Suspended 2-D photonic crystal aluminum nitride membrane reflector

Chong Pei Ho,^{1,2} Prakash Pitchappa,^{1,2} Bo Woon Soon,¹ and Chengkuo Lee^{1,2*}

¹Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3,

117576, Singapore

²National University of Singapore Suzhou Research Institute, Suzhou Industrial Park, Suzhou, China *elelc@nus.edu.sg

Abstract: We experimentally demonstrated a free-standing twodimensional (2-D) photonic crystal (PhC) aluminum nitride (AlN) membrane to function as a free space (or out-of-plane) reflector working in the mid infrared region. By etching circular holes of radius 620nm in a 330nm thick AlN slab, greater than 90% reflection was measured from 3.08µm to 3.78µm, with the peak reflection of 96% at 3.16µm. Due to the relatively low refractive index of AlN, we also investigated the importance of employing methods such as sacrificial layer release to enhance the performance of the PhC. In addition, characterization of the AlN based PhC was also done up to 450°C to examine the impact of thermo-optic effect on the performance. Despite the high temperature operation, the redshift in the peak reflection wavelengths of the device was estimated to be only 14.1nm. This equates to a relatively low thermo-optic coefficient $2.22 \times 10^{-5} \text{ K}^{-1}$ for AlN. Such insensitivity to thermo-optic effect makes AlN based 2-D PhC a promising technology to be used as photonic components for high temperature applications such as Fabry-Perot interferometer used for gas sensing in down-hole oil drilling and ruggedized electronics.

©2015 Optical Society of America

OCIS codes: (230.5298) Photonic crystals; (160.5293) Photonic bandgap materials; (310.6860) Thin films, optical properties.

References and links

- T. M. Jordan, J. C. Partridge, and N. W. Roberts, "Non-polarizing broadband multilayer reflectors in fish," Nat. Photonics 6(11), 759–763 (2012).
- T. D. Corrigan, D. H. Park, H. D. Drew, S.-H. Guo, P. W. Kolb, W. N. Herman, and R. J. Phaneuf, "Broadband and mid-infrared absorber based on dielectric-thin metal film multilayers," Appl. Opt. 51(8), 1109–1114 (2012).
- 3. W. Shen, X. Sun, Y. Zhang, Z. Luo, X. Liu, and P. Gu, "Narrow band filters in both transmission and reflection with metal/dielectric thin films," Opt. Commun. **2**(282), 242–246 (2009).
- A. S. Chadha, D. Zhao, S. Chuwongin, Z. Ma, and W. Zhou, "Polarization- and angle-dependent characteristics in two dimensional photonic crystal membrane reflectors," Appl. Phys. Lett. 103(21), 211107 (2013).
- Y. Shuai, D. Zhao, A. S. Chadha, J. H. Seo, H. Yang, S. Fan, Z. Ma, and W. Zhou, "Coupled double-layer Fano resonance photonic crystal filters with lattice displacement," Appl. Phys. Lett. 103(24), 241106 (2013).
- F. L. Hsiao and Y. T. Ren, "Computational study of slot photonic crystal ring-resonator for refractive index sensing," Sens. Actuators A Phys. 205, 53–57 (2014).
- H. Li, L. Yan, Z. Guo, W. Pan, K. Wen, H. Li, and X. Luo, "Enhanced focusing properties using surface plasmon multilayer gratings," IEEE Photon. J. 4(1), 57–64 (2012).
- M. Carras, G. Maisons, B. Simozrag, M. Garcia, O. Parillaud, J. Massies, and X. Marcadet, "Room-temperature continuous-wave metal grating distributed feedback quantum cascade lasers," Appl. Phys. Lett. 96(16), 161105 (2010).
- L. Lu, F. Li, M. Xu, T. Wang, J. Wu, L. Zhou, and Y. Su, "Mode-selective hybrid plasmonic Bragg grating reflector," IEEE Photon. Technol. Lett. 24(19), 1765–1767 (2012).
- Z. Yu, P. Deshpande, W. Wu, J. Wang, and S. Y. Chou, "Reflective polarizer based on a stacked double-layer subwavelength metal grating structure fabricated using nanoimprint lithography," Appl. Phys. Lett. 77(7), 927– 929 (2000).
- 11. A. Liu, F. Fu, Y. Wang, B. Jiang, and W. Zheng, "Polarization-insensitive subwavelength grating reflector based on a semiconductor-insulator-metal structure," Opt. Express **20**(14), 14991–15000 (2012).

