Micro-fluidic photonic crystal vertical cavity surface emitting laser

K. Samakkulam, J. Sulkin, A. Giannopoulos and
K.D. Choquette

The first monolithic micro-fluidic photonic crystal vertical cavity surface emitting laser (VCSEL), wherein the horizontal and vertical micro-fluidic channels lie within the VCSEL, is reported. The micro-fluidic photonic crystal VCSEL is created with two principal steps after fabrication of the VCSEL. The first step is integrating the two-dimensional photonic crystal with the VCSEL structure. The photonic crystal creates singlemode operation, and acts as the vertical micro-channels. After creating the photonic crystal pattern in the VCSEL, the oxide layer is selectively wet etched to form the horizontal channel. Preliminary results obtained from the introduction of fluid into the micro-channels are presented.

Introduction: The advantages of vertical cavity surface emitting lasers (VCSELs) such as lower divergence circular output beam and the feasibility of dense two-dimensional laser arrays [1], combined with the ability to operate in single fundamental mode, have diversified the applications of VCSELs. A recent application has been the integration of micro-fluidic channels with the VCSEL as a means for the ultra-sensitive detection of fluid, cells, and particulates [2]. Early work employed a micro-fabricated fluid channel between the surface of a VCSEL and a glass dielectric mirror [3]. The sensing mechanism of the device depended upon the variation in the resonator internal loss with a change in refractive index of the fluid flowing through its cavity [4]. In the above work the flow structure is fabricated outside the VCSEL and the direction of flow is restricted to the horizontal direction.

In this Letter we demonstrate the first monolithic micro-fluidic photonic crystal VCSEL, wherein the micro-fluidic channel lies within the VCSEL. Our design also has micro-channels in both the horizontal and vertical directions. The photonic crystal pattern serves a dual purpose of acting as the vertical micro-channels, and also helps in achieving singlemode operation. The vertical channels are connected to the underlying horizontal channel, which is created by selectively etching a buried oxide layer. The preliminary sensing results obtained from the introduction of fluid in micro-channels are also presented.

Experiment: The VCSEL device structure contains a bottom n-type 36-period distributed Bragg reflector (DBR) consisting of alternating layers of $Al_{0.16}Ga_{0.84}As$ and $Al_{0.92}Ga_{0.08}As$, an undoped active region with five GaAs quantum wells, and a top p-type 21-period DBR, all of which were grown by metal organic vapour phase epitaxy and designed for an operating wavelength of 850 nm. A backside contact (AuGe/Ni/Au) was deposited to form an ohmic contact to the n-type substrate, and top ring contacts (Ti/Au) were lithographically patterned and formed by liftoff after the metal deposition. The epilayers are etched through the active region before oxidation of the approximately quarter wavelength thick (roughly 50 nm) high aluminium containing the AlGaAs layer in the top DBR. The oxide layer defines the confinement of current to the gain region in the active layer (approximately 5 × 5 μm for the devices reported here) as well as the horizontal fluid channel.

Several methods have been employed for achieving single fundamental mode operation in vertical cavity surface emitting lasers (VCSELs), including small oxide aperture confinement [5], surface relief etching [6], hybrid oxide-implant structures [7], and photonic crystal structures [8, 9]. In our design we employ the photonic crystal structure to create singlemode confinement, where the hole pattern created also acts as vertical channels. Electron beam lithography was used to define the circular hole patterns with hole diameters ranging from 1 to 5 μm, and freon reactive ion etching (RIE) was used to transfer the pattern to an SiO_2 mask. Inductively coupled reactive ion etching (ICP-RIE) is used to etch vertical holes to the oxide layer of the VCSEL.

The last step in the fabrication process is the removal of the oxide layer to create the horizontal fluid channel. The oxide layer is wet-etched using 1:12 KOH (45% w/w):H_2O solution [10]. The etch rate for removing the oxide is approximately 2.5 μm/min. The schematic of the device structure with the vertical and horizontal micro-channels is shown in Fig. 1.

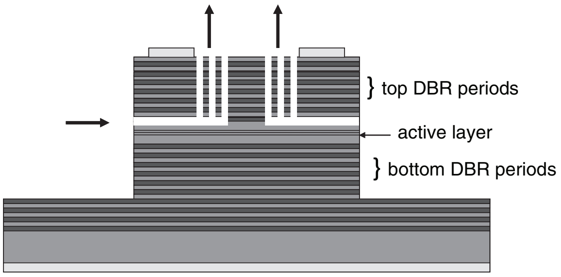

Fig. 1 *Cross-section of micro-fluidic photonic crystal VCSEL*
Photonic crystal hole pattern creates vertical micro-channel; etched oxide layer creates horizontal channel

Results and discussion: We studied the sensing ability of the micro-fluidic photonic crystal VCSEL by introducing fluids into the horizontal micro-channel. The passage allows the fluid to flow through to the patterned holes in the top of the VCSEL as shown in Fig. 2. All of the following data were taken while fluids, either deionised water or acetone passed through the patterned hole at the top of the VCSEL.

