Hybrid Integration of Photonic Crystal Membrane Lasers via Postprocess Bonding

J. D. Sulkin, *Student Member, IEEE*, and K. D. Choquette, *Fellow, IEEE*

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Department of Electrical and Computer Engineering,
University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA

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Abstract: Photonic crystal (PhC) lasers in InGaAsP membranes are bonded after fabrication to a sapphire substrate. The processed devices are held to the sapphire by van der Waals forces and do not require a high temperature anneal. PhC H2 defect cavity devices are found to lase continuous wave and line defect heterostructure devices lase pulsed, both under optical excitation. Postprocess bonding allows extensive fabrication on the native substrate before being transferred to a new substrate, which may be useful for making more complex nanophotonic devices and/or electrically injected devices.

Index Terms: Photonic crystal lasers, integrated nanophotonic systems, semiconductor lasers.

1. Introduction

Photonic crystal (PhC) membrane lasers offer many promising advantages that make them appealing for future on-chip optical communication [1], [2] and sensing [3] applications. Since their first demonstration in 1999 [4], PhC membrane lasers have been shown to have small mode volume [5], high quality (Q) factor [6], low threshold power [7], and a lithographically tunable emission wavelength [8]. Recent developments have shown improvements in the practicality of these devices, including high-speed, low-power modulation [1], and high-power edge emission [9]. The latter is important for coupling to in-plane on-chip waveguides. One major limitation is practical electrical injection, although laser diode operation has been reported [10].

Hybrid integration of PhC membranes onto low-index, thermally insulating substrates has proven to be critical to the practical development of these lasers [8], [11]. While continuous wave (CW) photopumped operation has been reported in a few instances in air-suspended membrane devices [1], most CW PhC lasers have been demonstrated using membranes bonded onto different substrates [8], [11]. Sapphire has been the substrate material of choice due to its high thermal conductivity [11], which aids in CW operation, although other substrates have been successfully used to achieve CW lasing [12]. Bonded membranes also have the advantage of being more mechanically robust and may enable future integration with silicon photonics and Si-based electronics. These advantages come at the cost of higher refractive index (compared with air), which reduces the quality (Q) factor of PhC membrane lasers by increasing coupling into the substrate [11].

Several different bonding techniques have been reported, including BCB bonding [13] and Au/In bonding [12], although most reports of PhC membranes on sapphire use wafer direct bonding [8],

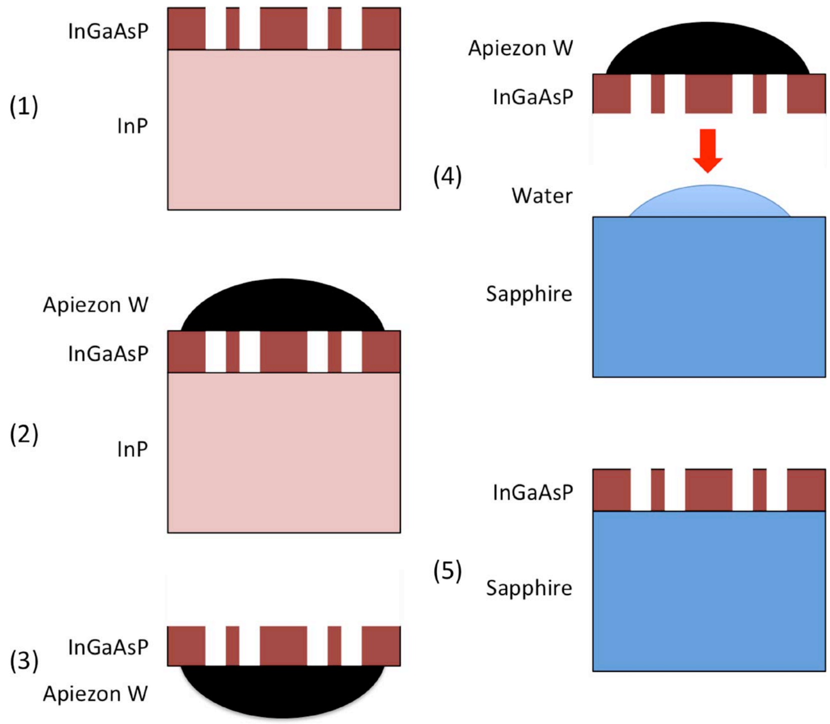

Fig. 1. The fabrication steps for postprocess bonding of fabricated PhC membrane lasers.

