Stamp Printing of Silicon Nanomembrane Based Flexible Photonic Devices

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Abstract: We demonstrate for the first time stamp printing of silicon nanomembrane based photonic devices onto flexible substrate utilizing protection layer and suspended configuration. The propagation loss of the transferred waveguide is ~1.1dB/cm.

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Since the discovery that thin single crystal films can also possess extreme flexibility, yet retaining bulk material properties [1, 2], new opportunities in the flexible electronics and photonics have been explored, including paper-like displays [3], flexible silicon integrated circuits [4], Fano filters [5], epidermal electronics [6], etc. The silicon nanomembrane (SiNM) is usually generated by etching the buried oxide layer (BOX) of silicon on insulator (SOI) wafer with hydrofluoric acid (HF). In contrast to the rapid progress in SiNM based electronics, very little progress has been made on in-plane flexible photonics. One important reason is that in-plane photonic devices usually have large length to width ratio (>1000:1) and more complicated geometries, leading to unequal undercut etching time for different regions. Therefore, some parts of the SiNM are fully released, while other areas are still held by BOX, causing shifts, wrinkles and cracks. Besides, possibly due to the formation of the -Si-O-Si- bonds between the released SiNM and the handle silicon, in some cases, it is very difficult to peel the SiNM up after undercut etching. To solve these problems, we propose a stamp printing method utilizing protection layer and suspension structure (pedestals). With this approach, up to 5.7cm long waveguide, photonic crystal waveguide (PCW) and multimode interference (MMI) couplers, with feature size ranging from 200 nm to 30 μm, can be transferred with high repetitiveness. The measured loss of the transferred waveguide is ~1.1dB/cm. We believe this work could open an entirely new field with a wide range of useful applications.

30 μm wide, 8 mm long waveguides are fabricated on a commercially available SOI from SOITEC with 250 nm single crystal silicon, 3 μm BOX and 500 μm handle silicon, as shown in Fig. 1(a). Detailed fabrication process can be found in Ref.[7]. To form the pedestals, the patterned chip is put into a 6:1 buffered oxide etchant (BOE) for 5 mins to partially remove the silicon dioxide underneath the waveguide, as shown in Fig.1(b). Then, ~1.7 μm thick AZ 5214 photoresist is spin coated, which fills the exposed edges under the waveguides, forming polymeric pedestals. An array of holes with diameter of 100 μm and pitch of 200 μm are patterned on the resist to let the etchant penetrate for BOX removal, as shown in Fig. 1(c). The sample is hard baked at 110 ^{o}C for 3 mins, and then put into a beaker filled with HF vapor. After completely removing the BOX, the SiNM, protected by the photoresist, settles down to the handle silicon. Oxygen plasma is used to remove the photoresist everywhere, except the region underneath the nanomembrane, as shown in Fig. 1(d). The center region of the SiNM sags down and contacts the underlying substrate. The contact area can be controlled by tuning the dimensions of the pedestal through adjusting the first step BOX etching time. The etching time is controlled in order to initiate sufficient delamination formation between the SiNM and the silicon surface during retrieval with an elastomeric stamp. Bringing the polydimethylsiloxane (PDMS) stamp into contact with the released SiNM and then peeling it back at high speed lifts the SiNM structure from the handle silicon as shown in Fig. 1(e). A 125 μm thick polyimide film (Kapton, DuPont) is cleaned with Acetone and Methanol. NOA 61 (Norland Optical Adhesive) is spin coated at a speed of 4000 rpm for 60s, forming a film thickness of ~7 μm. The epoxy is pre-cured for 10 mins (7.5 mW/cm^2). Then, the “inked stamp” is brought into contact with the pre-cured epoxy film. The film is cured from top side down through the PDMS, and the stamp is slowly retrieved, leaving SiNM on the flexible substrate, as shown in Fig. 1(f). The whole sample is put into an oven at 60^{o}C for 12 hours to achieve better adhesion. The scanning electron microscope (SEM) images for the corresponding steps are shown in Fig. 1(g~i).

Fig.2(a) shows the sample after transferring. The flexibility of the SiNM, NOA 61 and Kapton makes it very difficult to prepare the end facets of the SiNM waveguide for light coupling. Therefore, we first use reactive ion etch (CHF_3/O_2) to etch the end of the waveguide and the NOA 61 underneath. Then, the Kapton substrate is diced less than 14.5 μm away from the edge of waveguide in order to enable light coupling using a polarization maintaining (PM) lensed fiber with working distance of 14.5 μm and spot diameter of 2.5 μm. The cross section of the prepared facet is shown in Fig. 2(b). The output light from the waveguide is collected with multimode fiber with a mode diameter of 50 μm. Through a top down infrared camera, as shown in Fig. 2(c), the output spot can be clearly observed, indicating strong light emission. The measured total insertion loss is ~25 dB for 7 mm transferred waveguide, which is about 6 dB more than the waveguide before transfer, as shown in Fig. 2(d). This is possibly due to the increase of facet roughness caused by the mechanic vibration during the dicing process. To measure the propagation loss of the waveguide, a structure shown in Fig. 2(e) is transferred. Through varying ΔL, the length of the waveguide can be changed by 2.6 cm. The measured loss is ~1.1 dB/cm in the region from 1530 nm to 1600 nm. This transfer technique has been used to also transfer intricate devices such as 1x6 MMI coupler and PCW, with a minimum feature size of 2 μm and 200 nm, as shown in Fig. 2(f) and 2(g), respectively, which are not feasible to be transferred using previously reported approaches [4-6].

