Design and implementation of silicon-based optical nanostructures for integrated photonic circuit applications using Deep Reactive Ion Etching (DRIE) technique

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ABSTRACT

In this paper, we present the fabrication of nano optical elements by means of deep reactive ion etching technique (Bosch process) on a silicon-on-insulator substrate. The nano structures are fabricated in a two step process. The first step consists of direct-writing nanoscale patterns on PMMA polymer by electron beam lithography. These nano patterns are then transferred to the silicon surface by a low temperature and low pressure deep reactive ion etching (DRIE) process using PMMA as a mask. The low temperature and low pressure conditions in the DRIE process minimize scalloping in the nanoscale features. We found that the etch rate is highly dependent on the aspect ratio of the structure. We have used the DRIE method to fabricate a negative-index photonic crystal flat lens and demonstrated the focusing properties of this flat lens using a near-field scanning optical microscope.

Keywords: Photonic Crystals, Deep reactive ion etching, negative refraction, Near Field Scanning Optical Microscope.

1 INTRODUCTION

Photonic crystals (PhCs), a periodic structure of holes made in a dielectric medium with the hole size and lattice spacing comparable to the wavelength scale, are artificially engineered structures capable of manipulating and shaping optical signals in optoelectronic devices [1-4]. Nanoscale photonic crystals is expected to add new functionalities to the next generation of optical integrated circuits by providing novel ways of losslessly routing and modulating light, thereby enhancing the performance of micro-nano-optoelectronic devices. Among semiconductor materials, silicon (Si) has been adopted as the material of choice for PhCs applications [5-9] mainly because of its compatibility with CMOS electronics and its availability. The high-index contrast of core silicon to the cladding silicon dioxide (SiO_2) layer on a silicon-on-insulator (SOI) substrate, allows the confinement of light. The semiconductor industry has developed a plethora of techniques to etch silicon which includes reactive ion etching (RIE) [10,11], inductively coupled plasma (ICP) [12], electron-cyclotron-resonance (ECR) [13], and time multiplexed inductively coupled fluorine plasma, and chemically assisted ion-beam etching (CAIBE) systems [14]. Deep Reactive Ion Etching has been utilized by the MEMS community to etch high aspect ratio structures at the microscale on silicon substrates [15]. Even though DRIE etching has been utilized in realizing various MEMS devices [16], the fabrication of silicon nanophotonic structures and their optical applications has been relatively unexplored. Here we present our recent results on the nanofabrication of negative-index photonic crystal lens on a SOI substrate by DRIE technique, and then demonstrate the negative refractive index fingerprint of a photonic crystal flat lens (i.e. a focusing effect) by near-field scanning optical microscopy (NSOM).

2 DESIGN OF THE FLAT LENS

As illustrated in Figure 1, the flat lens consists of a 5μm wide 500 μm long waveguide, triangular lattice PhC1 (lattice constant a=560nm and hole diameter 2r=480nm) square lattice PhC2 (a=420nm, 2r=0.85a), and a 22 μm wide and 61 μm long air cavity. The widths of the PhC1 and PhC2 are 8 μm and 6 μm, and their lengths are 47 μm, respectively.

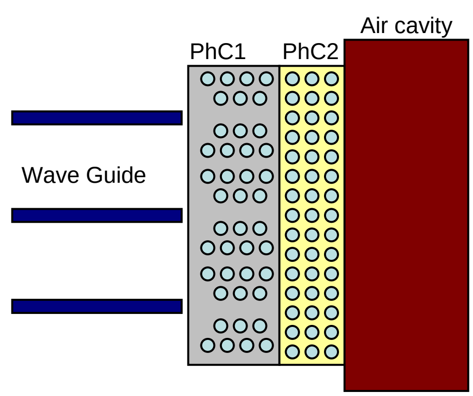

Figure 1: A drawing of the photonic crystal flat lens (PhC2) and adjacent point-source generating waveguides (PhC1). (The dark shaded areas are etched).

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3 FABRICATION OF THE NANOPHOTONIC LENS

The SOI substrates are fabricated using amorphous silicon grown on SiO_2. First, a silicon wafer is cleaned by a standard RCA clean process. Then, a 500nm SiO_2 cladding layer is thermally oxidized on the silicon substrate. An amorphous 600nm silicon guiding layer is then deposited using a plasma enhanced chemical vapor deposition system. A schematic of the high-index contrast waveguide system ($Si/SiO_2/Si$) is illustrated in Figure 2a. A 600nm layer of polymethyl methacrylate (PMMA) layer (A7 950 K) is next spun on the SOI wafer.

