Improving the acousto-optical interaction by an introduction of a planarisation SiO2 layer

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This paper introduces a planarisation SiO2 layer into the configuration of ZnO-silicon-on-insulator for constructing an acoustical resonant cavity to enhance the acoustic density on a silicon-on-insulator waveguide. The improved configuration with a planarisation SiO2 layer can increase the acousto-optical interaction by about three times and 20% compared with acousto-optical configuration of ZnO pads only in an interdigital transducer region and all over a silicon on insulator. Moreover, an introduction of a planarisation SiO2 layer can reduce acoustic reflection on optical waveguide and optical waveguide loss for an acousto-optical device on silicon-on-insulator optical waveguides.

Introduction: Integrated optics on silicon-on-insulator (SOI) materials has received increasing attention in recent years [1–3]. SOI is arguably the most significant material platform for photonics due to the promise of monolithic integration with electronic circuits [4–6]. Various approaches have been developed to control light of optical waveguides [7–13]. Surface acoustic wave (SAW) is general technology to control the optics and generated using interdigital transducers (IDTs) for an acousto-optical (AO) interaction in integrated optics [14,15]. The AO interaction can provide a well-established process for controlling light, which have an excellent compromise between speed and size, and can be implemented in almost any material platform such as silicon, (In, Ga) P or LiNbO3 [13,16,17].

However, silicon does not exhibit a piezoelectric effect, and the silicon layer does not effectively guide acoustic modes, which tend to leak towards the bulk [8]. In order to generate and guide acoustic modes in SOI waveguide, remarkable demonstrations of forward stimulated Brillouin scattering in silicon have been reported in recent years [9–11]. However, these required that the underlying oxide layer of SOI is etched away and that silicon waveguides and membranes remain suspended, it will be difficult to integrate with other optical waveguide device on SOI. Munk et al. reported to launch the SAWs in SOI through absorption of modulated pump light in metallic gratings and thermoelastic expansion [8]. This method does not require piezoelectric actuation, and the suspension of membranes. However, this method is complex and lower integration.

The hybrid integration of additional materials is a potential promising method to solve the non-piezoelectric effect of silicon for higher integration and flexible design of AO device [14, 18, 19]. Some researchers introduce a piezoelectric material into the surface of SOI wafer for the generation and propagation of SAW on SOI optical waveguides [14, 18–20]. The IDTs are located on the surface of the piezoelectric film to generate SAW. The ZnO is the general piezoelectric material due to good piezoelectric properties and high electro-mechanical coupling coefficient [20,21].

This paper introduces an improved configuration with a planarisation SiO2 layer to improve AO interaction on SOI wafer. A Mach–Zehnder (MZ) structure is taken as an example to explore AO interaction of the improved configuration. As a comparison, AO interaction on SOI technology is discussed for three configurations of depositing ZnO only in the region of IDTs, depositing ZnO all over SOI and depositing ZnO all over SOI with a planarisation SiO2 layer. The acoustic propagation along the Si/SiO2 layer and the modulation of an AO device based on MZ are discussed to evaluate the improved configuration with a planarisation SiO2 layer.

Theory: SAW is used to control the optics of optical waveguides for AO interaction in integrated optics. The SAW is always generated in a piezoelectric material by applying an electric potential to the electrode fingers of the IDTs on the surface of the solid [14, 22]. The applied electric field will introduce mechanical displacements in the piezoelectric material. The behaviour of SAW in the piezoelectric material can be described using an equation of motion of a particle:

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial^2 T_{ij}}{\partial x_j}$$

where $\rho$ is the density of the material, $u_i$ are the components of the mechanical displacement, $x_i$ are the coordinates, the stresses $T_{ij}$ is related to both elastic strain and electric field strength in the medium.

The piezoelectric constitutive relations is

$$T_{ij} = c_{ijkl} S_{kl} - \epsilon_{ijkl} E_k$$

$$D_j = \epsilon_{ijkl} S_{kl} + \sigma_{jk} E_k,$$

where $c_{ijkl}$ is the elastic stiffness constants when the electric field strength $E_k$ is constant, $\epsilon_{ijkl}$ are the piezoelectric stress constants, $S_{kl}$ are the elastic strain, $\sigma_{jk}$ are the permittivity constants.

The mechanical strain tensor can be calculated by [23]

$$S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right),$$

where $u_i$ are the displacements and $x_i$ are the coordinates.

The refractive index of the optical waveguide changes periodically by SAW due to the AO effect [24, 25]:

$$\Delta n_j = -\frac{1}{2} p_{ijkl} D_{kl} S_{ij},$$

where $p_{ijkl}$ is the coefficient of elasticity.

Simulation: In order to evaluate AO interaction on SOI technology, three AO configurations on MZ structure are presented in Figure 1. Among them, Figure 1(a) shows the structure of MZ, Figure 1(b) shows that ZnO is deposited only in the region of the IDTs, Figure 1(c) shows that ZnO is deposited all over the SOI and Figure 1(d) shows that ZnO is deposited all over the SOI with a planarisation SiO2 layer. SAW is generated by IDTs on the left of SOI wafer and propagates in both left and right horizontal directions. To the right, SAW will pass through two optical waveguides of MZ structure on SOI technology, the refractive
index of the two waveguide will change due to the elastic strain of the medium by SAW.

