Opt Quant Electron (2012) 44:605–611
DOI 10.1007/s11082-012-9586-8

INVITED PAPER

Semiconductor nanomembranes for integrated silicon photonics and flexible Photonics

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Received: 30 October 2011 / Accepted: 4 May 2012 / Published online: 15 May 2012

Abstract Crystalline semiconductor nanomembranes (NMs), which are transferable, stackable, bondable and manufacturable, offer unprecedented opportunities for unique and novel device applications. We review here nanophotonic devices based on stacked semiconductor NMs on Si, glass and flexible PET substrates. Photonic crystal Fano resonance-based surface-normal optical filters and broadband reflectors have been demonstrated with unique angle and polarization properties. Flexible photodetectors and solar cells have also been developed based on the NM stacking processes. Such NM stacking process can lead to a paradigm shift on silicon photonic integration and hybrid organic/inorganic flexible photonics.

Keywords Photonic integration · Photonic crystals · Semiconductor nanomembranes · Flexible photonics · Silicon photonics

1 Introduction

The recent emergence of inorganic semiconductor nanomembrane (NM) technology (Rogers and Huang 2009; Schmidt and Eberl 2001; Scott and Lagally 2007; Yuan et al. 2006; Yang et al. 2008; Zhou and Ma 2010), in the form of extremely thin *single-crystal* semiconductor sheets that are extremely flexible, bendable, foldable, transferable and heterogeneously stackable with combined merits of high optoelectronic performance and mechanical properties, has

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offered an important and practical alternative in lieu of organic semiconductors for high performance flexible electronics and photonics. The very thin single-crystalline semiconductor membranes released from a substrate and transferred to a new host requires a sacrificial layer that is selectively removed with an etchant that does not attack the desired film. This concept has evolved over many years but has only recently found its real traction. High quality single crystalline silicon NMs (Si NM) have been transferred to various foreign substrates, such as glass, flexible PET (polyethylene terephthalate) plastics, etc., based on low temperature transfer and stacking processes, developed by many groups (Schmidt and Eberl 2001; Yuan et al. 2005, 2006, 2007; Yuan and Ma 2006; Scott and Lagally 2007; Rogers et al. 2001). In the last few years, significant progresses have been made by Ma's group on record high speed flexible electronics, and high performance flexible Ge photodetectors, based on transferable Si/SiGe NMs (Yuan et al. 2006, 2007, 2009). Many excellent results have also been reported by (Zhang et al. 2006; Roberts et al. 2006; Scott and Lagally 2007) and (Sun and Rogers 2007; Kim et al. 2008a,b; Rogers and Huang 2009) on the unique electronic, photonic, thermoelectronic, and mechanical properties associated with this new class of inorganic flexible semiconductor membrane material system.

Recently, employing a slightly modified transfer process, we have demonstrated Fano filters based on patterned Si NMs transferred onto transparent low index glass and flexible PET substrates (Zhou et al. 2009). Here, we review and report the design, fabrication and characterization of these unique photonic devices, for applications in narrow-band filters, broadband reflectors, flexible photodetectors, and LEDs (Yang et al. 2008; Qiang et al. 2008; Yang et al. 2009, 2010).

