



Ridge waveguide using highly oriented BaTiO₃ thin films for electro-optic application



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ARTICLE INFO

Article history:

Received 30 January 2013

Received in revised form 5 May 2014

Accepted 7 May 2014

Available online 5 June 2014

Keywords:

BaTiO₃

Waveguide

Electro-optic

SiO₂ ridge

ABSTRACT

In this work, 750 nm-thick BaTiO₃ thin films with highly (001) preferred orientation were grown on single crystal MgO substrates by RF-sputtering. Hydrogen silsesquioxane (HSQ) resist material based ridge waveguides, which were fabricated on BaTiO₃ thin films, were formed by e-beam lithography. Au electrodes were deposited on top of the BaTiO₃ films beside the waveguide. Propagation losses of the BaTiO₃ ridge waveguide were 3–5 dB/cm in transverse electric polarization. The measured electrooptic coefficient value (r_{51}) was 110 pm/V, which is three times larger than the electrooptic coefficient ($r_{33} = 30.8$ pm/V) of single crystal LiNbO₃. SiO₂ strip waveguide formed by HSQ exhibited light propagation with loss lower than 5 dB/cm. This result demonstrates potential possibility of creating highly oriented and/or epitaxially grown BaTiO₃ waveguides and optical components on oxide substrates.

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1. Introduction

Perovskite BaTiO₃ materials have attracted a great deal of attention, in recent years, for its high electro-optic coefficient, as well as its piezoelectric properties, given its lead-free nature [1–4]. Its large electro-optic coefficient, for example, could enable the fabrication of highly miniaturized optical modulators for fiber-optic based data transmission systems [5]. The electro-optic effect describes the change to the index ellipsoid due to an applied electric field. Currently, electro-optic devices are largely fabricated on bulk LiNbO₃ single crystals and are combined with other optical and electronic components in hybrid form. Even with its much lower

electro-optic coefficient, LiNbO₃ has been the material of choice given its ability to be grown as large, high quality single crystals. Recent developments in the fabrication and characterization of thin film optical components (e.g., waveguides, sources, modulators, and detectors) suggest that integrated optical systems on silicon will soon materialize [6]. Miniaturization places a premium on materials such as BaTiO₃ with much higher electro-optic coefficients (e.g., $r_{42} = 1640$ pm/V compared to $r_{42} = 20$ pm/V for LiNbO₃), higher data rates and/or lower operating voltages. Much progress has been achieved in recent years in the growth of high quality oxide films [7,8]. In particular, there has been a great deal of effort expanded in the growth of a number of ferroelectric oxides, including BaTiO₃, onto Si in support of ferroelectric-based non-volatile memories [9,10]. By extension, the development of thin film optical modulators, capable of being integrated into a Si-based device platform, can be envisioned [11]. However, several key criteria must be satisfied when integrating BT electro-optic thin films onto Si substrates. First the BaTiO₃ films must be grown in an epitaxial fashion, highly oriented along the (001) direction, to optimize the electro-optic effect [12–14]. Second, the BaTiO₃ films must be sufficiently spatially separated from the Si substrate to optically decouple the BaTiO₃ based device from the lossy Si substrate. Lastly, the layers separating BaTiO₃ from the underlying Si substrate should have an index of refraction lower than BaTiO₃ to insure confinement of light within the waveguides and should be chemically stable in contact with both Si and BaTiO₃. In this letter, we report on *c*-axis oriented BaTiO₃ thin film electro-optic waveguide modulator fabricated on MgO, via e-beam lithography.

