

Multilayers for high- T_c superconducting electric field effect devices

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Abstract

Epitaxial multilayers, consisting of a $\text{PrBa}_2\text{Cu}_3\text{O}_{7-x}$ buffer layer, ultrathin $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ and SrTiO_3 , have been grown for application in electric field effect devices. Different analytical techniques indicate a sharp interface between the layers and good dielectric properties of the SrTiO_3 -layer. First measurements show clear modification of the superconductor's current-voltage characteristics upon applying electric fields of 0.1–1 MV/cm.

1. Introduction

Superconducting three-terminal devices can be realized by modulating the carrier density in a superconducting thin film or weak link by applying an electric field perpendicular to the surface of the superconductor [1]. High- T_c materials are expected to show larger field effects than low- T_c materials do, owing to their low carrier density.

Several groups have already reported on electric field effects in thin layers of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) [2–4]. However, the problem of making electrical contacts to the ultrathin YBCO-layer remained unsolved, especially for non-inverted structures. Also in ultrathin films, the superconducting properties are generally strongly depressed, probably due to interdiffusion and stress at the interfaces of the substrate-YBCO-dielectric heterostructure.

We fabricated and studied structures consisting of ultrathin YBCO, in situ covered by SrTiO_3 . SrTiO_3 is chosen because of its reported high dielectric constant, especially at low temperatures [5], and the compatibility with the crystal structure of YBCO. Ramp type YBCO/YBCO bilayers were used for good electrical contact. We also studied the effect of using a PrBCO buffer layer between the substrate and the YBCO-layer to reduce interdiffusion and stress at this interface.

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2. Device preparation

All layers were grown using 90° off-axis RF magnetron sputtering at 13 Pa in an Ar/O_2 (3:2) atmosphere at substrate temperatures between 740 and 760°C .

The first step in the fabrication of the structures was the deposition of a relatively thick (~ 100 nm) YBCO-layer. This layer was etched in a 0.7 % HF-solution (to remove outgrowths and droplets). By using soft-baked photoresist and Ar-ion beam etching under an angle of 40° , two facing ramps were formed. After removing the photoresist and in situ low-power Ar-beam cleaning, the YBCO- SrTiO_3 or PBCO-YBCO- SrTiO_3 multilayer was deposited.

The thick YBCO-layer is used to make the electrical contacts to the thin YBCO-channel via the ramps. By chemically etching SrTiO_3 in a 2 % HF-solution, followed by cleaning the surface in an Ar-plasma and sputtering of 100 nm Au, we received typical contact resistances between 10 and 100 Ω .

The multilayer was structured into bridges of 50 μm width and of 20 to 200 μm length, using Ar-plasma etching.

To be able to make electrical contacts to the gate electrode, without running the risk of shorts to the YBCO-layer, the complete structure was coated by a thick (300 nm) insulating layer of PMMA. At the gate electrode and at the other electrical contacts the PMMA was removed by reactive ion etching in an O_2 -plasma. Finally a silver layer was evaporated and structured in an Ar-plasma in order to make leads to the gate electrodes. A top view of the complete structure, with a cross-section of the gate-region, is drawn schematically in figure 1.

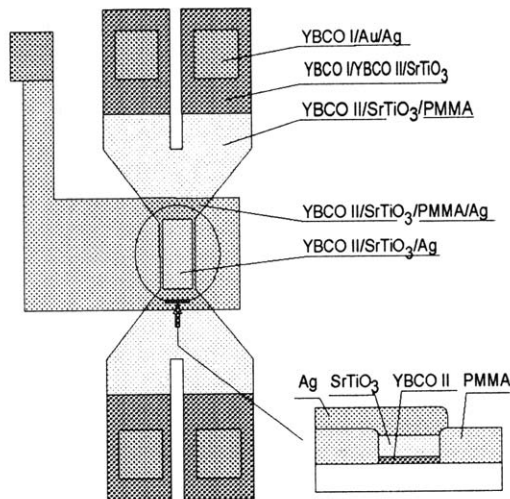


Figure 1. Schematic of the completed structure.

