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Novel postetch process to realize high quality photonic crystals in InP

N. Shahid, S. Naureen, M. Y. Li,^{a)} M. Swillo, and S. Anand^{b)}

School of Information and Communication Technology, Royal Institute of Technology, Electrum 229, 164 40 Kista, Sweden

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Thermally driven reflow of material during annealing was positively used to obtain near-vertical sidewall profiles for high-aspect-ratio nanostructures in InP fabricated by dry etching. This is very promising for achieving high optical quality in photonic crystal (PhC) components. Nearly cylindrical profiles were obtained for high-aspect-ratio PhC holes with diameters as small as 200–350 nm. Mini stop bands (MSBs) in line-defect PhC waveguides were experimentally investigated for both as-etched and reshaped hole geometries, and their spectral characteristics were used to assess the quality of PhC fabrication. The spectral characteristics of the MSB in PhC waveguides with reshaped holes showed significant improvement in performance with a transmission dip as deep as 35 dB with sharp edges dropping in intensity more than 30 dB for ~ 4 nm of wavelength change. These results show potential for using high extinction drop-filters in InP-based monolithic photonic integrated circuit applications. Finally, it is proposed that other nanostructure geometries may also benefit from this reshaping process. © 2011 American Vacuum Society.

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I. INTRODUCTION

In recent years there has been significant research on two-dimensional (2D) photonic crystals (PhCs), owing to their interesting optical properties and their potential applications in optical communications. InP-based PhCs have attracted much attention because both active and passive components can be realized, and also they are compatible for integration with conventional photonic components on InP substrate. Although several PhC devices such as filters, lasers, and waveguides have been demonstrated, it is commonly recognized that fabrication of PhCs with higher optical quality is essential for low-loss components.

PhC waveguides have been investigated extensively for their unique slow light^{1–3} and dispersion control^{4–6} properties. An interesting property of these waveguides is the so-called mini stop band (MSB), or mode-gap, which originates from energy transfer between forward and backward propagating modes.^{7,8} This effect has been investigated not only from a fundamental physics point of view, but also for device applications such as pulse compression,⁹ coarse wavelength selection,^{10,11} optical filters,¹² selective mirroring in PhC lasers,¹³ and fluid sensors.¹⁴ However, the optical characteristics of the MSBs are closely linked to the optical loss, thus requiring significant improvement in the quality of fabricated PhCs.

Because the vertical light confinement is weak for PhCs in low vertical index contrast structures (e.g., InP/GaInAsP/InP), PhC holes (typically 200–300 nm in diameter) have to be etched down to at least $2 \mu\text{m}$ to ensure good overlap between the modal profile and the PhC holes.¹⁵ In addition,

the sidewalls of the etched holes must be as vertical as possible for low optical loss.¹⁶ Significant advances have been made in this regard. For example, etch depths up to $3\text{--}5 \mu\text{m}$ have been obtained by chemically assisted ion beam etching^{15,17} (CAIBE) or by inductively coupled plasma reactive ion etching^{18–20} using halogen chemistry. However, irrespective of technique and chemistry, the etched PhCs' (circular) holes are invariably either conical or "cylindroconical," with nearly vertical sections on the order of $1\text{--}2 \mu\text{m}$ (with the total depth being typically $4 \mu\text{m}$). Prolonged exposure to ion-bombardment during etching increases sidewall damage^{20,21} and degrades the material properties, which is undesirable, especially for active devices. These observations suggest that these etching processes have fundamental limitations and that a postetch process step may be required to achieve vertical sidewalls. It has been shown that material reflow during the overgrowth step in the fabrication of distributed feedback (DFB) lasers reduces the sharpness and aspect ratios of the gratings.^{22–24} Efforts are made to suppress this phenomenon,^{22–24} but it can be advantageously applied to reshape etched nanostructures such as PhC holes and trenches (slots). Such an annealing process may also be beneficial in reducing the etch-induced damage.

In this study, we demonstrated that as-etched high-aspect nanostructures [one-dimensional (1D) and 2D PhCs] in InP-based materials can be significantly improved in terms of sidewall verticality using material reflow by annealing. The spectral characteristics of MSBs in line-defect (three row missing) multimode PhC waveguides are used as quality indicators of PhC fabrication. The measured spectral characteristics of MSBs in the PhC waveguides with reshaped holes were significantly improved compared to those in as-etched PhC waveguides. MSBs with transmission extinction ratios as high as 35 dB and sharp edges where intensities dropped more than 30 dB over less than a 4 nm wavelength change

^{a)}Permanent address: State Key Laboratory for Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China.