The nanostructures are realized with a two-step process: Electron beam lithography (EBL) is used as a primary pattern generator to define patterns on the PMMA resist. The pattern is then transferred to the silicon surface by DRIE with PMMA layer as the mask. The process flow for realizing Si nanophotonic devices is illustrated in Figure 2. The DRIE process for etching nanostructures utilized etch and passivation cycles (SF_6 gas to etch and C_4F_8 to passivate, Bosch process, Surface Technology Systems ASE HRM) with the final device as shown in (Figure 2d).

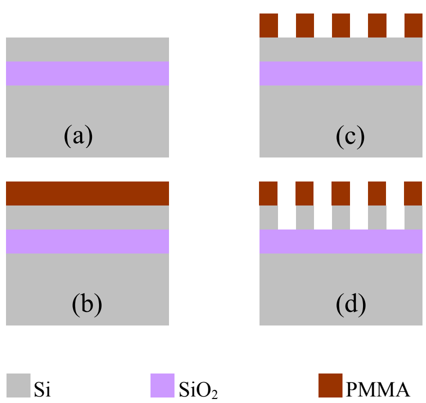

Figure 2: Process flow for the fabrication of a photonic crystal flat lens on SOI.

We have taken into account multiple aspects of nanostructure fabrication (e.g. scalloping, feature dependent etch rates, etc…) and optimized etch parameters to create functional nanophotonic structures. Our study indicates that the etch rate was highly dependent on the aspect ratio of the structures. We also found out that the low temperature and low pressure etching approach significantly reduced the width of scalloping routinely formed during the DRIE process due to the alternating cycles of etch and passivation. Figures 3 and 4 show the scanning electron microscope (SEM) images of arrays of circular patterns and the flat lens.

4 RESULTS

The focusing property of the flat-lens was experimentally investigated with Near Field Scanning Optical Microscope (NSOM). A sketch of the experimental setup is shown in Figure 5.

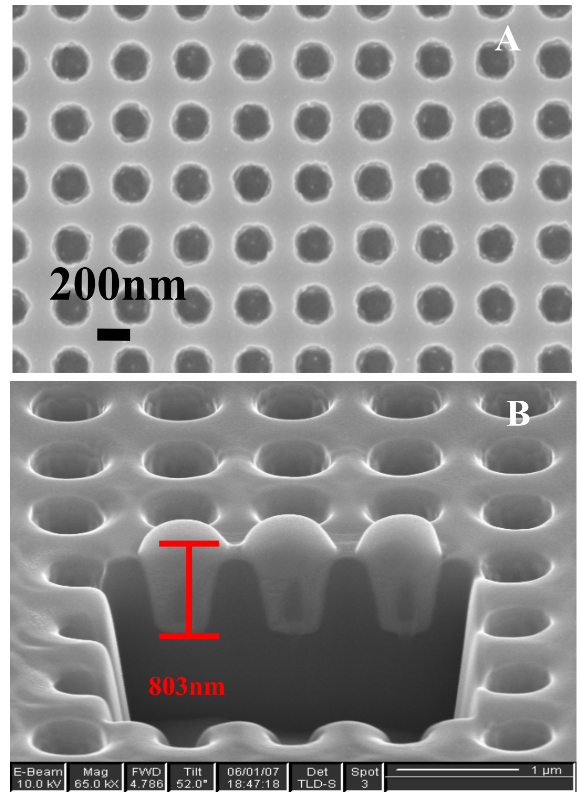

Figure 3: Scanning Electron Microscope (SEM) images of (a) 200 nm circular patterns, (b) cross section of 803nm deep and 500nm wide holes.