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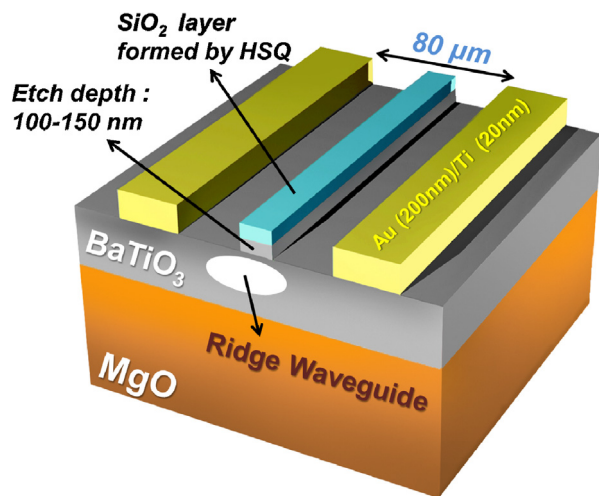
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Peer review under responsibility of The Ceramic Society of Japan and the Korean Ceramic Society.





Scheme 1. Schematic diagram of SiO₂ strip loaded BaTiO₃ ridge waveguide structure.

2. Experimental

The BaTiO₃ films were deposited on MgO(100) substrates at 550 °C by RF reactive sputtering. A disk-type BaTiO₃ target of 2-in. diameter was used. The BaTiO₃ films were synthesized using a fixed RF power (120 W) and an Ar/O₂ (ratio 1/1) atmosphere with total pressure of 30 mTorr. Hydrogen silsesquioxane (HSQ) resist was spun onto 1 μm-thick BaTiO₃ films. Ridge waveguides were patterned by e-beam lithography. The exposed HSQ was transformed into SiO₂, which serves as a mask for subsequent etching of BaTiO₃. The SiO₂ remains as a cladding on the waveguide. The BaTiO₃ films were wet chemically etched utilizing a 1:1:20 HCl:H₂O₂:H₂O solution.

The ridge waveguide dimensions were 3 μm wide, with a ridge step height of 0.15 μm on a 1 μm thick BaTiO₃ film. As a design parameter, the chip length was 6 mm and the crystal orientation of BaTiO₃ was (001). 200 nm thick Au electrodes, with a 20 nm thick Ti adhesion layer, were deposited onto the BaTiO₃ films with 80 μm electrode gaps. A schematic diagram of the BaTiO₃ ridge waveguides is illustrated in Scheme 1.

3. Results and discussion

Fig. 1 shows X-ray diffraction patterns of the BaTiO₃ thin films, deposited on MgO single crystal substrates, with thicknesses ranging from 200 to 1000 nm. All BaTiO₃ films showed a highly (001) preferred orientation. Discrete diffraction spots, with fourfold symmetry, were observed when a BaTiO₃(110) plane was used as the diffraction plane (not shown). This result revealed that all BaTiO₃ films grew epitaxially on MgO(100) substrates. Similar growth behaviors of perovskite thin films on single crystal substrates have been previously reported elsewhere [15–17]. A full width half maximum (FWHM) of 0.8097 for the (100) reflection of 750 nm thick BaTiO₃ films points to a very well crystallized film. Compared to the 750 nm thick BaTiO₃ film, the 1 μm thick BaTiO₃ film showed slightly reduced crystallinity, with FWHM of 1.527. By atomic force microscopy, rms values of surface roughness of the 750 nm thick and 1 μm thick BaTiO₃ films were found to be 0.863 nm and 5.16 nm, respectively. Film orientation and surface roughness are important since they impact propagation loss.

A Metricon 2010 system was used to measure the ordinary and extraordinary indices of the BaTiO₃ films. The refractive indices of the transverse electric (TE) and transverse magnetic (TM) modes, measured for BaTiO₃ waveguides on MgO, are listed in Table 1. The

