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Development of high-yield fabrication technique for MEMS-PhC devices

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Abstract: We propose a high-yield fabrication processing technique for the MEMS (micro electro mechanical system) modulators integrated with two-dimensional photonic crystal waveguides. Polysilicon microactuators for evanescent modulation was successfully developed by using the vapor hydrofluoric-acid releasing technique for stiction-free sacrificial release, during which the SOI photonic-crystal waveguides were protected under the LPCVD silicon nitride film. Post-release anneal was found to be needed to remove the byproduct made by the reaction of hydrofluoric acid with silicon nitride film. Preliminary optical modulation result (-2 dB modulation with 86 V) was experimentally obtained.

Keywords: optical modulators, electrostatic actuators, photonic integrated circuits, 2-dimensinal photonic crystal waveguide

Classification: Micro- or nano-electromechanical systems

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1 Introduction

Optical waveguides of high index contrast has significant effect in reducing the device size of photonic integrated circuits (PIC). In particular, photonic crystal (PhC) wavegiude can be designed to have sharp bending corners with ideally zero propagation loss, which is necessary for the ultimately small device sizes. Silicon is an enabling material for such waveguides because of the high refractive index and the micro/nano fabrication compatibility [1].

We have developed a fabrication process that is compatible with MEMS-PhC devices [2, 3] by using the polysilicon surface micromachining technique combined with the silicon-on-insulator (SOI) bulk micromachining technique. The original concept of MEMS optical modulator combined with the conventional optical waveguides has been proposed by Dangel and Lukosz in 1997 [4]. PhC version of such micromechanical optical devices are studied by Takahata et al.; they used an AFM (atomic force microscopy) for mechanically altering the characteristics of a PhC wavelength filter [5]. Kanamori et al. independently used a microfabricated metal cantilever to construct a MEMS-PhC type optical switch [6]. Different from their work, our study is focused to make yet smaller lightwave circuit systems by using the PhC waveguides integrated with MEMS optical modulators. Compared with the solid-state optical modulators such an electro-absorption modulator integrated with a ring resonator [7], MEMS-type modulators are generally slow in switching speed and cannot be used for fast packet switching applications. However, MEMS-PhC based devices can be made as small as a few microns in principle thanks to the relatively large contrast of refractive index change effectively induced by the micro/nano mechanical motion.

2 MEMS-PhC Modulator Design

Figure 1 illustrates the PICs with micromechanical modulator suspended over the PhC waveguide for optical intensity modulation; a pair of silicon-

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nanowire waveguides are attached for in- and out-coupling of low loss. The suspended structure is driven to the close vicinity of the waveguide, where it is called the evanescent field, by using the electrostatic attraction force from the counter electrodes. The light traveling in the waveguide experiences the change of effective refractive index, and is intensity-attenuated by the evanescent coupling with the suspended silicon beam. Finite Difference Time Domain (FDTD) method was used to estimate the optical intensity modulation for the device with a silicon piece of 5 um wide and 10 um long (measured in parallel with the waveguide) is suspended at a 300 nm height over the PhC waveguide; we found 5 dB attenuation when the piece was brought into a 200-nm-gap, where electrostatic pull-in was expected. Modulation could be controlled in an analog manner by gradually changing the position in the first 100 nm range.