- 12. Y. Shuai, D. Zhao, G. Medhi, R. Peale, Z. Ma, W. Buchwald, R. Soref, and W. D. Zhou, "Fano-resonance photonic crystal membrane reflectors at mid- and far-Infrared," IEEE Photon. J. 5(1), 4700206 (2013).
- Z. X. Qiang, H. Yang, S. Chuwongin, D. Zhao, Z. Ma, and W. D. Zhou, "Design of Fano broadband reflectors on SOI," IEEE Photon. Technol. Lett. 22(15), 1108–1110 (2010).
- S. Fan and J. D. Joannopoulos, "Analysis of guided resonances in photonic crystal slabs," Phys. Rev. B 65(23), 235112 (2002).
- C. P. Ho, P. Pitchappa, P. Kropelnicki, J. Wang, Y. Gu, and C. Lee, "Development of Polycrystalline Silicon Based Photonic Crystal Membrane for Mid-Infrared Applications," IEEE J. Sel. Top. Quantum Electron. 20(4), 94–100 (2014).
- C. Xiong, W. H. Pernice, and H. X. Tang, "Low-loss, silicon integrated, aluminum nitride photonic circuits and their use for electro-optic signal processing," Nano Lett. 12(7), 3562–3568 (2012).
- 17. S. Ghosh and G. Piazza, "Photonic microdisk resonators in aluminum nitride," J. Appl. Phys. **113**(1), 016101 (2013).
- M. Stegmaier and W. H. Pernice, "Broadband directional coupling in aluminum nitride nanophotonic circuits," Opt. Express 21(6), 7304–7315 (2013).
- C. P. Ho, P. Pitchappa, P. Kropelnicki, J. Wang, Y. Gu, and C. Lee, "Characterization of polycrystalline silicon based photonic crystal suspended membrane for high temperature applications," J. Nanophotonics 8(1), 084096 (2014).
- J. Teng, P. Dumon, W. Bogaerts, H. Zhang, X. Jian, X. Han, M. Zhao, G. Morthier, and R. Baets, "Athermal Silicon-on-insulator ring resonators by overlaying a polymer cladding on narrowed waveguides," Opt. Express 17(17), 14627–14633 (2009).
- M. Han and A. Wang, "Temperature compensation of optical microresonators using a surface layer with negative thermo-optic coefficient," Opt. Lett. 32(13), 1800–1802 (2007).
- E. S. Kang, W. S. Kim, D. J. Kim, and B. S. Bae, "Reducing the thermal dependence of silica-based arrayedwaveguide grating using inorganic-organic hybrid materials," IEEE Photon. Technol. Lett. 16(12), 2625–2627 (2004).
- B. Guha, J. Cardenas, and M. Lipson, "Athermal silicon microring resonators with titanium oxide cladding," Opt. Express 21(22), 26557–26563 (2013).
- N. Wang, F. L. Hsiao, J. M. Tsai, M. Palaniapan, D. L. Kwong, and C. Lee, "Numerical and experimental study on silicon microresonators based on phononic crystal slabs with reduced central-hole radii," J. Micromech. Microeng. 23(6), 065030 (2013).
- T. Wang, X. Mu, P. Kropelnicki, A. B. Randles, and C. Lee, "Viscosity and density decoupling method by using higher order Lamb wave sensor," J. Micromech. Microeng. 24(7), 075002 (2014).
- D. B. Nash, "Mid-infrared reflectance spectra (2.3-22 μm) of sulfur, gold, KBr, MgO, and halon," Appl. Opt. 25(14), 2427–2433 (1986).

