Transfer and characterization of silicon nanomembrane based photonic devices on flexible polyimide substrate

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ABSTRACT

In this paper, we report the transfer and characterization of in-plane silicon nanomembrane based photonic devices on a Kapton polyimide flexible substrate. Compared with electronic devices and surface normal optical devices, in-plane photonic devices have stringent requirements on transfer precision because any shift in the position or breakage can affect the performance of devices. Therefore, a supporting layer consisting of a photoresist is exploited to protect the device during the transfer process. A modified stamp-assisted transfer technique is employed in order to transfer nanomembrane devices onto the flexible film and the transfer of large aspect ratio (up to 4000) waveguides and 1x6 multimode interference (MMI) couplers on a flexible Kapton substrate is demonstrated. A two-step cleaving method is developed in order to prepare the facets of the transferred waveguides and in-plane light coupling into a 60μm wide, 8mm long flexible waveguide from a lensed fiber is demonstrated. This demonstration opens limitless possibilities for a whole new area of high performance flexible photonic components using silicon nanomembrane technology.

Keywords: silicon nanomembrane, flexible photonics, silicon on insulator,

1. INTRODUCTION

Flexible electronics and photonics have attracted a lot of attention in the past decade owing to their potential utility for a wide range of applications. Single crystal silicon forms the fundamental backbone of modern microelectronic industry. However, by far the devices are limited to rigid substrates which can not satisfy the growing demand for flexible electronics and photonics seen in the last few years. Encouraging successes in this emerging field include flexible and rollable paper-like displays [1], flexible silicon integrated circuits [2], photonic crystal filters [3, 4], smart skins [5], etc. Among all the transferable materials, single crystal silicon-based nanomembrane may be most promising for both electronic and photonic devices [3], because it not only possesses high carrier mobility and mechanical durability, but is also optically transparent in the near infrared region. However, transferring in-plane photonic components onto flexible substrates is still a great challenge because the photonic devices are sensitive to any kind of shifting or fracture [6].

There are three methods to fabricate and transfer silicon nanomembranes on other target substrates, such as flexible substrates, as indicated in Table 1. In back polish method, a silicon wafer is bonded to the flexible substrate and polished down to the desired thickness. However, it is difficult to polish the wafer down to several hundred nanometers while maintaining good uniformity. An alternative approach is to bond the patterned silicon on insulator (SOI) wafer top side down on the flexible substrate and perform deep silicon etch to remove the handle wafer [7]. The dry etch stops at the buried oxide layer, and therefore, the thickness of the nanomembrane is set by the silicon device layer. This method consumes a large amount of silicon, making it a very expensive solution, although the yield is considerably higher than other methods. Peel up and stamp printing methods are believed to have lower cost because the handle wafer can be recycled. In the peel up and stamping methods, free-standing silicon nanomembrane is obtained by immersing the SOI wafer into hydrofluoric (HF) acid solution. The HF solution selectively etches the buried oxide away and releases the silicon nanomembrane from the SOI wafer. For the two methods, it is crucial to have the released silicon nanomembrane settle and conformally bond with the handle wafer via weak Van der Waals forces. In order to ensure this, the thickness of the buried oxide layer must be small enough. In order to transfer the nanomembrane onto the flexible substrate using the peel up method, a flexible substrate coated with a sticky layer on one side is used to peel the nanomembrane from the handle wafer. This method requires the adhesive has stronger adhesion to the flexible substrate than to the silicon wafer,

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otherwise the adhesive will be peeled off and adhere to the handle silicon wafer during the peel up process. Materials that satisfy these requirements, and at the same time providing good optical and electrical characteristics, are very limited. Stamp printing provides a solution to this problem through transferring the silicon nanomembrane based device onto an intermediate media first, before transferring the nanomembrane onto the flexible substrate in the final step. The fact that the adhesion between the silicon nanomembrane and the polydimethylsiloxane (PDMS) stamp is strong at high peeling speeds, while weak at low peeling speeds makes PDMS a good option for the stamp materials [8]. This special property can be further enhanced by using appropriately designed microstructures on the surface of the stamp [9].

Table 1. Comparison of the nanomembrane transfer methods

Methods	Advantage	Disadvantage
Back polish	■ High yield	■ Not suitable for alignment and multilayer stacking ■ The yield depends upon the bonding quality ■ High cost
Peel up	■ Simple	■ Not suitable for alignment and multilayer stacking ■ Material Issues
Stamp printing	■ Suitable for alignment ■ Can transfer multiple materials ■ High potential for mass production ■ Low cost	■ Complicated Process ■ Transferring delicate photonic components is difficult

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Stamp printing method has been used for transferring various membrane based components [10-12], including silicon nanomembrane based electrical circuits. However, this method cannot be applied to transfer in-plane photonic devices because the devices usually have large length to width ratio and are sensitive to shifting and breaking. In this work, we modified the stamp printing method in order to facilitate transfer of delicate photonic devices. Detailed transfer process steps and preliminary testing results are also included in this paper.

