Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 282-283

E-3-4

Photoelastic Effect in Silicon Ring Resonator

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1. Introduction

Signal delay in metal interconnection becomes serious problem to limit performances of ultra large scale integrated circuits. Optical interconnection is promising method to overcome this problem. Optical modulator is necessary for optical interconnection. Recently, Jacobsen *et al*. reported stress induced Si becomes electro-optic material [1]. They fabricated Mach-Zehnder interformeter (MZI). We propose ring resonator optical modulator as shown in Fig. 1. Ring resonator is smaller than MZI, therefore, it is suitable for integration. But the influence of stress to the shift of resonance wavelength is complex and difficult, because stress raises not only electro-optic effect as described above but also change of refractive index [2]. In this paper, we introduce stress to Si mechanically and estimate the change of refractive index of stress induced Si, which is known as photoelastic effect.

2. Experimental

The race-track resonator as shown in Fig. 2 was fabricated. Resonance wavelength λ_{res} of race-track resonator with circumference l is given by

$$\lambda_{res} = n_{eq}\frac{l}{m}, \tag{1}$$

where n_{eq} is equivalent index of waveguide and m is an arbitrary integer.

By electronic beam lithography and the reactive ion etching, silicon-on-insulator wafer was patterned and the race-track resonator was obtained. The cross sectional structure of the waveguide is shown in Fig. 3. Figure 4 shows the gap image between waveguide and race-track resonator.

Measurement system for the ring resonator is shown in Fig. 5. Wavelength dependence of race track resonator was measured by using tunable laser and IR vidicon camera. Method of inducing stress to sample is shown in Fig. 6. The Si substrate is warped by rotating screw. The position dependence of slope angle was measured by using the measurement system as shown in Fig. 7. The curvature radius R and the strain $\Delta x/x$ are calculated from this measurement because those values are related to slope angle and position on Si substrate. The strain $\Delta x/x$ of surface on Si substrate is related to curvature radius R and the thickness of Si substrate D as shown in Fig. 8 where D is 250 μm. The curvature radius R is approximated to $(180x)/(\pi\theta)$ for small angle θ.

3. Results and Discussion

We estimate shift of resonance wavelength $\Delta\lambda_{res}$ when stress is induced. From eq. (1), the relative shift $\Delta\lambda_{res}/\lambda_{res}$ is given by

$$\frac{\Delta\lambda_{res}}{\lambda_{res}} = \frac{\Delta l}{l} + \frac{\Delta n_{eq}}{n_{eq}}, \tag{2}$$

where Δl and Δn_{eq} are variation of circumference of race-track and equivalent index of waveguide.

3.1 Measurement of the strain

The position dependence of slope angle of strained Si substrate is shown in Fig. 8. The curvature radius is found as 865 mm. This result leads that the strain $\Delta x/x$ in Fig. 7 is $(1.5\pm0.1)\times10^{-4}$. The sample holder is designed so that the strain is induced only one direction. For this reason, circumference of race-track is expanded into one direction and relative variation of circumference of race-track $\Delta l/l$ is $0.72(\Delta x/x)$. The coefficient of 0.72 is appeared from the fact that the circumstance of the race-track resonator consists of vertical and horizontal components with respect to the stress direction. From eq. (2), this effect occurs the relative shift of resonance wavelength of $(1.1\pm0.1)\times10^{-4}$.

3.2 Relative shift of resonance wavelength

Figure 10 shows the wavelength dependence of the race track resonator characteristics without stress. The peak position of drop port agree with the valley position of through port. Therefore, this wavelength dependence comes from resonance characteristics. Next, we measured output for through port around resonance wavelength with and without stress as shown in Fig. 11. The relative shift $\Delta\lambda_{res}/\lambda_{res}$ is $(2.1\pm0.3)\times10^{-4}$.

The two effects of stress for the shift of resonance wavelength are shown in Fig. 12. The effect of relative variation $\Delta n_{eq}/n_{eq}$ from stress is found as $(0.9\pm0.4)\times10^{-4}$. Relative variation of refractive index of Si was reported as −10-57 % of certain strain [3]. Our measurement results agree with this value within error under the same strain.

4. Conclusion

We have investigated the stress dependence of the resonance wavelength of the Si race-track resonators. We have succeeded in separation of the reasons to expansion of the circumference length of the race-track resonator and the pure photoelastic effect. And the photoelastic effect of Si agree with the value in ref. 3 within error.

Acknowledgements

This work was supported in part by 21st Century COE program "Nanoelectronics for Tera-Bit Information Processing", from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

[1] R. S. Jacobsen *et al*., Nature **441**, 199 (2006).
[2] D. K. Biegelsen, Phys. Rev. Lett. **32,** 1196 (1974).
[3] H. Rho *et al*., J. Appl. Phys. **90**, 276 (2001).

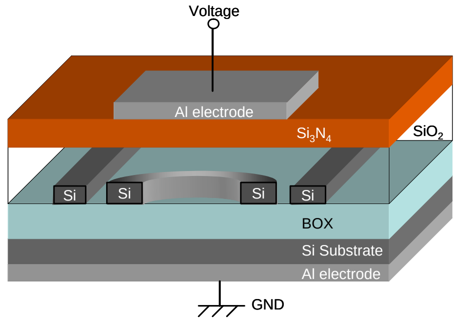

Fig. 1 Cross sectional structure of ring resonator optical switch. Si_3N_4 layer induces stress and Si becomes electro-optic material. Light is modulated by applying electric field between electrodes.