The input light from a semiconductor laser (central wavelength of 1550 nm) source carried by a single mode lensed fiber was butt-coupled into the cleaved end of a 5 µm wide planar waveguide fabricated in the backplane of the PhC lens. The single mode lensed fiber mounted on a six-axis micro-positioning stage is capable of focusing light in free space (FWHM < 3.0 µm in air). The other end of the planar waveguide was interconnected to the triangular lattice PhCs1 (as seen in Figure 1) slab. The PhC1 was designed to exhibit photonic band gap at 1550nm with the goal to realize a point source like object. This was accomplished by introducing a series of defects in the form of missing air holes in PhC1 during the fabrication process [17]. Light propagating through the defects in PhC1 creates a point like source in the vicinity of PhC2 (as seen in Figure 1). A high sensitivity infrared camera (Hamamatsu Model C2741) connected to a microscope port aids the initial alignment for optimizing IR light coupling from the optical fiber to the waveguide.

Based on our calculations and of similar devices that are published [18-23], the flat-lens PhC2 is expected to form a point-like image in the backplane. The scattered light from

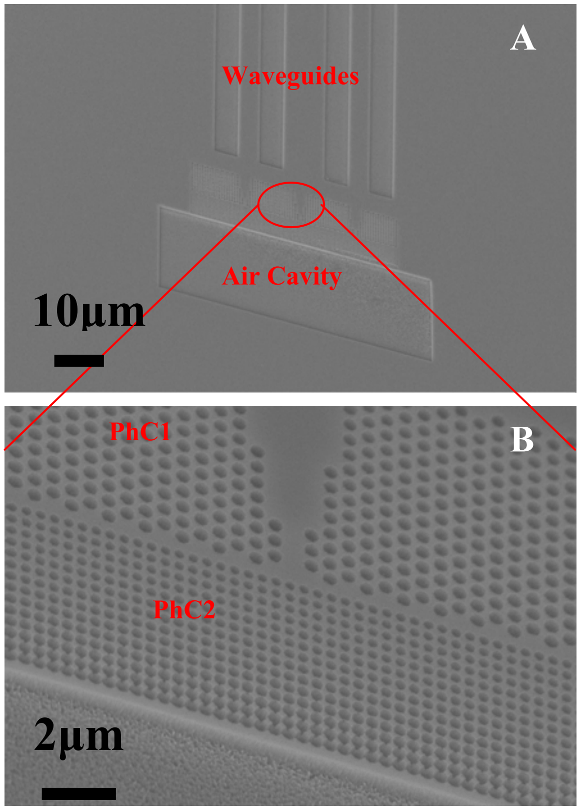

Figure 4: A) SEM image of a flat lens after the fabrication, B) Magnified image of A.

the point source formed near the PhC2-air interface was captured by an IR camera from top. The device and IR measurements are shown in Figure 6a. The focal region was further probed by NSOM technique to obtain a high resolution image.

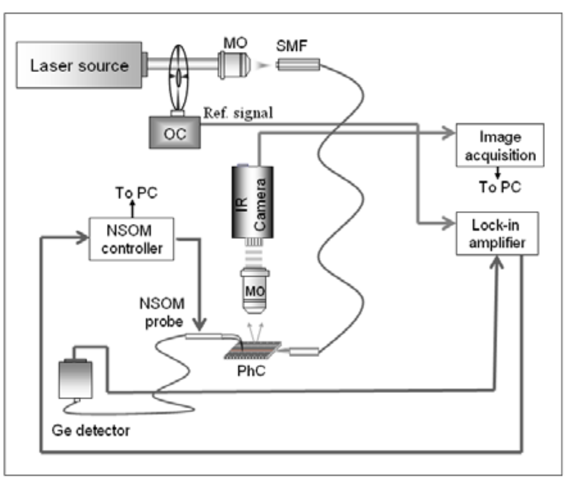

Figure 5: Experimental arrangement for NSOM detection and IR imaging of the PhC lens. MO: Microscope objective; SMF: Single Mode Fiber; OC: Optical Chopper.

The NSOM used a 250 nm aperture diameter, metalized, and tapered fiber probe raster scanned in the air cavity etched next to the PhC2. The output end of the fiber probe was connected to nitrogen cooled Ge detector (North Coast Scientific Corp. Model # EO-817L). Additionally, a typical lock-in amplifier was utilized to optimize the detection scheme. The reconstructed NSOM image is shown in Figure 6b. The focused image appears approximately 1.5 µm away from the trailing edge of the flat lens PhC2. The prominent light focusing features are evident in the overlaid contour plots of the image. The measured full width at half maxima (FWHM) of the focused spot is ≈1.8λ. The measured results demonstrate that focusing by a flat lens is possible with the measurements matching our computations [24].

