NANOMECHANICAL OPTICAL DEVICES FABRICATED WITH ALIGNED WAFER BONDING

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ABSTRACT

This paper reports on a new method for making some types of integrated optical nanomechanical devices. Intensity modulators as well as phase modulators were fabricated using several silicon micromachining techniques, including chemical mechanical polishing and aligned wafer bonding. This new method enables batch fabrication of the nanomechanical optical devices, and enhances their performance.

1. INTRODUCTION

A large range of integrated optical (IO) devices can be made based on the IO nanomechanical effect. According to this effect, the effective refractive index of a waveguide can be modulated by a movable element that is driven into the evanescent field over distances in the order of magnitude of 100 nm (Fig. 1). Examples of such a device are IO intensity modulators, phase modulators, tunable wavelength filters, as well as all optical pressure sensors.

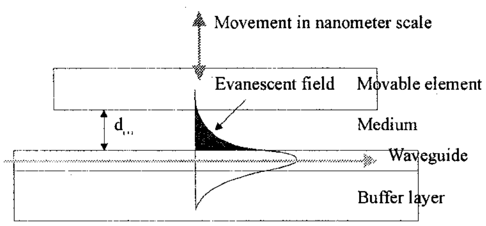

Fig. 1. Schematic representation of the IO nanomechanical effect.

While the theory of the IO nanomechanical effect is straight-forward, the realisation of these devices remains a great challenge. The difficulties originate from that one is trying to fabricate *nano* mechanical devices with *micro* machining technologies. The requirements of the IO nanomechanical devices are very rigid. The gap between the movable element and the waveguide surface is typically a fraction of the wavelength of the guided light (~ 0.5 to 1.5 μm). This gap should be very uniform, specially for the tunable wavelength filter. The movement of the element is small and should be very stable particularly for the phase modulator and the tunable wavelength filter. In order to achieve such an accurately defined gap, stresses in the membrane-element unit must be very low. The energy for driving the element should be as low as possible, etc. So far no fabrication method has been found to fulfil all these requirements.

Using this IO nanomechanical effect, Lukosz et al. have demonstrated several devices [1-3]. The movable elements were assembled onto the substrates that contain channel waveguides by means of an optical contact bonding technique. This technique is very useful for quickly demonstrating the working principle of the IO nanomechanical devices. However, the bonding is weak, reversible and not on wafer scale. Therefore it is less suitable for commercial production.

Here we propose a two wafers technique. This means we fabricate the movable elements and the optical waveguides separately on a wafer scale, and then combine both wafers together using the aligned wafer bonding technique. Silicon bulk micromachining techniques are used in fabricating the membranes and elements. Chemical mechanical polishing (CMP) is essential in achieving wafer scale voids-free bonding. Using these techniques, we have designed and fabricated the intensity modulator and the phase modulator. Details on the design, optimisation, and characterisation of these devices will be reported elsewhere. In this paper, we will present the fabrication technologies and experimental results. Stiction of the element to the waveguide wafer surface will be discussed. And a method for preventing stiction will be given.

2. DESIGN CONSIDERATIONS

2.1. The channel waveguides

The used channel waveguide is schematically shown in Fig. 2. The most important feature is the high refractive index and the small thickness of the Si_3N_4 waveguide layer. This assures that a large part of the modal field can stick into the air/element [1]. The thickness of the phase modulator waveguide was designed for a maximum effect. Unfortunately this results in a very shallow ridge, required to assure the mono-modal behaviour of the waveguide. The waveguide for the intensity modulator was therefore chosen to be somewhat thicker. This relaxes the technological requirements for the ridge, while the absorbing effect is still very large.

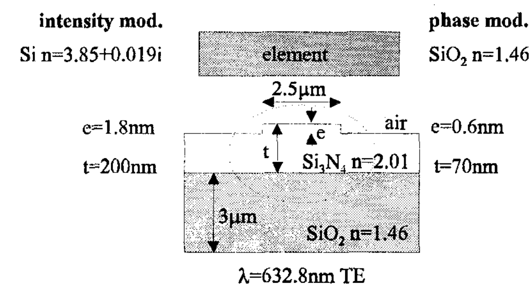

Fig. 2. Schematic of the IO design of the intensity modulator and the phase modulator.