2 Crystalline semiconductor nanomembrane transfer

Heterogeneous integration is currently the most promising approach to high performance photonic devices (also applicable to high-speed electronics), considering the tremendous difficulty to engineer indirect bandgap materials (e.g., Si and Ge). This argument is evidenced by the recent successes on the hybrid Si evanescent laser, the photonic devices based on the InP-bonding-to-Si structure (Park et al. 2005; Bowers et al. 2006), and the InAs/Si heterogeneous electronics made by Intel and IBM. Over the last few years, Ma's and Rogers' groups have developed different types of NM transfer and stacking processes on Si, Ge, GaAs, InP, etc. Very high performance electronics based on transferable Si/SiGe NMs were already reported (Yuan et al. 2005, 2006, 2007; Yuan and Ma 2006). Figure 1 shows a general process flow for crystalline NM release, transfer and stacking. The source material (e.g., SOI, GeOI, III–V multi layers with a sacrificial layer) is first being patterned into membrane (or strip forms) down to the sacrificial layer (Fig. 1a, b). Top membrane layers are then released by undercutting the sacrificial layer (Fig. 1c), with fully released membrane settles down on the handling substrate via van der Waals force (Fig. 1d) (Note: this in-place bonding case only applies to thin sacrificial layers. For thick ones, please refer to another paper from Rogers' group (Mack et al. 2006). Finally NM transfer process can take place with either a *Direct flip transfer or stamp-assisted transfer* processes (Fig. 1e, f). In the *direct flip transfer* process, an adhesion layer is applied on the host (foreign) substrate first. The NM to be transferred can be picked up by the host substrate directly to complete the transfer. The adhesion layer (e.g., glue) can be dissolved afterwards, if needed. In the *stamp-assisted transfer* process, a stamp (e.g., PDMS) was used to press toward the handling substrate, and lift up the NM to be transferred. Then the NM attached to the stamp was picked up and attached to a new host substrate, which can be coated with glue, if needed. Slowly peeling off the stamp or

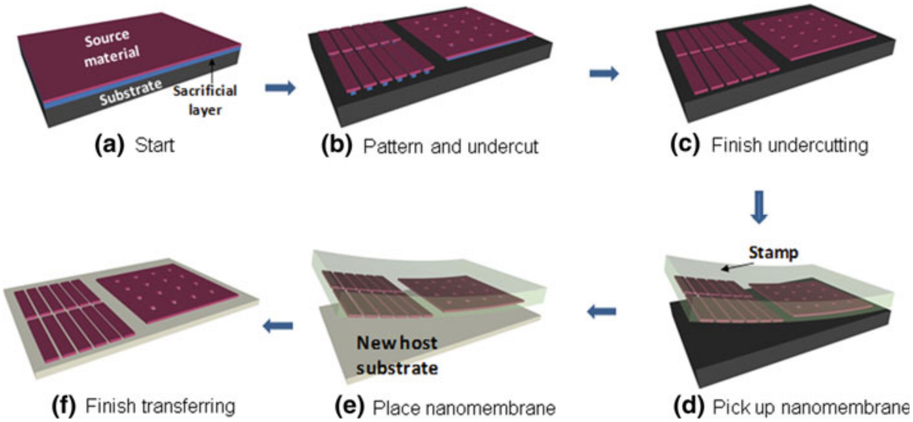

Fig. 1 General process illustration for crystalline semiconductor membrane release, transfer and stacking. **a** Begin with source material (e.g., SOI, GeOI, III–V multi layers with a sacrificial layer). Metallization can be applied here, if needed. **b** Pattern top layer into membrane (or strip forms) down to the sacrificial layer. **c** Release membrane by undercutting the sacrificial layer and fully released membrane settles down on the handling substrate via van der Waals force ("in-place bonding"). **d** Bring a stamp (e.g., polydimethylsiloxane, or PDMS) toward the handling substrate, press and lift up. **e** Apply the stamp with membrane attached to a new host substrate (which can be coated with *glue*, but not necessary). **f** Slowly peel off the stamp or remove the stamp with shear force, leaving the membrane to stay on the new host substrate. Multiple layers can be applied by repeating the process flow

