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Flexible In-plane Photonic Devices Based on Transferrable Si Nanomembranes on Polyimide Film

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Abstract. The flexible electronics and photonics have attracted a lot of attentions in past decade because of their potentially wide applications. A general method to fabricate nanomembrane flexible device involves two steps. At first, a nanomembrane on top of a sacrificial layer is patterned. Then, the nanomembrane is freed by high selective etching of the sacrificial layer and then weakly bonds to the handle substrate by Vander Waals forces. Later on, the released devices are transferred to the target flexible substrates. Notable successes include paper-like display, flexible silicon integrated circuits, photonic crystal filter and sensor skins, and so on. However, the progress in flexible photonic device is still limited to surface-normal devices such as photonic crystal filter. This type of devices usually has a large area and/or same dimensions which makes the transfer much easier than in-plane photonic device. This paper reports the transfer of in-plane Silicon nanomembrane photonic devices on polyimide flexible film. Employing a slightly modified transfer process, passive optical components, such as optical waveguide and multimode multimode interferometer, are successfully transferred on to Kapton polyimide film.

1. Introduction

Plenty of technologies require large-scale integration of different types of components fabricated separately, which cannot be realized through conventional microelectronic fabrication processes because of the different nature of materials. Examples of these systems that rely heavily on heterogeneous integration range from integrated photonic systems that contain III-V semiconductor lasers and silicon waveguides, to biomedical applications that usually involve organic tissues and inorganic sensors. Integrating electronic and photonic devices on flexible substrates provides a promising solution to these applications. Encouraging successes in this emerging field include but not limited to paper-like displays [1, 2], flexible silicon integrated circuits [3], photonic crystal filter [4, 5] and sensor skins [6] , and so on. Among all the transferable materials, Single crystal Si nanomembrane may be the most promising for both the electronic and photonic devices [4], because it not only has high carrier mobility and is mechanically robust, but also is transparent in the near infrared region. However, transferring in-plane photonic components on to flexible substrates are still a great challenge because of the dimension and shape sensitivity of the photonic devices [7].

Transfer printing technic is one of the prevalent method to integrate different components on flexible film. A typical transferring process includes two steps. First, a thin functional layer is deposit onto a sacrificial layer. In the following step, the sacrificial layer is removed and the functional layer is released and transferred to a flexible substrate [8]. The sacrificial layer needs to be very thin to let the functional layer bonded to the handle substrate through Van der Waals force. The typical value is ~200nm. If the sacrificial layer is too thick, special design is necessary to anchor the functional layer onto the handle substrate during the releasing procedure [2, 9]. In this paper, we introduce a new method to transfer photonic devices with 3 μm buried oxide layer as sacrificial layer.

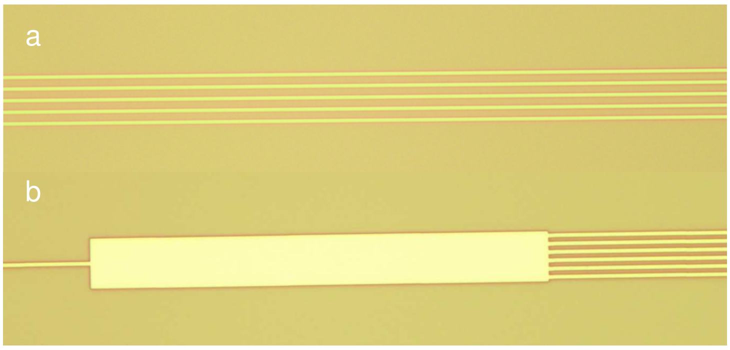

Figure 1. Silicon nanomembrane photonic components before transfer. a) 2 μm waveguide; b) 1×6 MMI

2. Fabrication Process

Photonic crystal waveguide devices are fabricated on commercially available SOI from SOITEC with 250nm top silicon layer and 3μm buried oxide. The silicon is first oxidized to create a 50nm thick top oxide layer which serves as a hard mask for the silicon etch. This oxidation consumes 20nm of silicon, leaving a final silicon thickness of 230nm. The photonic devices are patterned using electron beam lithography. After electron beam lithography and developing, a 20 nm nickle layer is deposited and a standard lift-off process is used to remove the extra nickel. The pattern is transferred to the silicon oxide hard mask by reactive ion etching (RIE). An HBr/Cl2 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 removed by buffered hydrofluoric (BHF). Fig. 1 shows the pictures of the fabricated 2 μm waveguide and the 1×6 multimode interference (MMI) coupler, which will be used for transfer described in the following.

