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High- T_c -based Josephson-junctions and SQUIDs by mechanically induced growth disorder

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Abstract: We have developed a simple method for the reproducible production of high- T_c based Josephson junctions and SQUIDs. By producing a very weak deformation into the substrate surface by a diamond needle before deposition of the thin high- T_c -film, the film shows a growth disturbance in the region of the deformation with quite interesting features, resulting in a Josephson junction. The substrate deformation is characterized by Atomic Force Microscopy and the film growth over the deformation is examined by Scanning Electron Microscopy. The junctions produced by this method show RSJ-like behaviour in their current-voltage characteristics and Shapiro-steps at all temperatures between 4.2 and 89K, when exposed to microwave power. The $I_c R_n$ -products are variable in a wide range and can be very high for properly chosen film thicknesses. SQUIDs produced by this method show voltage modulations due to dc-flux of up to $12\mu\text{V}$ peak to peak at 77K for low SQUID-performance parameters $\beta \ll 1$. For $\beta \gg 1$ the modulations are between 3 and $5\mu\text{V}$ at 77K. Finally the noise in SQUIDs produced by this method is examined. It is shown that the noise power is in the region of that of step edge junctions.

1. INTRODUCTION

Due to the short coherence length in High- T_c -superconductors, there had to be developed new and sophisticated methods for the production of Josephson-junctions and SQUIDs with these materials. Step-edge-[1, 6], biepitaxy-[2], bicristal-[3], ramp-type-[4], and SNS-junctions[5] are the most important ones. All these methods have in common that they are either unflexible in design or in their superconducting properties as critical current I_c or the $I_c R_n$ -product. The method introduced in this paper allows for the reproducible production of Josephson-junctions and SQUIDs in a wide parameter range. It consists of a very weak deformation made into the substrate surface by a diamond needle before film deposition. The method allows for high flexibility in design.

2. PREPARATION

2.1 Preparation and Characterization of the Deformation

The deformation of the substrate surface is produced by a commercially available diamond needle. When pressing the needle onto the substrate with a pressure of 2.5-250GPa, the substrate is moved linearly with a velocity of 0.3-0.5mm/sec.

Atomic Force Microscopy- (AFM-) examinations show, that the deformation has a width of about $1\mu\text{m}$ and a depth of 30 to 70nm. Enhanced edges on both sides are generated, which are part of the

Figure 1: AFM-linescan of the substrate deformation produced by the diamond needle.

deformation, as they cannot be removed by chemical or mechanical cleaning. A typical AFM-result is shown in figure 1.

As the width to depth ratio of the deformation is much larger than 10:1, the resulting Josephson-junctions are not of the step-edge type, as for these a tilt angle of at least 45° is required[6]. SrTiO_3 as well as NdGaO_3 were used as substrate-materials. With both materials equal properties of the deformation and of the later deposited high- T_c -film were observed.

2.2 Preparation and Characterization of the thin Film

The thin $\text{YBa}_2\text{Cu}_3\text{O}_7$ -film is deposited onto the substrates with the previously described deformation by dc-sputtering. We sputter from a stoichiometric and planar target in on-axis geometry in pure oxygen atmosphere and at high pressure[7]. The thin $\text{YBa}_2\text{Cu}_3\text{O}_7$ -films grown by this method onto substrates without deformation have a critical temperature T_c of 90-93K in ac-susceptibility measurements with a sharp transition of smaller than 1K. X-ray diffraction measurements in Bragg-Brentano-geometry show that the films are completely c-axis oriented (only (00 l)-peaks are seen) and that there is no indication for any other phases. The critical current density j_c has a value of 4 to $6 \cdot 10^6 \text{ A/cm}^2$ at 77K and of 3 to $4 \cdot 10^7 \text{ A/cm}^2$ at 4.2K.

2.3 Scanning Electron Microscopy (SEM) of the Growth Disturbance

The films deposited onto substrates with deformation were examined by SEM. In figure 2a a SEM-picture of the film-growth over the substrate deformation is shown for a 40nm thick film on SrTiO_3 . The width of the deformation is approximately $1\mu\text{m}$ and is indicated by the white lines. The film grows homogeneously over nearly the whole disturbed region by forming growth steps. Only in a very narrow area of a width of approximately 100nm (shown by the arrows) the growth of the film is heavily disturbed. Over this region contact is established only by nanobridges of width between 150 and 250nm. Between these bridges there is no film-growth at all. It is assumed that the resulting Josephson contacts are due to these nanobridges.