2.2. The membrane-element structure

A schematic representation of the structures of the membrane and the movable element is shown in Fig. 3. The rectangular movable element is located in the centre of the four side clamped rectangular membrane. Both the membrane and the element are designed symmetrically in order to achieve symmetric and uniform movement of the element. The membranes and elements of this design can be fabricated from a silicon substrate using bulk micromachining techniques, e.g. KOH etching.

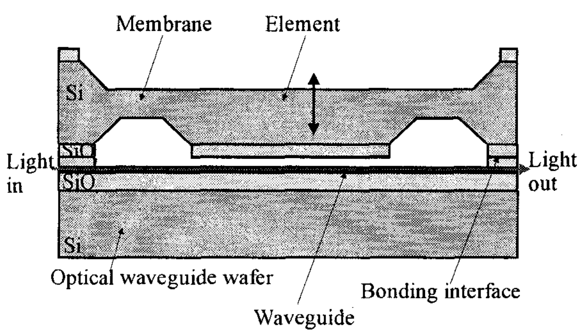

Fig. 3. Cross section of the IO nanomechanical device. The SiO_2 layer on the mechanical element is only applied for the phase modulator, not for the intensity modulator.

The gap between the element and the channel waveguide is realised by fusion bonding the membrane wafer to the patterned and etched plasma enhanced chemical vapour deposition (PECVD) SiO_2 layer that is on top of the waveguide wafer. Thus the thickness of this PECVD SiO_2 layer defines the height of the gap. Before bonding, the PECVD SiO_2 layer has to be polished. With this method, a very accurate and uniform gap thickness can be realised.

The geometry of the element and the membrane has been optimised such that the driving force and gap non-uniformity are low.

3. FABRICATION TECHNOLOGIES

3.1. Fabrication of the channel waveguides

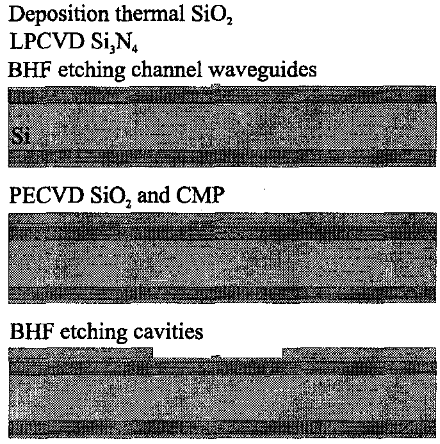

Fig. 4. Fabrication process for the IO waveguide channels

The fabrication process for the optical wafer started with the thermal growth of a 3 μm thick SiO_2 layer on top of a 3 inch silicon substrate. Then a low pressure chemical vapour deposition (LPCVD) Si_3N_4 layer was deposited on the oxidised wafer. Alignment marks were patterned and etched on the backside of the optical wafer for the later aligned wafer bonding. Then channel waveguides were fabricated on the front side of the wafer by means of photolithography and BHF etching. After that, a PECVD SiO_2 layer of 1 μm thickness was deposited on the front side of the IO waveguide wafer. After smoothening the PECVD SiO_2 layer using CMP, cavities were patterned and etched with BHF solution (Fig. 4).

3.2. Fabrication of the membranes and movable elements

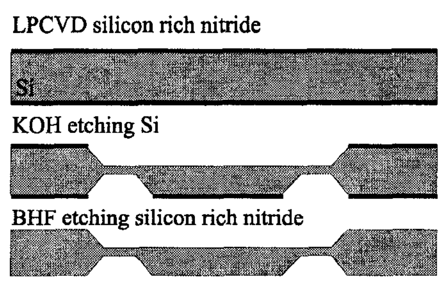

Fig. 5. Fabrication process for the membranes and movable elements of the intensity modulator.