To simulate AO interaction in MZ structure on SOI technology, a model describing the SAW generation in a piezoelectric material is coupled with an optical model describing the propagation of the light waves in the waveguides. Based on Equations (1)–(5), a finite element method (FEM) was executed for the analysis of an AO interaction on the optical waveguides. In order to reduce the reflection of sound waves, a perfectly matched layer boundary condition is used in the FEM model. In the simulation, SAW is generated by 10 pairs of electrode fingers. Each of the electrodes has a width of 1.4 μm, the wavelength of the generated SAW will be 5.6 μm. The thicknesses of silicon waveguide, SiO2 planarisation layer and ZnO layer are 220, 500 and 1.7 μm, respectively. The ZnO thickness of 1.7 μm is determined as shown in Figure 4. The SiO2 planarisation layer is 500 nm to keep the optical waveguide under strong acoustical strength because SAWs are confined to within roughly one wavelength of the surface. The constants of ZnO, Si and SiO2 are given in Tables 1 and 2 used in the simulation.

Results and discussion: The acoustic amplitude of three configurations on SOI technology is calculated as shown in Figure 2. One can see that the SAW vibrates strongly at IDTs position and travels in both directions. The region of IDT works as a resonant cavity of acoustics due to SAW reflection. The position of optical waveguides is remarked using the black spots in the figures.

Figure 2(a) shows the distribution of SAW for the configuration of depositing ZnO pads only in IDT region. The SAW amplitude has an abrupt decrease by 44% at the edge of ZnO layer when leaving the region of IDT. This means that the propagation of the SAW is severely affected by discontinuities of ZnO layer. A configuration by extending ZnO layer all over SOI wafer is provided to avoid discontinuities of ZnO layer in Figure 1(b). Figure 2(b) shows the distribution of SAW for the configuration by extending ZnO layer all over SOI wafer. The SAW can keep a strong propagation when leaving the region of IDT and has better SAW distribution on the position of the optical waveguides, compared with the configuration of depositing ZnO pads only in IDT region.

Figure 2(c) shows the distribution of SAW for the improved configuration with a planarisation of SiO2 layer. Compared with Figure 2(b), one can observe that although there is a little decrease of acoustic strength, a planarisation of SiO2 layer leads to obvious steeper distribution of SAW on the optical waveguides. Based on Equations (4) and (5), a steeper distribution means a strong strain tensor and results in a larger difference of effective refractive index for the optical waveguides. It means an introduction of a planarisation of SiO2 layer construct an acoustical resonant cavity due to the constructive interference of reflected acoustic waves from the interface of different layers.

In order to further verification of an improved AO modulation by an introduction of a planarisation of SiO2 layer, an AO MZ structure on SOI technology is taken as an example to explore the AO interaction. In the MZ structure, the two arms of optical waveguides are separated by 1.5-time acoustic wavelength for the opposite phase on the refractive index change. The optical waveguides on SOI technology work on a single-mode. The optical waveguide is 220 nm × 450 nm.

The difference of effective refractive index (∆n) by SAW is shown in Figure 3 for the three AO configurations based on MZ structure. The improved configuration of ZnO all over SOI with a planarisation SiO2 layer can increase the AO interaction by about three times compared with configuration of ZnO pads only in IDT region, and increase the AO interaction by about 20% compared with configuration of ZnO deposition all over SOI. A planarisation SiO2 layer leads to a stronger strain tensor and results in a larger difference of effective refractive index for the two waveguides on SOI technology by SAW.

The depth of ZnO with the difference of effective refractive index by SAW is shown in Figure 4. One can observe that the difference of effective refractive index (∆n) by AO interaction reaches the top at the 1.7 μm thickness of ZnO. With the increase in ZnO depth, more acoustic wave will move into ZnO layer, which will reduce the AO interaction.

Conclusion: This paper introduced a planarisation SiO2 layer to improve the AO interaction on SOI technology. The SAW distribution for three AO configurations of ZnO pads only in IDT region, ZnO all over SOI and ZnO all over SOI with a planarisation SiO2 layer were calculated and compared. An AO configuration based on MZ structure was taken as an example. The results showed that an introduction of planarisation...
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FIG 3 The difference of effective refractive index ($\Delta n$) by surface acoustic wave (SAW) with the width of the optical waveguides for the three acousto-optical (AO) configurations with ZnO pads only in an interdigital transducer (IDT) region, ZnO all over silicon on insulator (SOI) and ZnO all over SOI with a planarisation SiO$_2$ layer.

FIG 4 Variation of difference of effective refractive index ($\Delta n$) by surface acoustic wave (SAW) with the depth of the ZnO for the proposal structure.

This section discusses the role of SiO$_2$ layer in increasing the AO interaction and its impact on the ZnO deposition process. It also highlights the importance of SOI technology in this context.

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Conflict of Interest: The authors declare that there is no conflict of interest.

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