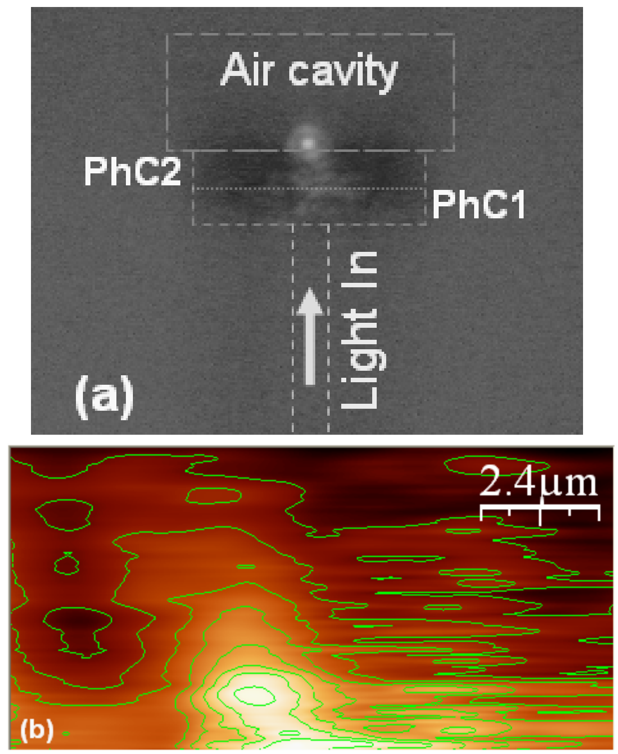

Figure 6: Experimental demonstration of point-source imaging with SOI flat-lens (a) Infrared camera image taken from the top and (b) the corresponding high resolution image of the focal region obtained with a NSOM scan.

5 CONCLUSION

Utilizing a DRIE process, we fabricated a Photonic crystal flat lens on a SOI substrate. Utilizing the flat lens, focusing of light with a wavelength of 1550 nm is demonstrated with the measured results matching our calculations. Demonstrating focusing on silicon enables new opportunities for CMOS based nanophotonic devices.

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REFERENCES

[1] S. John, “Strong Localization of Photons in Certain Disordered Dielectric Superlattices”, Phys. Rev. Lett., vol. 58, no. 23, pp. 2486-2489, 1987.

[2] E. Yablonovitch, “Inhibited Spontaneous Emission in Solid-State Physics and Electronics”, Phys. Rev. Lett., vol. 58, no. 20, pp. 2059-2062, 1987.

[3] J. S. Foresi, P. R. Villenevue, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, H. I. Smith, and E. P. Ippen, ‘‘Photonic-band gap mirocavities in optical waveguides,’’ Nature (London), vol. 390, pp. 143–145, 1997.

[4] M. Notomi, “Theory of light propagation in strongly modulated photonic crystals: Refraction like behavior in the vicinity of the photonic band gap”, Phys. Rev. B, vol. 62, pp. 10696-10705, 2000.

[5] A. Shinya, M. Notomi, I. Yokohama, C. Takahashi, J.-I. Takahashi, and T. Tamamura, “Two-dimensional Si photonic crystals on oxide using SOI substrate”, Optical and Quantum Electronics, vol. 34, pp. 113-121, 2002.

[6] W. Bogaerts, D. Taillaert, B. Luyssaert, P. Dumon, J. Van Campenhout, P. Bienstman, D. Van Thourhout, R. Baets, V. Wiaux, and S. Beckx, “ Basic structures for photonic integrated circuits in Silicon-on-insulator”, Opt. Exp.,vol. 12, issue 8, pp. 1583-1591, 2004.

[7] Y. Wang, Z. Lin, C. Zhang, F. Gao, and F. Zhang, “Integrated SOI Rib Waveguide Using Inductively Coupled Plasma Reactive Ion Etching”, IEEE Journal of selected Topics in Quantum Electronics, vol. 11, no. 1, 2005.

[8] R. D. L. Rue, H. Chong, M. Gnan, N. Johnson, I. Ntakis, P. Pottier, M. Sorel, A. M. Zain, H. Zhang, E. Camargo, C. Jin, M. Armenise, and C. Ciminelli, “Photonic crystal and photonic wire nano-photonics based on silicon-on-insulator” New J. Phys., vol. 8 (256). pp. 1-15, 2006.