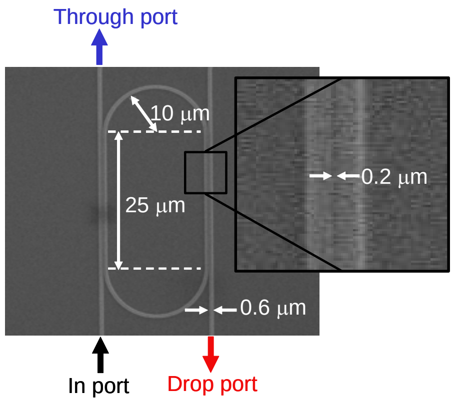

Fig. 2 SEM photograph of the fabricated race-track resonator.

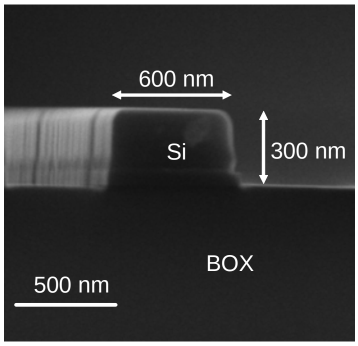

Fig. 3 Cross sectional SEM photograph of the waveguide. Thickness of the BOX layer is 1.1 μm.

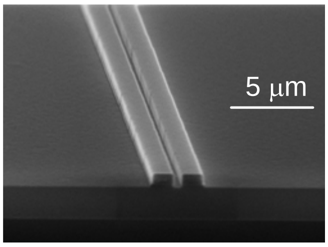

Fig. 4 SEM photograph of the gap between waveguide and race-track resonator.

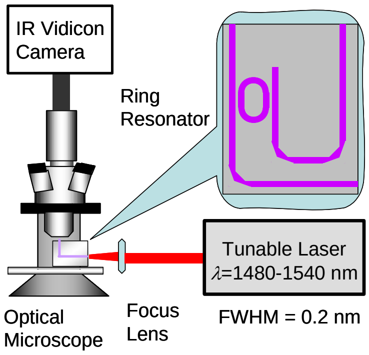

Fig. 5 System used to measure wavelength dependence of the ring resonator characteristics.

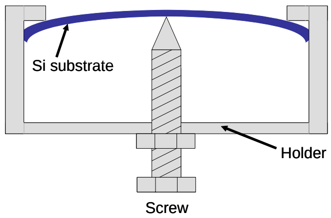

Fig. 6 Method of inducing stress to Si substrate.

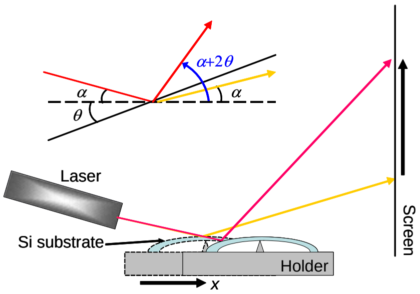

Fig. 7 Measurement for slope angle θ of strained silicon by using laser.

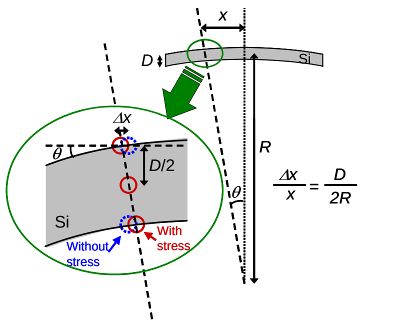

Fig. 8 Estimation of displacement of strained Si substrate from slope angle θ.

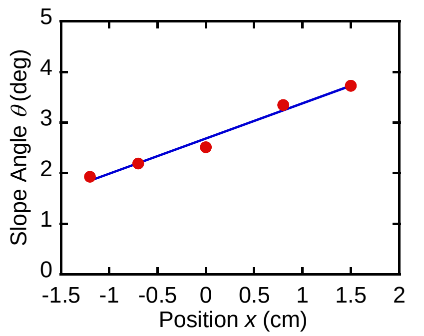

Fig. 9 Position dependence of slope angle of strained Si substrate. Horizontal point is at -3.9 cm and the curvature radius is found 865 mm from this result.

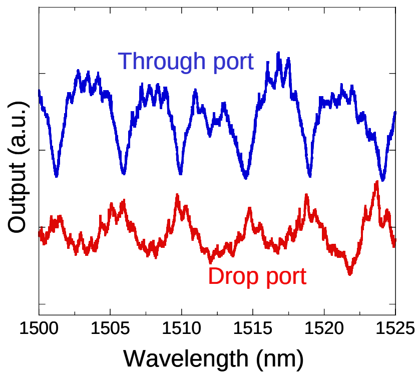

Fig. 10 Resonator characteristics of the fabricated race-track resonator without stress.

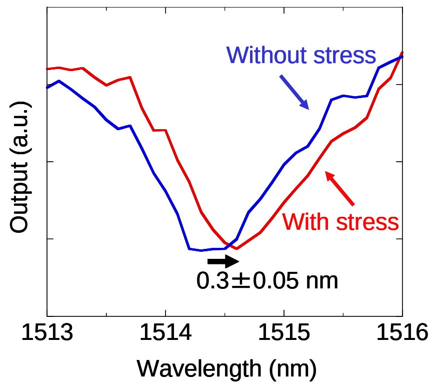

Fig. 11 Output of through port of the fabricated race-track resonator. The shift of the resonance wavelength is 0.3±0.05 nm.

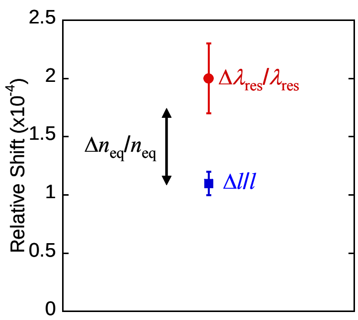

Fig. 12 Comparison among two effects of stress, the shift of circumference and refractive index of race-track resonator, and the shift of resonance wavelength.