

Silicon Nanomembranes For High Performance Flexible Photonic Interconnects and Devices

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ABSTRACT

In this paper, we demonstrate the practicality of using silicon nanomembranes for use in high performance flexible photonic interconnects and devices. Using two silicon nanomembrane transfer schemes, we demonstrate successful transfer of several photonic building blocks including large aspect ratio (>4000) and long ($>5\text{cm}$) strip waveguides, band engineered slow light ($n_g > 30$) photonic crystal waveguides, 1xN (1x2 and 1x6) multimode interference couplers etc, on a flexible Kapton polyimide substrate. A two-step cleaving method is also developed and implemented to facilitate testing of the transferred flexible photonic components for the first time. Upon cleaving, the propagation loss in transferred ultralong strip waveguide ($\sim 5.7\text{cm}$) is found to be 1.1dB/cm, which is comparable to that of waveguides on SOI.

Keywords: Silicon nanomembranes, silicon-on-insulator, flexible photonics, multimode interference couplers, photonic crystal waveguides, slow light, true time delay

1. INTRODUCTION

Over the last several years, thin single crystal nanomembranes have found to possess extreme flexibility, yet retaining bulk material properties [1, 2]. Using such nanomembranes, new properties of nanomembranes for use in the flexible electronics and photonics have been studied and explored [3-12]. Among all transferrable single crystal semiconductors, silicon nanomembrane (SiNM) is one of the most promising materials because it possesses not only high carrier mobility and mechanical durability, but also optical transparency in the near infrared region, thus making it suitable for developing high performance flexible optoelectronic devices. A conventional way of transferring SiNM devices onto other substrates is via the use of stamp printing method [4, 5]. In this method, the patterned SOI chip is put in a buffered HF solution in order to selectively remove the buried oxide layer (BOX). Upon removal of the BOX layer, the released SiNM settles on the handle wafer and is bound to it via Vander Waals forces. An elastomeric stamp, such as one prepared using PDMS, is then brought in conformal contact with the settled NM. The stamp is then pulled away, peeling the SiNM from the handle wafer onto itself. The target substrate is then coated with an adhesive layer. The PDMS is then brought into contact with the target substrate. The PDMS stamp is then pulled away. Due to larger adhesive force between the SiNM and the adhesive, compared to that between the SiNM and the PDMS stamp, the SiNM is transferred onto the target substrate. Through this approach, important progresses have been made in flexible electronics and surface normal photonics, including flexible and rollable paper-like displays [13], flexible silicon integrated circuits [14],

nanostructure Fano filters [15], smart skins [16], etc. 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, which leads to unequal undercut etching time for different regions. Therefore, some parts of the SiNM are fully released from the BOX (buried Oxide), while other areas are still held by BOX. This phenomenon causes shifts, wrinkles and cracks in the SiNM which is detrimental to the performance of the in-plane photonic devices even with <500 nm thick BOX. In this paper, using two silicon nanomembrane transfer schemes, we demonstrate successful transfer of several photonic building blocks including large aspect ratio (>4000) and long (>5 cm) strip waveguides, band engineered slow light ($n_g > 30$) photonic crystal waveguides, $1 \times N$ (1×2 and 1×6) multimode interference couplers etc, on a flexible Kapton polyimide substrate. The first method based on a modified stamp assisted transfer technique, utilizes a supporting layer consisting of a photoresist to protect the device during the transfer process. The second method based on a modified bonding technique involves a two step process - 1) bonding of silicon-on-insulator (SOI) wafer onto flexible substrate, and 2) removal of bulk silicon wafer. Both these methods have demonstrated their suitability for development of flexible photonic interconnects and devices. Unlike silicon nanomembrane components on a rigid substrate such as glass, silicon nanomembrane devices transferred on flexible substrates suffer from the lack of a reliable cleaving process for waveguide facet preparation. Therefore, a two-step cleaving method is developed and implemented to facilitate testing of the transferred in-plane flexible photonic components for the first time. This demonstration of true flexible photonic components opens limitless possibilities for the deployment of high performance flexible photonic components using silicon nanomembrane technology in a variety of applications including communication, sensing, medicine, agriculture etc.

