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Design and investigation of a novel silicon/ferroelectric hybrid electro-optical microring modulator

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A silicon (Si) and lanthanum-doped lead zirconium titanate (PLZT) hybrid microring modulator based on silicon-on-insulator (SOI) platform is designed theoretically and investigated numerically in this paper. The heterogeneous integration of PLZT film with Si material enables the waveguide to acquire both excellent electro-optical property and strong mode confinement capacity. Such hybrid microring modulator (100 μm in radius) has a PLZT rib-loaded cladding and is integrated with optimized tuning electrodes. The simulation results demonstrated that the Si/PLZT hybrid microring modulator could operate at 14 GHz with a relative high modulation efficiency (< 0.8 V cm), which is much better than the other proposed Si/ferroelectric modulators. Meanwhile, under a driving voltage of 20 V, our modulator exhibits an extinction ratio of 32 dB at 1550.22 nm wavelength and a resonant wavelength tunability of 25 pm/V for TE mode. With these outstanding performances, the Si/PLZT hybrid microring modulator holds a great potential as a reliable on-chip device for optical communications and links.

1. Introduction

Si waveguide modulators show great promise in high speed and low cost on-chip optical communications. With the rapid development of complementary metal oxide semiconductor (CMOS) fabrication technologies, SOI-compatible optical devices operating at telecom wavelengths were investigated extensively, such as Mach-Zehnder modulators (MZMs) [1–6], electro-absorption modulators (EAMs) [7–10] and waveguide ring resonators (WRRs) [11–17]. WRRs are the most commonly used components for integrated optical circuits owing to their simple structure and high tolerance.

Up to now, most of the typical SOI-based modulators are dependent on the plasma dispersion effect. It is difficult for them to obtain a low insertion loss (IL) and a large modulation bandwidth or depth simultaneously [18]. In comparison, electro-optical (EO) modulators utilizing Pockels effect are considered to be more reliable than those carrier dispersion-based ones. But the EO effect of Si is so weak that the conventional Si-based devices can hardly be used for EO modulation. Hence, hybrid EO modulators that combine Si with EO materials are prosperous candidates for the application in photonic interconnection network systems. Among these materials, EO polymers stand out due to their large EO coefficients (EOCs), high optical transparency and extensive compatibility. These advantages promote the study on silicon-organic hybrid (SOH) modulators [19–21]. For example, MZMs and WRRs with EO polymer claddings have been developed recently [22–26], which have an impressive modulation bandwidth up to 100 GHz. Despite the above mentioned benefits of the SOH modulators, some issues still need to be resolved (e.g., aging, reliability, stability, and size). On the other hand, the perovskite ferroelectric thin films, including (Pb, La), (Zr, Ti)O_3 (PLZT), $BaTiO_3$ (BTO) and $LiNbO_3$ (LN), have attracted considerable attentions for their high refractive indexes and long-term reliability. In recent years, researchers have experimentally realized Si/LN and Si/BTO hybrid WRRs [27–30] with small footprint, high modulation frequency and large extinction ratio (ER). Compared with LN and BTO, PLZT thin film has better optical isotropic properties. Moreover, the EOC of the PLZT film is in the range of 30–100 pm/V, which is larger than that of the LN film (3~31 pm/V) [31] and close to that of the BTO film (23–200 pm/V) [32–34]. So there is a great prospect for the realization of Si/PLZT hybrid modulators.

In our previous work, we have experimentally demonstrated the PLZT waveguides and switches [35–37]. On this basis, a Si/PLZT hybrid microring modulator based on SOI platform is presented and investigated theoretically. The proposed Si/PLZT hybrid waveguide consists of a Si stripe and a PLZT rib, which is loaded on a SOI substrate. In comparison with the conventional rib or multilayer waveguide, this structure not only utilizes Si stripe to maintain strong mode confinement capacity, but adopts PLZT rib as cladding layer to

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keep majority of the optical power in the PLZT film. Thus, our device is very compact and owns a high resonant wavelength tunability. Additionally, the Au coplanar travelling-wave electrodes are extended to the top of the PLZT rib, which is helpful for the improvement of modulation efficiency. The calculated results show that the Si/PLZT hybrid microring modulator (100 μm in radius) exhibits a large ER of 32 dB at 1550.22 nm with a voltage of 20 V and a resonance tuning of 25 pm/V for TE mode. The RF simulation also confirms that the modulation bandwidth of such modulator could reach nearly 14 GHz, which is higher than the most appeared Si/ferroelectric modulators. Besides, it is demonstrated that the polarization state of the input lighwave signal could be modulated effectively. Though there are still some aspects (e.g., modulation efficiency, driving voltage etc) need to be improved, the modulator described here has many advantageous performance characteristics, such as large ER and low insertion loss (IL), over the Si modulators based on p-n junction. We believe it could be a promising supplement for the integrated hybrid optical modulators.