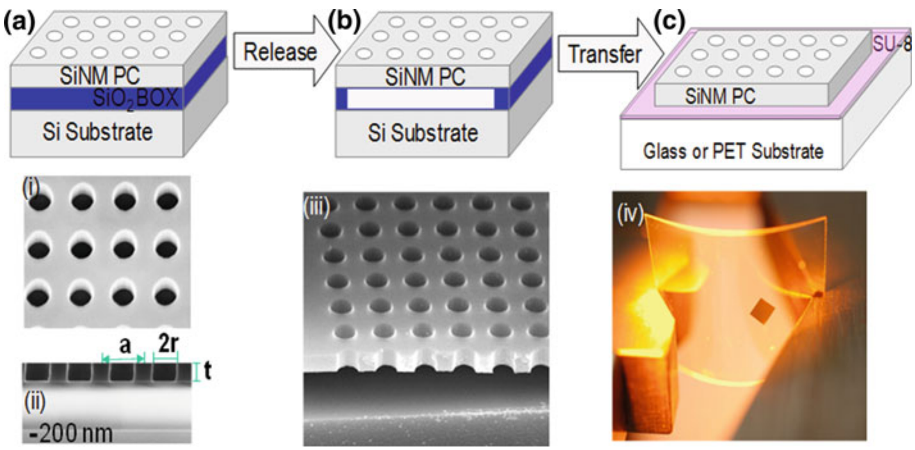

Fig. 2 Modified process for air hole PCS NM structure transfer. Single layer NM pattern (**a**), release (**b**), and transfer (**c**) process, along with experimental results (*bottom*): (*i*) SEM image of top and (*ii*) cross-sectional view of patterned Si NM on SOI, (*iii*) SEM images of patterned SiNM after BHF etching of BOX layer underneath the pattern area, (*iv*) a micrograph of a 3 × 3 mm patterned NM transferred onto 1 × 1" flexible PET substrate

removing the stamp with shear force, the NM can be left on the new host substrate (Meitl et al. 2006).

Based on NM transfer processes, high quality photonic crystal (PC) structures have been successfully transferred onto glass or PET substrates, as shown in Fig. 2. PC air hole structures were first fabricated with the target wavelength of 1,550 nm on 260-nm thick silicon-on-insulator (SOI) wafers using e-beam lithography and plasma dry-etching processes. Shown in Fig. 2a are a schematic (top) and scanning electron micrographs (SEMs, bottom) of the patterned PC SOI structures, respectively. The periodicity and air hole radius in this structure are 600 and 108 nm, respectively (Yang et al. 2008; Qiang et al. 2008). The patterned PC SOI structures were subsequently immersed in aqueous diluted HF solution (49 % HF: DI water =1:4) for several hours to etch away the BOX (buried oxide) layer selectively (Fig. 2b). Once the top patterned PC SiNM was completely released, it was rinsed in DI water and transferred onto PET flexible plastic or glass substrates (Fig. 2c). A micrograph is shown in Fig. 2c, iv, where a large piece of NM was transferred onto a flexible (curved) PET substrate.

3 Fano filters and reflectors

Fano resonance effect in PC structures has been investigated for Fano filters and reflectors based on transferred SiNMs on glass and flexible PET substrates. The measured and simulated Fano filter transmission characteristics are shown in Fig. 3. The experiment was conducted with an unpolarized and focused broadband QTH (quartz tungsten halogen) lamp source. At certain spectral locations, close to 100 % transmission was obtained. A dominant dip was observed at the target wavelength of 1,547 nm (denoted as λ_1) and other two dips were observed at around 1,417 nm (λ_2) and 1,393 nm (λ_3), respectively. The measurement results agree well with simulation results.

By properly choosing the lattice parameters, broadband reflectors can also be realized. Following the similar design and fabrication process used for Fano resonant filter, we have also demonstrated broadband Fano resonance membrane reflectors (MRs), on Si and on glass substrates (Yang et al. 2009). Shown in Fig. 4 are the measured and simulated reflection spectra for a Fano reflector fabricated on SOI substrate, Notice close to 100 % reflection was obtained for these samples, without and with SiO_2 deposition layer on top (Yang et al. 2009). Based on the transfer printing technique discussed early, fabricated SiMRs on SOI substrates can be transferred onto glass or other foreign substrates. The results are shown in Fig. 5, where a complete SiMR structure was successfully transferred onto glass substrate, with impressive 100 % peak reflection. This also indicate the high quality transfer of NM printing transfer process.

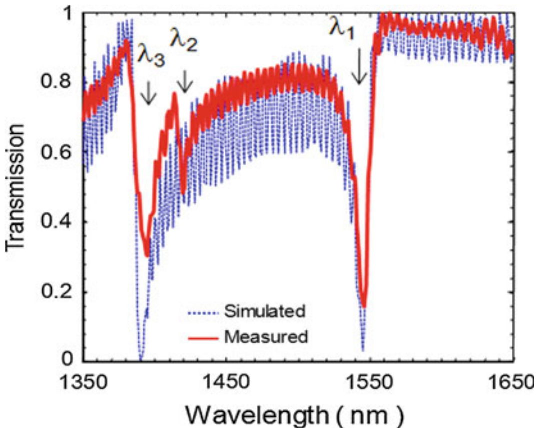

Fig. 3 Measured and simulated surface normal transmission spectra for the fabricated patterned SiNM Fano filters on glass substrates