2. MODIFIED STAMP PRINTING METHOD UTILIZING PEDESTALS

In our previous work, we demonstrated the possibility of transferring photonic crystal waveguides (PCW) and multimode interference (MMI) couplers onto flexible polyimide substrate through the conventional direct peeling up approach [17]. Without elastomeric stamp, the adhesion between surfaces is difficult to control, resulting in a low transfer yield. Besides, possibly due to the formation of the $-\text{Si-O-Si}-$ bonds between the released SiNM and the handle silicon [18], in some cases, it is very difficult to pick the SiNM up after undercut etching, even with highly adhesive surfaces, for example, scotch tapes. We modified the stamp printing method by forming pedestals that help us better control the adhesion between SiNM and handle wafer, thus leading to a higher transfer yield [19]. In order to demonstrate this technique, a $30\mu\text{m}$ wide, 8 mm long waveguide is fabricated with commercially available SOI from SOITEC with 250 nm thick single crystal silicon, 3 μm thick BOX and 500 μm thick handle silicon. The SOI is first oxidized to create 45 nm top oxide layer, which serves as a hard mask for silicon etching. This oxidation consumes 20 nm of the top silicon layer, leaving a silicon layer of 230 nm. After electron beam lithography (JEOL JBX-6000), a 20 nm nickel layer is deposited and a standard lift-off process is used to invert the pattern. The pattern is then transferred to the silicon oxide hard mask by reactive ion etching (RIE). The metallic layer is then removed by piranha cleaning. An HBr/Cl_2 RIE etch is used to transfer the pattern to the silicon layer, as shown in Fig. 1(a). To form pedestals, the patterned wafer is put into a 6:1 buffered oxide etch (BOE) for 5 minutes in order to partially remove the silicon dioxide underneath the waveguide, as shown in Fig. 1(b).

Then, AZ 5214 photoresist is spin coated at 4000 rpm for 30 seconds, resulting in a film thickness of $\sim 1.7 \mu\text{m}$. The resist also fills the exposed edges under the waveguides, thus forming polymeric pedestals, as shown in Fig. 1(c). Array of holes with diameter of $100 \mu\text{m}$ and pitch of $200 \mu\text{m}$ are patterned on the resist to let the etchant penetrate for BOX removal. The sample is hard baked at 110°C for 3 mins, and then put into a beaker filled with HF vapor. HF vapor can be generated simply by covering a beaker with concentrated HF solution. The etch rate is $\sim 50 \mu\text{m/h}$, which can be controlled by opening holes with different sizes on the cover. After completely removing the BOX, the SiNM, which is protected by the photoresist, will settle down onto the handle silicon. The supporting layer and vapor etching sufficiently prevent the SiNM from the shifting caused by the fluid flows during HF etching.