^{b)}Author to whom correspondence should be addressed; electronic mail: anand@kth.se

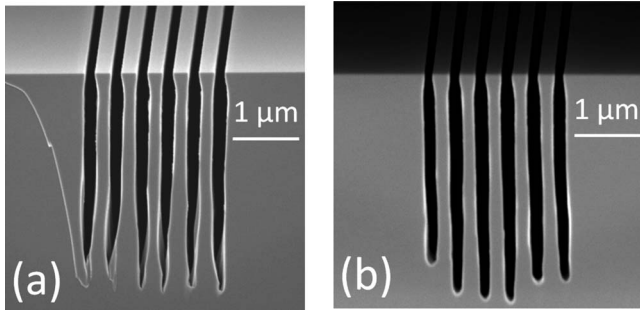


FIG. 1. Cross-sectional scanning electron microscopy (SEM) images of (a) 1D-slot as-etched and (b) reshaped 1D-slot after annealing.

were demonstrated for 50- μm -long waveguides. Reshaped PhCs show promise for achieving high-optical-quality (low-loss) photonic components.

II. EXPERIMENTAL METHODS

The InP/InGaAsP/InP low index contrast slab was grown by metal organic vapor phase epitaxy on InP substrate. The InP cap and GaInAsP core lattice matched to InP ($\lambda_{\text{gap}} = 1.22 \mu\text{m}$) were 200 and 420 nm thick, respectively. For preliminary investigation of annealing effects on the profiles (shape and roughness) of high-aspect-ratio nanostructures both 1D and 2D PhC test structures were fabricated. 1D air slots of 100 μm length were made with widths in the 150–350 nm range and pitches in the range 400–600 nm. These 1D test structures are relevant to on-chip distributed Bragg reflectors (DBRs) at optical communication wavelengths. The 2D PhC test structures had hole-diameters in the range of 200–350 nm. The PhC waveguides oriented in the Γ - K direction with three missing rows (here referred to as W3 PhC waveguides) in a triangular lattice of air-holes have a period of 420 nm and are 120 rows long. Hereafter, we will use the term PhC waveguide to mean a W3 PhC waveguide. The PhC waveguide section was inserted in between two 1.2- μm -wide access-ridge waveguides, each approximately 0.75 mm long. The PhC patterns were made by electron beam lithography using ZEP520 as the resist. The patterns were then transferred in to a 260-nm-thick SiO₂ mask using CHF₃-based reactive ion etching. Subsequently, the PhCs were etched using Ar/Cl₂ CAIBE. Details of the etching process and process conditions are given in Ref. 15. After etching, the test structures and PhC waveguides were annealed at 630 °C under PH₃ for 2 min—typical conditions for regrowth. The main purpose of this annealing step was to reshape the etched PhC holes by reflow of material around the exposed surfaces. The SiO₂ mask is retained during this step to ensure that any eventual material reflow affects only the exposed sidewalls.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the cross-section of an etched 1D-slot structure (representative). The slot width is 150 nm and the period is 400 nm. As seen from the figure, the as-etched profiles are irregular (e.g., bending) and are also strongly

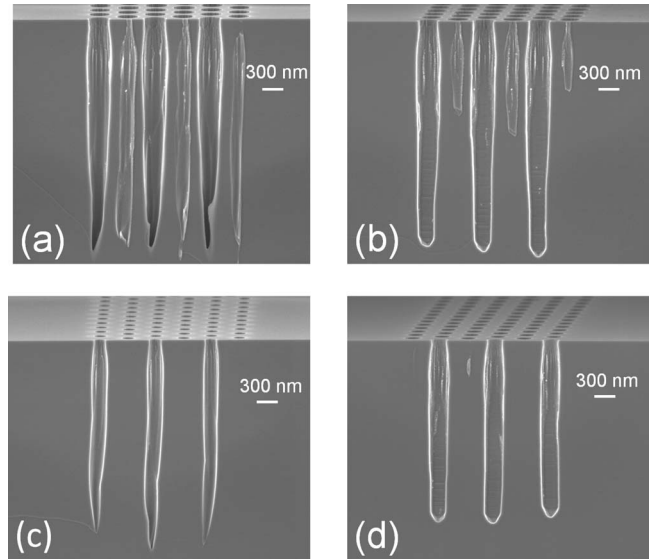


FIG. 2. Cross-sectional SEM images of [(a) and (c)] PhC as-etched and [(b) and (d)] reshaped PhC after annealing.