1. Introduction

For the realization of many optoelectronic devices and photonic elements such as Fabry-Perot interferometers, the role of optical reflectors is extremely important. To achieve high reflective surfaces, multiple methods have been employed. One such method is through the use of one-dimensional (1-D) photonic crystal (PhC), which is formed by depositing thin films with alternating refractive index [1–4]. While 1-D PhC forms a highly reflective surface with very low losses, it faces the problem of having restricted choice of materials as well as stern control of the refractive index of the individual layers. In order to overcome these drawbacks, the use of two-dimensional (2-D) PhC as reflector has been found to be a promising technology due to their exceptional optical performance and extremely compact size [5–12]. 2-D PhC reflector is realized through the patterning on a single layer of dielectric and it displays Fano resonance which is a characteristic of extremely high reflection [13–15]. Due to the high refractive index contrast of Si, the use of Si allows the realization of ultracompact devices. However, Si prohibits several important active functionalities, which include light emission, second harmonic generation and electro-optic effect due to its centrosymmetric crystal structure [16–18]. In addition, Si is also susceptible to refractive index fluctuation with changes in their operating temperature. This is known as thermo-optic effect and its effect can be quantified by the following equation:

$$\Delta \lambda = \Delta T \left(\frac{\lambda_0}{n_0} \right) \left(\frac{\Delta n}{\Delta T} \right), \tag{1}$$

#235762 - \$15.00 USD © 2015 OSA Received 10 Mar 2015; revised 9 Apr 2015; accepted 9 Apr 2015; published 15 Apr 2015 20 Apr 2015 | Vol. 23, No. 8 | DOI:10.1364/OE.23.010598 | OPTICS EXPRESS 10599 where n_0 is the refractive index at 25°C, $\Delta n/\Delta T$ is the thermo-optic coefficient and ΔT is the change in temperature. With a relatively high thermo-optic coefficient of $1.70 \times 10^{-4} \text{ K}^{-1}$, Si is unsuitable for applications with high as well as changing operating temperatures [19]. In order to minimize the impact of such temperature changes for applications where such thermo-optic effect is detrimental, research are done to compensate the refractive index change in the material [20]. For example, research has been done to introduce polymer cladding, which have negative thermo-optic coefficient, to the photonic device [20–23]. However such method faces the problem of integration with CMOS process, as well as reliability concerns due to high sensitivity on the polymer thickness. Other methods such as the use of temperature feedback circuits increase the power usage and require larger footprint [23]. In view of these problems, it is largely desired to have a CMOS compatible material to be used as the photonic device and also achieve high independence from operating temperature changes.

Due to progression in epitaxial film deposition, research involving the use of aluminum nitride (AlN) as photonic material has gained speed. AlN has a large bandgap of 6.2eV which allow a transmission window from 200nm to 13.6µm. AlN is also a CMOS compatible piezoelectric material and this allows AlN to be used in high performance electromechanical devices that include the use of surface acoustic wave [24] and lamb wave resonator [25]. AlN also display second order non-linearity which makes AlN film a high quality Pockels materials. More importantly, AlN has a high thermal conductivity ($\kappa_{AlN} = 285$ W/m.K) and small thermo-optic coefficient (dn/dT = 2.32×10^{-5} K⁻¹) compared to Si [16]. This makes AlN very attractive as a new material to be used in photonic designs for applications with fluctuating operating temperatures. One such use is the formation of the mirrors needed for a Fabry-Perot interferometer. The peak reflection wavelength of the mirror is instrumental in the performance of the interferometer. When the peak reflection wavelength changes with temperature, the transmitted output of the interferometer will have varying wavelength and the quality factor will deteriorate. Hence, it is highly desirable for mirrors in such Fabry-Perot interferometer to be insensitive to temperature.

In this study, we present the design and characterization of an AlN based 2-D PhC reflector working in the mid infrared wavelengths. The study on using AlN as the material for a 2-D PhC reflector is lacking currently, especially at elevated temperatures. We designed the peak reflection wavelength to be around 3.3µm which is an important wavelength range for gas sensing applications such as methane detection [19]. Through our measurement, high reflection of more than 90% was observed from 3.08μ m to 3.78μ m. Due to the relatively low refractive index of AlN ($n_{AIN} = 2.2$), we also employed the use of sacrificial layer release of silicon dioxide (SiO₂) to enhance the performance of the PhC. Characterization of the AlN based PhC reflector is done up to 450°C to examine the effect of such temperature changes on the performance of the AlN based PhC. From experimental results, despite the increasing temperature to 450°C, the redshift in the peak reflection of the PhC is estimated to be 14.1nm. In comparison, the redshift in the peak reflection wavelength of a Si based PhC is 75nm [19]. Such insensitivity to thermo-optic effect makes AlN based PhC a promising technology to be used as photonic components for high temperature applications in harsh environment such as gas sensing in down-hole oil drilling and ruggedized electronics.