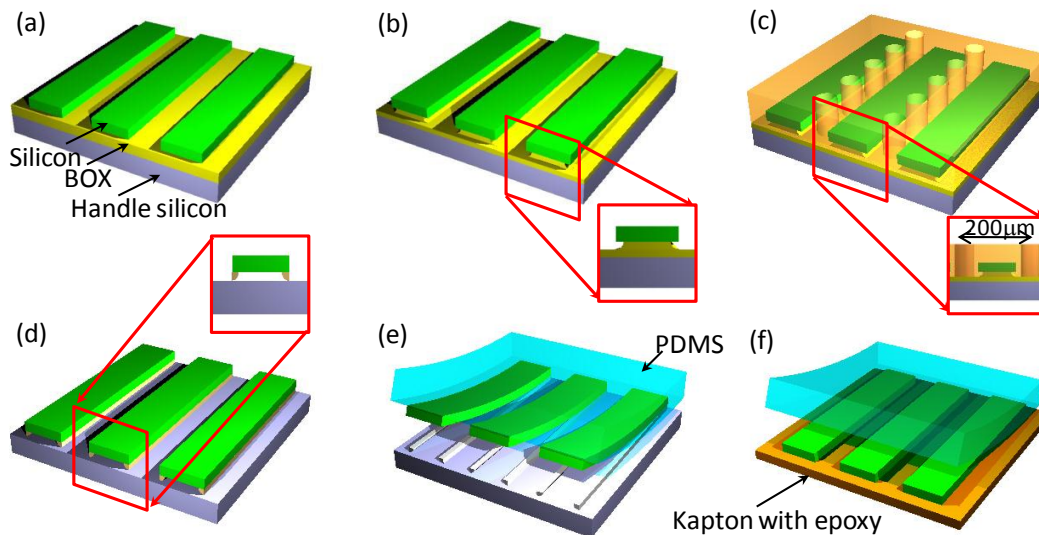


Fig. 1. Schematic illustration of the stamp printing process exploiting a suspension structure. (a) The patterned SOI chip. (b) Illustration of chip after first undercut etching. (c) Application and patterning of the supporting layer. (d) SiNM suspension on pedestals after complete undercut etching. (e) Peeling up of the released SiNM with PDMS stamp. (f) Printing of SiNM devices onto a polyimide film [19].

The result can be further improved by heating the sample up during the undercut etching process to let the by-product water from the chemical reaction evaporate. After gently cleaning and drying the sample with nitrogen, 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. This controllability is important because, when the contact area becomes too large, it becomes very difficult to peel the SiNM off. The etching time is controlled in order to initiate sufficient delamination formation between silicon nanomembrane and silicon surface during retrieval with an elastomeric stamp. The etching time is optimized to 5 minutes, forming a pedestal $\sim 200 \text{ nm}$ high.

A polydimethylsiloxane (PDMS) stamp is prepared by mixing base and agent with a ratio of 6:1, and cured at 90°C for 2 hours. The stamp is bonded to a glass slide through oxygen plasma surface activation and 2 hour 90°C annealing. Bringing the stamp into contact with the substrate and then peeling it back at high speed lifts the SiNM structure from the handle silicon through initiating delamination at the interface between the pedestals and the SiNM, 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 with a film thickness of $\sim 7 \mu\text{m}$. The epoxy is pre-cured for 10 minutes. 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°C for 12 hours to achieve better adhesion between NOA 61 and SiNM. The fully cured NOA 61 has good transmission at 1550 nm with a refractive index of ~ 1.54 . The scanning electron microscope (SEM) and the optical microscope images for the corresponding steps outlined in Fig. 1 are shown in Fig. 2.

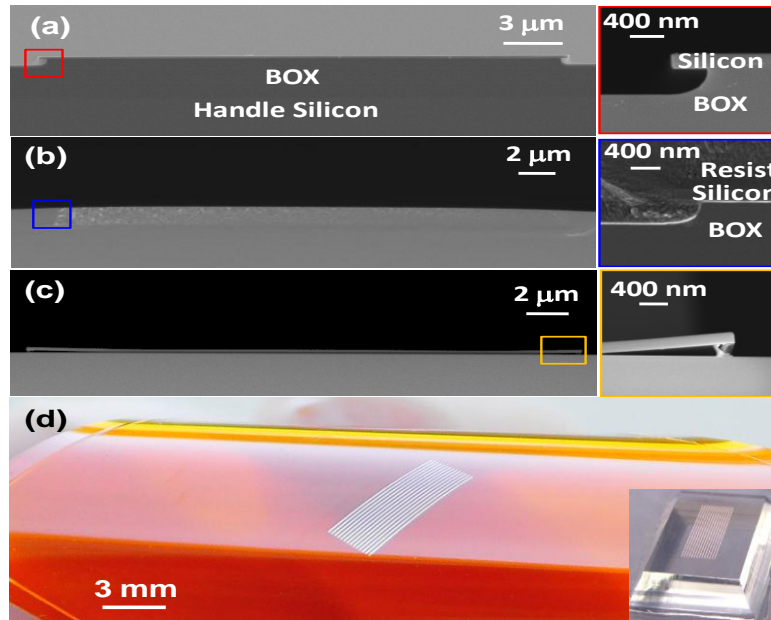


Fig. 2. (a~c). SEM image of the cross section of the SiNM. (a) After BOE etching for 5 min. (b) After spin casting photoresist. (c) After full undercut etching and removing photoresist with oxygen plasma. (d). Transferred SiNM waveguide showing good flexibility and the PDMS “inked” with SiNM (inset) [19]