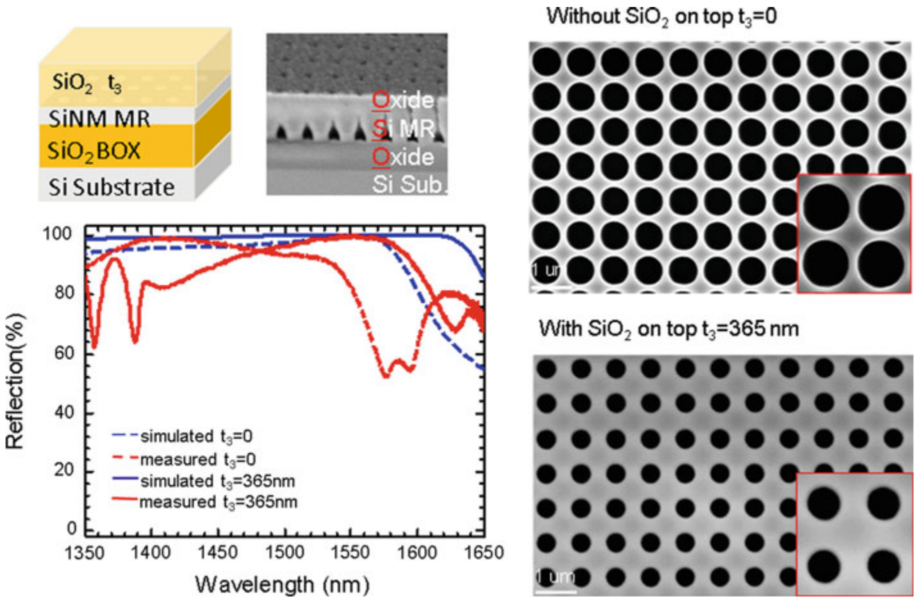

Fig. 4 Measured and simulated reflection spectra for a Si membrane reflector (SiMR) with $a = 880$ nm, $r/a = 0.45$, $t_{Si} = 340$ nm and $t_{ox} = 1$ μm. Shown on the top are the complete SiMR structure schematic and SEM image. Shown to *the right* are two top view SEMs for the SiMR structures without and with top SiO_2 deposition

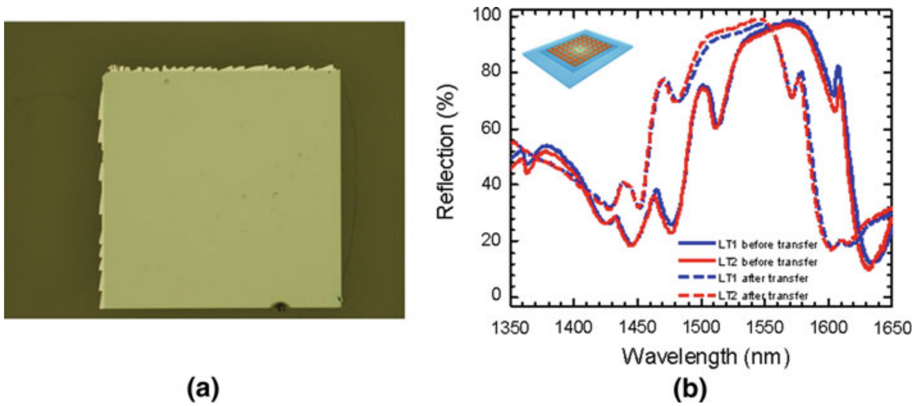

Fig. 5 **a** A micrograph image of a fabricated SiMR transferred onto glass substrate; **b** Measured reflection spectra for two membrane reflectors (LT1, LT2) before transfer (on SOI) and after transfer (on glass)

4 Flexible photodetectors and LEDs

We have also developed a frame-assisted membrane transfer (FAMT) process for the transfer of large-area crystalline semiconductor NMs, especially for the fragile material systems (e.g. GaAs, InP compound semiconductors) (Yang et al. 2010). Large area flexible photodetectors, solar cells and LED arrays all have been demonstrated experimentally, as shown in Fig. 6 based on transferred InP nanomembranes. The measured flexible InP p-i-n photodetector

