Broadband Membrane Reflectors on Glass

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***Abstract*— We report here high-performance broadband membrane reflectors based on crystalline silicon nanomembrane photonic crystals. A modified polydimethylsiloxane stamp transfer technique is developed for transferring large-area silicon membranes to glass substrates. Polarization-independent broad reflectivity at 1550-nm wavelength band was obtained from Si membrane reflectors, on both silicon and glass substrates. The experimental results also agree well with simulation results.**

***Index Terms*— Photonic crystals, printing transfer, structures, subwavelength.**

I. Introduction

SURFACE-NORMAL ultra-compact broadband reflectors (BBRs) are essential components for numerous optoelectronic device applications, such as microcavities, lasers, photodetectors, solar cells, sensors, and reconfigurable photonics, etc [1]. As an alternative to the conventional multi-layer distributed Bragg reflectors (DBRs), single layer, high index-contrast sub-wavelength grating (HCG or SWG) structures that can be used as ultra-compact broadband reflectors hold great promises for a wide range of device applications [2-4]. However, basic one-dimensional SWG structures are intrinsically polarization-dependent. Recently, more complicated grating structures have been proposed for polarization independent reflectors [5, 6].

Two-dimensional photonic crystal slab (2D PCS) structures, on the other hand, can be used to realize both polarization dependent and independent operations, with proper dispersion engineering and structural optimizations. Based on Fano resonance principles in 2D PCS, both high-Q narrow band filters and low-Q broadband reflectors can be realized for surface-normal operations. [7]. In recent years, devices based on Fano resonances such as narrowband filters [8–10] and broadband reflectors [11, 12] have been reported. We previously also demonstrated 2D PCS based broadband reflectors on silicon-on-insulator (SOI) substrates, and reported a post-process technique for spectral-trimming of reflection band [13].

Employing a modified polydimethylsiloxane (PDMS) stamp transfer technique, we report here single-layer broadband membrane reflectors on glass substrates, based on transferred crystalline silicon nanomembranes (Si NM) [14]. Polarization independent reflection properties were also obtained, both theoretically and experimentally.

In what follows, we first introduce a generic structure of Fano BBR based on post-fabrication technique. Subsequently, we consider the impact of substrate and analyze two types of Fano BBRs, for both spectral resonance blue- and red-shifts, by effectively reducing the index layer below Si device layer and increasing the index layer above Si device layer, respectively. Finally, a conclusion is given.

II. Modified PDMS-Assisted Printing Process for Large Area Uniform Photonic Crystal Nanomembrane Transfer

The membrane reflector design was carried out based on three dimensional finite difference time-domain (3D FDTD) simulations [10, 15]. With the control of the design parameters, broadband reflectors with various spectral bandwidths and different peak reflections can be realized. For the membrane reflector structure designed on SOI substrate, with target wavelength around 1550 nm band, we choose top Si layer thickness t of 340 nm. Square lattice photonic crystal structure is chosen for the reflector design, with lattice constant a of 980 nm, and the ratio of air hole radius to the lattice constant r/a of 0.27.

The PCS structure was first fabricated on SOI substrates, based on standard e-beam lithography patterning technique and plasma dry-etching processes [10]. Following the formation of PCS structures on SOI substrates, the patterned SiNM reflectors were then transferred onto glass substrate, based on a modified PDMS printing transfer technique.

The PDMS-assisted NM printing process has been developed for various semiconductor NM transfer processes [16] [17, 18]. The printing process is highly sensitive to the adhesion forces between PDMS stamp and the patterned NM structure, as well as the forces between the patterned NM structure and the host foreign substrates. In order to transfer large area patterned Si NM reflectors, which have relatively large air hole region, the PDMS stamp is made less sticky but stiffer by using a mixture of polymer base and curing agent with a ratio of 5:1.

