Surface-normal Fano filters based on transferred silicon nanomembranes on glass substrates

H. Yang, H. Pang, Z. Qiang, Z. Ma and W. Zhou

Surface-normal optical filters are reported based on Fano resonances in patterned single crystalline silicon nanomembranes (SiNM), which were fabricated and transferred onto transparent glass substrates using a disruptive wet transfer process. The measured filter transmission results agree well with the design using a three-dimensional finite-difference time-domain technique. Using the SiNM wet transfer and stacking process, vertically stacked ultra-compact surface normal filters, switches, modulators and spectrally-selective photodetectors will become feasible.

Introduction: Photonic crystal slabs (PCS), with in-plane periodic modulation of dielectric constant introduced in a high-index guiding layer, offer one of the most promising platforms for large-scale on-chip photonic integration. The out-of-the-plane optical mode coupling in the PCS is feasible with the Fano or guided mode resonance (GMR) effect [1–3], where the in-plane guided resonances above the lightline are also strongly coupled to the out-of-the-plane continuum radiation modes owing to the phase matching provided by the periodic lattice structure. Therefore, the guided resonances can provide an efficient way to channel light from within the slab to the external environment, and vice versa [4, 5].

Crystalline semiconductor nanomembranes (NMs), which are transferable, stackable, bondable and manufacturable, offer unprecedented opportunities for some unique and novel electronic and photonic devices suitable for vertically stacked high-density photonic/electronic integration. High-quality single crystalline silicon NMs (SiNM) have been transferred onto various foreign substrates, such as glass, PET plastics etc. [6–9]. Record high-speed electronic devices on flexible substrate were reported recently [8, 10]. Employing a slightly modified transfer process, we report here the first experimental demonstration of Fano filters, based on transferred single crystalline SiNMs on glass substrates, as well as on flexible PET substrates. Such a spectrally-selective filter component can be used as the building block for a suite of flexible and vertically stacked ultra-compact high-performance photonic devices, such as switches, modulators and spectrally-selective photodetectors.

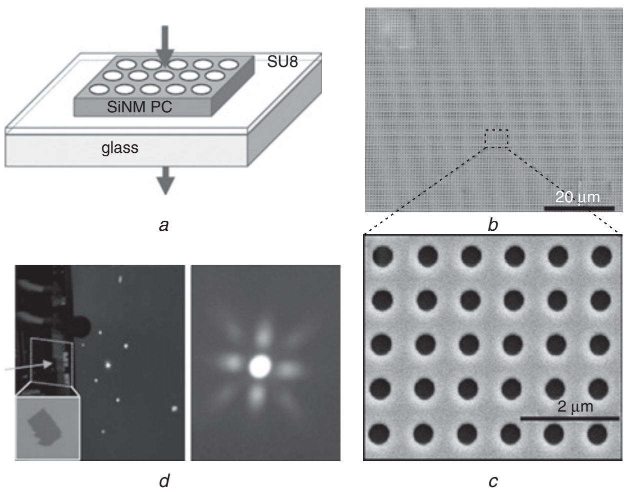

Fig. 1 *Schematic of patterned silicon nanomembrane photonic crystal structures (SiNM PC) transferred onto a SU8-coated glass substrate; scanning electron micrographs (SEM) of fabricated large-area PC patterns with square lattice airhole patterns; and diffraction pattern obtained with green laser source (left, with the arrow showing the incident laser beam direction) passing through the SiNM on glass (shown as the dashed square), and with broadband QTH lamp source (right)*

a Schematic of photonic crystal structures
b, c SEMs
d Diffraction pattern
Inset: Micrograph of fabricated Fano filter structure on glass substrate

Filter design and fabrication: The surface-normal Fano filter is schematically shown in Fig. 1*a*, where a patterned photonic crystal (PC) structure with square lattice airholes is formed in a SiNM that is transferred onto a glass substrate. The filter design is based on a frequency-dependent three-dimensional (3D) finite-difference time-domain (FDTD) technique. For the asymmetric air-SiNM-glass structure (Fig. 1*a*), the SiNM thickness (t) is 270 nm, and the substrate index is 1.45–1.48 for glass and PET substrates. The design parameters for the airhole radius (r) and the lattice constant (a) are chosen with the target filter operation wavelength (λ) of 1.55 µm. The starting material is a silicon-on-insulator (SOI) wafer with a 270 nm top Si layer, and a 3 µm-thick buried oxide (BOX) layer on the Si substrate. The PC was first fabricated on the SOI wafer using a standard ZEP520A e-beam lithography technique and an HBr/Cl_2 chemistry based reactive-ion etching (RIE) process. Shown in Figs. 1*b* and *c* are the scanning electron micrographs (SEM) of the fabricated large area PC patterns (~5 × 5 mm), where the high-quality uniform patterns are formed with optimised fabrication processes. Note that the large-area pattern is generated here only for the purpose of a simplified testing scheme, where a focused beam can be easily aligned to the patterned PC area for a transmission test. In practice, the typical patterned PC device area is only about ten times the period of the lattice constant a, or 5–10 µm in lateral dimension for the device with an operation wavelength of 1.55 µm.

The patterned PC SOI structure was subsequently transferred onto a glass or a polyethylene terephthalate (PET) substrate, based on a modified wet transfer process [10]. The structure was immersed in aqueous diluted HF solution (49% HF: DI water = 1:4) for several hours to etch away the BOX layer selectively. Once the top patterned PC SiNM was completely released, it was rinsed in DI water and transferred onto glass or PET flexible plastic substrates. It is worth noting that an optional SU8 coating on the glass may be used for improved adhesion and mechanical stability for the final device structure. The transferred high-quality SiNM PC patterns were verified with diffraction pattern measurements, as shown in Fig. 1*d*, with a micrograph shown in the inset being the transferred PC patterned SiNM on the glass substrate under test. A well-defined diffraction pattern was observed with a continuous-wave green laser source passing through the SiNM on the glass substrate. Also shown to the right of Fig. 1*d* is the highly ordered diffraction pattern obtained with a focused broadband quartz tungsten halogen (QTH) light source passing though the device.