Unlike electronic devices, photonic devices usually have high length to width ratio which makes the transfer more difficult. The performance of photonic devices can be degraded by tiny shifting or breaking during the transfer procedure. Therefore, providing mechanical supporting during the transfer process becomes a necessary, especially when the buried oxide layer is as thick as 3 μm. Fig. 2 illustrates the transfer process. From top side down, the structure after previous steps is 230nm function layer, 3μm buried oxide layer and 0.5 handle silicon (Fig. 2a). Photoresist AZ 5209 is spun on (4000 rpm, 30sec) to provide mechanic support to the devices during the etching procedure after pretreating the chip by Hexamethyldisilazane (HMDS). After baking at 95℃, the photoresist is patterned to open several specially designed windows to let the etchant pass in. Hard bake at 110 ℃ is carried out after developing with AZ 726MIF (Fig.2b). Since the buried oxide layer is too thick, the

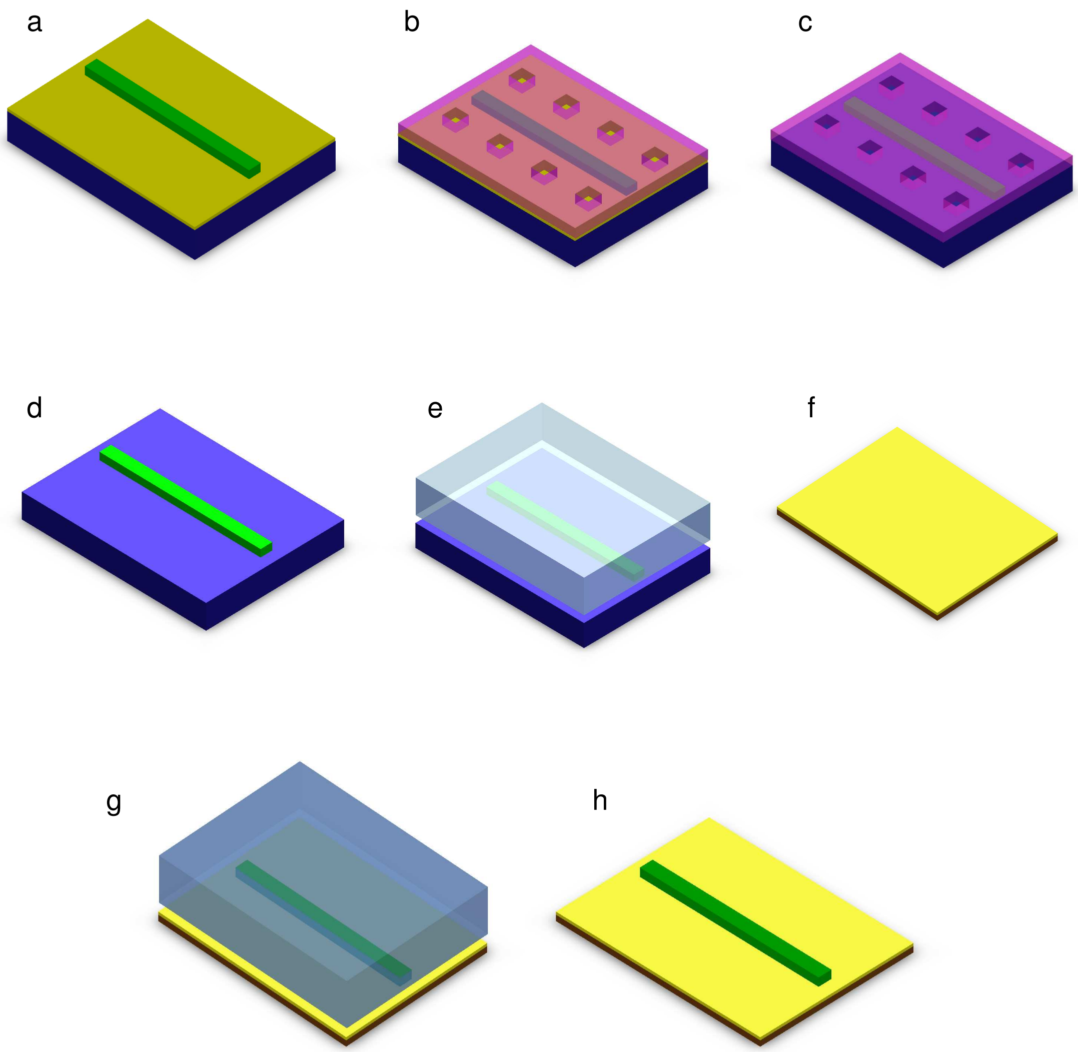

Figure 2. Transfer process flow chart. a. starting from SOI; b. form the supporting layer and open the etching window; c. release the function layer with HF vapor; d. strip the photoresist by oxygen plasma; e. using PDMS to peel up the device; f. prepare the target Kapton substrate; g. bring the inked PDMS into contact with the target substrate and remove PDMS slowly; f. the device is transferred to target substrate