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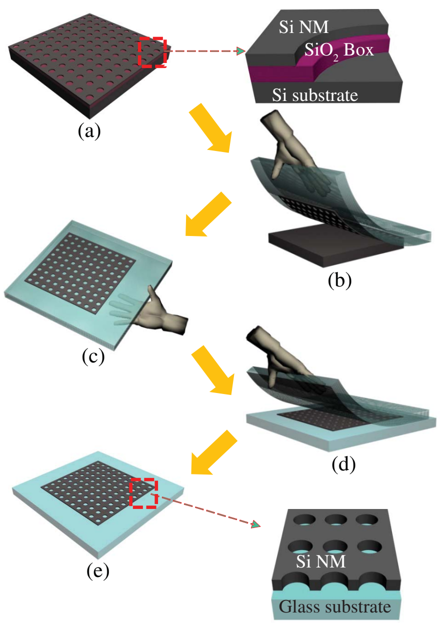

Fig. 1. PDMS NM printing process flow. (a) Fabricated Si membrane reflector on an SOI substrate. (b) Top Si NM is released and picked up by a PDMS stamp. (c) Si NM is intermediately transferred on PDMS stamp. (d) Si NM is being printed on recipient (glass) substrate. (e) Transferred SiNM on final glass substrate.

The PDMS-assisted NM printing process is illustrated schematically in Fig. 1. The Si membrane reflector is first fabricated on the SOI substrate (Fig. 1(a)), followed by patterned Si NM release process, by immersing the patterned SOI structure in buffered hydrofluoric acid (HF) solution to remove a buried oxide layer. A PDMS stamp, with optimal adhesion force, is used to pick up the released/detached patterned Si NM reflector structure (Fig. 1(b)). With PDMS stamp as the transfer media (Fig. 1(c)), patterned Si NM reflector structure is then printed to the foreign substrate (glass in this case, Fig. 1(d)). Special care is taken on the PDMS stamp itself and the NM picking-up and printing (peeling-off PDMS) speed. A constant speed during the entire printing process and optimal handling force are applied. After the printing, the transferred membrane reflector on glass substrate (Fig. 1(e)) is ready for further characterizations.

III. MR Reflector Characteristics

For simplicity and numerical expediency, we limit the study to surface normal incidence. We also assumed the size of designed pattern infinite. The design is then based on three-dimensional finite-difference time-domain (3D FDTD) technique where the refractive indices of Si and SiO_2 used in the simulation are 3.48 and 1.45, respectively.

A. Impact of Substrate

Shown in Fig. 2(a, b) are optical microscope images of a 2mm $\times$ 2mm sized membrane reflector, transferred to a glass substrate. With optimized PDMS printing transfer process, high quality NMs have been successfully transferred without any visible defects. Also shown in Fig. 2(c-d) are scanning electron microscope (SEM) images of the transferred membrane reflector on glass substrate, with different zoom levels. It is also worth noting that such high quality transfer of large area crystalline semiconductor nanomembranes is essential in maintaining high reflectivity performance for the transferred reflectors on glass substrates.

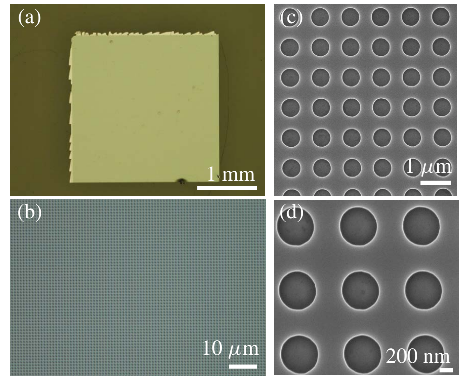

Fig. 2. (a) and (b) Optical microscope images. (c) and (d) Scanning electron microscope (SEM) images of transferred Si NM on glass.

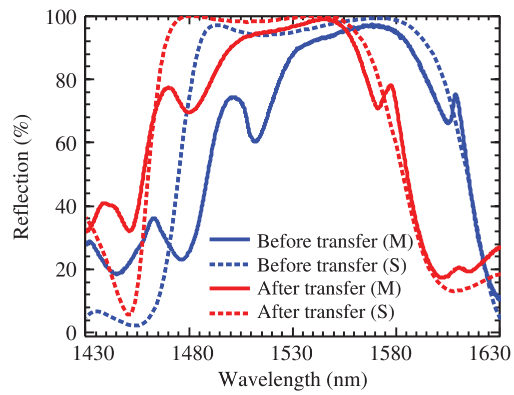

Fig. 3. Measured ("M") and simulated ("S") Si NM membrane reflector reflection spectra on SOI (before transfer) and on glass substrate (after transfer).

