FABRICATION OF INTEGRATED BIMORPHS WITH SELF ALIGNED TIPS FOR OPTICAL SWITCHING IN 2-D PHOTONIC CRYSTAL WAVEGUI DES

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***Abstract* —This paper presents the fabrication technology for a novel class of photonic devices. This technology integrates silicon 2-D photonic crystal (PhC) waveguides and electrostatically actuated bimorph cantilevers with tips that are self-aligned relative to the holes of the PhC. The bimorph cantilevers modulate the propagation properties of the slab PhC depending on the proximity of the tips to the holes. The integrated devices have been successfully fabricated on wafer scale by surface micromachining techniques. First experiments with these devices have shown 80% throughput modulation using a square wave drive signal of 0 to 8 V at 1 kHz.**

***Keywords :* bimorph, opto-mechanical modulation, photonic crystal waveguide, self aligned tips.**

I- Introduction

Photonic crystals are periodic dielectric materials having a photonic band gap; a frequency range for which the light propagation is prohibited [1]. A row of missing holes in the PhC constitutes an optical waveguide, with the possibility to create sharp bends with low optical loss. Having a dynamic control on the PhC waveguide characteristics allows for the realization of modulated optical devices such as switches, attenuators and tunable filters which can form the miniaturized photonic components for integrated optical circuits. Propagation properties of a photonic crystal waveguide (PhC-WG) can be controlled by a variety of methods such as with electro-optics, liquid crystals, charge injection or by perturbation with an AFM tip [2]. Modulation by an integrated micro electrostatic actuator has advantages such as compactness of the device, ease of integration, designable switching speed (trade-off between switching voltage and switching speed) and near zero dissipation in the stationary state [3].

Silicon on Insulator (SOI) based air bridge PhCs have two distinct properties: a high index contrast which enables strong out of plane confinement and a symmetric cladding which promotes symmetry of the TE like and TM like slab modes. Also the air light line is higher than the silica light line, which increases the operating bandwidth of the device. However its geometry makes it difficult for monolithic integration with mechanical or electrical structures. In this paper we describe the fabrication technology for a novel class of devices where electrostatically actuated bimorph cantilevers are monolithically integrated with SOI based 2-D air bridge PhC-WG, on wafer scale, using surface micromachining techniques. The bimorph cantilevers, equipped with tips, can change the propagation properties of the PhC slab depending on the proximity to the holes. Since in high optical index contrast structures the exponentially decaying evanescent fields extend typically only a few hundred nanometers into the air cladding the required cantilever strokes for switching can be accordingly small. This implies that for fast actuation stiff cantilevers with resonance frequencies in the MHz range can be used. The integrated bimorph discussed here consists of an upper layer, which acts as the electrode and a lower layer that acts as a dielectric. The thermal missmatch between the layers and the deposition-induced stresses make it bend upward in the off-state [4]. The bimorph is actuated by application of a voltage between the upper electrode and the substrate. For the proof of concept, optical modulation of the integrated device is demonstrated.

II- Design

Figure 1 (A) shows the schematic illustration of the top view of the integrated device and (B) the cross-sectional view of the device in Y-direction. PhC-WGs and their access waveguides are fabricated on SOITEC SOI wafers by the silicon photonics platform ePIXfab [5], established at IMEC, Leuven. The thickness of the silicon device layer is 220 nm and that of the handle wafer is 700 µm. Before integration, the lower cladding is a 2 µm thick thermal oxide (refractive index n = 1.45) and the upper and side claddings are air (n = 1.0). After the integration lower and upper claddings are air.

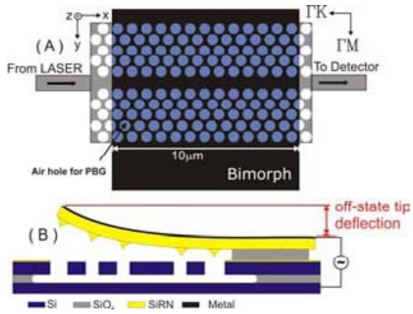

Figure 1: *Schematic illustration of the integrated device (A) top view (B) cross-sectional view in the Y-direction.*

The PhC-WG, designed to operate in the C-band (1530 – 1565 nm) of the telecommunication wavelengths, has a hole diameter of 270 nm and a periodicity of 440 nm. The waveguide in the PhC is formed by a line defect caused by removing a single row in the ΓK direction.

