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Biepitaxial Josephson junctions and SuFET technology for the preparation of HTS-JoFETs

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Abstract

Biepitaxial Josephson junctions and superconducting field effect transistors (SuFET) were fabricated in order to combine both techniques to a Josephson junction field effect transistor (JoFET). The Josephson junctions show RSJ-like behaviour. At 30 K a critical current density of $J_c \approx 10^4$ A/cm² and an $I_c R_N$ -product of 0.1 mV were obtained. The oscillation of Shapiro steps with applied microwave field can be well fitted by the RSJ-model. SuFETs with CeO₂ as dielectric show, for fixed charge transfer, results comparable to SrTiO₃-based SuFETs. The downset of the resistive transition of a six-unit-cells thick YBa₂Cu₃O_{7- δ} layer is 44 K and the largest field effect obtained so far is 1.5 %. Preliminary results on JoFETs show a drastic change in the critical current density and in the specific junction resistance, however the $I_c R_N$ -product remains still in the typical range. The insulating properties are degraded compared to SuFETs.

1 Introduction

The influence of an electric field on the transport properties of an ultrathin high temperature superconducting film was investigated by various research groups [1] [2] [3][4]. The charge carrier density can be modulated by applying a voltage from a metal gate across a dielectric material to the ultrathin YBa₂Cu₃O_{7- δ} film. The largest field effects in SuFETs obtained so far have a modulation of charge carrier density in the range of ten percent [5]. Due to the smallness of the field effect an application of a SuFET is unlikely.

Recently, the influence of an applied electric field on ultrathin YBa₂Cu₃O_{7- δ} films containing weak links was reported [6]. The weak links were induced by a substrate with submicron grooves. Only moderate effects were obtained in the normal conducting regime. But in the superconducting regime the field effect was very large. So a shift in T_c of up to 25-30 K was observed. For a 45° grain boundary Josephson junction on a bi-crystal substrate an enhancement of the Josephson supercurrent up to 70 % at positive voltage was obtained [7]. This is in contrast to results obtained at SuFETs, which show an enhancement of the critical current density at negative voltage.

A JoFET is not only of interest for studying the physics of grain boundary Josephson junctions. The application of a tunable Josephson junction in high- T_c SQUIDS opens up the possibility to reduce the difference in critical current of the two junctions [8]. In order to realize such a device it is necessary to have a planar-Josephson-junction technology as well as a SuFET technology with high quality interfaces between dielectric and superconductor. Considering these items we have decided to use biepitaxial Josephson junctions, first prepared by Char et al [9].

2 Biepitaxial Josephson junctions

2.1 Preparation

Biepitaxial Josephson junctions have been prepared on MgO substrates. It is a well known fact that MgO substrates become contaminated in air. In order to clean the surface the MgO substrates are cleaned in an ultrasonic bath of ethanol. Before the deposition, the substrates are annealed in 700 mbar O₂ at 800°C. In order to further improve the crystalline quality, a thin MgO layer (≈ 10 nm) is deposited at 590°C by on-axis RF sputtering. In the same atmosphere of $8 \cdot 10^{-2}$ mbar Ar and $6 \cdot 10^{-2}$ mbar O₂ a thin CeO₂ layer (≈ 20 nm) is sputtered in situ at 560°C. Then on one part of the substrate the CeO₂ layer is removed by ion beam etching ($U_{\text{Beam}} = 500$ V, $J_{\text{Beam}} = 0.5$ mA/cm²), so that the substrate is only partly covered with CeO₂. Before YBa₂Cu₃O_{7- δ} is deposited by DC sputtering using an inverted cylindrical magnetron [10] in a mixed atmosphere of $4 \cdot 10^{-1}$ mbar Ar and $2 \cdot 10^{-1}$ mbar O₂, an annealing step in 700 mbar O₂ at 800°C is necessary to improve the crystalline quality on the etched part of the substrate. X-ray diffraction measurements show the desired orientation YBa₂Cu₃O_{7- δ} [110]||CeO₂[100]|| MgO[100] on the one part of the substrate and YBa₂Cu₃O_{7- δ} [100]||MgO[100] on the other part. To pattern the single junctions and SQUIDS, standard photolithographic methods with dilute phosphoric acid are used.

2.2 Electrical Properties

Fig.1a

Fig.1b

Fig. 1 (a) Resistive transition of three junctions with different width (20 μm (0.38 Ω), 40 μm (0.21 Ω) and 60 μm (0.11 Ω)). The resistance values are normalized to the junction resistances R_N . (b) There is a linear relation between the width of resistive transition and the square root of the normal resistance (see text).