For the intensity modulators based on the absorption mechanism, the movable elements were fabricated from single crystalline silicon, and no optical buffer layer was necessary. The process started with a 3 inch, double side polished, <100> oriented silicon wafer. After growing a low stress LPCVD silicon nitride masking layer, membranes were patterned on both sides of the wafer. Then membranes were etched with 25 % KOH solution at 75 °C. Time stop technique was used to define the thickness of the membranes (Fig. 5).

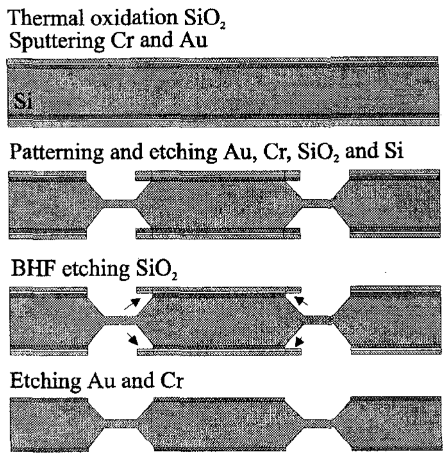

Fig. 6. Fabrication process for the membranes and movable elements of the phase modulators using Cr-Au as KOH etching mask.

For the phase modulators, a (transparent) thermal SiO_2 buffer layer on top of the silicon movable elements is required. In this case, a Cr-Au layer was used as the mask layers for KOH etching. This process started with growing a thermal SiO_2 layer on a 3 inch, double side polished and <100> oriented silicon wafer. Then Cr (20 nm thickness) and Au (300 nm thickness) were sputtered on both sides of the oxidised wafer. Next the membranes were patterned at both sides of the wafer by etching the Au, Cr and thermal SiO_2 layers using photo resist as a mask layer. The thermal SiO_2 layer was etched in a BHF solution. The next step is etching the membranes in 25 % KOH solution at 75 °C from both sides of the wafer. Before finally removing the Au-Cr masking layers, the remaining SiO_2 cantilevers underneath the compensation structures for KOH etching were removed in BHF (Fig. 6).

3.3. Chemical mechanical polishing of PECVD SiO_2

Before direct bonding can be applied between PECVD SiO_2 and Si or thermal SiO_2, a CMP process on the PECVD SiO_2 layer surface is necessary [4].

In the CMP process, a MECAPOL E460 polishing machine, which has a single head polisher, was used. When using a Semisperse 25 slurry and a UR 100 pad, the removal rate of PECVD SiO_2 is about 300 nm/min at a work pressure of 1 bar and a rotation speed of 60 rpm. It was found that 30 seconds polishing is sufficient to achieve an atomically smooth surface for the PECVD SiO_2 layer. Fig. 7 shows the surface roughness of PECVD SiO_2 before and after CMP as measured with an atomic force microscope (AFM). The root mean square (RMS) roughness of PECVD SiO_2 was reduced with a factor of 10 after polishing.

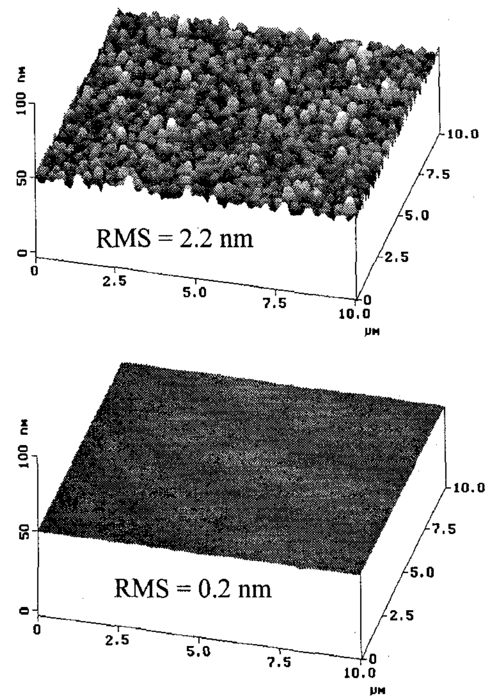

Fig. 7. PECVD SiO_2 surface topographies before (top) and after (bottom) CMP, measured with an atomic force microscopy.

