Electrically and magnetically tunable microwave device using (Ba, Sr) TiO$_3$/Y$_3$Fe$_5$O$_{12}$ multilayer

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Abstract. Ferroelectric (Ba$_{0.6}$Sr$_{0.4}$)TiO$_3$ (BST) thin films have been deposited by pulsed laser deposition onto single-crystal Y$_3$Fe$_5$O$_{12}$ (YIG) substrates with/without a MgO buffer layer. The structure and microwave properties of the BST films have been investigated as a function of substrate orientation and O$_2$ deposition pressures (50–800 mTorr). The crystallographic orientation of BST film varies with the deposition conditions. The dielectric properties of the ferroelectric were measured using interdigitated capacitors deposited on top of the BST film. BST films exhibit high tunability (20%–40%) and high dielectric $Q = 1/\tan \delta$ (30–50) with a dc bias field of 67 kV/cm at 10 GHz. A coplanar waveguide transmission line was fabricated from a (001)-oriented BST film on (111)YIG which exhibited a $17^\circ$ differential phase shift with an applied dc bias field of 21 kV/cm (10 GHz). An equivalent differential phase shift was achieved with a magnetic field of 160 Gauss.

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Expressed by the following:

$$\Delta \phi = \frac{2\pi f l}{c} \left( \sqrt{\varepsilon_{\text{eff}} \mu_{\text{eff}}} - \sqrt{\varepsilon_{1} \mu_{1}} \right),$$

where $f$ is the operating microwave frequency, $l$ is the length of transmission line, $c$ is the speed of light in vacuum, and $\varepsilon_{\text{eff}}$ and $\mu_{\text{eff}}$ are effective dielectric constant and permeability of device, respectively, and superscript 1 and 2 are for the zero bias and applied bias states, respectively. The characteristic impedance $Z_0$ of the CPW transmission line is related as:

$$Z_0 \propto \frac{\sqrt{\mu_{\text{eff}}}}{\sqrt{\varepsilon_{\text{eff}}}}$$

From (1) and (2), it is clear that $\Delta \phi$ and $Z_0$ can be engineered by changing $\varepsilon_{\text{eff}}$ and/or $\mu_{\text{eff}}$.

In this paper, we report the growth and characterization of ferroelectric/ferrite multilayers to demonstrate independent control of the characteristics of the transmission line, and to lay the foundation for the development of a constant impedance device. The selected materials for the ferroelectric/ferrite multilayer structure are pulsed laser deposited BST thin films and LPE-grown single-crystal Y$_3$Fe$_5$O$_{12}$ (YIG), respectively. Jia et al. [8] recently reported the growth of BST films on polycrystalline YIG with buffer layers and microwave properties at 100 kHz. BST films show a large dielectric constant change and low loss with dc bias electric field at $\approx 10$ GHz [1, 5] and YIG shows a large permeability change and low loss with applied magnetic field at $\approx 10$ GHz [3, 9].

1 Experiment

Single-phase (Ba$_{0.6}$Sr$_{0.4}$)TiO$_3$ (BST) films were deposited using pulsed laser deposition (PLD) onto LPE-grown single-crystal (001) or (111)YIG ($\approx 100 \mu$m thick) on single-crystal Gd$_2$Ga$_5$O$_{12}$. A short pulse of KrF excimer laser (2480 Å, 30 ns FWHM) was focused on to the rotating BST target with energy density of $\approx 2 J/cm^2$ in flowing O$_2$ at pressures between 50 and 800 mTorr. PLD provides unique advantages for the deposition of multi-component oxide
films because it reproduces the stoichiometry of the target in the deposited film [10]. To grow (001)-oriented epitaxial BST films on (001)YIG, a thin layer of MgO has been deposited on YIG prior to the BST deposition. An MgO layer was deposited from a single-crystal MgO target at temperature between 750–850°C in flowing O2 at pressure 50 mTorr. The thicknesses of the MgO and BST were \( \approx 1000 \) and \( \approx 5000 \) Å, respectively. The structure of the multilayer films were measured by X-ray diffraction (XRD) using a Rigaku rotating-anode X-ray diffractometer and a Huber 4-circle X-ray diffractometer using Cu \( K_{\alpha 1} \) radiation. Cross-sectional views of the multilayer films were investigated by a Philips CM-30 transmission electron microscopy (TEM). Microwave properties of the BST films on YIG were measured at 0.1–20 GHz range by an HP 8510C network analyzer using interdigitated capacitors and CPW transmission lines fabricated from depositing Au/Ag by e-beam evaporation through a PMMA lift-off mask [11]. Dielectric constants were extracted using a modified conformal-mapping partial-capacitance method from the measured capacitance and dimensions of the capacitors [12].