[14]. In this procedure, a III–V semiconductor membrane (such as InGaAsP grown on InP) is brought in contact with a sapphire substrate and heated to high temperature (400 °C–500 °C). The substrate is then removed by a wet etch, leaving a membrane on sapphire that is ready for subsequent device fabrication steps. Typically, this further processing involves electron-beam lithography to define the PhC pattern. Hence, membranes bonded to host substrates are prepared first, followed by PhC device fabrication.

We demonstrate here PhC membrane lasers that have been integrated onto a low-index substrate via postprocess bonding. PhC H2 defect cavity [15] lasers are found to operate CW under pulsed excitation. In contrast to previous reports, all processing steps to define the PhC cavity are performed on the native InP substrate, and the completed devices are subsequently transferred to a sapphire substrate. The processed devices are held to the sapphire by van der Waals forces [16], [14] and thus, high-temperature annealing is avoided. This postprocess bonding is useful if device fabrication involves more than a single electron-beam step, particularly if contact optical lithography or high-temperature rapid thermal annealing is involved, such as is needed for diode devices [17]. High-temperature or direct contact can cause cracking or other damage to the bonded membrane due to thermal or mechanical stress.

We also demonstrate pulsed optically pumped lasing of a line defect heterostructure (LDH) PhC laser bonded to sapphire in the manner described above. This type of laser has been demonstrated to have significant in-plane emission [9] and is an especially good candidate for on-chip optical communication applications [1], [11].

2. Fabrication and Design

The membrane contains five InGaAsP quantum wells, is approximately 255 nm thick, and is grown on an InP substrate. PhC designs are etched into an SiO_2 mask by conventional electron-beam lithography, followed by optical lithography to define large mesas (125 μm on a side) around the PhC patterns. The PhC holes and the mesas are then simultaneously transferred into the

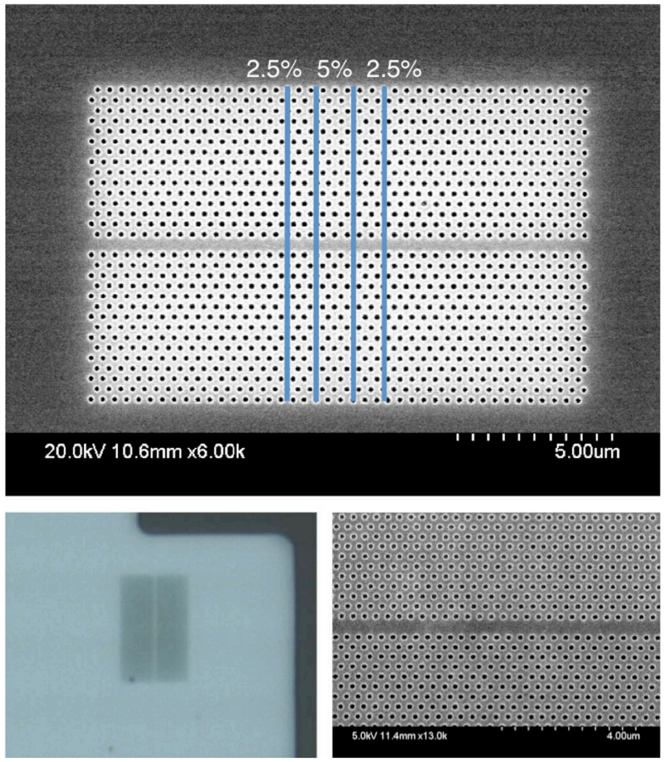

Fig. 2. (Top) Scanning electron micrograph (SEM) of a type-B LDH after fabrication but prior to bonding. The percentages indicate the amount that the period is shifted in the marked regions. (Bottom, left) Optical image and (bottom, right) SEM of a type-B LDH after bonding. The bottom images correspond to the device whose data is shown in Fig. 5.

membrane by an inductively coupled plasma reactive-ion etch (ICP-RIE) step. The main purpose of the mesas is to prevent cracking in the membrane during bonding, but they would also be useful for electrical isolation if these devices were electrically injected.