After CMP, the wafers underwent brushing, DI water rinsing and RCA cleaning (cleaning in H_2SO_4 (1) + H_2O (5) + H_2O_2 (1) solution at 80 °C for 20 minutes), in order to remove slurry particles and possible sodium hydroxide contamination.

3.4. Aligned wafer bonding

After fabricating the waveguide wafer and the membrane wafer, the aligned wafer bonding technique was used to assemble these two wafers together.

Prior to bonding, the optical and membrane wafers were cleaned in RCA solution at 80 °C for 20 minutes. Then both wafers were cleaned in Pirana solution (H_2SO_4 (1) + H_2O_2 (3)) at 100 °C for 20 minutes. Finally, wafers underwent boiling in hot nitric acid (69 % HNO_3 at 95 °C) for 15 minutes. Between each step, DI water rinsing was done.

The room temperature (RT) bonding of both wafers was carried out with an Electronic Visions double sided mask aligner. This mask aligner allows an alignment accuracy of about 1 μm. Special attention should be paid to prevent contamination of the wafers during loading.

After RT bonding, the wafer pair was annealed at an elevated temperature to enhance the bond strength. The annealing has been done at temperatures from 500 °C to 850 °C for 1 to 10 hours. The resulting bonding strength was between 1 to 3 J/m^2. Higher annealing temperature results in higher bond strength.

4. EXPERIMENTAL RESULTS

Using above described method, nanomechanical optical intensity modulators and phase modulators have been made. Depending on the size of the devices, several to dozens of devices can be made on one 3 inch wafer pair (Fig. 8). SEM images that show the cross section of the intensity modulator are presented in Fig. 9 and 10.

The nanomechanical optical intensity modulators driven by electrostatic force have been tested, Fig. 11. An extinction ratio as high as 43 dB was measured. This result is about two times higher than the extinction ratio of typical IO devices such as a Mach-Zehnder based switch, which is about 20 dB. The driving voltages for the intensity modulator were between 5 to 30 V.

Preliminary test results on the phase modulators show effective refractive index changes of approximately 2‰ for driving voltages up to 100V.

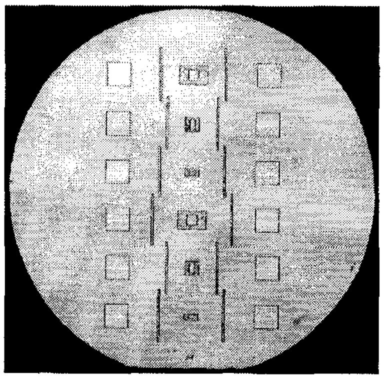

Fig. 8, 6 phase modulators fabricated on one 3 inch wafer pair.

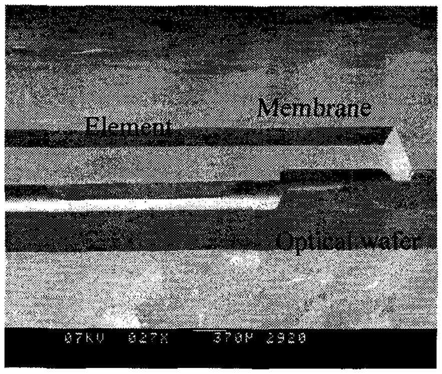

Fig. 9. SEM photo showing the cross section of an intensity modulator.

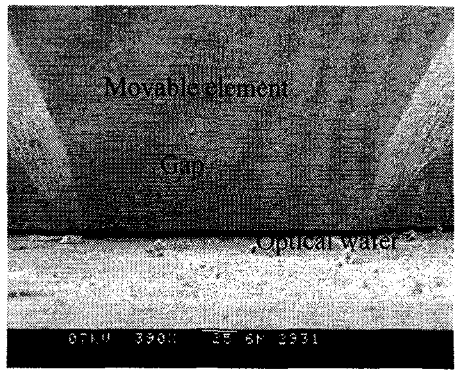

Fig. 10. A close look of the gap between element and optical wafer.

