measurements show an increase in divergence angle of the laser beam when fluids are present, as depicted in Fig. 12. The increase of the far-field divergence angle indicates a decrease of the transverse mode size that is consistent with a blue-shift of the laser emission wavelength. The similar performance for both pulsed and CW operation suggests that fluid cooling is not responsible. The wavelength shift of the peak emission of the microfluidic VCSEL with the introduction of fluids is potentially useful for sensing. The sensitivity of these devices in microfluidic systems is under investigation.
IV. SUMMARY

We have designed and fabricated a large variety of oxide-confined PhC VCSELs. The fabrication is based on a tolerant and low-cost manufacturing process using optical lithography. The PhC VCSELs demonstrate single-mode characteristics ($I_{\text{max}} > 1.5 \text{ mW}$, $\text{S} / \text{M} > 35 \text{ dB}$) using the same PhC pattern for VCSEL wafers operating at 780, 850, and 980 nm emission. The maximum single-mode power obtained is 1.6 mW at 980 nm, although no effort to maximize output power (such as reducing the output mirror reflectivity) has been pursued.

Based on the PhC VCSEL manufacturing process, microfluidic VCSELs are also fabricated. The structure incorporates horizontal and vertical channels, fluid reservoir, and separate metal contact pad to allow for robust microfluidic VCSELs. Pulsed and CW measurements are performed on microfluidic VCSELs and a shift to shorter wavelength of the laser emission is consistently observed when deionized water is present.

We have shown that single-transverse-mode VCSELs can be fabricated for a wide operating range of wavelengths using a universal PhC design. This effect arises from the effective index produced by the PhC. The fabrication procedure utilizes standard lithography and etching processes, and yields devices that exhibit promising reliability. We also find that the etched holes can serve as fluid channels, enabling these devices to be suitable for sensing applications. Therefore, it is expected that this device structure will provide new opportunities for VCSEL applications.

REFERENCES


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