function layer is weakly bonded to the handle silicon when either hydrofluoric (HF) or BHF is utilized to remove the sacrificial layer, which causes shifting and breaking. To address the critical issue, in our process, HF vapor is used instead of solution so that the shifting of the device can be minimized. HF vapor is generated simply by cover the beaker because HF is volatile. The etching rate is ~50 μm/h in our process. It can be adjusted to any desired value through opening holes on the cover. After the buried oxide layer is completely removed, the chip is moved to another beaker with acetone where the residue of HF can be cleaned thoroughly by the acetone vapor. Later on, the chip is baked at 65 ℃ to evaporate the water generated by the reaction of the HF and buried oxide so that the device can be tightly bonded to the silicon handle wafer (Fig.2c). Then, the photoresist is removed by oxygen plasma (200W, 13sccm, 10min), as shown in (Fig.2d). The PDMS is prepared by mixing the base and agent with a ratio of 8.5:1.5 and curing at 70 ℃ for 90 mins [2]. The optimized PDMS dimensions are 0.8 by 2 by 2cm. PDMS can be reused after cleaned by ethanol and tried by nitrogen. Bringing the prepared PDMS into conformal contact with the released photonic device and peel it up at high speed (Fig.2e) [10]. It has been demonstrated that at high peeling speed the adhesion between PDMS and silicon nanomembrane is larger than the Van der Waals force between silicon nanomembrane and the handle wafer [10]. The inked PDMS is shown in Fig. 3b.

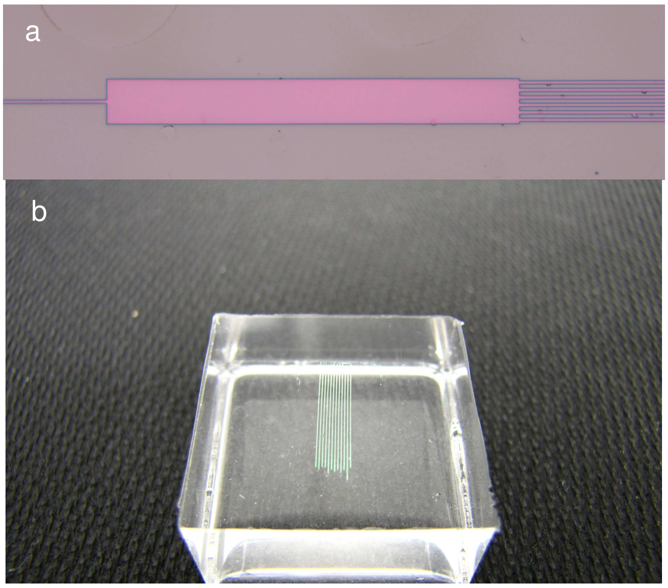

Figure 3. a. the released device settles down to the silicon substrate; b. inked PDMS(the waveguide in this picture is 60μm).

