Stress-optical Effect Analysis on Silicon-on-Insulator Planar Waveguide

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***Abstract*—Stress application can be used to modify the optical properties of a device. The stress-optic effect has been experimentally measured in strained silicon, making it a promising candidate material for realizing active photonic devices, such as optical modulators and switches. In this paper, we investigated the stress-optic effect induced by applied strain gradient in the silicon optical waveguides. The relation between stress-optic effect, strain, birefringence and the change in the optical properties is investigated. The structure of nanometer waveguide is analyzed by using the Multiphysics modeling to show the effects of stress analysis. The stress effects are then evaluated by the Structural Mechanics modules.**

***Index Terms*— Birefringence; Silicon Photonics; Strain; Stress-Optical Effect,**

I. Introduction

Recently, the study of stress-optic effect in silicon photonic structures has gained remarkable interests in a wide field of applications. Essentially, the characteristic of light is representative of its amplitude, phase, frequency and polarization. Any of these parameters may be changed due to the external influences of stress, strain, temperature and so on. This may lead to an anisotropic change in the material refractive index and thus, material birefringence. The possibility of controlling the refractive index is necessary for some optical applications. In recent years, strain silicon photonics have been growing attention by many researchers working in the photonic integrated circuits (PICs), mainly for devices fabricated on the silicon-on-insulator (SOI) [1]-[6]. SOI is widely utilized due to the wide range of advantages, such as low cost and easy integration with the conventional CMOS technology. However, the controlling of birefringence becomes challenging due to the SOI high index contrast material. Therefore, current researches have been focusing on analyzing the stress-optical effect in order to reach the minimum birefringence value [7]-[8]. It is a pre-requisite to accurately analyze the residual thermal stress generated in the SOI waveguide in order to control the existence of birefringence during fabrication. Thus, adversely affecting the transmission of light and performance of the devices. In contrast, birefringence can also be used to improve the physical properties of nanometers waveguide, such as microelectromechanical (MEMS) [9-10]. The stress-optic effect in the optical waveguides, which is great enough to adjust the refractive index profile, significantly, is eventually required in designing an active photonic device, such as optical modulators. A suitable core size of SOI waveguides should be compromised between the low birefringence and the competitively compact device size [11]-[13]. Therefore, in this research paper, the effect of variation waveguide geometry to the stress-induced birefringence will be studied, demonstrated and analyzed on a 0.3-µm thick SOI waveguide. A fundamental knowledge of the effect of stress-optic is crucially important in photonic device modeling, as well as to help reducing birefringence during fabrication by optimizing the device design geometry. Therefore, a quantitative understanding of stress distributions in SOI waveguides and their impact on the optical properties of devices is mandatory to the design engineers.

Commercially available FEM solver software by Comsol® Multiphysics was utilized to solve the strain and modal distribution in the waveguide. Under proper boundary conditions, Comsol® solves the static equilibrium equation that satisfies stress-strain relations, thermal effects and strain-displacement relations.

II. Theory

The existence phenomenon as the stress-optical effect can cause changes in the silicon refractive index through the photo-elastic effects. During the fabrications process, due to the different thermal expansion coefficients of core and cladding material, the waveguide will become strained. This stress will cause the indices to become anisotropic and increases the birefringence in the waveguide.

It is crucial to understand the method of stress analysis where it started with the calculation of stress distribution and changes in the refractive index due to the stress-optic effect. Then, the birefringence and propagation properties are obtained and performed by the new refractive index. In this research, the effect of induced stress in the waveguide is determined by using generalized plain strain [14]. The new refractive indices are given by:

$$n_x = n_0 - C_2\sigma_x - C_1(\sigma_y+\sigma_z) \quad (1)$$

$$n_y = n_0 - C_2\sigma_y - C_1(\sigma_z+\sigma_x) \quad (2)$$

$$n_z = n_0 - C_2\sigma_z - C_1(\sigma_x+\sigma_y) \quad (3)$$

where C_1 and C_2 are the stress-optic coefficients and n_0 is the isotropic refractive index of the unstressed waveguide material. Meanwhile, n_x, n_y and n_z are the principal diagonal components of the anisotropic refractive index tensor when stress-optic effect is united. For the mode analysis, the Wave Optics Module's Electromagnetic Waves, which is the Frequency Domain is used and the wave is assumed as:

$$E=E(x,y)\,e^{j(\omega t-\beta z)}=(E_x(x,y),\,E_y(x,y),\,E_z(x,y))\,e^{j(\omega t-\beta z)} \quad (4)$$

where ω is the angular frequency, β is the propagation constant and the effective mode index, $n_{eff}=\beta/k_o$. The simulation is set up with the electric field components E=E (x,y,z) as dependent parameters.

