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Si/SiO_2 Bilayer Beam Structure for Photoelastic Control of Si Photonic Devices

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1. Introduction

In Si photonics, resonator structures such as microring [1] and photonic crystal cavities [2] are widely studied for wavelength filters, optical modulators and light-emitting devices. For such devices, the resonance wavelength, i.e., the operation wavelength, is determined by the structural parameters and the refractive indices. However, Si has a large thermo-optic coefficient of 1.9×10^{-4} K^{-1} in 1.5 μm wavelength and 295 K [3], resulting in the poor stability of resonance wavelength under a temperature fluctuation. In order to lock the operation wavelength under a temperature fluctuation, we have recently proposed the use of microbeam (micro-cantilever) structure with an elastic deformation, on which the photonic devices are formed [4]. Applying a (electro-)mechanical stress to bend the Si beam, the refractive index of Si changes due to the photoelastic effect. As a proof of concept, Si microbeam structure has been fabricated from a Si-on-insulator (SOI) wafer, and based on the photoluminescence (PL) measurements, a reduction of bandgap energy more than 0.2 eV has been achieved under a uniaxial strain of 1.5% [4]. This indicates the change in the extinction index, which should accompany the change in the real part of refractive index.

In this paper, a microbeam structure of Si/SiO_2 bilayer, shown in Fig. 1, is proposed to efficiently induce the photoelastic effect in Si. Contrary to the previously-studied microbeam of Si single layer [4], a tensile strain is generated throughout the Si layer by applying a downward bending. Simulated strain distribution and a fabrication of Si/SiO_2 bilayer beam are presented. PL spectra are also shown, suggesting the change in the refractive index due to the bending.

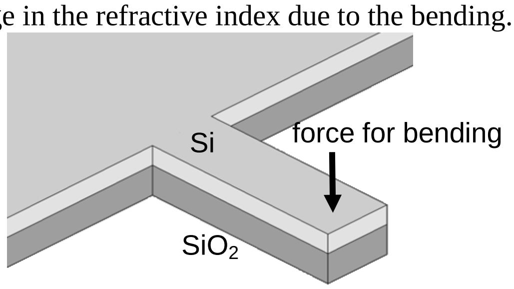

Fig. 1. Schematic structure of Si/SiO_2 bilayer beam.

2. Simulated distribution of stress in Si beams

For the simple microbeam structure of Si single layer, tensile and compressive stresses are simultaneously generated under a deformation on the top and bottom sides of Si beam, respectively, as shown in Fig. 2(a). Although a stress as large as 500 MPa can be generated near the surfaces of fixed edge of Si beam, the stress remains to be almost zero at the center of Si beam in the vertical direction. Since the mode for the propagated light in the photonic devices is usually located at the center of Si film, the photoelastic effect could not be large enough. The difference of polarity of stress between the upper and lower regions would be also unfavorable to use the photoelastic effect.

In order to shift the light confinement towards the upper part of Si beam, we propose a microbeam structure of Si/SiO_2 bilayer, shown in Fig. 1. As shown in Fig. 2(b), a tensile stress is generated thoughout the Si film of Si/SiO_2 bilayer beam structure. Since the lower half of the beam, having a compressive stress, is replaced by a lower-index SiO_2, the light should propagate in the tensile-stressed Si in the upper part.

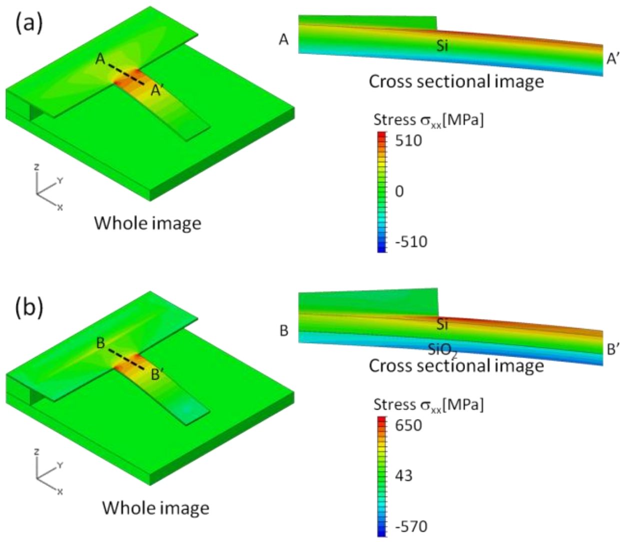

Fig. 2. Simulated stress σ_{xx} distributions for microbeam structures of (a) Si single layer and (b) Si/SiO_2 bilayer.