3. Analysis of the multilayer structure

3.1 X-ray diffraction

X-ray diffraction measurements, using a Debye-Scherrer diffractometer with Cu-K α source, were performed to reveal the crystal structure. In the pattern of a structure consisting of 30 nm YBCO and 100 nm SrTiO₃, all diffraction peaks from the YBCO-layer correspond to (001)-reflections, showing c-axis oriented growth. The value of the c-axis parameter is 11.67 Å, which indicates that there is no oxygen deficiency. The SrTiO₃ shows strong (a00)-reflections and no other peaks were observed.

3.2 Rutherford Backscattering Spectroscopy

Rutherford Backscattering (RBS), 2 MeV, He⁺, was performed to detect if any interdiffusion takes place between the different layers of the structure. A relatively thin SrTiO₃-layer was used in this experiment to avoid a large influence of possible non-uniformities in the thickness of this layer.

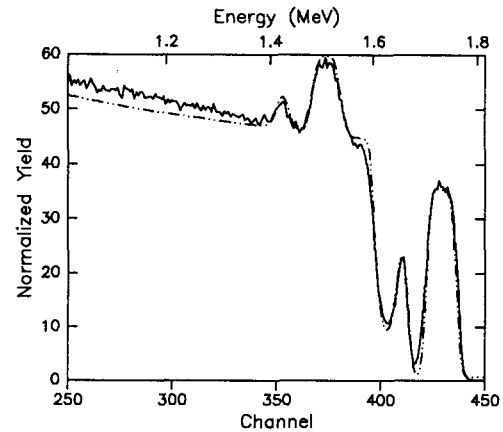


Figure 2. Random spectrum and best simulation fit.

Figure 2 shows the random spectrum (solid line) of a multilayer consisting of ~ 65 nm YBCO and ~ 25 nm SrTiO₃, and a simulated spectrum with no interdiffusion taken into account.

Adding a ~ 5 nm interdiffusion layer between the the YBCO and the SrTiO₃-layer results in a slightly better fit at the low energy edge of the Ti-peak, but this is within the resolution of the instrument, while also a thickness variation in the upper layer may cause such a shift.

3.3 Auger Electron Spectroscopy

Auger sputter profiling (3.5 keV Ar⁺, on PHI SAM 600, Perkin Elmer) on the same sample showed results in accordance with the RBS-measurements. Within the resolution of the experiments (5 nm and ~ 5 at %), no interdiffusion was observed.

3.4 Transmission Electron Microscopy

In figure 3 a low magnification TEM-image is shown. The thickness of the YBCO-layer is 15 nm. The uniformity of both layers over a large distance and the sharpness of the YBCO/SrTiO₃-interface are clearly visible.

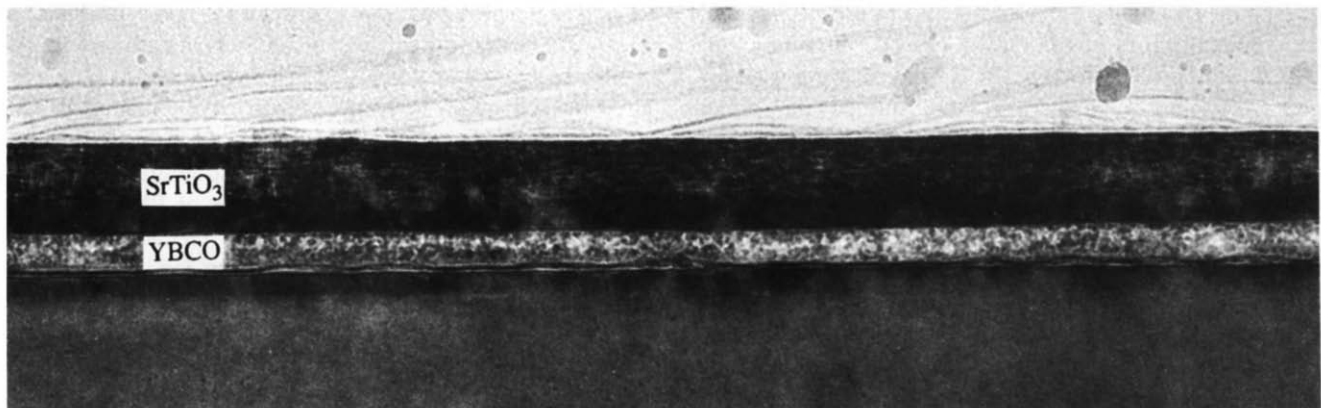


Figure 3. Low magnification TEM-image of 15 nm YBCO covered by ~ 60 nm SrTiO₃.