2. FABRICATION PROCESS

The photonic devices are fabricated on commercially available SOI wafers (SOITEC) with 230 nm top silicon layer and 3 μm buried oxide, as shown in Fig. 1a. The silicon device layer is first oxidized to create a 50 nm thick top oxide layer which serves as a hard mask for the silicon etching. This oxidation consumes 20 nm of silicon, leaving a final silicon thickness of 230 nm. The photonic devices are patterned using electron beam lithography. Following this, a 20 nm nickel layer is deposited using electron beam evaporation and a standard lift-off process is used to realize image reversal. The pattern is transferred to the silicon oxide hard mask using reactive ion etching (RIE). A HBr/Cl_2 RIE etch is then used to transfer the pattern to the silicon layer. Finally, the metal is removed by piranha cleaning. The top oxide layer is then removed using buffered hydrofluoric (BHF), as shown in Fig. 1b.

As mentioned in previous section, unlike electronic devices, photonic devices usually have high length to width ratios, which makes the transfer more difficult. The performance of photonic devices can be impaired by any small shifting or nanomembrane fracture during the transfer procedure. Therefore, providing mechanical support during the transfer process becomes necessary, especially when the buried oxide layer is >300nm. Before releasing the nanomembrane by etching the underlying BOX layer, a photoresist is spun cast over the device layer in order to provide mechanical support to the devices during transfer. After baking, the photoresist is patterned to open several specially designed windows for etchant penetration. Hard bake is carried out after developing (Fig.1c). If either HF or BHF is utilized to remove the sacrificial layer, shifting and breaking of nanomembrane devices is possible due to the thick buried oxide layer. In order to address this critical issue, HF vapor, instead of solution is used to minimize shifting of devices. Upon complete removal of the buried oxide layer, the residual HF is cleaned thoroughly using acetone vapor. Following this, the chip is baked at 65 ℃ in order to evaporate the water generated by the reaction of the HF and buried oxide so that the device bond well with the silicon handle wafer (Fig.1d). The photoresist is then removed using Acetone and Oxygen plasma, as shown in (Fig.1e).