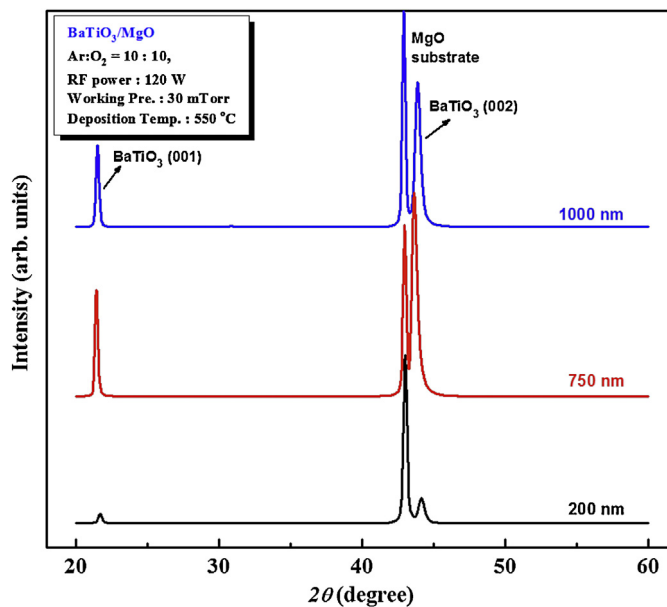


Fig. 1. X-ray diffraction pattern of BaTiO₃ thin films with various thicknesses.

Table 1
Optical properties of BaTiO₃ films.

Mode	<i>n</i>	<i>a</i> (dB/cm)
TE	2.198	3–5
TM	2.217	>15

wavelength dispersion of the index of refraction is shown in Fig. 2. The refractive index decreases slightly as wavelength increases (normal dispersion).

The relative transmitted optical power at 1550 nm is shown plotted in Fig. 3 as a function of voltage for a number of voltage ramps in both increasing and decreasing directions. The effective electro-optic coefficient (*r*₅₁) calculated from these measurements was 100–110 pm/V, compared with *r*₅₁ of 30 pm/V for single crystal LiNbO₃. Ten voltage cycles were traversed to insure reproducibility. All measurements showed similar and relatively uniform electro-optic properties.

Fig. 4a shows SiO₂ strip waveguide formed by HSQ on a BaTiO₃/MgO structure and Fig. 4b exhibits light propagation through SiO₂ strip loaded BaTiO₃ ridge waveguide. Propagation loss was measured to be lower than 5 dB/cm. Light propagation was clearly observed as shown in Fig. 4b. We expect that further

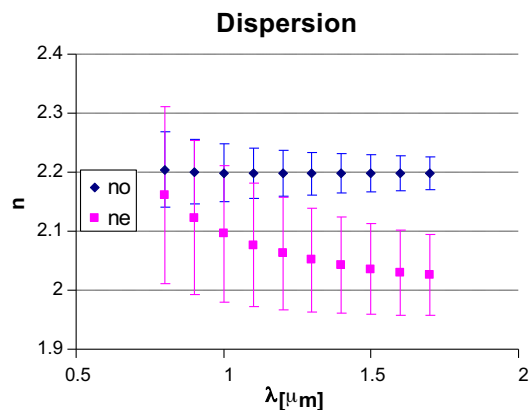


Fig. 2. Ordinary and extraordinary indices of BaTiO₃ thin films as a function of wavelength.