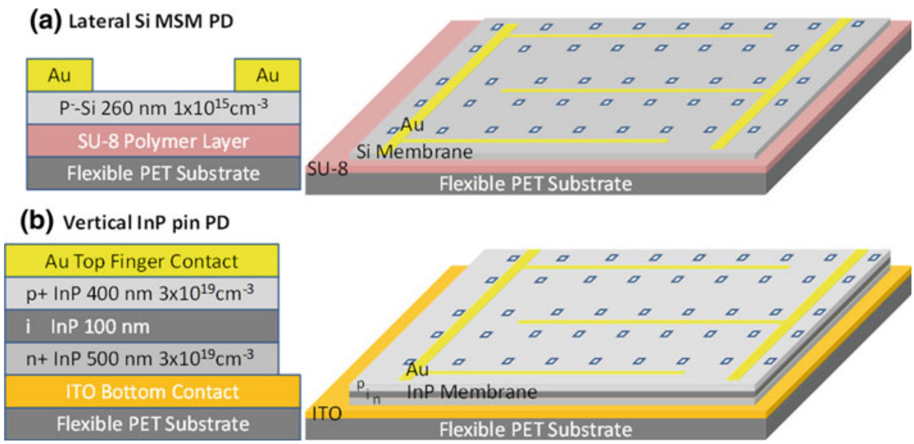

Fig. 6 Schematics of (**a**) a lateral Si MSM photodetector (PD), and (**b**) a vertical InP p-i-n photodetector, based on transferred crystalline semiconductor nanomembrane processes

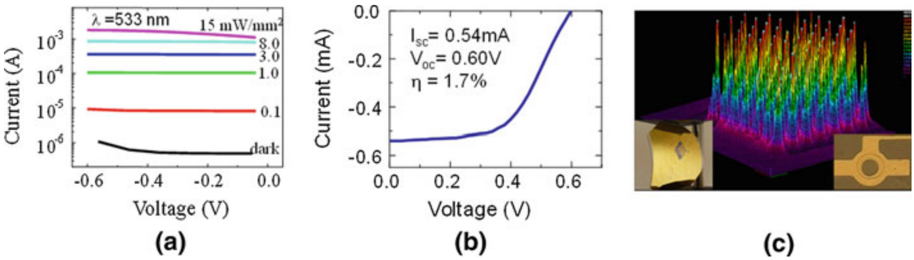

Fig. 7 **a** Flexible InP photodetectors under bending: measured photocurrent with 533 nm light sources at different optical power; **b** Flexible InP solar cells under bending: measured current under standard AM solar simulator test conditions at room temperature; **c** Flexible InP LED arrays under bending: measured Isometric and top view (*inset*) LED array light beam

performance characteristics under bending (bending radius = 32.3 mm) are shown in Fig. 7a. Dark current of 1 μA was obtained for a 3×3 mm^2 device. The measured current–voltage curve for the flexible InP solar cell under bending (bending radius = 42.1 mm) is shown in Fig. 7b. We obtained photovoltaic solar cells with open circuit voltage of 0.62 V, and power efficiency of 1.44 %. Higher efficiency cells are feasible with optimized structural design by optimal absorption, light trapping, and photon recycling. We also demonstrated 8×8 flexible InP LED arrays, based on a modified transfer process. Beam profiles of flexible crystalline InP LED arrays were also investigated for different bending radii (Fig. 7c).

In summary, we reviewed here nanophotonic devices based on stacked semiconductor NMs on Si, glass and flexible PET substrates. Photonic crystal Fano resonance-based surface-normal optical filters and broadband reflectors have been demonstrated. Flexible photodetectors and solar cells have also been developed based on the NM stacking processes. Such NM stacking process can lead to a paradigm shift on silicon photonic integration and hybrid organic/inorganic flexible photonics.

Acknowledgments This work is supported in part by US AFOSR MURI program under Grant FA9550-08-1-0337, and in part by US ARO under Grant W911NF-09-1-0505.

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