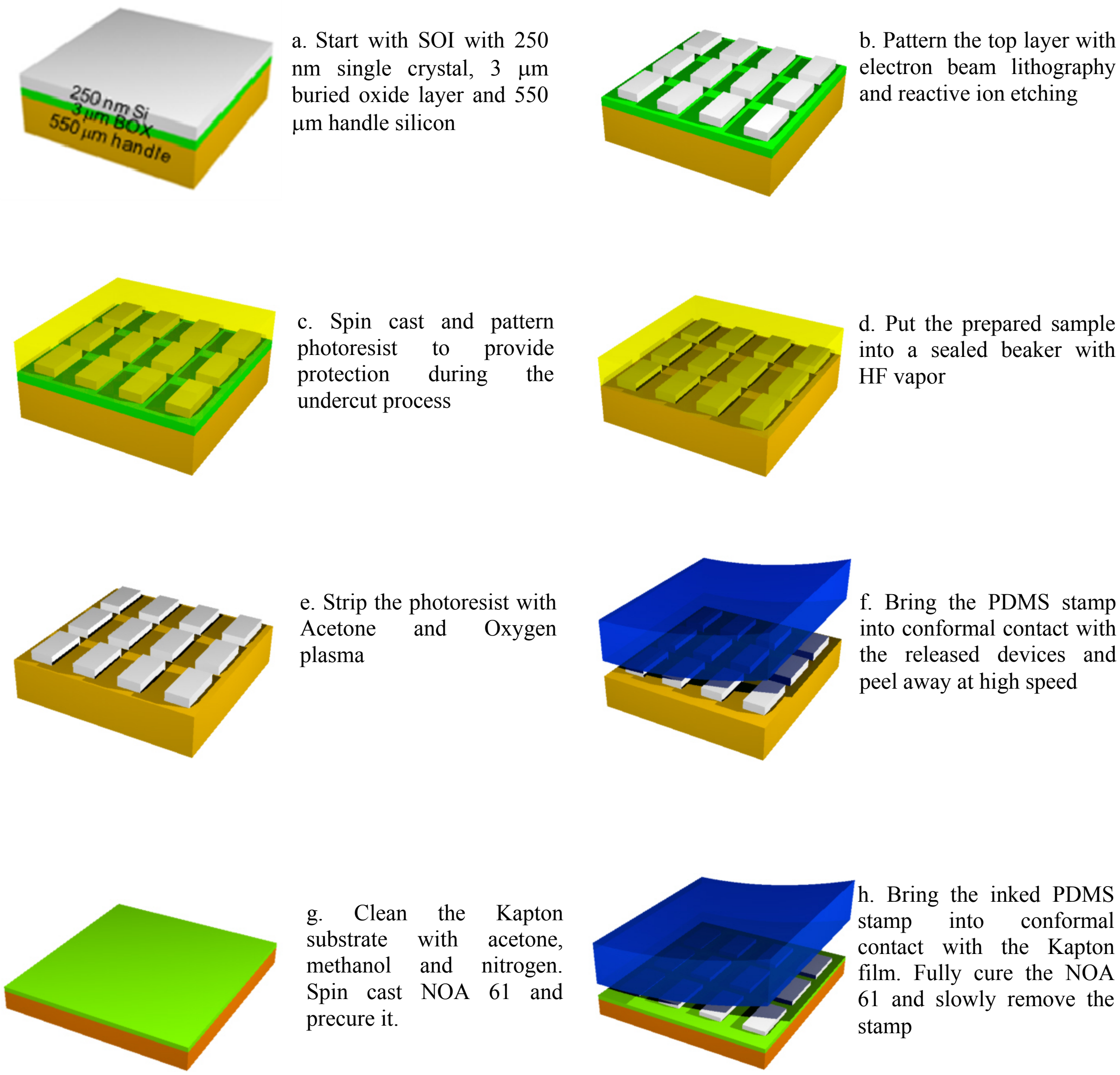

Figure 1 Process flow of for transferring silicon nanomembrane based photonic devices on to flexible substrate

The PDMS stamp is prepared by mixing the base and agent with a ratio of 5:1 and curing at 90 ^{o}C for 60 mins. The base and agent ratio is chosen to make the PDMS rigid enough to prevent the bending induced breaking of the devices during the printing process. The PDMS is bonded to a glass slide after treating the surface of PDMS and glass slide with minor Oxygen plasma and bringing the treated surfaces into contact under pressure. The assembly is then put in an oven for two hours in order to strengthen the bonding. The Oxygen plasma can neither be too strong nor too weak. Strong Oxygen plasma increases the roughness of the PDMS surface, while the surface of PDMS cannot be activated with weak Oxygen plasma. The prepared PDMS stamp is then brought into a conformal contact with the released photonic device on the handle wafer, and is peeled up at high speed, leading to the transfer of nanomembrane device from the handle wafer onto the PDMS stamp (Fig.1f). It has been observed that at high peeling speeds, the adhesion between PDMS and silicon nanomembrane is larger than the Van der Waals force between silicon nanomembrane and the handle wafer [8].

The Kapton film is cleaned by acetone and methanol before use. A gentle oxygen plasma or UV exposure could improve the adhesion between the adhesive and the Kapton surface. Later on, NOA (full name) 61 is spun cast on the Kapton substrate to a thickness of 5 μm [Fig. 1g]. The advantage of using NOA 61 is that it has good optical characteristics and low shrinkage during the curing procedure. NOA 61 is pre-cured for 5 mins with 100W UV lamp. Then, the 'inked' PDMS is brought into contact with NOA 61on the Kapton substrate and cured together through illuminating NOA61 from the top. After fully curing the NOA 61, the PDMS stamp is removed at low speed, leaving the devices on the Kapton substrate [Fig. 1h]. We fabricated and transferred several photonic components including multimode interference (MMI) couplers, strip waveguides etc. Fig. 2a shows a microscope released multimode interference (MMI) coupler. The shape and position after buried oxide removal are preserved, indicating that the protection layer is effective. A picture of the inked PDMS containing 60μm wide waveguides is shown in Fig. 2b.

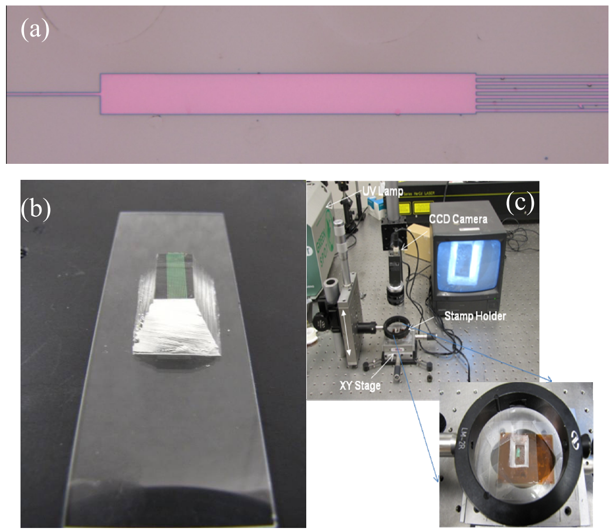

Figure 2 Pictures showing (a) released multimode interference (MMI) coupler with no shifting; (b) the inked PDMS (with 60μm waveguides); (c) set up for nanomembrane transfer

