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Gigahertz-rate optical modulation on Mach–Zehnder PLZT electro-optic modulators formed on silicon substrates by aerosol deposition

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Abstract: Mach–Zehnder (MZ) lanthanum-modified lead-zirconate-titanate (PLZT) electro-optic modulators were fabricated on a silicon substrate by aerosol deposition. The fabricated modulator has a reversed-ridge-waveguide structure (with a 1.8-μm-wide ridge) and electrodes for applying a voltage perpendicular to the PLZT core layer. The modulator also has an MZ interferometer structure in which the device length and the electrode length of phase shifter are 1.5 mm and 500 μm, respectively. Optical-characteristics measurements showed that the 2-GHz optical output signal was produced by the modulator. The optical performance proves the validity of using the modulators on silicon substrates for on-chip optical interconnects.

Keywords: optical modulator, aerosol deposition, PLZT, Mach-Zehnder interferometer

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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DOI: 10.1587/elex.6.1669
Received October 22, 2009
Accepted November 16, 2009
Published December 10, 2009

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DOI: 10.1587/elex.6.1669
Received October 22, 2009
Accepted November 16, 2009
Published December 10, 2009

IEICE Electronics Express, Vol.6, No.23, 1669–1675

1 Introduction

As miniaturized complementary-metal-oxide-semiconductor (CMOS) fabrication technology enters the multi-core era, problems with conventional electrical interconnects, such as increasing the number of global layers and operation speed degradation, have become critical. Moreover, as the number of repeaters in the electrical interconnects is increased to reduce a propagation delay, total power consumption must be increased. Using optical interconnects instead of the electrical interconnects will likely solve these problems. However, the overhead due to introducing optics, especially electrical to optical signal conversions, requires extra power [1, 2]. It is expected that small-size and low-power optical modulators on LSI chips will be the key technology for creating practical on-chip optical interconnections.

The modulators on LSI chips need to be compatible with the silicon CMOS fabrication process. Optical modulators on silicon substrates, such as carrier-injection-type silicon modulators using a micro-ring resonator [3] or a Mach–Zehnder (MZ) interferometer [4], carrier-depletion-type MZ silicon modulators [5], and electro-absorption modulators using the quantum-confined Stark effect in Ge/GeSi quantum wells [6] or the Franz-Keldysh effect in GeSi [7], have recently been demonstrated.

In contrast, modulators using material with high electro-optic (EO) coefficient, such as EO polymer [8], $LiNbO_3$ (LN) [9], (Ba, Sr)TiO_3 (BST) [10], are much more promising, because the smaller-size and lower-voltage modulators can be realized by exploiting the high-EO effect and because device operation is not limited in the wavelength range over $1.2\,\mu$m [2]. EO polymers have a relatively large EO effect at high frequency (about 165 GHz) [8]. However, since the refractive index difference, Δ, of a polymer waveguide is low (i.e., Δ of several percent), the size of the ring modulator is relatively large (ring radius of 1 mm). Moreover, the long-term reliability of EO polymer material should be improved. Moreover, LN materials are commercially used in high-speed modulators, but the EO coefficient of LN is relatively small (r_c of about 17 pm/V) [11], and the operation voltage of a ring LN modulator (ring radius of $100\,\mu$m) on LN is relatively high (about 100 V) [9]. BST is one kind of EO material to be integrated on a silicon substrate because a BST film is developed as a high-k dielectric film for a memory capacitor [10]. However, the operation voltage of BST modulators was relatively high, namely, 200 V, which is mainly applied to the upper and lower cladding layers, which have small dielectric constant ($\varepsilon_r = 3.9$) [10].

In this study, considering the aforementioned requirements and problems, we designed and fabricated MZ lanthanum-modified lead-zirconate-titanate (PLZT), (Pb, La)(Zr, Ti)O_3, electro-optic (EO) modulators on a silicon substrate by using aerosol deposition (AD). Moreover, we demonstrated its operation at frequencies up to 2 GHz.