2. Design, fabrication and characterization

The design of the AlN based PhC is shown in Fig. 1(a). The AlN based PhC is make up of a suspended AlN slab with a thickness of 330nm. The buried SiO₂ (BOX) is 1 μ m and acts as a sacrificial layer. Periodic patterning of air holes is etched into the slab, with the radius of each air hole being 620nm and the period being 1.95 μ m.



Fig. 1. (a) Schematic drawing of the suspended AlN PhC slab, and (b) SEM image of the fabricated AlN PhC slab.

Fabrication of the device begins with an 8" bare Si wafer and the BOX is deposited using plasma enhanced chemical vapor deposition (PECVD). A 330nm thick polycrystalline AlN layer is then deposited on the BOX using sputtering. The air holes are defined using photolithography and the AlN slab is etched using reactive ion etching (RIE). Finally, the AlN based PhC is made suspended when the BOX layer is removed by utilizing vapor hydrofluoric acid (VHF). The scanning electron microscope (SEM) image is shown in Fig. 1(b). The fabricated device matches very highly with the designed parameters with the radius of the air holes being 620nm and the period 1.95µm. Through cross-sectional analysis of etched AlN PhC slab, it is seen with a sloping sidewall with a measured angle of 79.8°. This is taken into account for the subsequent simulations done in Fig. 2(a). While the radius at the top of the membrane is maintained at the designed value, the radius of the air hole at the bottom of the membrane is drawn to be 60nm smaller to account for the effect of the sloping sidewall.



Fig. 2. (a) FDTD simulation of the AlN based PhC with various air hole radii and (b) experimental measurement of the AlN based PhC device with underlying BOX and without the BOX layer.

Simulation of the AlN based PhC is done using Lumerical Solutions which is based on the finite-difference time-domain (FDTD) method. The simulated results of the PhC with various air hole radii are presented in Fig. 2(a), where the refractive index of AlN is set to 2.2 and periodic boundary conditions are set on the sides of the unit cell. Based on the simulation, high reflection is expected from the AlN based PhC around 2.58µm when the AlN layer is released. As the radius of the air hole increases, the peak reflection wavelength experiences a redshift. With the presence of the BOX layer, in addition to a redshift of the peak reflection wavelength, the reflection drops sharply as well. Reflection measurement of the AlN based PhC is done using Agilent Cary 620 FTIR Microscope from 2μ m to 5μ m. The reflected signal is detected by using a Mercury Cadmium Telluride (MCT) detector and is normalized against a gold sample which is assumed to have around 97% reflection across the interested spectral region [26]. The effect of BOX on the performance of the AlN based PhC is examined in Fig.

2(b). As shown, the measurement results of the AlN based PhC with air hole radius of 620nm is presented. When the BOX layer is removed by using the abovementioned method of etching through the use of VHF, more than 90% reflection is measured from 3.08µm to 3.78µm. When the BOX layer is present, the peak reflection redshifts to higher wavelengths due to the increase of the refractive index of the cladding layer below the AlN based PhC membrane from 1 (air) to 1.44 (SiO₂). This leads to an increment of the effective refractive index of the device and hence moves the peak reflection wavelength to higher wavelength. In addition, with the presence of the BOX layer, the peak intensity of the measured reflection is only 81% which is significantly lower than the peak reflection of 96% when the BOX layer is removed. This is likely due to the low refractive index of AlN of 2.2. When the AlN based PhC is in contact with the BOX layer, there is high leakage into the BOX layer as it has a relatively high refractive index of 1.44. This exemplifies the importance of etching of BOX layer in order to enhance the performance of the AlN based PhC.



Fig. 3. (a) Experimental measurement of the effect of the change in the air hole radius on the performance of the AlN based PhC device (a) with underlying BOX and (b) without the BOX layer.

