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Preparation, Characterisation and Dielectric Properties of YBa$_2$Cu$_3$O$_{7-\delta}$/Insulator-Heterostructures

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Abstract. YBa$_2$Cu$_3$O$_{7-\delta}$/insulator/Au-heterostructures on SrTiO$_3$, LaAlO$_3$, substrates were prepared to study the properties of the materials SrTiO$_3$, BaTiO$_3$, and CeO$_2$. X-ray diffraction measurements in Bragg-Brentano geometry show c-axis-oriented growth for the superconductor and the insulators SrTiO$_3$ and CeO$_2$. Typical values for the rocking curve width of the different insulating films are between 0.4° and 0.8°. The highest breakdown fields are measured for the insulator SrTiO$_3$ with +37.5 kV/mm and -8.8 kV/mm. The permittivity for CeO$_2$ is independent of applied field and only weakly temperature dependent. This is in contrast to the perovskite type insulators, where the permittivity depends on temperature and field. The measured real- and imaginary parts of the dielectric constant differ as a function of frequency (20 Hz - 1 MHz) from the bulk-materials for all three insulators. This behaviour can be explained with a resistance in series and a conductance parallel to the capacitance.

1 Introduction

The development of high-$T_c$ three terminal devices is based on dielectric or ferroelectric thin films. For most devices it is advantageous to have insulators with permittivities and breakdown-fields as high as possible. Materials with perovskite-type structure are good candidates for this purpose. CeO$_2$ possesses a much lower dielectric constant but it is an interesting material for high frequency applications because of its low high-frequency-losses. Most of the research has been done on high-$T_c$ superconducting field effect transistors (SuFET), which consist of a very thin YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO)-film and a dielectric layer like SrTiO$_3$ or CeO$_2$ [1-4]. Using a ferroelectric material like BaTiO$_3$ or PbTiO$_3$ as insulator, it is possible to prepare non-volatile memory devices [5]. Unfortunately all devices showed only very small modulations of source-drain-current yet, because of the small electrostatic screening length of YBCO and the dielectric constant of the insulator which is reduced for thin films compared to the respective bulk-material. Consequently, we have investigated the dielectric properties of epitaxial YBCO/insulator-heterostructures with SrTiO$_3$, BaTiO$_3$ and CeO$_2$ as insulating layers.

2 Experimental details

The approximately 1000 Å thick YBCO-layers were deposited by dc-sputtering and the insulating films by rf-sputtering on SrTiO$_3$ or LaAlO$_3$-substrates. We sputtered from planar, stoichiometric targets in on-axis-geometry in pure oxygen atmosphere. The deposition pressure for YBCO was 3 mbar, for SrTiO$_3$ and CeO$_2$ 1 mbar and for BaTiO$_3$ 0.5 mbar. The insulators were grown about 100 °C below the YBCO deposition temperature to minimize interdiffusion between the two layers. After the sputter process the bilayers were cooled down to 450 °C and then annealed up to 12 h. Au-pads were thermally evaporated in a
separate chamber. During the sputtering process of the insulator a shadow-mask-technique was used to enable contacts to the YBCO-layer.

3 Characterisation

X-ray diffraction measurements in Bragg-Brentano-geometry showed c-axis-oriented growth for the films. An exception was BaTiO₃ where caused by the only weakly tetragonal structure, it was not possible to decide, whether there is c- or a-axis orientation. The rocking curve width of the different insulating films was 0.42° for the SrTiO₃ (200) reflex, 0.82° for BaTiO₃ (001) (see Fig. 1) and 0.48° for CeO₂ (200). The values for SrTiO₃ and CeO₂ agree with the results of other groups [4], while for BaTiO₃-films on YBCO rocking curve widths of 0.36° have been published [5].

![Figure 1: X-ray diffraction of BaTiO₃. a) θ/2θ-scan (Y = YBCO, B = BaTiO₃, Sub = substrate), b) rocking curve. The rocking curve width was found to be 0.42° for SrTiO₃ (002), 0.82° for BaTiO₃ (001) and 0.48° for CeO₂ (100).](image)

The electrical breakdown-field, determined by a 1 nA criterion in the current-voltage characteristic of the gate-electrode, is -8.8 kV/mm and +37.5 kV/mm for SrTiO₃, -9 kV/mm and +22 kV/mm for BaTiO₃ and -6.87 kV/mm and +5 kV/mm for CeO₂ (see Fig. 2). Although the gate-material is the same for all three insulators, they show different asymmetric breakdown-characteristics.