The resistive transition of three different junctions on the same chip is shown in Fig. 1a. The resistance values are normalized to the normal resistance R_N for each junction. R_N is the resistance close to the transition of the superconducting electrodes and coincides with the junction resistance at low temperature, as is typical for grain boundary junctions [11]. The resistive transition of the

junctions shows a foot-like structure due to thermally activated phase slippage (TAPS) [11]. Here the values for R_N of the three junctions (20 μm , 40 μm and 60 μm width) are 0.38 Ω , 0.21 Ω and 0.11 Ω . Gross et al.[11] predicted for grain boundary Josephson junctions that for any fixed value R/R_N the width of the resistive transition $\Delta T/T_c$ should vary with the normal resistance R_N in the following way : $\Delta T/T_c \propto \sqrt{R_N} k_B T_c / \Delta_i(0)$. This analysis is based on the Ambegaokar-Bartoff expression for I_c with a reduced energy gap $\Delta_i(T) \propto \Delta_0(T) \times (1-T/T_c)^{1/2}$ at the interface. According to Deutscher and Müller the energy gap at a superconductor-insulator interface can be reduced due to the short coherence length of the high T_c materials [12]. In Fig. 1b $\Delta T/T_c$ is plotted versus $\sqrt{R_N}$ for a fixed value $R/R_N = 0.2$. The good agreement between theory and experiment is shown by the plotted line, extrapolating to the origin of coordinates.

Fig.2a

Fig.2b

Fig. 2 (a) I-V curves and (b) differential resistance of a 60 μm ($R_N = 0.11\Omega$) wide junction at 30, 50, 60 and 70 K showing RSJ-like behaviour, the temperature independence of R_N , and the asymmetry of the critical current.

I-V-characteristics at various temperatures (30, 50, 60 and 70 K) for a 60 μm wide junction ($R_N = 0.11\Omega$) show typical RSJ-like behaviour (Fig. 2a). More clearly the difference in positive and negative critical current can be seen in Fig. 2b, where the differential resistance is plotted versus current. Also the independence of R_N on temperature can be seen. The I-V-curves were not measured in a magnetically shielded environment, so that trapped flux is believed to be the reason for the asymmetry. We want to point out that even in shielded environments we observed changes in critical current caused by probe currents on the same or other junctions nearby. In some cases, for applied magnetic fields (≤ 1 Gauss) we even observed "hysteretic" behaviour. We explain this with trapped magnetic flux, because the McCumber parameter β_c ($\ll 1$) was certainly smaller than unity. Here the maximum probe current was not larger than five times the critical current. Nevertheless, these junctions show Shapiro step oscillations described by the RSJ-model [13].

3 SuFET-technology

Usually SrTiO_3 , due to its high dielectric constant and good chemical compatibility, is used in SuFETs with $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. However, this is related to a high loss factor $\tan\delta$ leading to large dissipation already in the kHz-regime [14]. Hence, we have used CeO_2 as alternative dielectric

material for the SuFET technology. The preparation is described in detail in [15] and will be summarized here only briefly.

In order to make low-resistance contacts to the ultrathin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer, it is important to prepare thick $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ electrodes. Therefore, in a first step part of the SrTiO_3 substrate is covered by a SrTiO_3 mask when depositing ≈ 80 nm $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. Then the mask is removed ex-situ and the ultrathin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer and the insulator are deposited in-situ. The ultrathin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer and the contact pads are deposited at 810°C by DC sputtering using an inverted cylindrical magnetron in a mixed atmosphere of $4 \cdot 10^{-1}$ mbar Ar and $2 \cdot 10^{-1}$ mbar O_2 [10]. Then CeO_2 is deposited in-situ at 580°C from a ceramic target by on axis RF magnetron sputtering in an atmosphere of $8 \cdot 10^{-2}$ mbar Ar and $6 \cdot 10^{-2}$ mbar O_2 .

Fig.3a

Fig.3b

Fig. 3 (a) Symmetric breakdown characteristic of CeO_2 and asymmetric characteristic of SrTiO_3 . (b) Dependence of downset of resistive transition on thickness of ultrathin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer in SuFETs. No influence of the dielectric material can be seen.