A process flow for the bonding procedure is shown in Fig. 1. The first step is to melt an acid-resistant wax-like polymer (Apiezon W) onto the membrane at 125 °C, as recommended in [16] and [18]. Next, the InP substrate is removed by a wet etch of HCl:H_20 (4 : 1) at approximately 5 °C, leaving the membrane on the wax, which serves as a mechanical support. At this point, the membrane is susceptible to cracking while the wax is being handled. We have observed that the membrane is much more likely to crack if it is not etched into mesas, which allows the wax to flex. Next, the membrane, while still wet, is lightly pressed onto a sapphire substrate and left to dry for several hours. Finally, the wax is removed by soaking it in methylene chloride for approximately 20 min, leaving the membrane in its original orientation on the new substrate.

The resulting PhC devices embedded into the membrane mesas show no visible sign of damage from the transfer process. However, the yield is rather low, with fewer than 25% of the mesas successfully bonding to the sapphire (the remainder wash away during the methylene chloride soak). A likely cause is due to unintended etching into the InP substrate by the ICP-RIE. This leads to the wax being at a lower height than the bottom of the membrane, which means the mesas have to drop onto the sapphire substrate. A selective wet etch of the InGaAsP mesas [19] can be used instead of the ICP-RIE to alleviate this problem. Preliminary results using the selective mesa etch have shown that a yield of near 100% is possible.

Several different PhC patterns are fabricated as described above for study, including the H2 defect and LDH cavities mentioned earlier. For this latter design, a single row of holes in the $\Gamma - K$ direction is removed from a triangular lattice, forming a waveguide [11]. Confinement along the waveguide is achieved by increasing the lattice constant in the $\Gamma - K$ direction in the center of

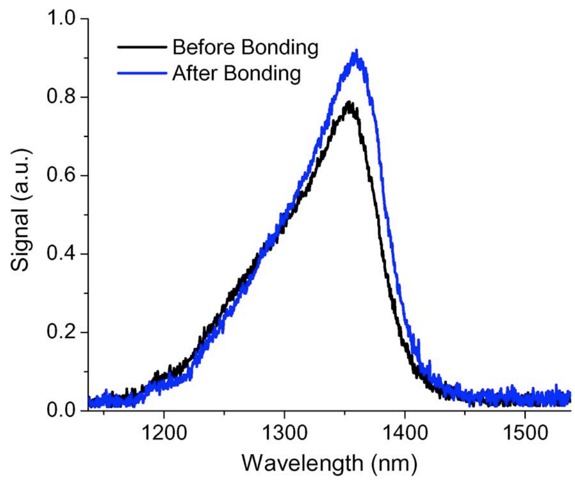

Fig. 3. Pulsed photoluminescence spectra of the InGaAsP membrane from before and after bonding. Spectra are measured near the center of a mesa.

the device by up to 5%. In addition, we follow the proposed design [11] in which one side of the waveguide is offset by half of a PhC period with respect to the other. This forms a so-called type-B heterostructure, which helps reduce out-of-plane emission and is especially important on substrates that have a relatively high index of refraction (compared with air), such as sapphire [11]. Images of a type-B LDH before and after bonding are shown in Fig. 2.

3. Characterization

All of the characterization results presented here are performed with a microphotoluminescence (μPL) measurement system. The μPL uses an objective lens to focus light from a 980-nm laser pump source onto a PhC membrane. The spot size is approximately 2–3 μm in diameter. Light output from the PhC laser is collected through the same lens and coupled into an optical fiber for measurement in an optical spectrum analyzer (OSA). The pump laser is powered by a current source that can operate both CW and pulsed. In pulsed mode, it is operated with a duty cycle of 2% and a pulsewidth of 0.1 μs.

To measure the effect of the bonding process on the optical properties of the membrane, bulk photoluminescence spectra are measured before and after bonding, as shown in Fig. 3. The measurements are made in pulsed mode and taken from the center of a mesa in both cases. No degradation in the photoluminescence power is observed, indicating that bonding induces no measurable damage to the membrane.