2 Results and discussion

The crystallographic orientation of the deposited BST thin film depends on the crystallographic orientation of the YIG substrate and the deposition conditions. Further, the deposition of a thin layer of MgO prior to the BST deposition can also influence the crystallographic orientation of the BST film. We investigated the BST film growth on (001) and (111)YIG substrates. The substrate temperature for the BST film deposition onto YIG was fixed at 850°C in order to grow a BST film with a large dielectric constant change with applied dc electric field.

Figure 1 shows XRD patterns obtained for BST films deposited onto (001)YIG substrates with/without a thin MgO buffer layer. Though the lattice mismatch is less than 3% between 3 times of the bulk lattice parameter of BST (3.965 Å) and that of YIG (12.380 Å), the deposited BST film on (001)YIG at 850°C without an MgO layer is a single phase and polycrystalline with a strong (011)BST reflection (Fig. 1a). This indicates that the orientation of BST grains in the film are randomly distributed like those in the BST bulk which has the strongest intensity at (011) reflection. It is worth noting that the lattice mismatch between BST and MgO is more than 6%, however, (001)-oriented epitaxial BST films are readily observed on (001)MgO.

To grow an epitaxial BST film on (001)YIG, a 1000-Å thick MgO buffer layer was deposited prior to the deposition of the BST layer. Figure 1b, c show XRD patterns of BST/MgO/YIG multilayers. The orientation of BST film deposited at 850°C on MgO/YIG shows a strong dependence on the MgO deposition temperature (750–850°C). Strong (002) reflections from BST and MgO are observed from BST/MgO layers deposited at 850°C and 750°C, respectively (Fig. 1b). The BST/MgO layers deposited at the same temperature (850°C) exhibit relatively strong (111) reflections of BST and MgO (Fig. 1c). The intensity of the MgO reflections are weak due to the thickness of MgO layers (\( \approx 1000 \) Å). The in-plane orientation was investigated by a 4-circle X-ray diffractometer. A BST(850°C)/MgO(750°C)/YIG multilayers grows epitaxially; (001)BST∥(001)MgO∥(001)YIG with a \( \approx 18.5^\circ \) rotation in in-plane direction between (010)BST∥(010)MgO and (010)YIG, which is the same as those reported from YBCO/MgO/YIG multilayers [13]. For the BST(850°C)/MgO(850°C)/YIG structure, surface normal direction has a very simple relationship ((111)BST∥(111)MgO∥(001)YIG). However, the in-plane orientation of the BST film is a little more complicated; (011)BST directions are parallel with (010) or (100)YIG directions, resulting in two BST variants, rotated by 90°. As a result, 12 (024)BST reflections, 6 reflections from each variant, were observed in a 4-circle X-ray diffractometer measurement (Fig. 2). A cross-sectional bright field image of BST/MgO/YIG (Fig. 3) studied by TEM shows columnar grains of BST films with 500–1000 Å column width, which is typical for the films grown by PLD. The column width of BST grains at the interface between BST and MgO is narrower than that at the interface BST and air, which indicates grain growth along in-plane direction during deposition.

Figure 4 shows XRD patterns for BST films grown on (111)YIG single crystals with different O2 deposition pres-