The dielectric constant ϵ_r of the typically 100 nm thick CeO_2 layers is ≈ 20 and almost temperature independent. The breakdown characteristic is symmetric, which is not the case for SuFET with SrTiO_3 as dielectric material. A breakdown field of $E_{bd} \approx 2 \cdot 10^8$ V/m has been achieved (Fig. 3a). The field effects for a fixed charge transfer are comparable in devices using CeO_2 or SrTiO_3 as dielectric, indicating that it is the change in the charge carrier density and not field-induced stresses that are responsible for the observed effects [16]. In the charge carrier enhancement mode (negative voltage) the achieved charge transfer amounts to $\Delta N = +2\mu\text{C}/\text{cm}^2$, which is 80% of the highest value obtained for SrTiO_3 -based SuFETs. The surface of the ultrathin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}/\text{CeO}_2$ bilayers shows no outgrowth or pinholes in AFM studies. The average roughness of the CeO_2 layer is only 3% of the total thickness. The resistive transition of a six-unit-cells thick $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer in a SuFET with CeO_2 has an onset at over 80 K and a downset at 44 K. This is similar to SuFETs with SrTiO_3 as can be seen in Fig. 3b. The largest field effect obtained so far with the use of CeO_2 as dielectric is 1.5 % for a six-unit-cells thick $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film [15].

4 JoFET-technology

To prepare a Josephson junction field effect transistor (JoFET) based on a grain boundary junction two problems have to be taken into account. First, the insulating properties of the dielectric may deteriorate when the dielectric is grown on the grain boundary. Second, the superconducting properties may change due to the preparation process of the dielectric. In addition the patterning technique may have an influence on the junction properties, when the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer has to be very thin (≤ 30 nm) in order to achieve sizable effects. Therefore we decided to use an inhibit patterning technique as described below.

4.1 Inhibit patterning

After ion milling of the CeO_2 seed layer the final junction area of the substrate is covered by a SrTiO_3 shadow mask. Analogously to the preparation of SuFETs, contact areas of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ are deposited at 810°C . Then gold pads are sputtered onto the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ contact areas through a metal shadow mask. The measurement geometry is achieved by inhibit patterning. Therefore an amorphous $\text{CeO}_2/\text{MgO}/\text{CeO}_2$ layer system is deposited through another metal mask, covering the contact area. $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ deposited on this amorphous layer system is insulating. We choose this layer system due to its chemical compatibility to $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. In order to avoid recrystallization of the amorphous layer at the later process step at high temperatures, all three amorphous layers are necessary. In the following preparation step $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and the insulating CeO_2 are deposited in situ without any shadow mask at the conditions described for SuFETs. In the last step the Au-gate electrodes of the JoFETs are sputtered through a third metal mask.

4.2 Preliminary results

Fig. 4 (a) Resistive transition of biepitaxial Josephson junction in JoFET structure. (b) I-V curves of same junction at 30 and 50 K.

In Fig. 4.1a the resistive transition of an inhibit patterned junction is shown. The specific normal conductance of a pure biepitaxial junction is about $50/(\mu\Omega\text{cm}^2)$. For a 150 nm thick and 200 μm wide junction in the JoFET structure the conductance is more than an order of magnitude smaller. In Fig. 4.b the I-V curves for this junction are shown at 30 and 50 K. At 30 K the I-V curve is still noise-rounded, so that the determination of the critical current $I_c \approx 25\mu\text{A}$ depends strongly on the

j_c -criterion. The normal resistance $R_N = 5 \Omega$ is taken from the slope of the I-V curve at higher voltages in good agreement with the foot point of the resistive transition. So the $I_C R_N$ -product has a value of 0.125 mV, typical for biepitaxial junctions. Work is in progress to investigate the reason for the drastic change in critical current density and specific conductance.

The largest achieved breakdown field E_{bd} in an inhibit patterned JoFET structure is $\approx 10^7$ V/m, a value one order of magnitude smaller than in SuFETs.

5 Summary

In summary, the preparation of biepitaxial Josephson junctions and superconducting field effect transistors has been described. The junctions are RSJ-like, and the results of the resistive transition support for high angle grain boundaries the idea of a reduced order parameter at the interface. SuFETs with CeO_2 have proven to be a possible alternative to SrTiO_3 based SuFETs in the charge carrier enhancement mode. The preparation of JoFETs faces the problem of changes in the junction properties. However, the $I_C R_N$ -product remains unchanged. So far the insulating properties are degraded compared to SuFETs.

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