Epitaxial and polycrystalline ferroelectric $BaTiO_3$ thin films used for optical switching

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Introduction

$BaTiO_3$ is an attractive material for electro-optical devices in thin film technology due to its large electro-optic coefficients[1], its high transparency in the visible and near infrared range and its favorable growth characteristics.

The $BaTiO_3$ (BTO) films used in our experiments have been grown by pulsed laser deposition (PLD). By modifying the growth conditions (substrate temperature, oxygen pressure and energy per pulse) we have grown epitaxial c-axis and a-axis thin $BaTiO_3$ films and also polycrystalline films on MgO substrates.

Mach-Zehnder waveguide modulators have been patterned using optical lithography and ion beam etching. The waveguides are of the ridge type, 3 µm wide with a ridge step height of 70 nm on a 1 µm thick $BaTiO_3$ film. They allow to propagate a single optical mode both at 633 nm wavelength and 1550 nm wavelength. A lithographic lift-off process with subsequent deposition of a metal layer of 10 nm Cr and 90 nm Au was used to prepare the electrodes. The length of the electrodes is 3 mm and the distance between adjacent electrodes is 10 µm. The modulator input and output faces have been cleaved.

Epitaxial $BaTiO_3$ thin film optical switches

c-axis films

The c-axis oriented $BaTiO_3$ films on MgO were grown by PLD using a laser power of 1100 mJ/pulse, a substrate temperature of 800 ºC at an oxygen pressure of 10^{-3} mbar. More detailed growing conditions and structural characterization of the films can be found in Ref. [2]. The measured damping coefficient of the planar waveguide is typically about 3 dB/cm.

The optical axis of the $BaTiO_3$ films is perpendicular to the substrate plane in this case, and the applied electrical field is perpendicular to the optical axis, as it is shown in Fig.1.

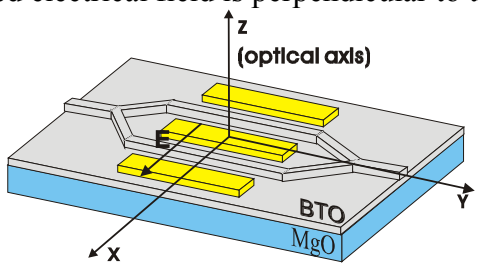

Figure 1. The geometry of the c-axis optical modulator and the orientation of the applied electrical field in respect with the crystallographic axes of the epitaxial $BaTiO_3$ film.

The TE polarized light given by a laser diode is end-fire coupled into the waveguide. The experiments were performed for two wavelengths: 633 nm and 1550 nm. The output of the waveguide is coupled to another single mode fiber, which leads to a silicon detector. Contact needles, supported by micromanipulators, are used to apply the voltage to the middle and to one outer electrode. The transmitted optical intensity is measured as a function of the applied voltage.

Figure 2 presents the result of the measurement for a c-axis modulator at 1550 nm wavelength, with an electrodes spacing of 10 μm.

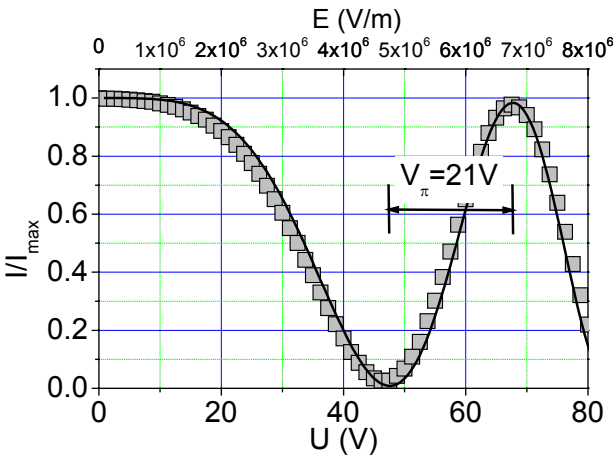

Figure 2. Intensity modulation of a c-axis film thin-film Mach-Zehnder modulator vs. applied voltage at 1550 nm. Dots are the measured data, the line is given by the theory.