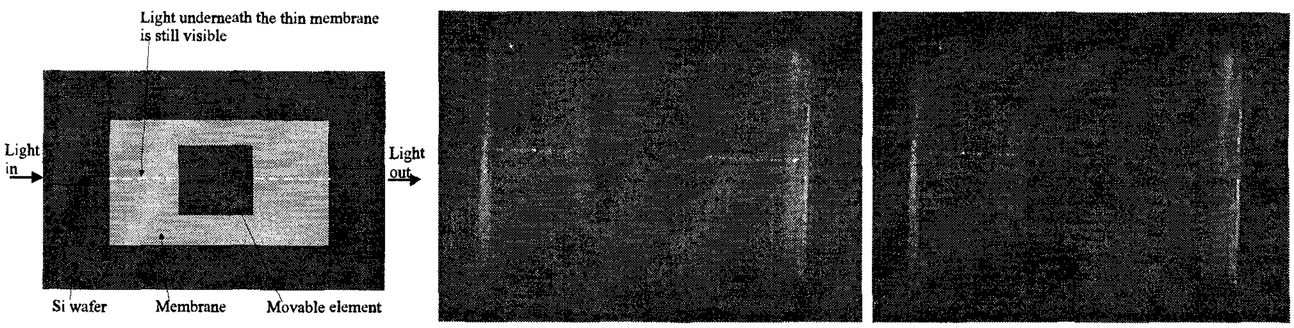

Fig. 11. Schematic view of the nanomechanical optical intensity modulator (left). Photos show that the light (the white beam) goes through the waveguide underneath the movable element (central square) when the device is not actuated (middle), and the light through the waveguide is attenuated underneath the mechanical element when a voltage is applied (right).

5. STICTION ELIMINATION

After wafer bonding, we observed very often that the movable elements are stuck to the optical wafer surface (Fig. 12). This stiction did not release spontaneously. We believe that the capillary force is responsible for the stiction of the elements. During RT bonding, due to random forces, the membrane is deflected downwards to the optical wafer. At that moment, the elements are stuck to the optical wafer surface because of the capillary force.

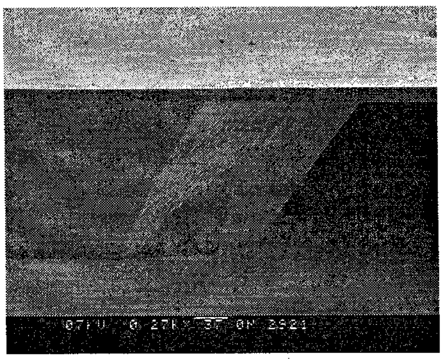

Fig. 12, SEM photo showing that one element is stuck to the surface of the optical waveguide wafer.

The adhesion condition of the element to the waveguide wafer surface can be derived. To simplify the analysis, we study the stiction condition of a square element to the optical wafer. The element is supported by a four side clamped square membrane, as shown in Fig. 2. In case a uniform force is applied on the surface of the element, the deflection of the element itself is supposed to be very small compared with that of the membrane. When the element gets contact with the wafer surface, the elastic energy stored in the membrane, U_e, is approximately given by [5]

$$U_e \approx \frac{16Ed_0^2h_1^3}{(k-1)^3l_e^2} \quad (1)$$

where d_0 is the gap, h_1 is the thickness of the membrane, l_e is the length of the square element, k is the length ratio of the membrane to the element and E is Young's modulus of the membrane.

The total surface energy between the two contacted surfaces is given by

$$U_s = l_e^2\gamma_s \quad (2)$$

where γ_s is the surface energy.

