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

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Abstract. $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ /insulator/Au-heterostructures on SrTiO_3 or 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 $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (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 [6].

Figure 1: X-ray diffraction of BaTiO₃. a) $\theta/2\theta$ -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).

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.

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 ϵ is shown in Fig. 5 as a function of frequency for SrTiO_3 . The real part ϵ' and imaginary part ϵ'' were derived from the measured capacitance C , the conductance G , and the geometry of the electrode contacts according to the following relations:

$$\epsilon' = \frac{d}{\epsilon_0 A} \cdot C \quad \text{and} \quad \epsilon'' = \frac{d}{\epsilon_0 A} \cdot \frac{1}{2\pi f} \cdot G$$

where ϵ_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 ϵ'' (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 . ϵ' decreases at the same temperature, where $\epsilon''(f)$ 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-diffractometry 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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