Large-Size Printed Broadband Membrane Reflectors by Laser Interference Lithography

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ABSTRACT

Large-area broadband reflectors based on photonic crystals can enable a number of optoelectronic and photonics devices. To create nano-scale patterns, electron-beam lithography and focused ion beam patterning techniques are commonly used. However, these methods are very slow and hard to form very large area patterns. Laser Interference Lithography (LIL), on the other hand, can be used to easily generate nano patterns with perfect ordering. LIL is maskless, fast and can generate large area nano pattern at low cost. In this study, two-dimensional photonic crystal slab structures were formed by the LIL patterning technique and reactive ion etching (RIE) process on silicon-on-insulator (SOI) wafer. Top patterned Si nanomembrane layer was then released from the SOI substrate by selectively etching away the buried oxide layer. This top Si membrane reflector (MR) was then picked up and printed onto glass substrate by employing an elastic stamp transfer printing technique.. High reflectivity broadband reflection reflectors on glass were obtained, with measured reflectivity of 92% around 1200 nm. Large area uniform patterns were verified experimentally with measured reflectivity from multiple measurement locations. The work can lead to high performance membrane reflector manufacturing based on very simple and cost-effective approach. The devices to be enable by the LIL patterning techniques shall have significant impact on future optoelectronic and photonic applications.

Keywords: broadband membrane reflectors, transfer printing, silicon nanomembrane, laser interference lithography

INTRODUCTION

Surface normal ultra-compact broadband reflectors are considered as the one of key components in optoelectronics applications such as microcavities, lasers, photodetectors, solar cells, sensors, and reconfigurable photonics, etc [1]. To create the nano patterns for these applications, conventional techniques such as nanoimprinting [2, 3], electron beam lithography [4, 5] and focused ion beam patterning [6] have been widely used.

Laser Interference Lithography (LIL) offers one of the most promosing approaches for the formation of large area nanoscale patterns with high throughput and potentially low cost [7]. Although LIL has the limitation that it can only fabricate simple periodic patterns, it is attractive alternative to conventional methods for application in which periodic patterns are desirable, including x-ray transmission gratings [8], photonic crystals [9, 10] and sub-micrometric sieves [11]. In this regard, fabrication of peridoic nano-structures with LIL enables to suggest the easiest method to achieve large size BBRs without losing performance aspect.

In this study, 2 cm^2 sized large area ultra-compact single layer membrane reflectors (MRs) were demonstrated based on LIL technique on two-dimensional photonic crystal slab (2D PCS) structure SOI wafer. Based on transfer printing technique, large area membrane reflectors on glass were also demonstrated.

EXPERIMENT

The MR fabrication process involves the patterning of photoresist by LIL on SOI wafer which has 340 nm single-crystal silicon layer on top of a 2,000 nm buried oxide (BOX) layer. Adhesion layer and photoresist were coated onto the wafer, yielding a resist thickness of 400 nm. The samples were then exposed in a Lloyd’s mirror interferometer [12], shown schematically in figure 1. The laser used for exposure is a frequency-doubled argon-ion laser with a wavelength of 257 nm and a output power of 0.16 mW/cm^2. The light is directed through a spatial filter, consisting of a focusing distribution of the initial laser beam focal length is 3.4 mm and the sample holder is around 1.2 m. For our setup typical exposure time is 140 sec.

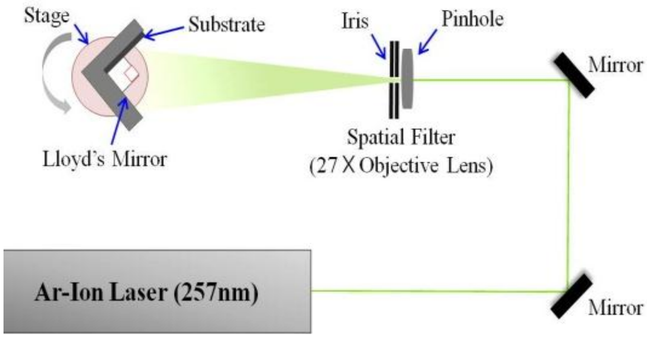

Figure. 1. Illustration of LIL system setup.

To create photoresist patterns with a square symmetry, two exposures by a rotation of 90 degree in between are applied. The periodicity, P, of the resist pattern is determined by [13],

$$P = \frac{\lambda}{2 \cdot \sin\theta} \tag{1}$$

where λ is wavelength of the laser used and θ is the incident angle to the specimen. Two beams are used: one travels directly to the specimen and another is reflected onto the specimen by a mirror. These two beams form an interference pattern on the specimen [14, 15]. Identical procedures were performed for further case studies, exploring the effects of the critical factors, namely, the exposure dosage, the half angle between the two incident beams, and the beam power. A single exposure generated 1D line pattern and 2D dot/hole patterns were generated from successive exposure with 90^{o} rotation of the sample. After development, hole array of diameter of 350 nm and pitch of 300 nm was patterned, followed by the dry-etched top Si with PR as an etching mask. The patterned top Si layer of SOI substrate, then, was immersed in the hydrofluoric acid (HF) to selectively undercut the buried oxide layer. The released Si layer referred to as Si nanomembrane (SiNM) reflector because of its' thin thickness. SiNM reflectors were then picked up and printed onto the glass substrate by employing a polydimethylsiloxane (PDMS) stamp transfer technique without adhesive layer. This PDMS-assisted printing process is highly sensitive to the adhesion forces between PDMS stamp and the patterned nanostructures, as well as the forces between the patterned nanostructures and the host foreign substrates. Also special care is taken on the PDMS stamp itself and the picking-up and printing (peeling-off PDMS) speed [16]. It's very critical to maintain a constant speed during the entire printing procedure. To bond the transferred SiNM reflector completely, RTA annealing at 800 ℃ was carried out at a nitrogen atmosphere.