tapered at the bottom. The other test patterns show similar profiles. Figure 1(b) shows the cross-section of an etched slot structure after annealing. Figure 1(b) shows the cross-section of an etched slot structure after annealing. The structures shown in Figs. 1(a) and 1(b) have the same geometrical parameters (slot width and pitch) and were etched together. It is evident from Fig. 1(b) that annealing clearly improved the profiles in terms of irregularities and sidewall verticality. We attribute this change in profiles to reflow of material (i.e., redistribution of material) occurring on the exposed (etched) surfaces. These results are of interest primarily for on-chip laser DBR-mirrors for which mirror loss due to tapering can be reduced. Figure 2 shows the results obtained for 2D PhCs. Here, the comparison is made for 2D PhCs having the same geometrical parameters (hole-diameter and period), and those were etched together. The as-etched hole profiles [Figs. 2(a) and 2(c)] show tapered bottom profiles and irregularities (bending) typical of deeply etched PhCs in InP. The upper part of the etched structure is reasonably vertical as typically observed.¹⁵ In striking contrast, as is evident in Figs. 2(b) and 2(d), material reflow not only removes (smoothen) any irregularities, but also results in nearly cylindrical hole profiles. Thus, imperfections in PhC due to variations in feature size and shape introduced at the pattern transfer step can be effectively reduced using material reflow. The observations clearly demonstrate that material reflow can be used positively to fabricate 1D and 2D nanostructures with vertical sidewalls.

Inspection of the slot (Fig. 1) and hole (Fig. 2) profiles suggests that reflow/redistribution of the material depends on the sidewall angle. The profiles in the upper portion where they are nearly vertical or slightly underetched are practically unaltered by annealing. This suggests that redistribution of the materials in those regions is not sufficient to smoothen out the sidewall roughness. However, the microscopic origin of the roughness in terms of the surface distribution of the

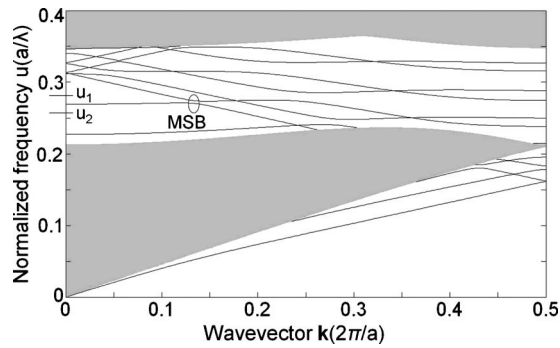


FIG. 3. Dispersion diagram of the PhC waveguide showing the region of interest where $u_1=0.275$ and $u_2=0.261$.

elements (e.g., In, P, Ga, and As) may also play a role. It is recognized that material reflow depends on the annealing temperature and duration, on the as-etched profile, and on the material composition at the surface. A detailed study of the effect of these parameters on the resulting hole shape is beyond the scope of this article. Our main emphasis is to demonstrate that such a postprocess step could significantly improve the quality of the photonic devices. Specifically, because our etch process is better optimized for air-hole scheme, the impact of the reshaping process on PhC devices is demonstrated using W3 PhC waveguides as an example. Spectral characteristics of MSBs are used to qualify PhC fabrication. Below, we discuss the optical measurements of the PhC waveguides.

The PhC waveguides were characterized by the end-fire technique. An amplified spontaneous emission source with a spectral range of 1530–1610 nm was used as the light source and was coupled into the cleaved facet of the input access-ridge waveguide through a focusing gradient index lens. The output light was collected by a microscope objective and split into two beams: one to an infrared camera for alignment and imaging and the other to an optical spectrum analyzer through a single mode fiber to measure the transmission spectra. Polarizers were used at both input and output of the sample to ensure that only transverse electric modes were excited in access waveguides. Conventional ridge waveguides were fabricated together with the PhC waveguides to serve as references for normalizing the transmission spectra.

Figure 3 shows the dispersion diagram calculated by the plane-wave expansion (PWE) method for the W3 PhC waveguide. The PWE calculations were made for an effective index of 3.24 and an air-fill factor of 42%.⁸ Refractive indices of 3.17 and 3.35 were used for InP and GaInAsP, respectively. As seen in Fig. 3, the mode-gap or MSB due to coupling between the first and fifth order modes^{7,8} occurs at approximately $u=0.27$, where u is the normalized frequency ($u=a/\lambda$). Given the period $a=420$ nm, this value of $u=0.27$ corresponds to the center wavelength of ~ 1556 nm. As a result of this mode-gap the transmission spectrum is expected to exhibit a dip in the corresponding wavelength region. The transmission spectrum for the PhC waveguide