Meanwhile, the stress depends on the operation temperature, given by:

$$\sigma=\sigma_{th}+\sigma_i \quad (5)$$

where σ_{th} is the thermal stress created by the mismatch $\Delta\alpha$ of the thermal expansion coefficient of silicon and silicon dioxide at the process where the reference temperature cools down to the operating temperature. Thus, the stress increases with temperature. The σ_{th} can be measured by:

$$\sigma_{th}=\frac{E}{1-v}\Delta\sigma\Delta T \quad (6)$$

where E is the Young modulus and v is the Poisson ratio.

III. Design and Simulation

In order to alter the optical properties of the photonics devices, the strain is introduced into the device. In this research, a strain layer, which is silicon dioxide was created on top of the device. Figure 1 shows the schematic diagram of a planar waveguide where the core and waveguide layers are made of silica, which is deposited onto a silicon wafer.

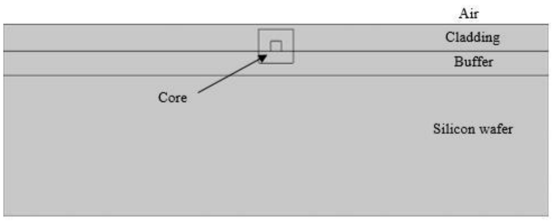

Figure 1: Schematic model of planar waveguide

Table 1 lists the design parameters of the proposed model of planar waveguide model. The cross-section of the core is set as 0.3 x 0.3 µm. The optical core and cladding are made of silicon and silicon dioxide where the refractive indices are 3.47 and 1.47, respectively. The other material properties, such as thermal expansion coefficient, Young's modulus and Poisson's ratio are listed in the table. The waveguide configuration is assumed to be deposited at the temperature 1000℃ and cool down at usual room temperature, 20℃.

Table 1
Design Parameter of Planar Waveguide

Symbol	Design parameter	Value
µm	Core cross-section	0.3 x 0.3
	Refractive index of Silicon	3.47
	Refractive index of Silicon dioxide	1.47
1/K	Thermal expansion coefficient of Silicon	$2.5e^{-6}$
1/K	Thermal expansion coefficient of Silicon dioxide	$0.35e^{-6}$
GPa	Young's modulus of Silicon	110
GPa	Young's modulus of Silicon dioxide	78
	Poisson's ratio of Silicon	0.19
	Poisson's ratio of Silicon dioxide	0.17
℃	Operation temperature	20
℃	Reference temperature	1000

IV. Results and Discussion

As shown in Figure 2, when strain is present in a structure (resulted in the cladding surface), the system deforms to reduce the stress. From Figure 2, it can be clearly seen that the stress relief occurs through wafer bending and through elastic deformation from edges and waveguide core. The edge of the waveguide experienced more bending as compared to the waveguide core, therefore the stress distribution inside the waveguides is less affected by the edge effect. Since the transmittance of the optical signal is highly determined by the waveguide core, the optical calculations were only conducted in a small area in the vicinity of the waveguide. By simulation, with the induction of different temperature condition, it causes different thermal strain effect over the structure and the stress value due to the reaction of the structure as listed in Table 2.

