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.

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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 °C 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.

![Image of Figure 2](image)

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 $V_{\pi}$ 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 $V_{\pi}$ 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 than 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]:

$$I_{out} = \left| \frac{1}{2} e^{\frac{\pi d}{\lambda} \left[ (n_e - n_o) \frac{1}{2} n_i E_i \right]} + \frac{1}{2} e^{\frac{\pi d}{\lambda} (n_e - n_o)} \right|^2,$$

$$U = \frac{V_{\pi}}{2}\pi$$
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 \( r_{c} = r_{33} - \left( \frac{n_o}{n_e} \right)^3 r_{13} \equiv r_{33} - r_{13} \) is an effective electro-optic coefficient.

The experimental results are shown in Fig. 3.

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 \( \mu m^2 \) 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 \( \mu m \) 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.

![Graph showing electro-optical response](image)

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.

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**References**