DOI: 10.1587/elex.6.1669
Received October 22, 2009
Accepted November 16, 2009
Published December 10, 2009

IEICE Electronics Express, Vol.6, No.23, 1669–1675

2 Device design and fabrication

2.1 Device design

The layer structure of the MZ PLZT EO modulator consists of a SiO_2 insulator (thickness t of 1 μm) over a silicon substrate, a lower electrode layer, a lower cladding layer (t = 0.5 μm), a core layer of PLZT (layer and outer slab thickness of 1.5 and 0.5 μm, respectively), an upper cladding layer (t = 0.5 μm), and an upper electrode layer, as shown in Fig. 1 (a). To reduce the influence of sidewall roughness caused by the etching process and to enhance the tolerance of patterning accuracy [12, 13], a reversed-ridge-waveguide structure, in which the core layer forms on the SiO_2 trench, was applied.

Moreover, a perpendicularly applied electric field, rather than a transversely applied electric field [14], is applied to the structure to increase the intensity of the electric field in the core layer and to exploit the EO effect of PLZT. As for the composition of the PLZT, 5% lanthanum and zirconium/titanium ratio of 30/70 were selected to attain low loss and high EO coefficient at frequencies above 10 GHz [2]. In addition, perovskite oxide, with dielectric constant ε_r of 150, which is nearer to that of PLZT ($\varepsilon_r = 400$ to 500 in gigahertz frequency range) than that of SiO_2 ($\varepsilon_r = 3.9$), was selected for the upper- and lower-cladding-layer material.

To calculate the optical-mode profile of the modulator waveguide by a beam-propagation method, the refractive indices of the SiO_2, PLZT, and perovskite oxide were 1.46, 2.4, and 2.05, respectively. The ridge width under single-mode condition was estimated to be less than 1.8 μm. At the ridge width of 1.8 μm, a single-mode was clearly observed, as shown in Fig. 1 (b).

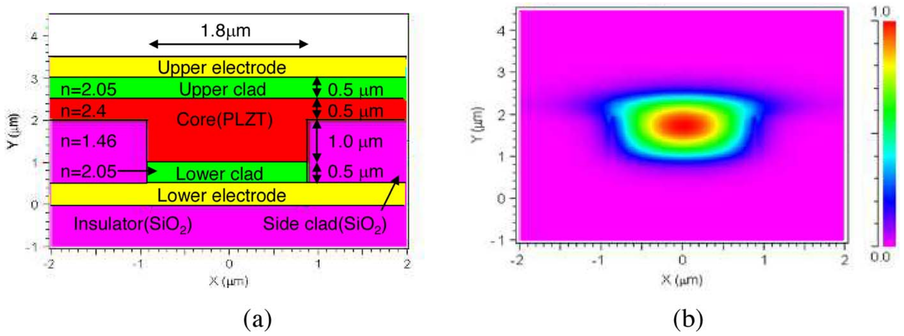


Fig. 1. Schematics of (a) PLZT optical modulator structure and (b) its calculated mode profile at the ridge width of 1.8 μm.

2.2 Device fabrication

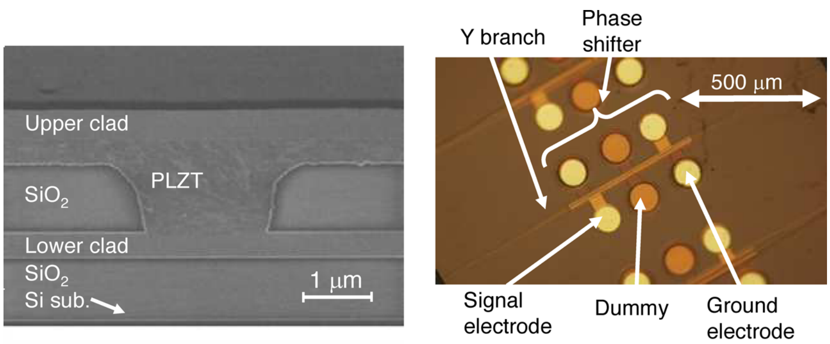
To fabricate MZ PLZT EO modulators on silicon substrates, an AD technique was applied to fabricate PLZT core layers [15]. The AD technique is based on impact solidification of submicron particles on a substrate [16]. The submicron particles, accelerated up to a velocity of 200 to 500 m/s, frac-