Such a method can also be used to transfer intricate photonic devices. Using this technique, we also demonstrate the transfer of delicate photonic devices such as 1x6 Multimode Interference Couplers (MMIs) and Photonic Crystal Waveguide (PCW) based true time delay lines, with a minimum dimension of 2 μm and 200 nm, respectively [as shown in Fig. 3(a) and 3(b)], which are not feasible to be transferred using conventional approach.

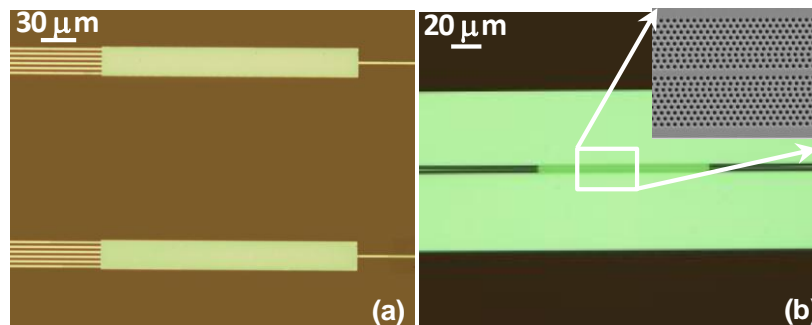


Fig. 3 (a) Transferred 1 by 6 MMI couplers. (b) Transferred photonic crystal waveguide true time delay line [19]

3. SOI BONDING AND HANDLE WAFER REMOVAL

For some devices, it is not possible to rely on BOX undercut etching and SiNM settling process. Even the slightest shift during the SiNM settling process, for example, in the case of a slot PCW consisting of four separate regions - two input/output waveguides, and two PCW regions on either side of the slot, whose relative positions need to remain unchanged during transfer process for successful operation, would completely destroy its functionality. In such cases, only a direct SOI bonding on the target substrate, and removal of back handle wafer would be a feasible route. Such a method would also be extremely beneficial if several device structures need to be fabricated simultaneously on a target substrate. Therefore, this technique relies on the availability of an unpatterned large area SiNM on a target substrate. A schematic of the transfer process for transferring large area SiNM onto a flexible Kapton substrate is shown in Fig. 4. The Kapton substrate is first bonded on a glass substrate using SU8 as an adhesive in order to provide a flat surface for subsequent processing steps. The SOI wafer is bonded upside down on the Kapton substrate with SU8 acting as an adhesive, as shown in Fig. 4(a). Since both of the Kapton and the SOI are not transparent in the UV region, the SU8 layer cannot be cured in an ordinary way. This problem can be solved by curing the SU 8 first and heating the sample up to glass transition temperature to let the SU 8 reflow. This requires high, uniform and consistent pressure which cannot be satisfied with home-made tool. As the crosslink of SU 8 relies on the generation of acid upon UV exposure as a result of proteolysis of triarylsulfonium hexafluorantimonium, the cationic photoinitiator, we came up with this idea of bringing one layer of cured SU 8 and one layer of uncured SU 8 together. The cured SU 8 provides the acid and the uncured SU 8 serves as a soft layer which makes bonding with simple set up possible. The whole stack is put into vacuum oven at 150 °C to reflow for 12 hours. During the reflow, pressure is applied to squeeze the air bubbles out. Picture of the setup we developed for the bonding step is shown in Fig. 5(a). A picture of SOI wafer bonded onto Kapton substrate is shown in Fig. 5(b).