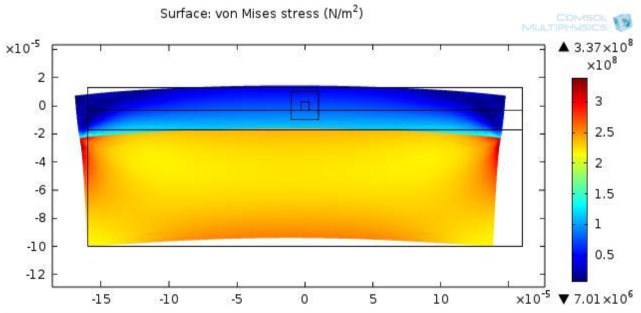

Figure 2: Deformed shape of planar waveguide

The induced temperature determines the amount of stress. The situation affects the waveguide structure and contributes to the change in optical properties in the core, mainly the refractive index. Figure 3 presents the study of the temperature sensitivity of the stress within the operation range from 10℃ to 80℃. It shows that higher temperature leads to a higher stress level with the rate of change of ~0.4 MPa/1℃. It is noted that the optical performance of the waveguide device can significantly change for large temperature variations. Therefore, in the next section, a study will simulate and evaluate to understand the influence of the temperature sensitivity, the effect of induced stress to the effective index and wavelength shift.

Table 2
Temperature versus the amount of stress

Temperature Variation (℃)	Stress (MPa)
10	$-3.42e^{-8}$
20	$-3.38e^{-8}$
30	$-3.36e^{-8}$
40	$-3.33e^{-8}$
50	$-3.29e^{-8}$
60	$-3.25e^{-8}$
70	$-3.21e^{-8}$
80	$-3.18e^{-8}$

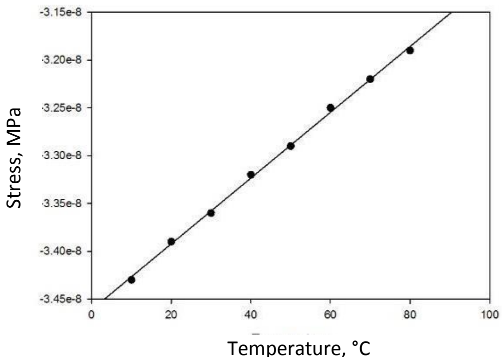

Figure 3: Temperature versus silicon dioxide film stress

The relationship between the geometrical parameters of the waveguide, which is the upper-cladding thickness and thermal expansion coefficient (TEC) doping amount to the birefringence induced are investigated. This study is important due to the fact that the film stress is highly sensitive to the deposition conditions [15].

A. Effect of Temperature on the Effective Index and Wavelength Shift

Similar simulation process has been performed to evaluate the effective index change and wavelength shift and the results are shown in Figure 4 and 5. The fluctuation in the index of refraction is the reason why the pressure fields on waveguides reflect linear birefringence. This investigation specified that the change in temperature brings to the change of the effective index. In this state, the change of material properties contributes to the wavelength shifting as depicted in Figure 5. The change of n_{eff} is in the order of $-0.4\text{x}10^{-6}/1$℃ where 1.465434 is shifted to 1.465430 from 10℃ to 20℃. Specifically, the intensity of the output light is significantly affected by this temperature. This analysis proves the ability of the device to shift the operation wavelength as temperature being applied, where it is significantly important in optical modulator application.