As the nanobridges are smaller or equal both in width and in thickness than the magnetic penetration depth λ in $\text{YBa}_2\text{Cu}_3\text{O}_7$, a Josephson effect could appear due to coherent vortex movement in the bridges[8, 9] without the assumption of any other weak link. Then the current-voltage- (I - V -) characteristics should have flux flow behaviour with $V \propto I^\alpha$. Additionally the dependence of the appearing Shapiro-steps on microwave power should behave in a totally other way than predicted by the Resistively Shunted Junction- (RSJ-) model[10], and the current-steps should not oscillate with increasing power. This is not the case as will be seen in the next section.

If the film thickness is more than approximately 80-100nm, the disturbance begins to be overgrown by $\text{YBa}_2\text{Cu}_3\text{O}_7$ and the nanobridges become larger in width, thickness and number. In figure 2b the growth disturbance of a film with a thickness of 80nm is shown. The heavily disturbed region of film growth has nearly disappeared and is hardly discernible. Only the $1\mu\text{m}$ wide deformation region can be observed (white lines). As a consequence the Josephson effect disappears. Therefore for the successful and reproducible preparation of Josephson junctions with the mechanically induced growth disorder, high quality ultrathin films with a controllable thickness between 10 and 80nm are required. The dc-sputtering method provides these films with control of the film thickness via the deposition time. However, the danger of superconducting shortcuts is quite high in this type of

Figure 2: (a) SEM-picture of a structured film with a thickness of 40nm. Inbetween the white lines the substrate deformation is located. The arrows show the nanobridges crossing the approximately 100nm wide heavily disturbed region. (b) SEM-picture of a film with a thickness of 80nm. The deformation made by the diamond needle can be well seen between the white lines, whereas the heavily disturbed region of film growth has nearly disappeared.

junction and cannot be excluded.

3. PROPERTIES OF THE JOSEPHSON JUNCTIONS

3.1 Resistive Transitions of the Junctions

In figure 3 the resistive transition $R(T)$ of a junction with a film thickness of 60nm is shown. It can be seen that the film properties did not suffer due to the very small film thickness, as T_c is as high as 92K. In the insert a small foot in the resistive transition is observable. Ambegaokar und Halperin (AH)[11] could relate the suppression in the critical current of Josephson junctions for small currents to Thermally Activated Phase Slippage (TAPS). In this model the phase difference over the junction can be statistically thermally activated and slips by a value of 2π . The dependence of the mean additional resistance R_p due to TAPS is given by AH:

$$R_p/R = 1/(J_o(\gamma/2))^2; \quad \gamma = hI_c(T)/2\pi e k_B T \quad (1)$$

with J_o the modified Bessel-function. Gross et al.[12] could fit their data for $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ -grain boundary Josephson junctions with equation 1 and found a γ -value of 1350, assuming a temperature dependence of the critical current near T_c as

$$I_c(T) = I_c(0) \cdot (1 - T/T_c)^2. \quad (2)$$

We are able to fit our data with the same assumptions satisfactory (see fig. 3) and get $\gamma = 26000$, which is more than one order of magnitude higher than found by Gross. This implies, if assumed that equation 2 were valid down to $T = 0$, an $I_c(0)$ -value of 50mA, corresponding to a critical current density $j_c(0)$ of $1 \cdot 10^7 \text{ A/cm}^2$. In reality, j_c is $5 \cdot 10^5 \text{ A/cm}^2$ at 4K and $4.5 \cdot 10^4 - 1 \cdot 10^5 \text{ A/cm}^2$ at 77K, which is still very high in comparison to other junction types.

3.2 Properties of the I-V-curves

As can be seen from fig. 4, the I-V-characteristics are RSJ-like and non-hysteretic (McCumber-parameter $\beta_c < 1$). For properly chosen film thickness the $I_c R_n$ -products can be quite high. By varying the film thickness, the $I_c R_n$ -product can be changed in several orders of magnitude, as the critical current of the junctions has a non-linear dependence on the film thickness. The I-V-curves can be fitted with the RSJ-model including thermal current noise. In the junction of fig. 4 a Gaussian distribution of the fluctuation currents with a FWHM of 0.04mA was assumed, which is quite low

Figure 3: (a) Resistive transition of a junction with a film thickness of 60nm. In the insert a small foot can be seen, which can be fitted by the expression of Ambegaokar and Halperin for TAPS in the case of small currents. The fit is shown in (b).

in comparison with the critical current. However, the mean part of the I-V-curve could not be fitted by the RSJ-model and additionally, a considerably high excess-current had to be assumed for the fit. On the one hand this excess-current could be due to shortcuts, on the other hand, different types of junctions show such excess-currents, and their origin is still unknown.