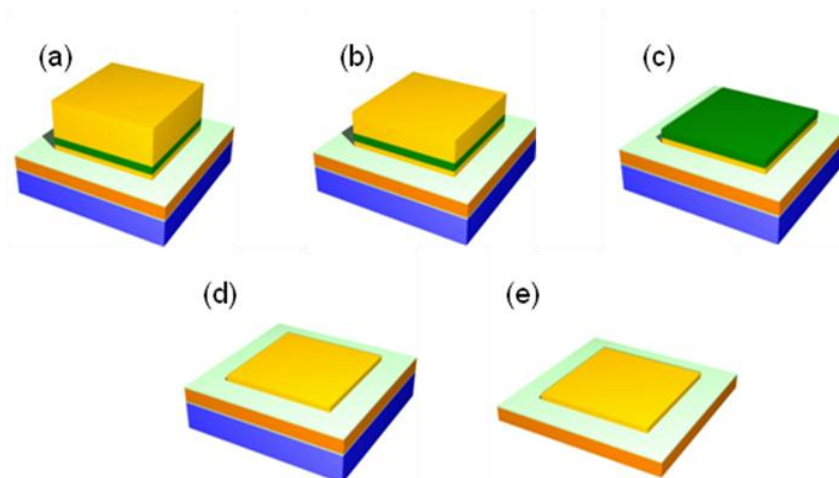


Fig. 4 Process flow for transferring large area SiNM onto flexible substrate

To remove the handle silicon, deep reactive ion etching (DRIE) is utilized. DRIE is a fast and high-selectivity etching tool. However, the chemical reaction produces too much heat and the top surface facing the plasma could be heated up to over 100 °C while the bottom of the stack is in contact with a helium cooled electrode whose temperature is ~10 °C. To overcome this problem,

the handle silicon is first thinned down to $\sim 150\mu\text{m}$ [Fig. 4(b)] through conventional mechanical polishing.

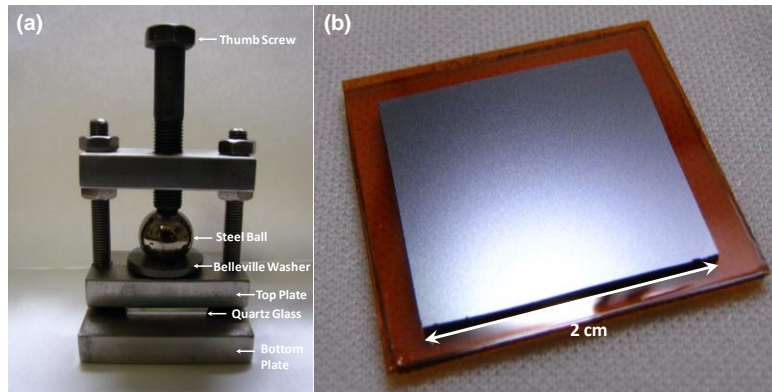


Fig. 5 (a) Bonding Tool. The pressure is controlled by rotating the thumb screw. The ball and the Belleville washer are used to extend the point pressure into plane pressure. Belleville washer also maintains the pressure during the reflow process in which the metal becomes soft. The bonding stack is put in between the two 1mm thick quartz plates. (b) the stack after bonding.

Then, the remaining $\sim 150\mu\text{m}$ silicon is removed by DRIE. The $3\mu\text{m}$ buried oxide serves as a stopping layer [Fig. 4(c)]. After that, the buried oxide layer is etched away by hydrofluoric acid, to produce large area single crystal SiNM on Kapton substrate bonded to glass, as shown in Fig. 4(d). Finally, the Kapton substrate is peeled away together with the SiNM [Fig. 4(e)], leaving large area SiNM only on the flexible Kapton substrate. Using this method, we have transferred $2\text{cm} \times 2\text{cm}$ area of unpatterned SiNM onto Kapton substrate, as shown in Fig. 6(a).

Using e-beam lithography, we fabricated several photonic devices including slow-light photonic crystal waveguides [20] and 1×2 MMI couplers on the transferred large area SiNM, as shown in Figs. 6(b) and 6(c), respectively. We are also currently developing slot photonic crystal waveguide based modulators on transferred SiNMs, which will be reported elsewhere.