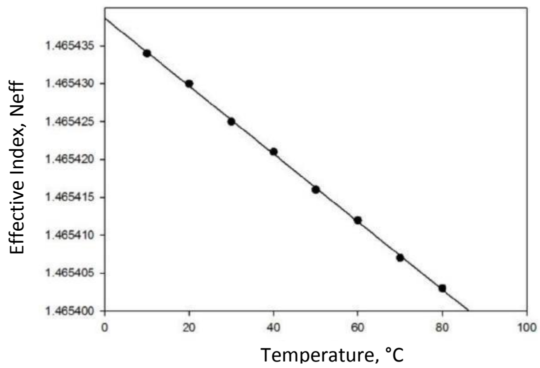

Figure 4: Effective Index versus wavelength

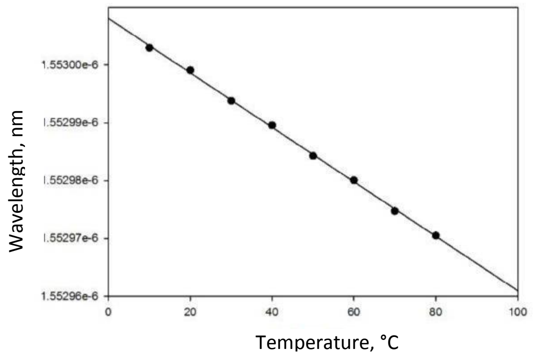

Figure 5: Temperature versus wavelength

B. Effect of Upper-Cladding Thickness to Birefringence

Strain can be resulted from the waveguide fabrication process and may also be intentionally included in device modeling for specific reasons. As mentioned before, the upper cladding made up from silica introduced strain to the SOI planar waveguide. By changing the upper-cladding thickness while maintaining the other parameters, birefringence changes were observed. Figure 6 depicts the effect of upper-cladding thickness, developed by increasing the doping amount to the birefringence. The upper-cladding thickness is directly proportional to the doping amount. The low birefringence is obtained with bulky upper-cladding size. For example, with the upper-cladding thickness of 0.7 and 0.8 µm, the birefringence produced is $-3.5353e^{-4}$ and $-3.4535e^{-4}$, respectively. It means that every upper-cladding width reduction of 0.1 µm increased the birefringence value.

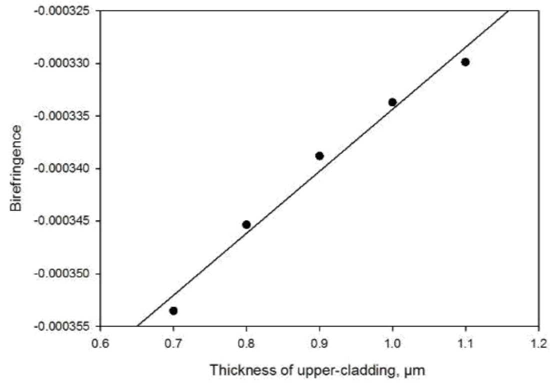

Figure 6: Birefringence versus thickness of upper-cladding

C. Effect of TEC doping amount to Birefringence

Figure 7 portrays the variation of upper-cladding TEC to birefringence. From Figure 7, it can be concluded that birefringence increases with the less amount of doping but the TEC will increase as well. It can be seen that the stress birefringence varies linearly with the TEC of the upper-cladding. For example, $0.29e^{-3}$ birefringence was obtained when the upper-cladding thickness and doping amounts are $0.55e^{-6}$ /K and 1.1 µm, respectively. Thus, the birefringence is less in the case of a deeply etched upper-cladding.

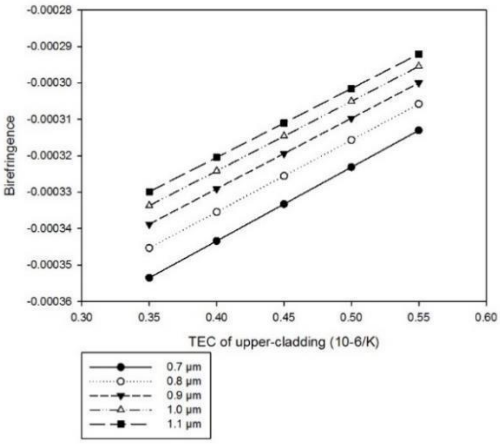

Figure 7: Birefringence versus thickness of upper-cladding and TEC

V. CONCLUSION

A quantitative analysis of stresses as well as induced birefringence was shown for the SOI planar waveguide. The stress induced birefringence in the silicon-on-insulator (SOI) is investigated by using generalized plain strain. Stress-optic effect analyzed the stress amount that was affected by thermal, which was ~0.4 MPa/1℃ distributed to the change of n_{eff} in the order of $-0.4x10^{-6}$/1℃. Moreover, it was demonstrated that the birefringence was greatly influenced by the geometrical parameters of waveguide where the experiment results strongly confirmed that the thickness of upper-cladding and the amount of TEC are two useful parameters for effective birefringence control. These studies would be beneficial in optimizing the waveguide design from the viewpoint of material selections, controlling the fabrication process and modulation method.

REFERENCES

[1] Peter C. Humphreys, Benjamin J. Metcalf, Justin B. Spring, Merritt Moore, Patrick S. Salter, Martin J. Booth, W. Steven Kolthammer, and Ian A. Walmsley, "Strain-optic active control for quantum integrated photonics," Opt. Express 22, 21719-21726, 2014.