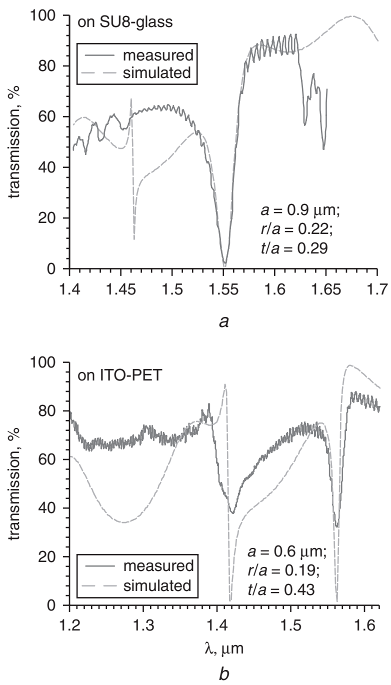

Fig. 2 *Measured and simulated transmission characteristics of Fano Filters*

a SiNM-on-glass sample
b SiNM-on-PET sample
Good agreement is seen on spectral dip location at 1.551 and 1.562 µm, for *a* and *b*, respectively
r, a, t and λ are PC airhole radius, PC lattice constant, slab thickness and wavelength, respectively

Filter characterisation and results: A broadband QTH light source was used for the transmission measurement of the fabricated Fano filters. The QTH light beam was focused onto the patterned PC area with an objective lens. The transmitted light is collected with a monochromator and a thermoelectrically cooled InGaAs detector. The transmitted signal was normalised to the reference transmission signal measured with light transmitting through the glass substrate only. The measured and simulated Fano-filter transmission characteristics are shown in Figs. 2*a* and *b* for a SiNM-on-glass substrate sample and a SiNM-on-PET flexible substrate sample, respectively. The experimental results agree very well with the designed ones, with the target wavelengths of 1.551 μm for the glass substrate and 1.562 μm for the PET substrate. Another dip appears at 1.42 μm in Fig. 2*b*, for both measurement and simulation. But it is not clear why we did not see a dip experimentally at 1.46 μm in Fig. 2*a*. Further design and process optimisations can lead to higher quality factor (*Q*) filters with symmetric spectral responses that are suitable for ultra-compact surface-normal filters, switches and modulators. These devices are highly desirable in high-density vertical integration of photonic systems and flexible infrared photonics. Note that the asymmetric line shapes observed in the filter spectral responses, which is based on Fano resonance effect, originated from the coupling between the vertical continuum of radiation modes and the in-plane discrete resonant modes, as shown in Fig. 3. In Fig. 3, the top view and the cross-sectional view of the mode field profiles are shown for both the resonant and the non-resonant modes. For the Fano resonant modes, the modes are strongly confined to the photonic crystal slab region. In contrast, the non-resonant modes have a field intensity distribution that quickly radiates away from the slab and into the surrounding medium. Based on simulation, it is feasible to achieve very high spectral selective filters with high *Q* and symmetric spectral responses, by varying the design parameters to adjust the mode coupling and Fano resonance properties. This is essential in high-performance filter/switch/modulator applications, where high spectral selectivity and low insertion losses are required.

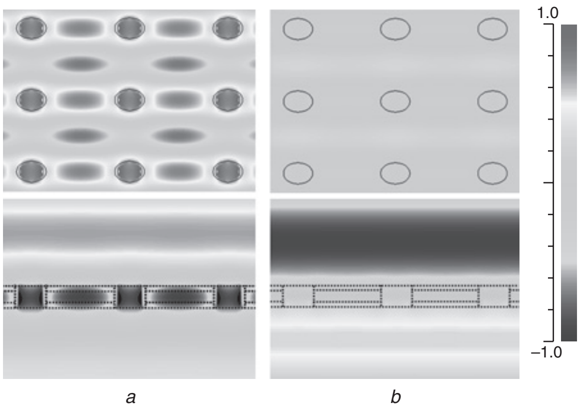

Fig. 3 *Top view (top) and cross-sectional view (bottom) of simulated field profiles for resonant mode and non-resonance mode*

a Resonant mode
b Non-resonant mode
Cross-sectional view shows strong interaction between vertical mode with in-plane guided resonance for resonance mode shown in *a*. However, for non-resonance mode, field intensity distribution quickly radiates away from slab and into surrounding medium

Conclusions: Surface-normal optical filters based on Fano resonances in patterned SiNMs on glass have been proposed, designed and fabricated, based on a disruptive nanomembrane wet transfer process. The measured filter transmission results agree well with designs using a finite-difference time-domain (FDTD) technique. Switches, modulators and photodetectors with high-quality factors suitable for high-density integration of photonic and electronic integration may be further realised based on the same operation principle and the nanomembrane technology. The flexible integration schemes of stacked SiNMs can lead to simplified device fabrication processes for high-performance flexible photonics and high-density photonic integration systems.

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H. Yang, Z. Qiang and W. Zhou (*Department of Electrical Engineering, University of Texas at Arlington, TX 76019, USA*)

E-mail: wzhou@uta.edu

H. Pang and Z. Ma (*Department of Electrical and Computer Engineering, University of Wisconsin-Madison, WI 53706, USA*)

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