2. Structure

As shown in Fig. 1(a), the Si/PLZT hybrid waveguide is composed of an ultra-thin Si stripe, a rectangular PLZT rib and two integrated Au electrodes. The dimensions of the rectangular PLZT rib are 0.4×1.7 μm^2 (height×width). And the Si core stripe embedded inside the PLZT rib is set to be 100 nm-thick and 400 nm-wide. With such a structure, the majority of the optical power could be confined in the PLZT film. In addition, the configuration of the Au electrode is modified and optimized, which shows a little difference from that of the common coplanar travelling-wave electrode. The total height of the Au electrode is nearly 1 μm, and the width is around 3 μm. In order to ensure a high intensity and a uniform distribution of the external electric field in the waveguide, Au electrodes are set to be in contact with the boundary of the PLZT rib. Here, the top Au electrodes belong to the extended parts of the bilateral coplanar travelling-wave electrodes.

The structure of the Si/PLZT hybrid microring modulator is shown in Fig. 1(b). The radius of the ring cavity is set to be 100 μm. While the gap spacing (d_g) between the bus and the ring Si stripe waveguides in the coupling region is kept within the range of 0–200 nm. In addition, half of the ring cavity is incorporated with two modified Au coplanar travelling-wave electrodes, which symmetrically locate on both sides of the Si/PLZT hybrid waveguide. At first, transparent PLZT film can be deposited on Si (100) SOI substrate by pulsed laser deposition (PLD) with an annealing temperature of ~700 °C [38]. The initial thickness of the deposited PLZT film is 100 nm. And then, a 100 nm-thick hydrogenated amorphous silicon layer is fabricated on the PLZT film by plasma-enhanced chemical vapor deposition (PECVD) at ~200 °C. Details of the deposition process can be seen in the Ref. [30]. After Si deposition, electron beam lithography (EBL) with photoresist (e.g., PMMA) can be used to define the Si stripe waveguiding structure, which are then etched into the PLZT layer via inductively coupled plasma or reactive ion etching (ICP or RIE). The next step is to deposit 300 nm-thick PLZT film on the chip through using sol-gel method. The spin-coated PLZT film can be further annealed in O_2 atmosphere at ~650 °C by rapid thermal annealing (RTA) [39]. Finally, the PLZT rib is assumed to be conducted by U-V exposure and ICP or RIE etching.

3. Analysis

The Pockels effect plays a dominant role in the EO modulation, which could induce a linear variation in the material's refractive index as a function of the electric field. In our study, the proportions of each element in the PLZT thin film are 92/8 (Pb/La) and 65/35 (Zr/Ti). With the doping level of La^{3+} increased from 0 to 8%, the difference between out-of-plane (c-axis) and in-plane (a-axis) crystal constants of the PLZT film gets smaller (i.e., the c/a ratio approaches 1) [40]. In this case, the values of the Pockels tensor elements for epitaxial PLZT (8/65/35) thin film are $\gamma_{13}=\gamma_{23}=\gamma_{33}\approx 45$ pm/V, $\gamma_{42}=\gamma_{51}\approx 8$ pm/V. Once a certain voltage is applied to the electrodes, static electric field will be generated in the PLZT rib, whose relative permittivity tensors are as follows [41,42]:

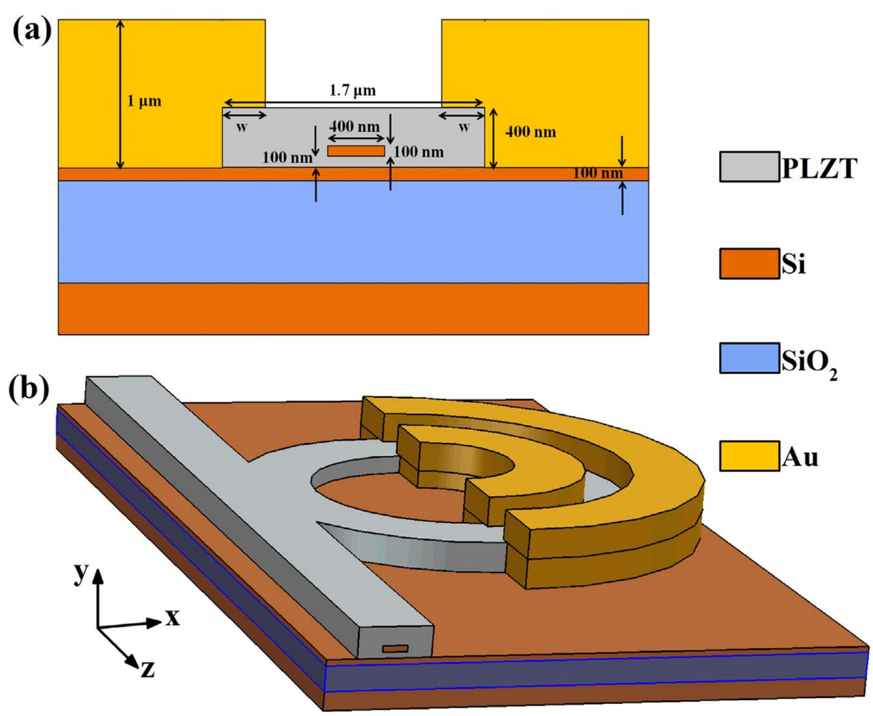

Fig. 1. (a) Cross-sectional view of the Si/PLZT hybrid waveguide with modified Au electrodes. (b) 3D scheme of the Si/PLZT hybrid microring modulator on a SOI substrate.