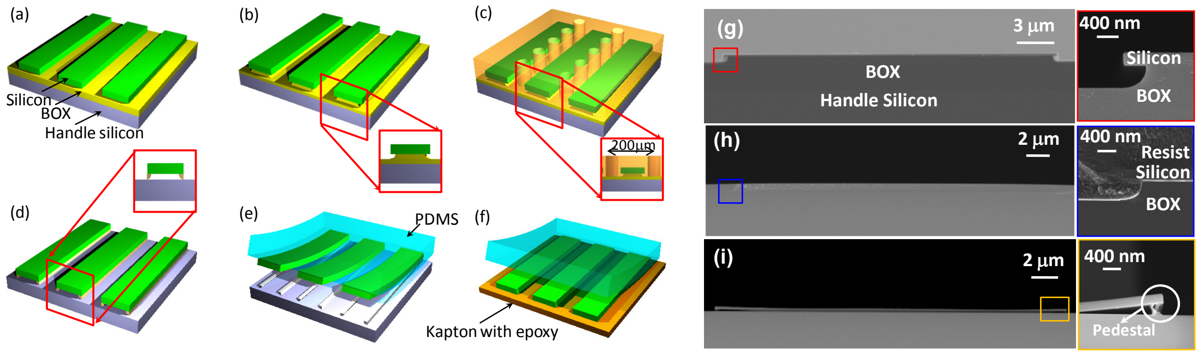

Fig. 1 Illustration of the stamp printing process exploiting a suspension structure. (a) The patterned SOI chip. (b) Illustration of chip after first undercut etching. (c) Formation of the protection layer and pedestals. (d) SiNM suspension on pedestals after complete undercut etching. (e) Peeling up of the released SiNM with PDMS stamp. (f) Printing of SiNM devices onto a polyimide film. SEM image of the cross section of the SiNM. (g) After BOE etching for 5 min. (h After spin casting photoresist. (i) After full undercut etching and removing photoresist with oxygen plasma.

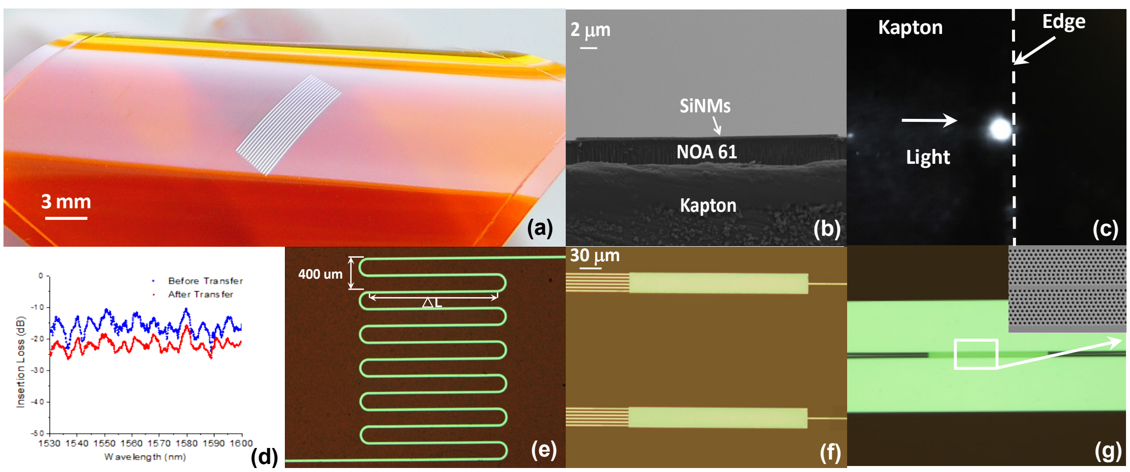

Fig. 2 (a) Transferred SiNM waveguide showing good flexibility. (b) SEM image of the cross section of the waveguide after transfer. (c) The output spot captured by a topside down IR camera. (d) The insertion loss of 7 mm SiNM based flexible waveguide (red) and the SOI based waveguide (blue) (e) The structure used to measure the propagation loss of the waveguide. (f) Transferred 1 by 6 MMI couplers. (g) Transferred Photonic crystal waveguide

In summary, we have developed a new stamp printing process based on supporting layer and suspension structure. With this method, SiNM based waveguide up to 5.7 cm long is transferred to flexible substrate, and the measured propagation loss is found to be ~1.1 dB/cm. Intricate SiNM devices such as MMI and PCW have also been transferred successfully using our technique.

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