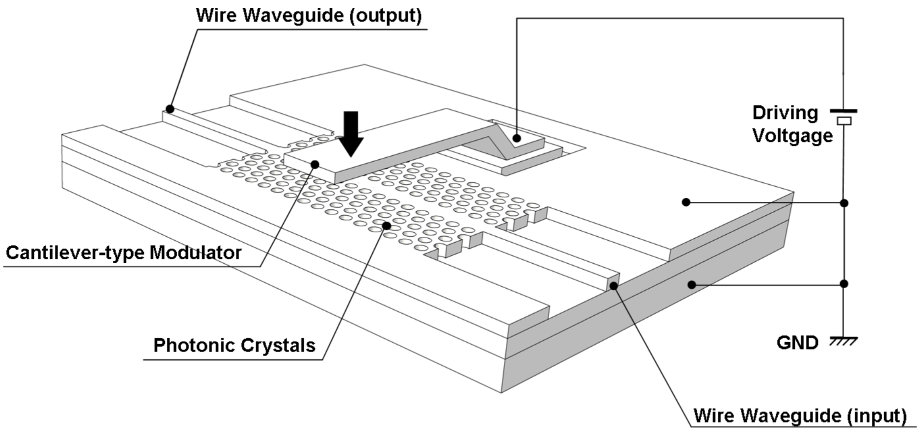

Fig. 1. Photonic crystals / Si-wire waveguide with MEMS/NEMS

3 Fabrication and experiment

As shown in the fabrication sequence in Figure 2, sub-micron structures of the photonic crystals and the waveguide were first made by the electron-beam (EB) lithography and high aspect-ratio dry etching in a 200-nm-thick active layer of an SOI wafer. The surface was then covered with a protective low-pressure chemical vapor deposition (LPCVD) silicon nitride layer of about 40 nm thick, which was chemically inert to the vapor of hydrofluoric (HF). The surface was again covered with a sacrificial LPCVD silicon oxide layer of over 300 nm thick, which corresponded to the initial separation of the optical modulator. After forming the anchoring sites, a structural layer of about 400-nm-polysilicon was deposited and patterned into the micro cantilevers or bridges. Finally, the micromechanical structures were sacrificial-released by the partial etching in wet HF, followed by the complete release in vapor HF [8], where SiO_2 reacted with HF to make volatile H_2O and SiF_4. At this moment, we frequently found a chemical byproduct as a result of vapor HF reaction with the underlying passivation silicon nitride layer. The residue

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was thought to be a mixture of NH_4HF_2 and $(NH_4)_2SiF_6$ [9], which were not volatile at room temperature. The residue was completely removed by annealing the device for 1 minute at 200 degree C.

Figure 3 (a) shows scanning electron microscope (SEM) images of the MEMS-PhC optical modulators. Cantilever structures over the PhC were successfully released without causing in-process stiction. Silicon-wire waveguides (designed to be 0.5 microns wide, measured to be 0.7 microns wide on SEM) was attached to the SOI PhC waveguide (PhC hole designed to be 0.4 microns in diameter at a 0.6 micron pitch) for low-loss input and output coupling with fibers, as well as to save processing time of EB lithography.

We used piezo-stage controller to position the single-mode optical fibers for coupling with the wire waveguide. Total insertion loss at a wavelength of 1580 nm was found to be 27 dB, which was mainly attributed to the optical coupling loss at the input and output ends of the waveguide and to the propagation loss of the PhC waveguide. Figure 3 (c) shows the waveform of the optical output modulated with a sinusoidal voltage of over 40 Vpeak with a bias voltage of over 40 Vdc (cantilever tip displacement 125 nm at