III- Fabrication

Figure 2 shows the fabrication flow for the integrated device. (a) PhC-WGs, are fabricated on an 8 inch SOI wafer by a 193 nm deep-UV lithography process at ePIXfab. This wafer is first diced into four pieces to fit into the 4 inch wafer systems of the MESA+ clean room. (b) On top of these wafers, first a 43 (standard deviation expressed in 3σ = 2.11) nm thick LPCVD [6] Silicon Rich Nitride (SiRN) layer (n = 2.202) is deposited which acts as a protective layer for the access waveguides during sacrificial layer etching (SLE). (c) This layer is etched from the backside of the wafer by reactive ion etching to later have access to the lower silicon electrode. In order to fabricate tips and to reduce losses during optical transmission, the protective nitride has to be removed from the PhC area of the wafer. For this reason, (d) a 93 (3σ = 1.00) nm thick TEOS (tetra-ethyl-ortho-silicate) layer is deposited as an etch mask layer and (e) a dark mask (Etch mask) is used to define the etch windows in the PhC area. After the lithography, the wafer is first ozone treated to make the TEOS layer hydrophilic and then chemically etched in BHF (1:7) to remove the TEOS from the etch windows. (f) After stripping the photoresist, the protective nitride is removed from the etch window by 85% H_3PO_4 at 180°C. The measured selectivity as found from the etch-rates was SiRN : TEOS = 1.83:1. The thickness of the remaining TEOS layer is 49 nm.

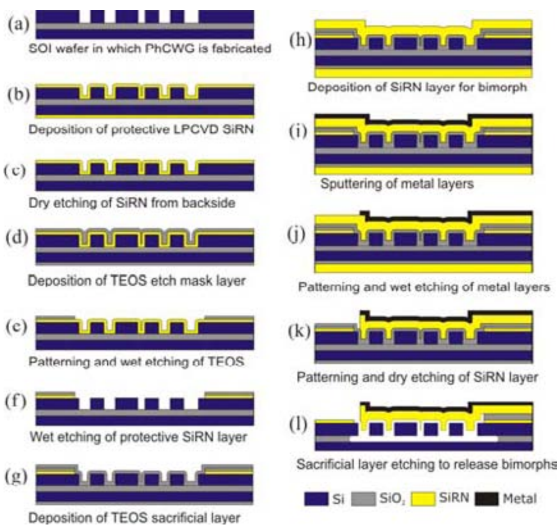

Figure 2: *2-D Fabrication flow*

(g) Following this, the SOI wafers are first coated conformally by a 105 (3σ = 1.48) nm thick TEOS sacrificial layer (SL) and then (h) by a 1061 (3σ = 41.75) nm thick SiRN layer (n = 2.18). (i) A 50-nm thick gold (Au) is chosen as the upper electrode layer. A thin layer of chromium (Cr) is used as an adhesive layer for gold where the thickness of Cr layer is selected to be as low as possible, to reduce the stress in the electrode layer. The measured total thickness of the electrode layer (Au + Cr) by Dektak-V.8 surface profiler is 62.93 nm.

After the pattern transfer from the masks, (j) Cr and Au layers are etched by wet chemical methods and (k) the SiRN bimorph layer by reactive ion etching. Finally, (l) SLE is done by BHF (1:7) followed by freeze drying release technology [6]. During SLE the lower cladding of the PhC is also etched though the PhC holes and through the sides of the PhC. This transforms the PhC into a symmetric air bridge membrane, having a larger transmission window. Timed SLE also defines the anchor point for the bond pads which are designed to be 300 µm x 300 µm. We have fabricated bimorphs with lengths varying from 40 µm to 100 µm at a fixed width of 10 µm for all cases.

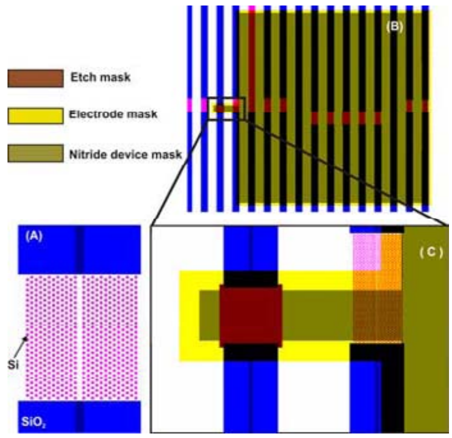

Figure 3: *Devices as drawn in the mask: (A) PhC-WG, (B) Bimorph with its bond pad on top of the PhC-WG and (C) zoomed view of the integrated device.*

The fabrication is a three-mask process where all the masks use positive photo resist for the UV lithography. The first mask is used to open the SiRN on the PhC-WG areas. The second mask is used for pattering the metal layers and the third mask is used for patterning the SiRN bimorph device layer. Figure 3 shows the different masks drawn for integrating the bimorph cantilevers with the PhC-WGs. Figures 4-7 show HRSEM images of the integrated device.