RESULT AND DISCUSSION

In order to investigate the correlation of theoretical and experimental hole size and pitch distance, LIL angle test by changing the incident angle by a mirror to the specimen was carried out with constant values of other parameters, such as exposure dosage and beam power.

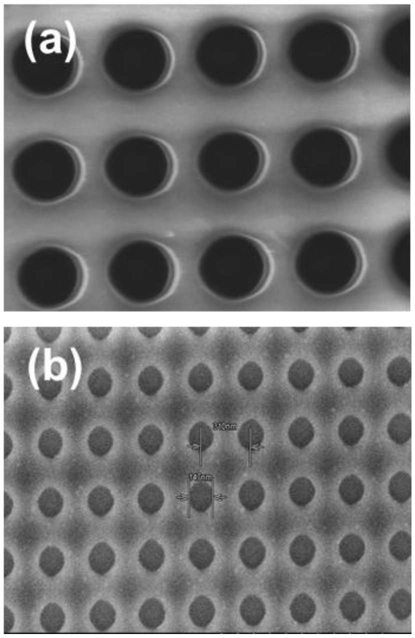

Figure. 2. (a, b) SEM images of hole allay pattern with substrate angles of 5° and 20° respectively.

Scanning electron microscope (SEM) images in figure 2 show various PR patterns with different LIL angle and result different hole size.

For the fabrication of BBR, we used 15° LIL angle and as SEM images shown in figure 3 (a), the real patterning result agrees well with the calculation value of 497 nm using equation (1). Shown in figure 3 (b) is sample image of a 2 cm × 2 cm sized Si NM MR, transferred to a glass substrate. With PDMS assist printing transfer process, large area and high quality NMs have been successfully transferred without any visible fractures.

Reflection was measured at normal incidence with a beam size around 100um and the spectra are shown in figure 4, for the reflectors before transfer (on SOI) and after transfer (on glass), respectively. The reflection of these MRs at different areas are also tested and shown with different curves.

In figure 4 (a), one can find the reflection of MR on SOI has more than 80% and as high as 92% of reflection of the multiple points on the sample in the range of near IR, above 1200 nm of wavelength.

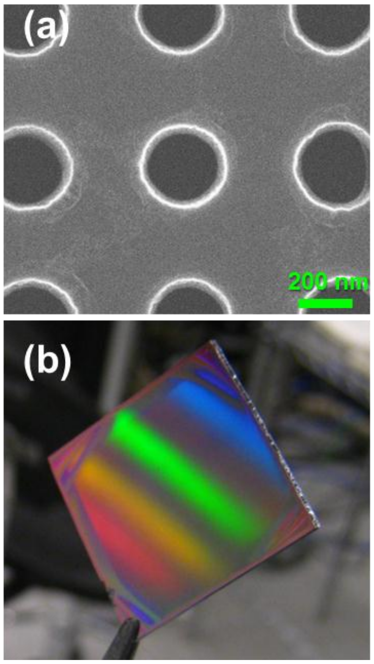

Figure. 3. (a) SEM images of hole allay pattern on SOI substrate, (b) LIL patterning image after dry-etching a top Si layer and descuuming of PR.

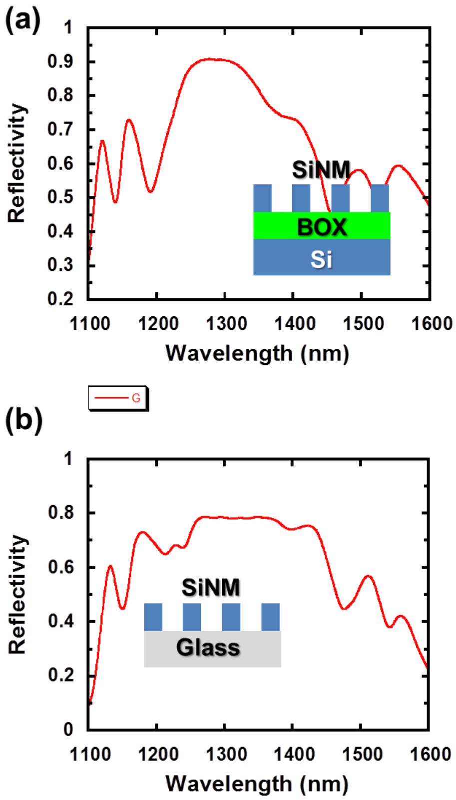

Figure. 4. Measured reflection spectra at different locations on the BBR (a) before and (b) after transferring, respectively.

For the MR on glass, as shown in figure 4 (b), one can find the reflection has a little degradation comparing with those of MR before transfer. This may be due to the surface roughness of the glass substrate.

CONCLUSION

In conclusion, very large-size broadband silicon nano membrane reflectors on glass substrates were fabricated and demonstrated by LIL technique and transfer printing technique. Reflection as high as 92% in the range of near IR, (above 1200 nm of wavelength) was achieved. Reflection can be further improved by improving process environment. The work can lead to high performance membrane reflector manufacturing based on very simple and cost-effective approach. The devices to be enabled by the LIL patterning techniques shall have significant impact on future optoelectronic and photonic applications.

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