The measured (denoted as "M" in Fig. 3) and simulated ("S") reflection spectra are shown in Fig. 3, for reflectors before transfer (on SOI) and after transfer (on glass), respectively. The measured spectra agree well with the simulated results. Some degradation is evident in the measured reflection spectra at the shorter wavelength band, mostly due to certain fabrication non-uniformity associated with the large area photonic crystal structure on SOI substrate. Spectral blue-shift is also observed after the membrane reflector is transferred from the original SOI substrate to the glass substrate, mostly due to the relatively lower refractive index of glass substrate and slightly larger air hole radius due to BHF undercut etching in SiNM transfer process. More importantly, the reflector peak reflection and the reflection band do not degrade after being transferred to glass substrates. This indicates the uniform, high quality large area patterned transferred NMs, owing to the excellent PDMS transfer process.

To investigate the polarization property, we utilize a Newport precision linear polarizer in our test setup to control

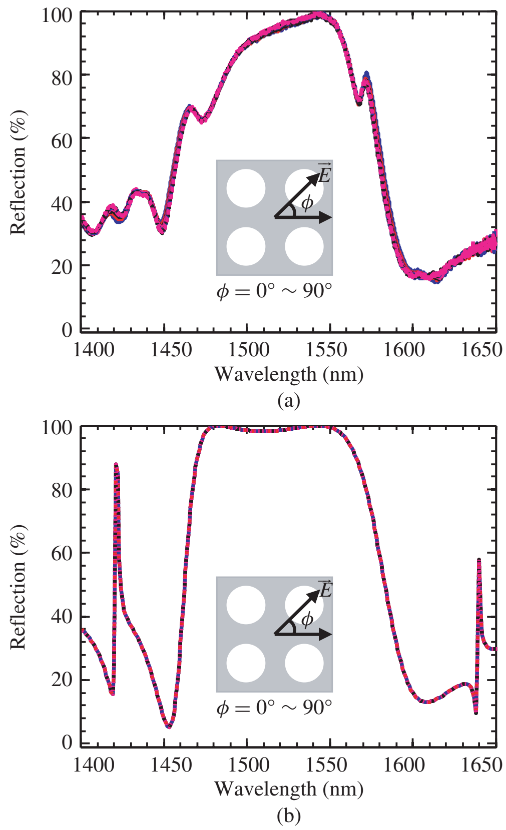

Fig. 4. (a) Measured and (b) simulated polarization-dependent reflection spectra for the fabricated membrane reflector on glass substrate. Notice the spectra overlaps with each other for different polarization angles.

the incident beam polarization angle. By controlling the polarization angle, the measured, along with the simulated, reflection spectra are shown in Fig. 4. The incident beam polarization was swept from $\phi = 0°$ (as defined in Fig. 4(a)), for TM polarized beam, which has electric field parallel to ΓX direction of PC pattern, to $\phi = 90°$ for TE polarized beam, which has a perpendicular electric field to ΓX direction. The measured reflection spectra overlap with each other under normal incident condition. The simulated polarization dependent reflection spectra are shown in Fig. 4(b). The polarization independent feature is also expected for such square lattice photonic crystal membrane reflectors, owing to the high symmetric properties of the square lattice structure. It is also worth mentioning that polarization dependent reflectors can also be engineered, by the control of the lattice structure (e.g., rectangular lattice, hexagonal lattice, etc.), and the change of air hole shape (e.g. elliptical or rectangular shapes, etc.).

IV. Conclusion

In summary, polarization independent ultra-compact Fano resonance broadband membrane reflectors on glass substrates were fabricated and demonstrated with a modified PDMS stamp printing processes. The reflectors' TE and TM resonance remain the same during scanning the polarization angle. The PDMS stamp printing process developed here can also be applied to other type of materials and structures, with different surface area fill factors (due to patterning).

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