DOI: 10.1587/elex.6.1669
Received October 22, 2009
Accepted November 16, 2009
Published December 10, 2009

IEICE Electronics Express, Vol.6, No.23, 1669–1675

ture on the surface of the substrate, forming a dense nano-crystalline ceramic layer. Unlike epitaxial growth, AD is insensitive to an underlayer, meaning that optoelectronic integration on a silicon substrate is possible.

Figures 2 show images of the MZ PLZT EO modulator fabricated on a silicon substrate by AD. Fig. 2 (a) shows a cross-sectional scanning-electron-microscope (SEM) image of the PLZT waveguide. A PLZT core layer was formed by AD on a reversed ridge SiO_2 trench. It shows that AD can produce high-quality PLZT layers not only on a plain surface but also on a trench surface. Fig. 2 (b) shows an overview microscope image of the MZ PLZT EO modulator. The optical modulator consists of two straight phase shifters and two Y-branches standing opposite each other. The total device length and the length of the electrode placed at the phase shifter are 1.5 mm and 500 μm, respectively. The distance between the two phase shifters is 10 μm, and the branch angle of the Y branch is about six degrees.



(a) (b)

Fig. 2. (a) Cross-sectional scanning-electron-microscope image and (b) overview microscope image of Mach–Zehnder PLZT EO modulator.

3 Characteristics of MZ PLZT EO modulator

The optical characteristics of the MZ PLZT EO modulator waveguide were measured with a transverse-electric-mode light. The MZ waveguide (with a 1.5-mm length) had an insertion loss of 34 dB. An optical transmission loss was 6 dB/mm and a coupling loss was about 10 dB/facet. Other losses in the MZ waveguide were expected to be excess losses of the Y branches and scattering losses of interfaces between waveguides with and without the electrode. The transmission loss is relatively high compared with that of a PZT waveguide previously reported (i.e., 4 dB/mm) [12]. To reduce the transmission loss, the transparency of the AD films should be increased.

When an optical CW light with a wavelength of 1550 nm was injected from a CW laser light source into the PLZT modulator, an optical output signal was produced by the modulator under the condition that its electrical signal was input through a bias-tee from several electrical sources, including a DC power supply and a synthesized signal generator (frequency range of

DOI: 10.1587/elex.6.1669
Received October 22, 2009
Accepted November 16, 2009
Published December 10, 2009

10 MHz to 10 GHz), electrically amplified by a RF amplifier. The output optical signal was amplified with an erbium-doped fiber amplifier (EDFA), and the amplified optical signal was filtered with a band-pass optical filter (BPF) with $\Delta\lambda$ of about 5 nm to reduce the amplified-spontaneous-emission noise of the EDFA around the optical signal wavelength. Then, the filtered optical signal was detected with a sampling oscilloscope triggered by the synthesized-signal generator.

When the 2-GHz input electrical signal, shown as Fig. 3 (a), was injected into the modulator without polling treatment, the offset voltage was 20 V and peak-to-peak voltage was 13 V. These offset and peak-to-peak voltages are about one-tenth smaller than that of other ceramic modulators [9, 10]. A 2-GHz optical output signal, shown in Fig. 3 (b), was produced by the modulator. The modulation extinction ratio at 2 GHz was 2.0 dB. It is expected that the modulator can be operated at lower voltage with polling treatment. Since the device capacitances were estimated to be 0.8, 0.3, and 0.15 pF at electrode lengths of 500, 200, and 100 μm, the 3-dB cut-off frequencies were 3.5, 7.6, and 13.6 GHz, respectively, by equivalent-circuit calculation, as shown in Fig. 3 (c). It is expected that the modulator can be operated at higher speed with shorter electrode length.