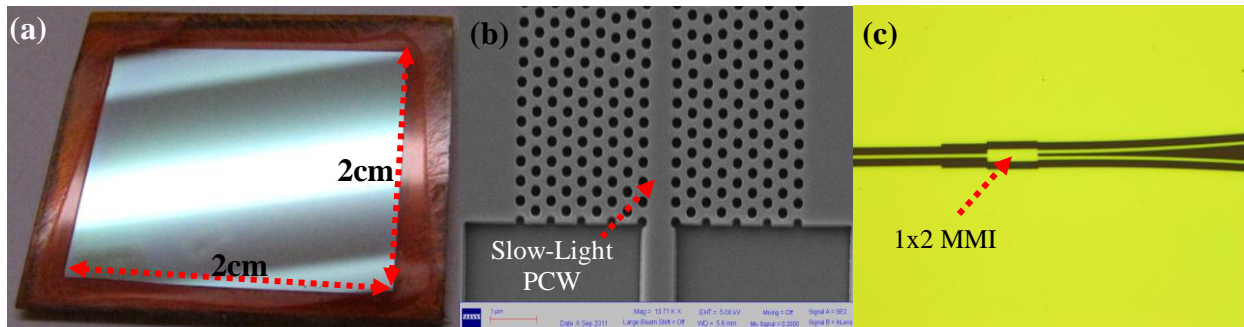


Fig. 6 (a) $2\text{cm} \times 2\text{cm}$ Silicon nanomembrane transferred onto Kapton substrate, (b) SEM image of photonic crystal waveguide fabricated on transferred SiNM and (c) Optical microscope image of fabricated 1×2 MMI.

Such a generic fabrication method paves the way for realization of high performance optical components on any substrate.

4. COUPLING LIGHT INTO IN-PLANE TRANSFERRED SINM PHOTONIC DEVICES

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 or SU8 and the Kapton substrate. The flexibility of the SiNM, NOA 61/SU8 and Kapton makes it very difficult to prepare the end facets of the SiNM waveguide for light coupling. Traditional cleaving technique is no longer feasible. Therefore, a different scheme is required to couple light into the transferred waveguides. A scheme for preparing the end facets in order to test the transferred waveguides is shown in Fig. 7.

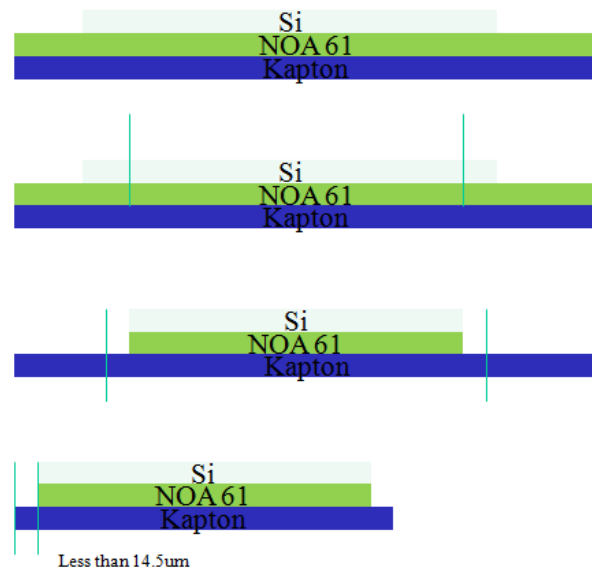


Fig. 7. Scheme for preparing end facets on the transferred SiNM based in-plane photonic devices