3.3 Influence of microwave power

When exposed to microwave power, the junctions show Shapiro steps at all temperatures between 4.2 and 89K. In fig. 5a the I-V-curves of a 50nm thick film on a NdGaO₃ substrate at 4.2K are shown for different microwave powers. The current steps oscillate with the microwave power. Due to the high excess-current, the oscillation does not behave as predicted by the RSJ-model. The first and second step begin to oscillate with increasing power before the width of the 0th step is zero for the first time. For higher microwave powers the oscillation is RSJ-like. The step modulation in dependence of the microwave power is shown in figure 5b.

3.4 Discussion

As the I-V-curves are RSJ-like and there is a current-step modulation in dependence of the microwave power, we assume that the origin of the Josephson effect in our junctions is not due to coherent vortex-motion in the nanobridges, but is dominated by an additional weak link (grain boundary or SS'S-type device with reduced order parameter in the superconductor S'), situated in the nanobridges.

For lower $T < 77K$, there often appear roundings in the I-V-curves, also not due to vortex motion but to more than one Josephson junction in line in the bridges which can well be identified in the derivatives of the I-V-curves.

4. PROPERTIES OF THE DC-SQUIDS

In fig.6a the voltage modulation of a dc-SQUID with a film thickness of 30nm at 77K and a SQUID-performance parameter $\beta = 2LI_c/\Phi_0 = 3$ [13] is shown in dependence of the bias current through the SQUID. The inductance L of the SQUID with a $10 \times 20 \mu m^2$ -hole is assumed to be 20pH and the critical current $I_c(77K)$ of the single junction (width $10 \mu m$) is 0.15mA, corresponding to $j_c(77K) = 4.5 \cdot 10^4 A/cm^2$.

The modulation depth is between $3-5 \mu V$ peak to peak ($dV/d\Phi = 9$ to $15 \mu V/\Phi_0$) for SQUIDS in the high β -limit. For lower temperatures $T < 77K$ the critical current increases by a factor of 5 to 10, so that the high β -limit for the critical current modulation ($\Delta I_c = \Phi_0/L$) is reached. In the low β -limit ($\beta \ll 1$), peak to peak voltage modulations of up to $12 \mu V$ could be reached at 77K, corresponding

Figure 4: (a) I-V-curve of a junction with a film thickness of 60nm at $T = 80\text{K}$ and its derivative. (b) Fit with the RSJ-model including thermal current fluctuations and the fit with the noise-free RSJ-model. The dotted lines in the insert are fits to Gaussian current distributions with FWHM of $0.04\text{mA} \pm 10\%$.

Figure 5: (a) I-V-curves for different microwave powers at 4.2K for a 50nm thick film on a NdGaO_3 -substrate. (b) Step-modulation in dependence of the microwave power.

Figure 6: (a) Voltage modulation in dependence of magnetic flux of a SQUID at 77K with $\beta = 3$ for different bias-currents. Additionally the I-V-curve is shown in the plot. (b) Voltage modulation of a SQUID at 77K with $\beta = 0.025$ in dependence of the bias-current.

Figure 7: Flux noise in a dc-SQUID at 77K.

to $dV/d\Phi = 36\mu\text{V}/\Phi_0$. The dependence of the voltage modulation of a SQUID with $\beta = 0.025$ on the bias current is shown in fig. 6b.

In fig. 7 the flux noise for a SQUID at 77K with linewidth of $10\mu\text{m}$ and a $10\times 20\mu\text{m}^2$ SQUID-hole is shown for frequencies between 1 and 400Hz. For frequencies higher than 5Hz the noise is in the same range as it is for step-edge junctions[14, 15]. For lower frequencies a significant increase of the noise power is observed, whose origin is not known. The peaks in the spectrum correspond to the line frequency of 50Hz and some instruments working at 60Hz and their harmonics.

As Josephson junctions for film thicknesses smaller than 20nm are possible by the method of mechanically induced growth disorder, they provide the ideal combination with High- T_c field effect devices, where ultrathin films are needed to have high field effects.

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