The r_{51} Pockels coefficient is involved in this case for the electro-optical response of the modulator, as it is shown in Ref. [3]. The line graph represents the theoretical response of the device with r_{51} = 48 pm/V. The measured values for the ordinary and extraordinary refractive indices used for determining of the r_{51} coefficient are n_o = 2.252 and n_e = 2.247. The refractive indices are measured at 1550 nm wavelength with a prism-coupling set-up [4].

A V_π of 21 V is measured at an applied electric field of about 6 V/μm, as is shown in Fig. 2. An improvement of the device performances can be achieved by lowering the electrodes separation and increasing the length of the active region (electrodes). Thus, a V_π of 15 V at an applied electrical field of 4.5 V/μm has been achieved by reducing the electrodes separation from 10 μm to 5 μm, at the same operating wavelength.

a-axis films

a-axis $BaTiO_3$ films (c-axis in-plane) were formed using a reduced laser power of 300 mJ/pulse and a substrate temperature of 850 °C. The samples showed a slightly higher damping coefficient then for the c-axis films of 4 dB/cm.

The Mach-Zehnder modulators have been fabricated in the same way like for the c-axis films. Because of the different film orientation, the applied electrical film is parallel with the optical axis of the film. Thus, the r_{13} and r_{33} Pockels coefficients are involved now, the output intensity is given by [3]:

$$I_{out} = \left| \frac{1}{2} e^{i\frac{\pi l}{\lambda}\left[(n_e - n_o) - \frac{1}{2} n_c^3 r_c E_z\right]} + \frac{1}{2} e^{i\frac{\pi l}{\lambda}(n_e - n_o)} \right|^2, \qquad (1)$$

where l is the length of the electrodes, n_o, n_e are the ordinary and the extraordinary refractive indices of the film, E_z is the driving electrical field and $r_c = r_{33} - \left(\frac{n_o}{n_e}\right)^3 r_{13} \cong r_{33} - r_{13}$ is an effective electro-optic coefficient.

The experimental results are shown in Fig. 3.

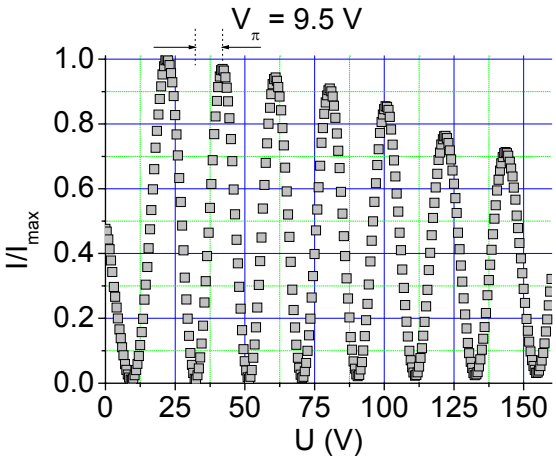

Figure 3. Intensity modulation of an a-axis film thin-film Mach-Zehnder modulator vs. applied voltage at 1550 nm. A half wave voltage V_π of 9.5 V can be observed.

An effective Pockels coefficient r_c of 56 pm/V has been estimated. The modulation depth is 99.1%, corresponding to a 20.5 dB extinction ratio.

Polycrystalline $BaTiO_3$ thin film optical switches

The integration of these devices on Si and on other substrates is desirable, but the very different thermal expansion coefficients of the isolating layer and of the $BaTiO_3$ film make this a difficult task. The replacement of the epitaxial $BaTiO_3$ layer by a polycrystalline layer simplifies a potential integration considerably, because the deposition temperature can be lowered and the optical separation layer to the substrate could be replaced by an amorphous SiO_2 layer. The polycrystalline films were grown on MgO substrates at relatively low temperature (400°C) by pulsed laser deposition at an oxygen pressure of $2x10^{-3}$ mbar. The polycrystalline films are still highly transparent with an estimated waveguide propagation loss of 4 dB/cm at 633 nm wavelength. Although polycrystalline, the BTO is still birefringent with n_o= 2.316 and n_e = 2.301.