The condition for preventing adhesion is

$$U_s < U_e \quad (3)$$

Or

$$\gamma_{sc} = \frac{16Ed_0^2h_1^3}{(k-1)^3l_e^4} \quad (4)$$

where γ_{sc} is the critical surface energy below which the contacted surfaces will be free of stiction.

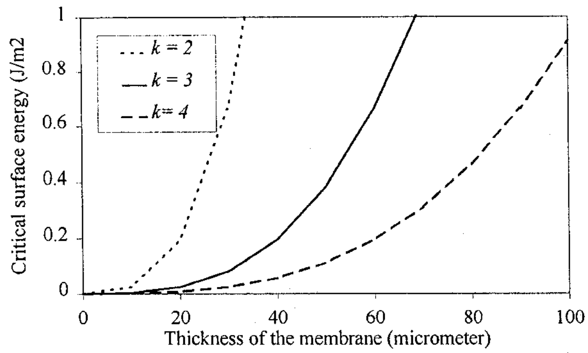

Fig. 13 Calculated critical surface energy as a function of the thickness of the membrane. In this calculation, E = 150 GPa, $d_0 = 8\times10^{-7}$ m, $l_e = 5\times10^{-4}$ m, and k = 2, 3, 4 respectively.

The surface energy for a hydrophilic silicon surface is about 0.1 to 0.3 J/m^2. The surface energy for a thin LPCVD layer that is deposited on top of oxidised silicon wafer is somewhat lower than prime grade polished silicon wafer. However, when the thickness of the membrane is thinner than 30 μm, the stiction between the movable element and the substrate covered with LPCVD Si_3N_4 layer is still possible, Fig. 13.

The adhesion of the elements to the substrate can be prevented in several ways. First, the membrane can be designed stiffer so that the recovery elastic energy is high enough to counterbalance the surface energy. The drawback of this measure is, however, that higher driving force is needed to activate the element. Second, the total surface energy of contacting surfaces can be reduced by decreasing the real contact area which can be achieved by roughening the waveguide surface or introducing bumps. Since roughening the whole waveguide surface will influence the performance of the waveguide channel, we decided to introduce bumps on the waveguide wafer surface within the contacting area but still 'far' (>50 μm) away from the waveguide channels. A schematic of the new design of a phase modulator that comprises of the bumps is shown in Fig. 14.

Of course there is a minimum height of bumps, under which the element surface is still possible stuck to the wafer surface. The design rule for the height of the bumps can be given by [6]

$$h \geq 2.6\left(\frac{R\gamma_s}{E}\right)^{1/2} \quad (5)$$

where h is half of the height of the bumps, R is half of the distance between the bumps.

According to the new design we have fabricated a new run of phase modulators. The bumps on the optical wafer were about 60 nm high. 6 phase modulators have been made on one wafer pair. And no stiction of the elements to the optical wafer surface were observed.

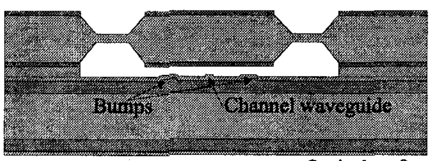

Fig. 14, Modified design of the phase modulator. Bumps have been designed on the waveguide wafers to prevent stiction.

6. CONCLUSIONS

A new method for fabricating the IO nanomechanical devices using silicon micromachining, CMP and aligned wafer bonding, has been demonstrated. Fabrication results on an intensity and a phase modulator show that this technology is very promising.

CMP is a essential process step to achieve voids-free wafer scale fusing bonding of the optical and the mechanical wafers.

For the intensity modulator, an extinction ratio of 43 dB has been achieved. The driving voltage is between 5 to 30 voltages. Even lower driving voltages are feasible after further optimisation of the structure. Preliminary results on the phase modulator show good future prospects.

Stiction of the elements to the waveguide surface was found to be a problem, that could be completely solved by introducing small bumps.

The aligned wafer bonding is also suitable for fabricating other IO nanomechanical devices, e.g. the IO tunable wavelength filters. In this case, further studies on the uniformity of the gap is necessary.

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