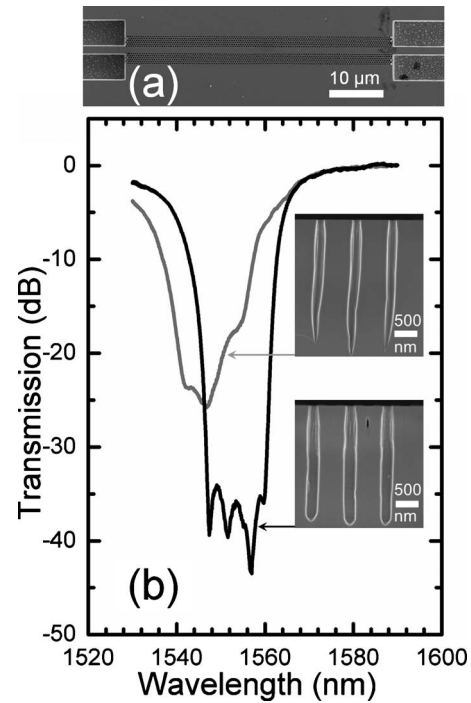


FIG. 4. (a) SEM top view of a fabricated PhC waveguide; part of the access-ridge waveguides is also visible. (b) Measured transmission spectra (normalized) comparing as-etched and annealed (reshaped) PhC waveguides.

was simulated using 2D finite-difference-time-domain (FDTD) and shows a MSB-dip in the wavelength region predicted by PWE calculations.

Figure 4(a) shows the top view of a fabricated PhC waveguide; parts of the access-ridge waveguides are also visible. Figure 4(b) shows the measured transmission spectra of two PhC waveguides of 50 μm length: one as-etched and the other with reshaped holes. In both samples, the characteristic dip in transmission due to the MSB effect is evident, and the wavelength range where it occurs agrees well with PWE calculations (Fig. 3). However, the difference in the samples' MSB spectral characteristics is striking. For the sample with reshaped holes, the measured dip due to the MSB (hereafter referred to as MSB-dip) is as deep as 35 dB. The transmission bandwidth for the MSB was 12 nm. The transmission at the edges dropped sharply—more than 30 dB for ~ 4 nm change of wavelength, approximately ~ 4 times steeper compared to the previous best result.⁸ The shape and depth of the MSB-dip for the as-etched sample [Fig. 4(b)] are comparatively inferior. These results clearly demonstrate that the reshaping procedure significantly improves the optical quality of PhC waveguides. In a previous work,⁸ 2D FDTD simulations including an effective loss parameter showed that as the loss increased, the MSB-dip became shallower. Based on those results, reduced extrinsic optical loss should result in steeper MSB-dips, as was observed for the samples with reshaped holes. The slope of transmission at the edges of MSBs was also comparable to that observed for 2D FDTD simulations. To account for the exact geometry of the holes,

a more rigorous analysis of the experimental data would need to be conducted using 3D simulations, but this is outside the scope of this study.

The PhC waveguides with reshaped profiles may be used as monolithically integrated passive filters in applications requiring very high extinction/rejection ratios. An interesting application example would be for DFB lasers where they can potentially be used as DBR-like mirrors for the light that propagates through the line-defect waveguide. The performance of the proposed waveguides as filters (stop-band extinction) may be limited by the presence of the third order mode. The third order mode can also be excited in the PhC waveguide, which can limit the observed MSB depth. Davano *et al.*¹² described broadband filters for monolithic photonic integrated circuits using the MSB effect. The demonstrated transmission extinction ratio for these filters is equal to 20 dB. It is worth noting that in our annealed PhC waveguides the obtained transmission extinction ratio was as large as 35–40 dB. The group velocity can be reduced because of dispersion arising from mode coupling between the fundamental and higher order modes at mode singularities.³ A low group velocity is a promising solution for enhancement of linear and nonlinear optical effects, buffering, and time-domain processing of optical signals. However, the use of slow light in such structures requires further investigation, specifically taking into consideration the optical loss and multimode nature of the waveguide. Sharp transmission edges of MSB can be expected to be very sensitive to changes in the material refractive index and/or to substances filled in the air-holes of PhCs. This could be of potential interest for sensing, tuning, and modulation applications and will be the subject matter of our future investigations.

IV. CONCLUSIONS

In conclusion, a postetch annealing step resulting in reflow of material around the exposed surfaces of the etched PhC holes significantly improved the sidewall verticality. Annealing can effectively reduce imperfections in PhCs which are caused by variations in feature size and shape introduced at the pattern transfer steps. The MSBs for PhC waveguides fabricated using a reshaping process exhibited excellent spectral characteristics. The transmission extinction ratios of more than 35 dB achieved for ~12 nm bandwidth in a simple waveguide transmission geometry may potentially be attractive for use in tunable band filters and on-chip mirrors. The sharp MSB edges realized in this work may apply to optical sensing, tuning, and modulation. Here, we have demonstrated the efficacy of the reshaping process using material reflow by annealing in the context of MSB in

PhC waveguides and InP-based materials, and we also propose that this process will be beneficial to other PhC devices, nanostructure geometries, and materials.

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