[9] S. Venkataraman, J. Murakowski, T. N. Adam, J. Kolodzey, and D. W. Prather, “Fabrication of high-fill-factor photonic crystal devices on silicon-on-insulator substrates”, J. Microlith., Microfab., Microsyst., vol. 2 no. 4, October, 2003.

[10] J. Arentoft, T. Serndergaard, M. Kristensen, A. Boltasseva, M. Thorhauge, and L. Frandsen, “ Low-loss silicon-on-insulator photonic crystal waveguides”, Electronics Letters 14th,vol. 38 no. 6,2002.

[11] L. O’Faolain, X. Yuan, D. McIntyre, S. Thoms, H. Chong, R.M. De La Rue, and T.F. Krauss, “Low-loss propagation in photonic crystal waveguides”, Electronics Letters 7th, vol. 42, no. 25, 2006.

[12] E. Bennici, S. Ferrero, F. Giorgis, C.F. Pirri, R. Rizzoli, P. Schina, L. Businaro, and E. Di Fabrizio, “a-Si:H based two-dimensional photonic crystals”, Physica E 16, pp. 539 – 543, 2003.

[13] M. Tokushima, H. Kosaka, A. Tomita, and H. Yamada, “Lightwave propagation through a 120° sharply bent single line-defect photonic crystal waveguide”, Appl. Phys. Lett., vol. 76, no. 8, pp. 952–954, 2000.

[14] M. Lončar, B. G. Lee, L. Diehl, M. Belkin, F. Capasso, “Design and fabrication of photonic crystal quantum cascade lasers for optofluidics”, Opt. Exp., vol. 15, no. 8, pp. 4499-4514, 2007.

[15] K.-S. Chen, A. A. Ayón, X. Zhang, and S. M. Spearing, “Effect of Process Parameters on the Surface Morphology and Mechanical Performance of Silicon Structures After Deep Reactive Ion Etching (DRIE)”, Journal of Microelectromechanical Systems, vol. 11, no. 3, pp. 264-275, 2002.

[16] C.-H. Choi and C.-J. Kim, The 13th lnternational Confercnce on Solid-State Sensors, Actuators and Mictosystems, pp. 168-171, 2005.

[17] Z. Lu, B. Miao, T.R. Hudson, C. Lin, J. A. Murakowski and D. W. Prather, “Negative refraction imaging in a hybrid photonic-crystal device at near-infrared frequencies”, Opt. Exp., vol. 15, no.3, pp. 1286-1291, 2007.

[18] T. Matsumoto, K. S. Eom, and T. Baba, “Focusing of light by negative refraction in a photonic crystal slab superlens on silicon-on-insulator substrate”. Optics Letters vol. 31, no. 18, pp. 2786-2788, 2006.

[19] A. Berrier, M. Mulot, M. Swillo, M. Qiu, L. Thylen, A. Talneau, and S. Anand,, “Negative refraction at infrared wavelengths in a two-dimensional photonic crystal”, Phys. Rev. Lett., vol. 93, no. 7, pp. 073902, 2004.

[20] P. V. Parimi, W. T. Lu, P. Vodo, and S. Sridhar, “Photonic crystals - Imaging by flat lens using negative refraction”, Nature 426, pp. 404-404,2003.

[21] P.V. Parimi, W.T. Lu, P. Vodo, J. Sokoloff, J. S. Derov, and S. Sridhar, “Negative refraction and left-handed electromagnetism in microwave photonic crystals”, Phys. Rev. Lett., vol. 92, no. 12, pp. 127401, 2004.

[22] E. Schonbrun, M. Tinker, W. Park, and & J. B. Lee, “Negative refraction in a Si-polymer photonic crystal membrane”, IEEE Photonics Technology Letters 17, no.6, pp.1196-1198, 2005.

[23] E. Schonbrun, T. Yamashita, W. Park, and C. J. Summers, “Negative-index imaging by an index-matched photonic crystal slab”, Physical Review B 73, pp. 195117, 2006.

[24] W. T. Lu and S. Sridhar, “Flat lens without optical axis: Theory of imaging”, Opt. Exp., vol. 13, no. 26, pp. 10673-10680, 2005.