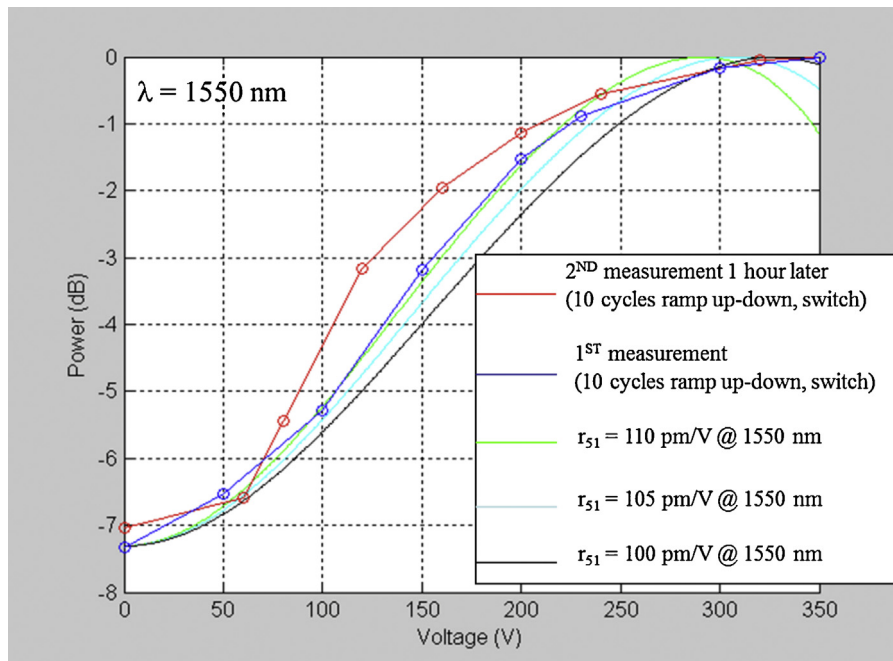


Fig. 3. Transmitted optical power at 1550 nm as function of applied voltage demonstrating electro-optic effect in BaTiO₃ thin film waveguides.

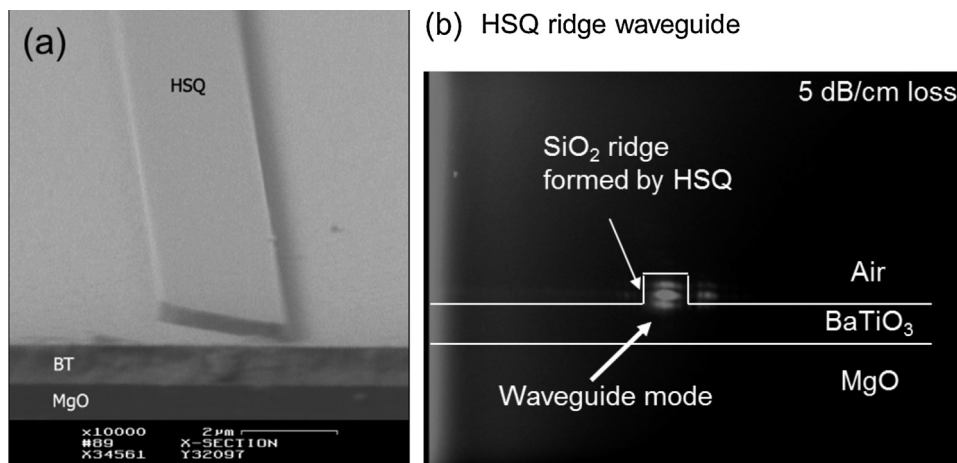


Fig. 4. SiO₂ strip loaded ridge waveguide patterned on highly oriented BaTiO₃ thin films grown on MgO single crystal substrate.

improvements in light propagation can be achieved by improving the quality of HSQ derived SiO₂ by annealing.

4. Conclusion

In summary, highly (001) oriented BaTiO₃ thin films were successfully deposited onto MgO single crystal substrates by RF sputtering. BaTiO₃ ridge waveguides were formed by e-beam lithography using HSQ resist material. The propagation loss of the BaTiO₃ ridge waveguide was 3–5 dB/cm in TE polarization. The measured electro-optic coefficient (r_{51}) was approximately 110 pm/V, three times larger than the electrooptic coefficient ($r_{33} = 30.8$ pm/V) of single crystal LiNbO₃. This confirms that BaTiO₃ thin films with highly preferred orientation can be a promising candidate for integrated electro-optic modulators.

Acknowledgements

This work was supported, in part, by Pirelli Labs and the MIT Microphotonics Center. Thanks go to Peter Rakich for assistance

with the optical measurements. This work was also supported by the Center for Integrated Smart Sensors funded by the Ministry of Education, Science and Technology as Global Frontier Project (CISS-2012M3A6A6054188).

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