The composition and the thickness of the sample were measured by Rutherford Backscattering Spectroscopy (RBS). The Ba: Ti ratio is 1: 1 within the resolution, in accordance with the initial target composition. In RBS/Channeling experiments, no channeling in the Ba signal could be detected, indicating that the $BaTiO_3$ films are not preferentially textured on the MgO substrate.

Grazing incidence X-Ray Diffraction (XRD) measurements were performed, confirming the films are polycrystalline. The lines are broadened, therefore it is difficult to distinguish between tetragonal and cubic phases of $BaTiO_3$. AFM measurements on a 1x1 μm^2 area gave an rms roughness of 0.9 nm, comparable with the epitaxial grown films. The in-plane and the out-of-plane refractive indices of the $BaTiO_3$ polycrystalline films with the thickness of around 1 μm have been measured using a prism coupling setup and the values measured at 633 nm wavelength are n_o =

2.316 ± 0.002 and n_e = 2.301 ± 0.002. The birefringence of the films is about 0.015 ± 0.002. The measured damping coefficient of the planar waveguide is 4 dB/cm.

Mach-Zehnder modulators have been fabricated using the same method like for the epitaxial films modulators, with identical geometrical characteristics.

The electro-optical response of the modulator for 633 nm (line) wavelength and 1550 nm (dots) wavelength is shown in Fig. 4.

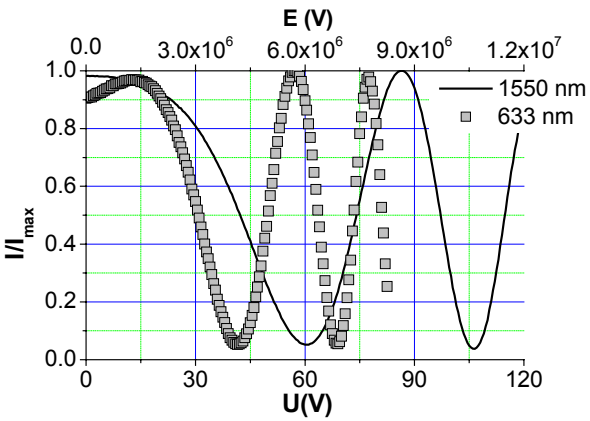

Figure 4. Response of the modulator while changing the applied voltage at 633 nm wavelength and 1550 nm wavelength. The voltage was applied to one arm of the modulator and the electrode spacing was 10 μm.

An effective electro-optic coefficient of r_{eff} = 24 pm/V at a bias of 6 V/μm has been estimated.

Identical optical modulators with smaller separation distance between the electrodes of 5 μm have been fabricated. Infrared measurements at 1550 nm wavelength show a V_π=17 V at 10 V/μm applied electrical field.

Conclusion

Epitaxial thin film $BaTiO_3$ Mach-Zehnder modulators with two different film orientation (c-axis and a-axis) have been demonstrated. For the c-axis film modulators, has been evaluated an r_{51} Pockels coefficient of 48 pm/V. In the case of the a-axis film modulators, an effective electro-optical coefficient r_c of 56 pm/V has been evaluated. Polycrystalline $BaTiO_3$ thin film modulators suitable for integration on Si have also been demonstrated, with an effective electro-optical coefficient of 24 pm/V.

Acknowledgements

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References

[1] M. Zgonik, P. Bernasconi, M. Duelli, R. Schlesser, and P. Günter, Phys. Rev. **B 50**, 5941 (1994)

[2] L. Beckers, J. Schubert, W. Zander, J. Ziesmann, A. Eckau, P. Leinenbach, Ch. Buchal, J. Appl. Phys. **83**, 3305 (1998)

[3] A. Petraru, J. Schubert, M. Schmid and Ch. Buchal, Appl. Phys. Lett. **81**, 1375 (2002)

[4] R. Ulrich and R. Torge, Appl. Phys. Lett. **12**, 2901 (1973)