3.5 Electrical measurements

The superconducting and normal state properties of the YBCO-layer were measured in YBCO/SrTiO₃ multilayers, which were structured into bridges of 20 μm width and 50 μm length. J_c was defined as the point where the voltage drop over the bridge-length was 2 μV , and T_c was determined by extrapolating the $I_c(T)$ -curve to zero.

As can be seen from table 1, the properties of the ultrathin YBCO-layer depend strongly on the thickness. A reason for the depressed properties of thinner layers may be an imperfect initial growth: interdiffusion and stress effects between the YBCO-layer and the substrate may lead to such degradation. A buffer layer of PrBCO has been used in the case of a 5 nm YBCO-layer. As can be seen from table 1, the superconducting and normal state properties of the YBCO-layer improved considerably.

Table 1. Normal state and superconducting properties of the YBCO-layer in the multilayer structure.

d	ρ_{300}	T_c^{on}	T_c	J_c
[nm]	$[\mu\Omega\text{cm}]$	[K]	[K]	$[\text{A}/\text{cm}^2]$
30	100	90	88	10^6 (77 K)
15	750	90	72	$2 \cdot 10^6$ (5 K)
10	4000	90	61	$5 \cdot 10^5$ (5 K)
5	35000	70	5.5	$7 \cdot 10^3$ (5 K)
5 ^{*)}	1000	90	27	$1.5 \cdot 10^5$ (10 K)

^{*)}: with 10 nm PrBCO buffer layer

The electric properties of the SrTiO₃-layer have been measured by a two-probe method. Typical I-V curves of YBCO/SrTiO₃/Ag-gate contact are shown in figure 4. We often observe the same asymmetry in the curve (solid line) as has been reported by other groups [2,3]. This may be caused by a Schottky-like interface between YBCO and SrTiO₃ or between SrTiO₃ and Ag. However, for some structures the I-V curve was more symmetric (dashed line)

The breakdown electric field (defined as $I_{\text{leak}} = 0.05 \mu\text{A}$) is usually $2 \cdot 10 \cdot 10^7$ V/m at 77 K and below. We sometimes observe improvement of this value after passing a relatively high current through the barrier. This may be caused by pinholes which are "blown up" by first breakdown.

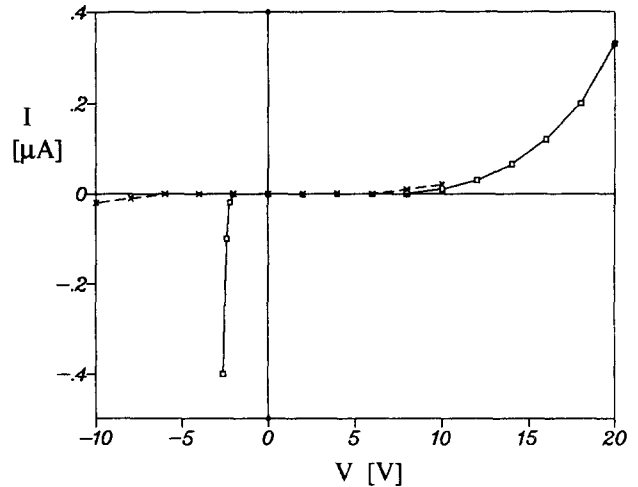


Figure 4. Breakdown behaviour of the SrTiO₃-layer.

4. Electric field effect measurements

All electric field effect measurements were performed using a six-terminal set up: standard four-probe measurement was used to determine the I-V characteristics of the superconducting channel under the gate, while the gate voltage was applied between the gate electrode and a sixth electrode, which had a low-ohmic contact to the superconducting bridge.

Clear and reproducible electric field effects were observed in all samples in which the thickness of the YBCO-layer was 10 nm or less. In figure 5 the I-V curve, taken at 10 K, of a 50 μm wide and 100 μm long bridge structured in a multilayer consisting of 10 nm PBCO, 5 nm YBCO and 120 nm SrTiO₃, is shown as a function of the applied gate voltage.