The pump light versus emitted light (L–L) curves and lasing spectra are measured for both H2 and LDH cavities, as shown in Figs. 4 and 5, respectively. In Fig. 4, the H2 bonded cavity lases with CW optical excitation. The change in wavelength as a function of incident power is measured to be 0.15 nm/mW. Assuming a change in wavelength with change in temperature of 0.05 nm/K [8], this gives a thermal impedance of 3 K/mW, which is consistent with prior reports [8]. The full-width at half-maximum (FWHM) of the below-threshold spectral line (for the mode with the longer wavelength of the two shown) is measured to be 1.01 nm, which yields an upper-bound Q-factor of 1381. In Fig. 5, the LDH cavity is shown to lase under pulsed operation. A below-threshold FWHM of 0.72 nm is measured for this device, giving an upper bound Q-factor of 1925.

The measured threshold pump powers in Figs. 4 and 5 are relatively high compared with previous reports [8]. Note that the bonding process is not a likely cause of degradation since the photoluminescence spectra before and after bonding in Fig. 3 match so closely. A possible cause for the high laser threshold may be rough sidewalls due to either the long methylene chloride soak or our ICP-RIE process (which is almost certainly nonoptimal and can be improved to reduce

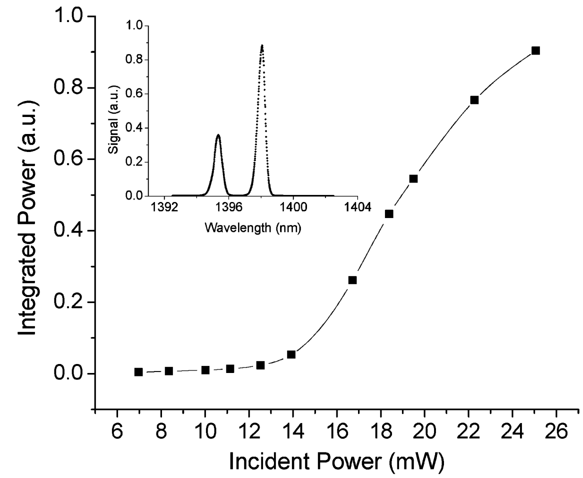

Fig. 4. CW L–L curve and above-threshold spectrum for a H2 PhC laser. The PhC period is 380 nm.

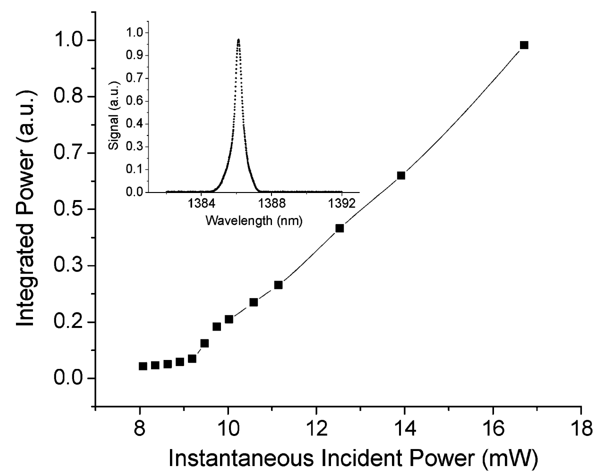

Fig. 5. Pulsed L–L curve and above-threshold spectrum for a LDH PhC laser. The PhC period is 350 nm.

roughness). The threshold may also be reduced by tuning the PhC lattice constant for better spectral alignment between the lasing mode and the peak of the gain. Reducing lasing threshold will be crucial for CW operation of the LDH.

4. Conclusion

We have demonstrated a novel method for bonding PhC membrane lasers to a low-index foreign substrate. This relatively simple technique has resulted in CW point-defect lasers and pulsed line-defect lasers, the latter of which may be important for future on-chip optical interconnect applications. Because the bonding is postprocess, extensive processing on the membrane can be first accomplished on the native substrate, without potential damage caused by cracking or thermal mismatch, which may be especially important for making more complex nanophotonic devices and/or electrically injected devices.

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