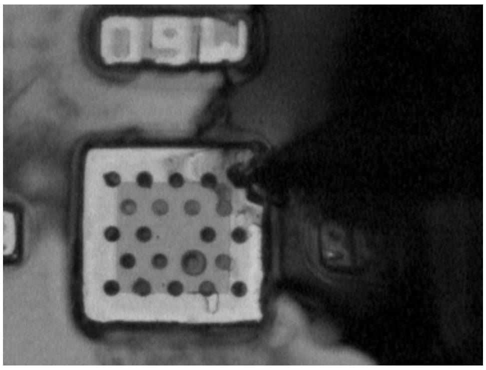

Fig. 2 *Water (drop entering from right) emerging from top facet of micro-fluidic photonic crystal VCSEL*

Room temperature continuous-wave (CW) measurements were performed to obtain output power against injected current characteristics and optical spectra for the VCSELs during operation. The threshold current is approximately 2 mA for the air-gap VCSELs with 5 × 5 μm apertures. Fluid is introduced to the lasers by inserting a droplet near the edge of the VCSEL mesa (see right hand side of Fig. 2) which emerges from some of the holes in the top facet. The anisotropy between the thickness of the horizontal channel compared to the diameter of the vertical holes probably limits the fluid flow in these devices. Fig. 3 shows the VCSEL singlemode spectra during and after the introduction of water operating at three times threshold. During the introduction of water in the micro-channels, a shift of 0.26 nm to shorter wavelength was noticed, and this shift was maintained when the operations were performed at higher injected current.

Continuous-wave measurements were also performed by introducing acetone in the VCSEL. Fig. 4 shows the optical spectra during and before the introduction of acetone operating at three times threshold. A shift of 2 nm to shorter wavelength was obtained, which was consistent for other devices with the addition of acetone. The shift in the lasing wavelength with the introduction of acetone is greater compared to that of water, which is consistent with the higher refractive index of acetone ($n = 1.36$) compared to that of water ($n = 1.33$). Because the spectral shift was the same at higher operation temperature, evaporative cooling is unlikely to be the cause of the spectral blue-shift. The sensing mechanism of the micro-fluidic VCSEL is still under investigation.

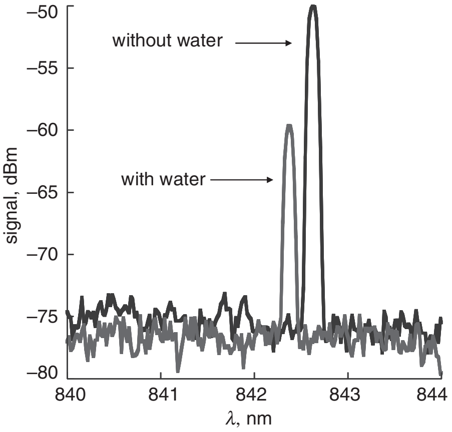

Fig. 3 *Optical spectrum with and without flow of water in micro-channels*

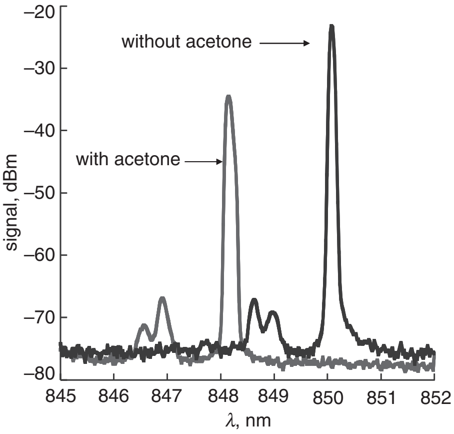

Fig. 4 *Optical spectrum with and without flow of acetone in micro-channels*

Conclusion: We have designed, fabricated and characterised monolithic micro-fluidic photonic crystal VCSELs. This design includes self-aligned vertical and horizontal channels. CW measurements indicate a shift to shorter wavelength of the singlemode spectrum which correlates with the refractive index of the fluids inserted into the laser. Integration of micro-fluidic channels with micro-cavity lasers may enable new sensing applications for VCSELs.

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K. Samakkulam, J. Sulkin, A. Giannopoulos and K.D. Choquette (*Micro and Nanotechnology Laboratory, Department of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign, 208 N. Wright St., Urbana, IL 61801, USA*)

E-mail: choquett@uiuc.edu

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