![Figure 2: Breakdown-field for a) BaTiO₃ and b) SrTiO₃ at T = 14 K. SrTiO₃ shows a more asymmetric breakdown-characteristic than BaTiO₃.](image)
4 Dielectric properties

The dielectric properties of the films were determined by measurements of capacitance and conductance as a function of temperature, field and frequency in a range from 20 Hz up to 1 MHz. In comparison to the bulk-materials, only a small temperature and field dependence of the dielectric constant were detected. The largest modulation observed for SrTiO$_3$ was about a factor 2 (see Fig. 3). This is similar to the results of references [7-9]. The measured dielectric constant of SrTiO$_3$ exceeds a maximum value at a temperature of 60 K and an applied gate field of about -1 kV/mm. The different amounts of the dielectric constant for bulk-materials and thin films are probably caused by interface charges (which leads to an internal voltage) and the high depolarisation-factor for thin films.

Figure 3: Temperature and field-dependence of the dielectric constant for the insulator SrTiO$_3$.

In contrast to bulk-materials, a remarkable frequency dependence of the real and imaginary dielectric constant was found for all three insulating materials (see Fig. 4). This behaviour is probably caused by the non-ideal insulating characteristics of the thin dielectric films and by the resistance of the YBCO film. This assumption is confirmed by simulations.

Figure 4: Temperature and frequency dependence of capacitance and conductance for a 2000 Å thick CeO$_2$-film. The value of the capacitance and the slope of the conductance decreases at approximately 100 kHz. This behaviour can be explained by the fact that a real capacitor possesses, besides an ideal capacitor, a parallel conductance and a resistance in series.
The real- and imaginary part of the complex permittivity $\varepsilon$ is shown in Fig. 5 as a function of frequency for SrTiO$_3$. The real part $\varepsilon'$ and imaginary part $\varepsilon''$ were derived from the measured capacitance $C$, the conductance $G$, and the geometry of the electrode contacts according to the following relations:

$$
\varepsilon' = \frac{d}{\varepsilon_0 A} \cdot C \quad \text{and} \quad \varepsilon'' = \frac{d}{\varepsilon_0 A} \cdot \frac{1}{2\pi f} \cdot G
$$

where $\varepsilon_0$ is the permittivity of vacuum, $d$ the thickness of the dielectric film and $A$ the contact area of the electrodes. The capacitance of the insulators decreases above a typical value of frequency $f$. At the same frequency there is a maximum of $\varepsilon''$ (or equivalent of the loss-factor $\tan(\delta)$). Since for a three-terminal device the field induced variation of the source-drain current is proportional to the real part of permittivity the maximum modulation of this current decreases above this frequency [10]. Consequently, it is advantageous to build devices with loss-factors as low as possible.

**Figure 5:** a) Real- and b) imaginary-part of the dielectric-constant as a function of frequency for the insulator SrTiO$_3$. $\varepsilon'$ decreases at the same temperature, where $\varepsilon''(f)$ possesses a maximum.

## 5 Conclusions

YBCO/insulator/Au-heterostructures with the insulators SrTiO$_3$, BaTiO$_3$ and CeO$_2$ have been investigated to optimize high-$T_c$ three terminal devices. X-ray-diffraction yields values of rocking curve width between 0.4° and 0.8° for the different insulators. The insulators' breakdown-fields are, especially for the perovskite-type materials, very asymmetric and amount to -8.8 kV/mm and +37.5 kV/mm for SrTiO$_3$. CeO$_2$ shows, in comparison to SrTiO$_3$ and BaTiO$_3$, only a small temperature and field dependence of permittivity. The complex dielectric constants, determined by measuring capacitance and conductance, show as a function of frequency a significant different behaviour compared to the respective bulk-material. The frequency dependence of the measured capacitance and conductance can be described with a resistance in series and a conductance parallel to the capacitor.

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References