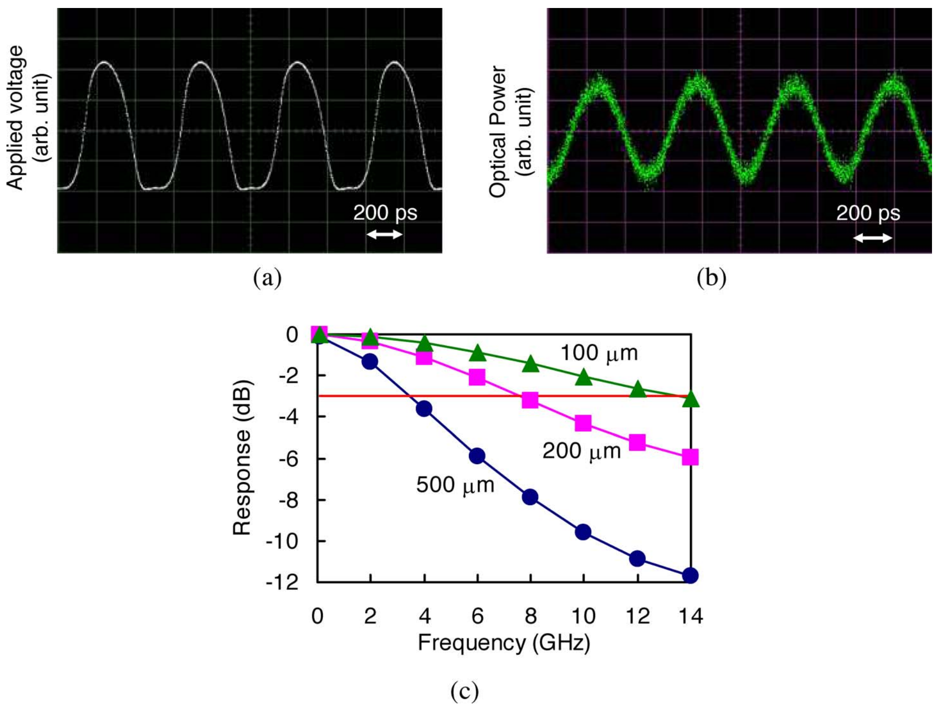


Fig. 3. Characteristics of the Mach–Zehnder PLZT EO modulator: (a) Input electrical signal, (b) output optical signal at 2 GHz, and (c) electrical response vs. frequency determined by equivalent-circuit calculation.

DOI: 10.1587/elex.6.1669
Received October 22, 2009
Accepted November 16, 2009
Published December 10, 2009

ELectronics EXpress

4 Conclusion

We developed Mach–Zehnder (MZ) lanthunum-doped lead-zirconate-titanate (PLZT), electro-optic (EO) modulators fabricated on a silicon substrate by aerosol deposition (AD). The fabricated modulator has a reversed ridge-waveguide structure (with a 1.8-μm-wide ridge) and also has an MZ interferometer structure (with a 500-μm-long electrode). Optical-characteristic measurements showed that with an offset voltage of 20 V and peak-to-peak voltage of 13 V, the modulator produced a 2-GHz optical output signal. This optical performance proves the validity of using the modulators on silicon substrates for on-chip optical interconnects.

Acknowledgments

The authors would like to thank H. Watanabe, N. Sumihiro, S. Tahara, T. Mogami, T. Nakamura, and M. Ishizaka for their helpful discussions. The authors would also like to thank J. Sone, M. Noguchi, and A. Kamei for preparing the samples. This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) in Japan.

DOI: 10.1587/elex.6.1669
Received October 22, 2009
Accepted November 16, 2009
Published December 10, 2009