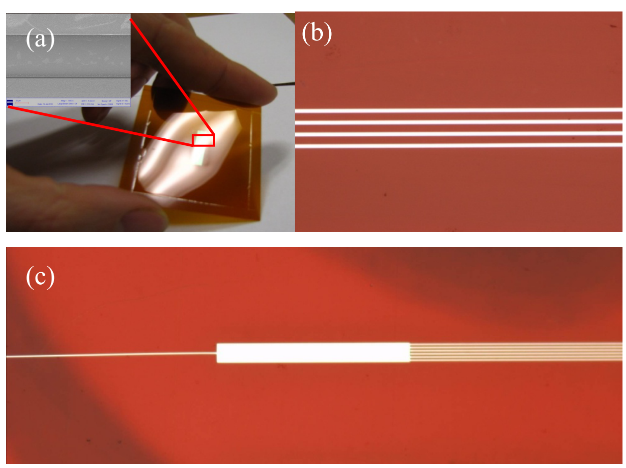

Figure 3 Transferred photonic components (a) microscope and SEM picture (inset) of 60 μm waveguides; (b) 2 μm waveguides; (c) 1 by 6 multimode interference (MMI) coupler

The process described above is realized using a simple set up, as shown in Fig. 2 c. The PDMS is mounted on the stamp holder at a small angle to reduce the formation of bubbles during the contacting procedure. The stamp is lowered and brought into a conformal contact with the released devices. Then, the stamp is peeled up quickly. During the printing process, the PDMS stamp is lowered down to contact the precured NOA 61 film on the Kapton substrate. The whole system is cured by illuminating UV light from the top of PDMS. The stamp is slowly removed from the substrate by rotating the knob of the moving stage after curing. Fig. 3a shows the transferred 60 μm straight waveguides on a 125 μm thick Kapton film. The transferred devices have high flatness as shown in the inset of Fig. 3a. Fig.3b shows the microscope picture of 2 μm wide, 8mm long straight waveguides we transferred. Fig. 3c shows a successful transfer of a 1x6 multimode interference (MMI) coupler.

3. PRELIMINARY TESTING RESULTS

A difficulty in characterizing the transferred flexible in-plane photonic devices is in preparing high quality facets. After transferring, there are three layers of different materials including silicon nanomembrane, NOA 61 and the Kapton substrate. Therefore, the traditional cleaving technique is no longer feasible. One option for coupling is to use grating coupler to couple light into the waveguide, but the flexibility of the substrate could change the periodicity of the gratings, and therefore, impair the efficiency of the grating. Another potential option is focused ion beam (FIB), but the process is very time consuming due to the large dimensions of the optical components. In this paper, we report a two-step cleaving method we developed to address the coupling problem. First; the device is cleaved using a high speed dicing saw with a resin blade In the second step, photolithography and reactive ion etching steps are carried out in order to reduce the roughness of the facets of the waveguide.

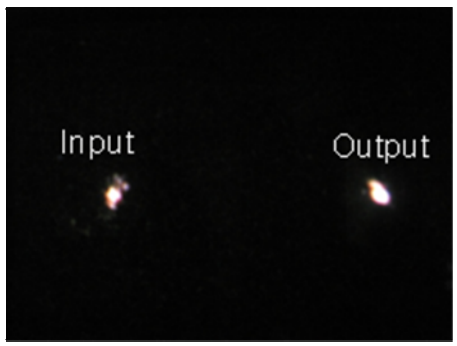

Figure 4 The top view of the input/output coupling of 60μm waveguide

The transferred devices, consisting of 60micron waveguides, were cleaved and tested on a Newport six-axis auto-aligning station. The light from a broadband amplified spontaneous emission (ASE) source (Thorlab ASE-FL7002) covering 1520~1620 nm was TE-polarized with an extinction ratio over 20 dB and butt coupled in/out through a polarization maintaining lensed fiber with a mode diameter of 3 um. Fig. 4 shows the top-down imaged input and output spots from the IR camera. which indicates the light is guided inside the waveguide.

4. CONCLUSION

In this paper, we introduce a modified stamp printing method, based on which we transferred silicon nanomembrane based optical components such as waveguides and MMI couplers onto a flexible Kapton polyimide substrate. A cleaving technique was developed to achieve good facet quality and coupling of light into a transferred 60μm waveguide was demonstrated using a lensed fiber. This demonstration opens limitless possibilities for a whole new area of high performance flexible photonic components using silicon nanomembrane technology.

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