We first use RIE (CHF_3/O_2) to etch the end of the waveguide and the NOA 61 underneath away. Then, the Kapton substrate is diced less than $14.5 \mu\text{m}$ away from the edge of waveguide in order to enable light coupling using a polarization maintaining (PM) lensed fiber with working distance of $14.5 \mu\text{m}$ and spot diameter of $2.5 \mu\text{m}$ [19]. The cross section of the prepared facet is shown in Fig. 8(a). The output light from the waveguide is collected with multimode fiber with a mode diameter of $50 \mu\text{m}$. Through a top down infrared camera, as shown in Fig. 8(b), the output spot can be clearly observed, indicating strong light emission. The measured insertion loss is ~ 25 dB for 7 mm transferred waveguide, which is about 6dB more than the waveguide before transfer, as shown in Fig. 8(c). 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. 8(d) is transferred. Through varying ΔL , the length of the waveguide can be changed by 2.6 cm. We successfully transferred ultralong waveguides with length 5.7cm, as shown in Fig. 8(d). The measured loss obtained from a set of different lengths of transferred waveguides is ~ 1.1 dB/cm in the region from 1530 nm to 1600 nm, which is comparable with the SOI based waveguide. Thus, such a modified cleaving and coupling scheme can immensely help realize practical photonic devices on flexible substrates.

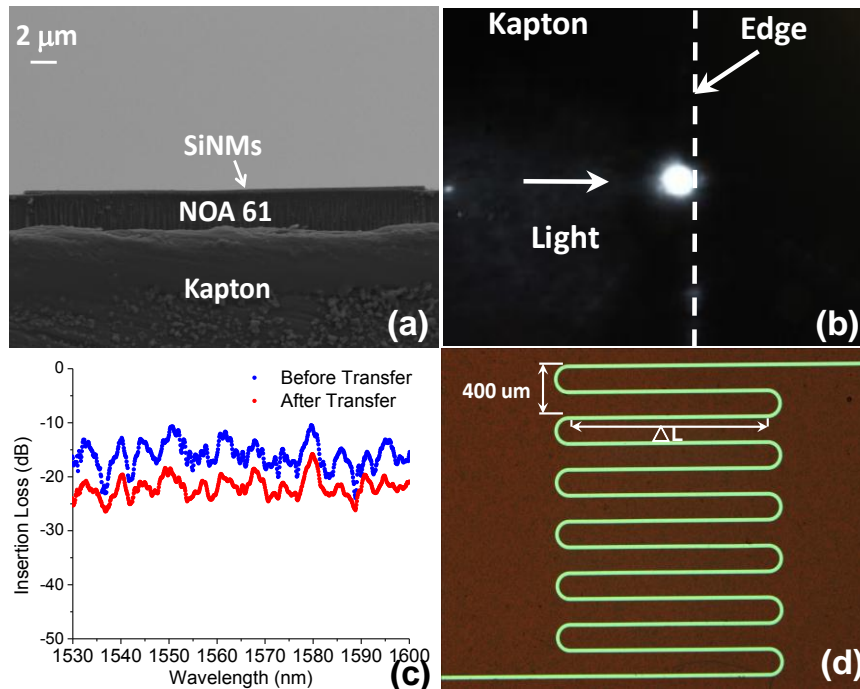


Fig. 8. (a) SEM image of the cross section of the waveguide after transfer. (b) The output spot captured by an upside down IR camera. (c) The insertion loss of 7mm SiNM based flexible waveguide (red) and the SOI based waveguide (blue) (d) The structure used to measure the propagation loss of the waveguide [19].

5. CONCLUSIONS

In conclusion, we developed two silicon nanomembrane transfer schemes - one based on a modified stamp printing method using pedestals and another utilizing SOI bonding on flexible substrate assisted with DRIE for handle wafer removal. Using these techniques, successful transfer of several intricate photonic components such as large aspect ratio (>4000) and ultralong ($>5\text{cm}$) strip waveguides, band engineered slow light ($n_g > 30$) photonic crystal waveguides, 1xN (1x2 and 1x6) multimode interference couplers, etc on flexible Kapton substrate, which are difficult to achieve using conventional techniques, was demonstrated. In order to demonstrate practical purpose of the flexible components, a light coupling scheme consisting of a two-step cleaving method was also developed. Using this method, successful coupling of light into 5.7cm long waveguides was demonstrated and the loss was measured to be $\sim 1.1\text{dB/cm}$, which is comparable to that of waveguides on SOI opening up opportunities for utilization of such flexible micro and nanophotonic components for the first time.

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