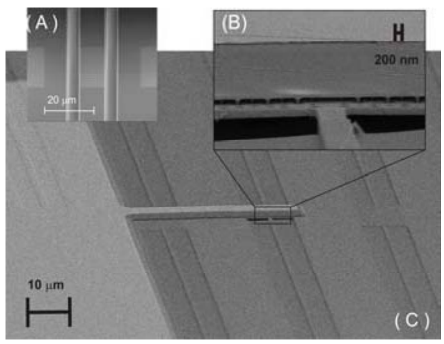

Figure 4: *SEM images of (A) grating couplers at the end of the access waveguides, (B) tips self aligned with respect to the holes of the PhCWG and (C) an integrated device.*

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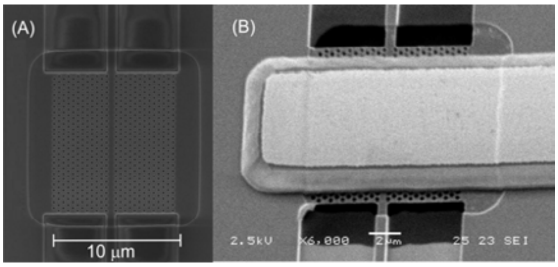

Figure 5: *(A) Top view of a PhC-WG after the protective nitride has been removed from the PhC area and (B) oblique view of the final integrated device.*

IV- Discussions on fabrication

One of the important steps to monitor was to check whether the protective nitride is completely removed from the PhC holes. In order to analyze this, the bimorph is removed from one of the integrated devices. Figure 6(A) shows this device where part of the PhC-WG membrane is broken apart. The top view shows partially etched lower cladding layer and the inset shows SiRN rings at the bottom of the PhC holes.

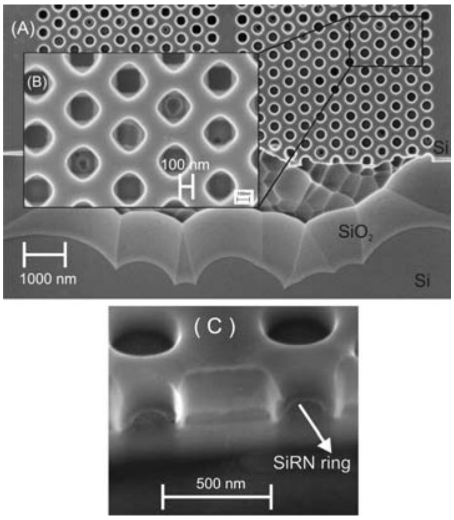

Figure 6: *SEM pictures of (A) Top view of PhC holes after freeze drying (B) SiRN rings inside the holes (C) Cross-sectional view after FIB milling.*

For a further investigation on the shape of the SiRN rings, we have milled PhC holes with focused ion beam (FIB) as shown in figure 6C. After milling, they were etched for 2 min using 1% HF to make the rings partially release. In order to compare the optical loss introduced by the SiRN rings we have compared the transmission of light through a planar waveguide and the PhC-WG. The losses in both waveguides are approximately the same indicating that the SiRN rings inside the holes do not introduce large optical losses.

From figure 6C, it is clear that the side walls of the PhC holes are not exactly at right angles but at an obtuse angle (< 10 degree). This geometry together with the conformal deposition makes the tips to be in conical shape. The depths of the tips are directly related to the thickness of the sacrificial TEOS layer. By increasing the thickness of SL greater than 135 nm (half of PhC hole diameter), PhC holes will be completely filled which later results in a flat bimorph having no tips. Hence for fabricating tips, thickness of SL should be less than 135 nm. Decreasing SL thickness further increases the diameter of the tips. Figure 7 shows the fabricated tips self aligned relative to the PhC holes. During SEM imaging bimorph advances close to the PhC-WG due to charging of the SiRN layer.