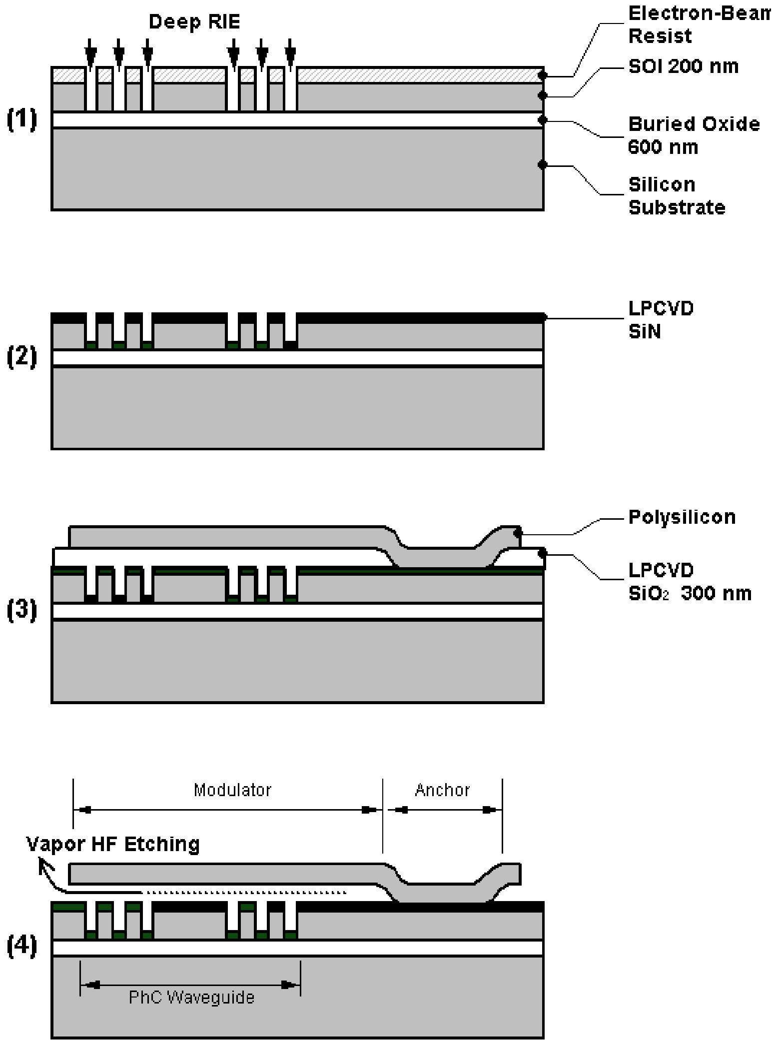

Fig. 2. Fabrication process flow

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67 Vdc measured by Laser Doppler Vibrometer), which was higher than our analytical simulation because the deposited polysilicon was found to have high electrical resistance, and that the polysilicon cantilever could not deliver the driving force to make electrostatic force effectively. Modulation depth of 2 dB at peak voltage of 86 V was experimentally observed as a proof-of-concept demonstration of the MEMS PhC modulator.

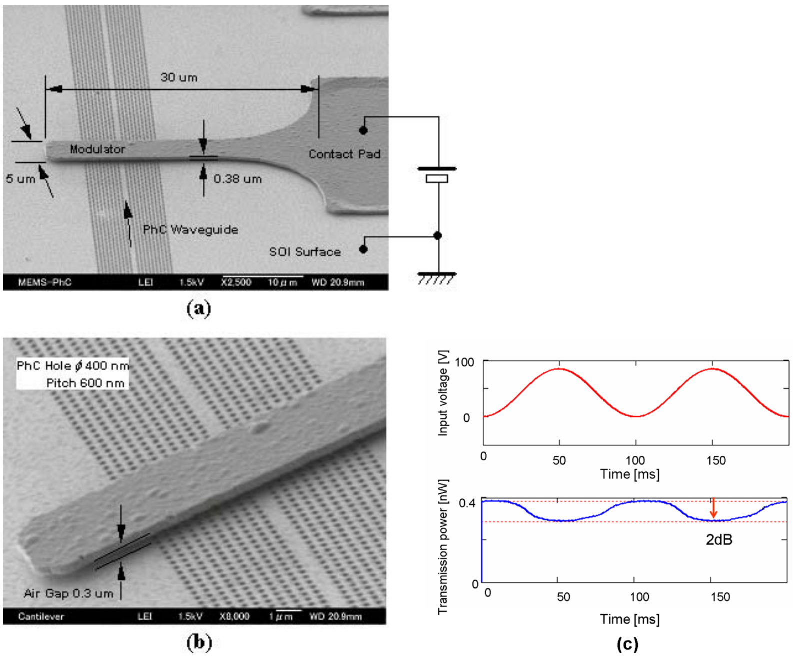

Fig. 3. (a) SEM pictures of cantilever type, (b) close up view of cantilever beam and (c) demonstration of the PhC modulator: modulation voltage and modulation waveform measured at the output port.

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