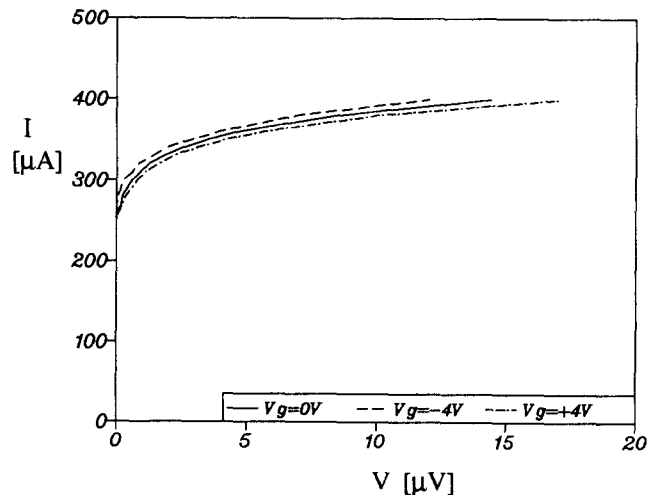


Figure 5. I-V curves of a 5 nm thick YBCO-layer as a function of the applied gate voltage.

The observed change of the I-V curves is in the correct direction. At positive V_g , the YBCO capacitor plate is charged negatively, i.e. depletion of positive carriers occurs. In this direction of the electric field, the superconducting properties of the YBCO-layer are depressed, as is seen in figure 5. At negative gate voltages, extra carriers are generated by the strong electric field near the YBCO/SrTiO₃-interface, causing an increase of the supercurrent through the YBCO-layer.

The observed effects can not be explained by heating effects or a leakage current through the barrier. Heating is excluded, since the dissipated heat rises extremely non-linearly with increasing gate voltage (see figure 4), while the change of the I-V curves of the YBCO-bridge does not. In addition, the observed enhancement could not be explained by this mechanism. Also the leakage current is certainly not the reason for the measured features. This current is much smaller than the observed changes of the transport current, and changing the direction of the transport current would result in a modulation in the opposite direction.

At low temperatures the absolute change of the transport current at any fixed voltage over the bridge is constant at a certain applied gate voltage, while at temperatures close to T_c the relative change of the transport current seems to be constant. From these features it is possible to estimate reliably the change of the critical current caused by the electric field. In figure 6 the relative change of the critical current is plotted as a function of the applied gate voltage, at different temperatures.

The linearity of the $\Delta I_c/I_c(V_g)$ -dependence and

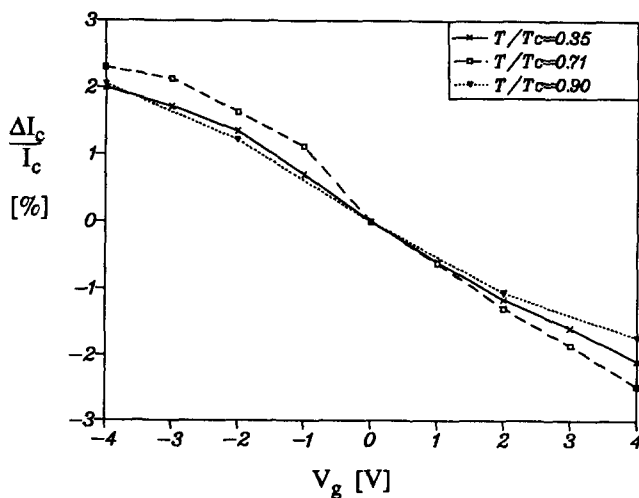


Figure 6. Relative change of the critical current as a function of the applied gate voltage, taken at different temperatures.

its nearly temperature-independence can be explained by a parallel-conductors model. The superconductor is thought to consist of two parallel conducting layers. One layer is within the charge screening length from the interface, and can be affected by the electric field; the other layer is outside this region and is therefore unaffected. We then expect $\Delta I_c/I_c \cong \Delta n/n \propto V_g$, which is in agreement with the experimental results.

5. Conclusions

We have grown epitaxial multilayers consisting of superconducting ultrathin YBCO-layers, down to 5 nm, covered by a SrTiO₃-layer with good dielectric properties. A thin PrBCO buffer layer has been used to improve the properties of the YBCO-layer in the sandwich.

The multilayers were structured into bridges covered by a gate electrode and successfully used in electric field effect experiments.

We observed clear and reproducible electric field induced changes in the I-V curves of all our samples in which the thickness of the YBCO-layer was 10 nm or less.

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