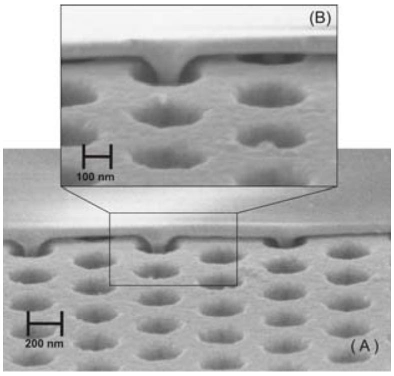

Figure 7: *Cross sectional of the self aligned tips.*

Another critical step during the fabrication is the selective etch of a thick (≈ 1 μm) SiRN layer from a thin (≈ 100 nm) TEOS layer. Non-uniformity in both the layers makes the situation complex and, hence, the uniformity in the deposited TEOS and the SiRN layers are very important to be monitored. The selectivity between SiRN and TEOS layers by reactive ion etching at 10°C, with 10 mTorr pressure, using CHF_3/O_2 gas mixture is SiRN : TEOS = 1.5:1. By carefully checking the thickness and uniformity of both the layers with dummy wafers and by analyzing the loading effect, we could successfully etch 1 μm SiRN layer with a 30 nm over etch into the SL.

Undesired etching of the silicon device layer by BHF with light during SLE was also critical. In order to avoid this, SLE was done in a dark environment.

The actual length of the fabricated bimorph is increased from the design length due to the undercut at the anchor points during SLE. The measured undercut by the optical microscope is 5.5 μm. In general this undercut will present itself as an increase of the effective bimorph length with associated lower resonance frequency and pull-in voltage [4].

Removing the protective SiRN from the PhC area leaves the conformal deposition of bimorph layer with a step (figure 5B). Due to this and by the upward deflection of the bimorph, the gap between the bimorph and the PhC-WG is varying along the length of the beam. The gap near the base of the bimorph is the combined thickness of the protective nitride layer, the remaining TEOS etch mask layer and the sacrificial TEOS layer. But the gap on top of the PhC-WG is only due to the thickness of the sacrificial layer and by the upward deflection of the beam.

V- Optical measurements

The optical modulation of an integrated device is measured using a set up as shown in figure 8. Infrared light (1530 nm) from a tunable laser of 1 mW output power is coupled to the input access waveguide with the help of a cleaved fiber end and grating coupler (figure 4-A), through a polarization maintaining fiber (PMF). Output light is recollected from an output grating by another cleaved fiber and is sent to the photodetector through a single mode fiber (SMF).

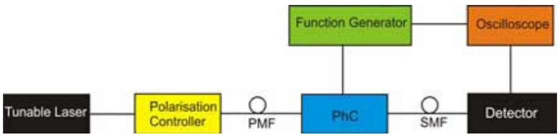

Figure 8: *Schematic representation of the optical modulation experimental set up.*

We have observed ON-OFF switching of the integrated device by applying a square wave drive signal of 0 to 8 V at 1 kHz (figure 9). The time constant for the signal rise time is 85 µs and that for the fall time is 95 µs. The time response of the bimorph is also measured by a Laser Doppler Vibrometer (Polytec MSA400). Figure 10 shows both the rise and fall time to be about 2 µs. Further investigations have shown that the increased time delay in the optical modulation measurement is caused by the slow response introduced by the photodetector.

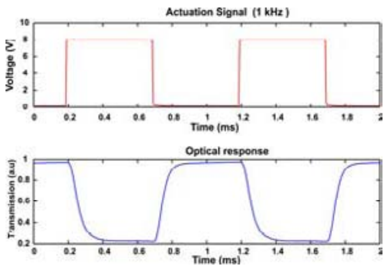

Figure 9: *Optical modulation at 1 kHz with a square wave drive signal of 0-8 V.*

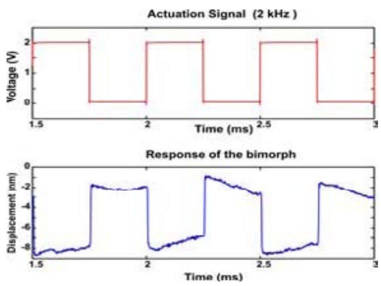

Figure 10: *Time response of the bimorph at 2 kHz with a square wave drive signal of 0-2 V measured by a Laser Doppler Vibrometer.*

VI- Conclusion

We have reported a fabrication process that enables the forming of electrostatically driven bimorph cantilevers with sharp tips that are self-aligned with respect to photonic crystal slab-waveguides (2D photonic crystal). This CMOS compatible wafer-scale technology allows for the fabrication of a new class of devices exploiting modulation of the (exceptional) waveguiding properties of PhC-WGs by changing the proximity of the tips to (and into) the holes of the PhC. As an example a MEMS integrated PhC-WG modulator has been fabricated. Optical modulation of the device at 1 kHz with a square wave drive signal of 0-8 V has been demonstrated.

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