3. Fabrication and PL characterization

3.1 Fabrication

As in ref. [4], microbeam structures of Si single layer can be simply fabricated, using a lithography and an etching of top Si layer of SOI structure, followed by an isotropic wet etching of underlying buried SiO_2 (BOX) layer in a HF solution. There should be several approaches to fabricate the Si/SiO_2 bilayer beam. Here, we fabricated as follows. First, a beam of Si single layer was fabricated from an SOI wafer (top Si of 250 nm and BOX of 3000 nm), similar to ref. [4]. An electron-beam lithography (EB) and a reactive ion etching (RIE) of Si with a mixture of Cl_2 and O_2 gases were carried out, followed by a dip in a diluted HF solution. The length of beam is 15 μm, while the width is 5 μm. Next, a thermal oxidation of Si was performed to cover the top and bottom surfaces (the sidewalls as well) with a SiO_2 layer. Here, a ~120-nm-thick SiO_2 was grown, remaining a 140-nm-thick Si layer. Then, the top SiO_2 layer was selectively removed with a dry etching, resulting in the formation of Si/SiO_2 bilayer beam. Figure 3 shows a typical optical microscope image. The beam showed an upward bending because of the strain relaxation in SiO_2, which is generated due to the difference of thermal expansion coefficient between Si and SiO_2. An undercut of SiO_2 as large as 8 μm is also seen at the edge of slab region, which may influence the strain in Si beam generated by the mechanical deformation.

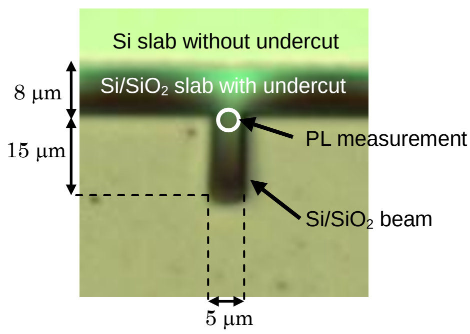

Fig. 3. A typical optical microscope image taken for a Si/SiO_2 bilayer beam

3.2 PL spectra

In order to observe the change in the refractive index under the mechanical stress, micro-PL measurements were performed at room temperature. As in ref. [4], a micro-prober tip was used to depress the free edge of beam, applying a strain at the fixed edge. Figure 4 shows typical PL spectra with and without the bending induced by the prober tip. Broad spectra around 1.1 μm were observed due to the interband transition in Si beam. Small oscillations are also found to be superimposed. This oscillation is derived from the Fabry-Perot resonances between the sidewalls of beam structure. In the case of small strain (depression of nominally 1.5 μm, the half of spacing between Si beam and Si substrate), the resonance peaks were shifted towards the longer wavelength. The observed red shift is probably ascribed to the increase of the refractive index of Si beam caused by the strain. However, the peaks were shifted towards the shorter wavelength by applying a further stress, where the bottom surface of beam was in contact with the surface of Si substrate (depression of 3 μm). Taking into account that the PL intensity was much smaller than that for the beam of Si single layer, the fabricated Si/SiO_2 bilayer beam might be damaged after the etching of thermally-grown SiO_2 layer on Si, causing a plastic deformation under the strong stress. The large undercut, extended to the slab region, may also influence the strain distribution, but further studies are necessary to clarify this point.

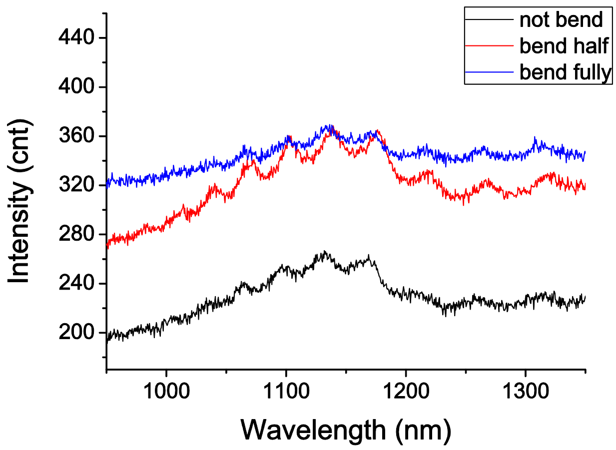

Fig. 4. Typical PL spectra obtained with and without mechanical deformation.

4. Summary

A microbeam structure of Si/SiO_2 bilayer was proposed to efficiently induce the photoelastic effect in Si. The fabricated beam showed the change in the resonance peak positions applying a mechanical stress, suggesting the change in the refractive index of Si.

References

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