[2] Hazura Haroon, Sahbudin Shaari, PS Menon, B Mardiana, AR Hanim, N Arsad, BY Majlis, WM Mukhtar, Huda Abdullah, "Design and characterization of multiple coupled microring based wavelength demultiplexer in silicon–on–insulator (SOI)," in *Journal of Nonlinear Optical Physics & Materials*, vol. 21, no. 1, pp. 1250004, 2012.

[3] Lei Yuan, Baokai Cheng, Jie Huang, Jie Liu, Hanzheng Wang, Xinwei Lan, and Hai Xiao, "Stress-induced birefringence and fabrication of in-fiber polarization devices by controlled femtosecond laser irradiations," Opt. Express 24, 1062-1071, 2016.

[4] J. Canning, W. Liu, and K. Cook, "Annealing and Regeneration in Optical Fibres," in Asia Communications and Photonics Conference 2015, C. Lu, J. Luo, Y. Ji, K. Kitayama, H. Tam, K. Xu, P. Ghiggino, and N. Wada, eds., OSA Technical Digest (online) (Optical Society of America, 2015.

[5] AR Hanim, B Mardiana, H. Hazura, Sahbudin Saari, "On the modulation phase efficiency of a silicon pin diode optical modulator", International Conference on Photonics (ICP) 2010, pp.1-3, 2010.

[6] Budi Mulyanti, P Susthitha Menon, Sahbudin Shaari, T Hariyadi, L Hasanah, H. Haroon, "Design and optimization of coupled Microring Resonators (MRRs) in silicon-on-insulator", Sains Malaysiana, vol. 43, no. 2, pp. 247-252, 2014.

[7] Tse-Jen Lu, Sheng-Chieh Tseng and S. H. Hsu, "Stress-induced modal dispersion on SOI waveguide," 16th Opto-Electronics and Communications Conference, Kaohsiung, pp. 497-498, 2011.

[8] Schriever, C.; Bohley, C.; Schilling, J.; Wehrspohn, R.B, "Strained Silicon Photonics", Materials, vol. 5, pp. 889-908, 2012.

[9] H.Haroon, M. Bidin, Hanim A. R, PS Menon, N Arsad, Z. F. M. Napiah, "Impact of coupled resonator geometry on silicon-on insulator wavelength filter characteristics", 2011 IEEE Regional Symposium on Micro and Nanoelectronics (RSM), pp.380-382, 2011.

[10] G. B. Montanari, F. Mancarella, R. Balboni, D. Marini,F. Corticelli, M. Sanmartin, M. Ferri, G. Bolognini, "Induced strain in silicon waveguides and couplers", Proc. SPIE 9367, Silicon Photonics X, 93671L (February 27, 2015); doi:10.1117/12.2078383.

[11] Alejandro Hernández, Victor Velasco, Miguel Orozco, Alfredo Márquez, "Control system for optic-fiber coating process based on photoelastic effects", Proc. SPIE 8351, Third Asia Pacific Optical Sensors Conference, 83510P (January 31, 2012); doi:10.1117/12.915691.

[12] Jun Zou, Xiang Xia, Guanting Chen, Tingting Lang, and Jian-Jun He, "Birefringence compensated silicon nanowire arrayed waveguide grating for CWDM optical interconnects," Opt. Lett. 39, 1834-1837 , 2014.

[13] Md. Faruque Hossain, Hau Ping Chan, Abbas Z. Kouzani, and Md. Osman Goni, "Generalized characteristics of photo-elastic birefringence in polymer strip waveguides," Opt. Mater. Express, vol. 5, 1030-1044 , 2015.

[14] Jingnan Cai, Yasuhiko Ishikawa, and Kazumi Wada, "Strain induced bandgap and refractive index variation of silicon," Opt. Express 21, 7162-7170, 2013

[15] P. Dumais, "Thermal Stress Birefringence in Buried-Core Waveguides With Over-Etch," in IEEE Journal of Quantum Electronics, vol. 47, no. 7, pp. 989-996, July 2011.