Kapton film is widely accepted as a durable material. It has a unique combination of electrical, thermal, chemical and mechanical properties and retains these properties over a wide range of industrial environments and applications. However, because of the lack of the adhesions between Kapton and SU-8, the SU-8 layer can be delaminated from the Kapton during the printing process and lead to a false transfer. Therefore, after cleaning the film with isopropyl alcohol (IPA) and drying with nitrogen, we spin coat a thin layer of Omnicoat to promote the adhesion (3000rpm, 30sec, bake at 200 ℃ for 2 mins). Then SU-8 2002 is spun on at 3000 rpm and soft baked at 65 and 95 ℃ for 1 min and 2 min, respectively (Fig.2f). Later on, bring the inked PDMS into contact with the film and peel the device up at low speed after curing with UV lamp for 5 mins and baking at 110 ℃ for 10 mins. Fully cure the SU-8 at 150℃ for 30mins.

3. Results and Discussions

With the transfer process described in previous section, we transferred several classes of photonic components including 2 μm waveguide (Fig. 4a), multimode interference coupler (MMI), shown in Fig.4b and c. The SEM images are not clear because of the charging of the SU-8. To coupling light in, the transferred device is bonded to glass slides and cleaved by high speed dicing saw with resin blaze. Newport six-axis autoaligner system is used to couple the 1550nm TE polarized light in. An infrared camera is mounted up-down to examine the output end of the waveguide. Fig. 4d shows the output spot, illustrating the light passes through the waveguide.

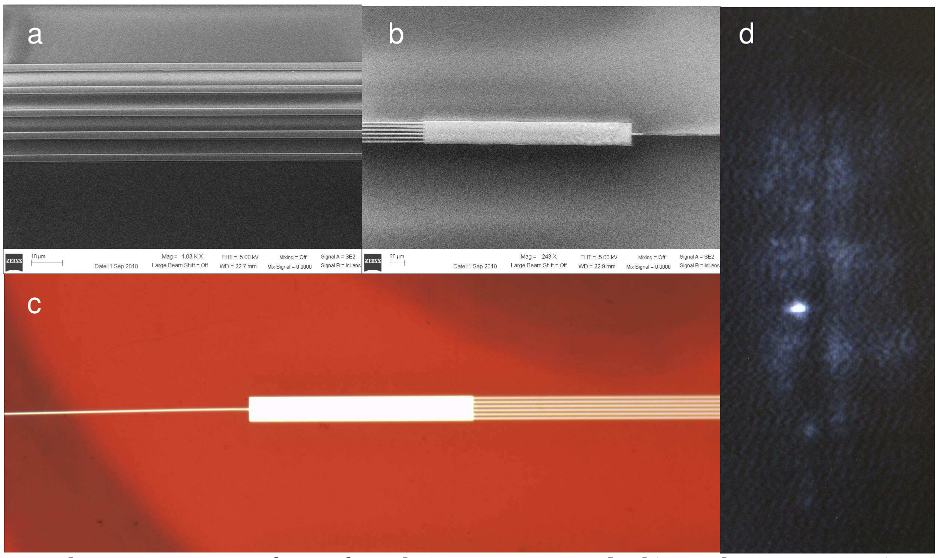

Figure 4. The SEM picture of transferred a) 2um waveguide; b) one by six MMI; c) Optical microscope picture of the transferred one by six MMI on Kapton film; d) the top down output infrared image when the waveguide is illuminated by 1550nm light

Nevertheless, how to couple light in and out is still a great challenge for the flexible photonic devices. The flexible substrate cannot be cleaved by ordinary methods used in silicon photonic devices based on natural cleavage. Surface normal coupling methods such as gratings will surely result in the increase difficulty of transfer.

4. Conclusion

In this paper, a method is proposed to transfer silicon nanomembrane photonic devices with thick buried oxide layer onto polyimide film. With this method, several types of devices are transferred successfully. Initial testing efforts show the promising future of this technique.

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