The effect of the change in the air hole radius on the performance of the AlN based PhC is also examined. The measurement was taken at room temperature (25°C) with higher resolution and the results are shown in Fig. 3. As presented, when the radius of the air hole increase from 600nm to 640nm, the peak reflection peak of the AlN based PhC blueshifts due to a decrease in the effective refractive index of the membrane with the replacement of AIN with air. For the AlN based PhC with BOX, the shift in the reflection is around 36nm from 4.00µm to 3.96µm. When the BOX is removed by using VHF, the reflection wavelength of the released AIN based PhC experience a blueshift from 3.43µm to 3.30µm. This equates to a shift of 130nm with the same radius change of the air hole. The seemingly lower shift in the peak reflection wavelength in the AlN based PhC with BOX can be attributed to the higher overall effective refractive index of the membrane. The change in the radius of the air hole brings about a much lower percentage change in the effective refractive index of the AIN based PhC with BOX than its counterpart without BOX. This thus has a smaller change in the peak reflection wavelength. Overall, the wavelength shift of the peak reflection is small considering the operating wavelength of the AlN based PhC. This indicates an added advantage of higher fabrication variation tolerance when using AlN. In the realization of the Fabry-Perot interferometer, this opens the possibility of a monolithic fabrication process where only a single etch step is required to define both mirrors from the top surface. The main issue is the widening of the PhC holes at the top layer in such an approach due to prolonged etching duration. With AlN as the material for the PhC mirror, such fabrication optimization effort can be minimized.

Thermo-optic effect on the AlN based PhC is done by placing the released membrane on a heating stage up to 450° C with a temperature controller ensuring that the temperature variation is less than $\pm 5\%$. At each temperature step, the AlN based PhC is left untouched in

the chamber for ten minutes before measurement is taken. This is to ensure that the temperature in the membrane and the chamber is stabilized for maximum accuracy.



Fig. 4. Measurement of the AlN based PhC of air hole radius of 620nm under various temperatures.

The measurement of the AlN based PhC with air hole radius of 620nm under various temperature conditions are shown in Fig. 4. At room temperature (25°C), the peak reflection wavelength of the AlN based PhC with air hole radius of 620nm is around 3.29µm. As the temperature increases, based on Eq. (1), the refractive index of AlN also increases. This raises the effective refractive index and induces a redshift in the peak reflection wavelength. At 450°C, the peak reflection wavelength of the AlN based PhC is around 3.31µm, with a 14.1nm redshift in wavelength. With n₀ and λ_0 being 2.2 and 3.29µm respectively, the thermo-optic coefficient is estimated to be $2.22 \times 10^{-5} \text{ K}^{-1}$, which is an order of magnitude lower than Si [20]. This proves to be extremely important for the use of AlN based PhC in applications such as the mirrors in Fabry-Perot interferometer working in harsh environments. Even at elevated temperatures, the low thermo-optic coefficient of AlN ensures that the peak reflection wavelength does not change drastically. This minimizes degradation in performance of the Fabry-Perot interferometer in term of its quality factor and its transmitted output wavelength, hence enhancing its robustness in various applications.

3. Conclusion

In conclusion, an AlN based PhC is fabricated and characterized as a highly reflective mirror working in the MIR wavelengths. The AlN slab is designed to be 330nm thick and the air hole radius is varied from 600nm to 640nm. Through measurement, the PhC with air hole radius of 620nm is shown to have greater than 90% reflection across 3.08µm to 3.78µm, with the peak reflection of 96% at 3.16µm. Characterization of the AlN based PhC is also performed at 450°C to examine the thermo-optic effect. Due to the minute increase in the refractive index of AlN at elevated temperatures, it is measured that the peak reflection redshift by 14.1nm when the temperature is at 450°C. The thermo-optic coefficient is estimated as $2.22 \times 10^{-5} \text{ K}^{-1}$. This is an order of magnitude lower than Si and is hence significantly better performing in high operating temperatures. This highlights the suitability of using AlN over Si as a photonic material especially when the applications involve high temperature fluctuation such as Fabry-Perot interferometer for gas sensing applications in down-hole oil drilling and ruggedized electronics.

Acknowledgments

The authors acknowledge the financial support from research grant of AcRF Tier 2-MOE2012-T2-2-154 at the National University of Singapore and National Natural Science Foundation of China (Grant No. 61474078) at National University of Singapore Suzhou Research Institute (NUSRI), Suzhou, China.