VORTEX MOTION AND JOSEPHSON EFFECT IN SUPERCONDUCTING MICROBRIDGES IN (001) and (105) ORIENTED $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ THIN FILMS

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Abstract - - Microbridges with dimensions smaller than the effective penetration depth λ_L , have been prepared in epitaxially grown (001) and (105) oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films. The current-voltage characteristics of these bridges show specific kinks and steps which can be attributed to discrete coherent vortex motion along single or multiple paths across the microbridges. The critical current of a configuration with two very small microbridges in parallel, shows periodic SQUID modulation at 4.2 K.

I. INTRODUCTION

The preparation of high T_c superconductor thin film structures with very small dimensions is important for measuring very local transport properties of the superconductor, e.g. across grain boundaries, for the realization of planar proximity effect devices and for minimizing white noise in superconducting quantum interference devices (SQUIDS), as pointed out in a recent paper [1]. Moreover, some interesting effects can be observed in thin film microbridges with sufficiently small dimensions.

Superconducting thin film microbridges will show full Josephson behaviour if their width and length are very small, typically less than a few times the coherence length ξ [2]. Larger microbridges with dimensions up to the effective penetration depth λ_L will also show some typical Josephson effects. The motion of the Abrikosov vortices across such microbridges, tends to be periodic. This is a result of the repulsive interaction between the vortices. Thus, Shapiro steps can be observed in the current-voltage ($I - V$) characteristics of small microbridges, due to coupling of the periodic vortex motion with the external microwave irradiation. Furthermore, specific kinks will appear (without microwave irradiation) in the $I - V$ characteristics of these small microbridges, at currents where the average number of vortices in the microbridge has an integer value. This has been discussed theoretically by Aslamazov and Larkin (AL) and others [3,4,5].

Preparation of microbridges in high T_c superconducting thin films, small enough to observe these effects, is very difficult. The coherence length in high T_c copper-oxide superconductors is much too small, i.e. ~ 2 nm in the ab -direction and even smaller in the c -direction, to realize bridges with dimensions $\sim \xi$. Even wider bridges with dimensions $\sim \lambda_L$ (typically ~ 200 nm) are very difficult to realize, because the ceramic superconductors are very sensitive to external influences which tend to de-

stroy the superconducting properties. For instance, ion bombardment or temperature increase can rapidly result in oxygen loss of the superconductor.

By now only a few results have been reported of structures in high T_c oxide superconducting films with dimensions smaller than λ_L [6,7,8,1]. Here we will discuss some of our experimental results obtained for microbridges, with w and l well below λ_L , structured in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) thin films.

II. PREPARATION

The bridges are structured in epitaxially grown films with thickness $d \approx 75$ nm, prepared by both laser ablation ((001) oriented films) and off-axis magnetron sputtering ((105) oriented films). Preparation of similar films and typical film qualities have been discussed elsewhere [9,10,11].

A trilayer electron beam resist technique is used for structuring the microbridges. The resist consists of a 700 nm thick bottom layer of AZ 1500 resist [12], a 20 nm thick thermally evaporated germanium barrier layer, and, on top, a 100 nm thick layer of positive developing electron beam resist AZ PF 514 [12]. A modified Philips SEM 500 electron microscope is used to pattern the resist. After development of the resist, the Ge film is reactively etched in a SF_6 plasma followed by anisotropically etching of the bottom resist layer in a low pressure oxygen plasma. Finally, the resulting photoresist structure is used as a mask for etching the YBCO films in an argon plasma (2.5 Pa pressure, -630 V self bias, 9 nm/min. etch rate). During a second standard photo lithographic process, the contact leads are defined and etched in a similar argon plasma. To minimize the deterioration of the YBCO film, all process temperatures are kept below 120 °C, and all contact with water and water based developers is avoided.

III. RESULTS

A. (001) oriented films

An example of a microbridge structured in an YBCO (001) film with length $l \sim 70$ nm and width $w \sim 225$ nm is shown in Fig.1a. Some residues are visible of material which has been redeposited during the etching process against the resist walls. After stripping of the resist, these depositions are left and can only be removed mechanically. Furthermore, a somewhat hilly surface structure is observed with typical lateral dimensions of the order 200 nm. It is very well possible that these small

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Figure 1: *a*: Scanning Electron Microscopy (SEM) picture of a structured microbridge in a (001) oriented YBCO thin film. The estimated width and length are resp. 225 and 70 nm. *b*: Some of the $dV/dI - I$ characteristics of the same microbridge.

'hills' are in fact screw dislocations, similar to those reported in literature [13]. Atomic Force Microscopy on our films, which can verify this possibility, is planned for the near future.

We determined the critical temperature of the microbridges from 4 points resistivity measurements with measuring currents $\sim 1 \mu\text{A}$ and a resistance criterion $R_c \sim 1/100$ times the normal state resistance at 100 K. The microbridges with widths larger than 350 nm and $l \sim 70$ nm have approximately the same T_c as the unstructured films (~ 88 K). Smaller microbridges show a gradual decrease of T_c with $T_c = 82$ K for $w \sim 175$ nm and $T_c \sim 40$ K (with a very broad transition starting near 90 K) for $w \sim 100$ nm. The latter value of w is only a rough estimation. An exact determination of the width is impossible due to the redeposited material at the edge of the microbridge. The decrease of T_c with decreasing width suggests that there is a gradual degradation of the superconducting properties over a distance of approximately 150 nm from the etched boundary. High critical current densities were determined for the bridges with $w \sim 175$ nm and larger, i.e. $J_c(55\text{K}) \approx 10^{11} \text{ A/m}^2$. ($dV/dI = 0.01 \Omega \sim R(100 \text{ K})/5000$ criterion).

Fig. 1b shows some of the differential $dV/dI - I$ characteristics of a bridge with $w=225$ nm and $l=70$ nm at temperatures near T_c . The differential characteristics show kinks which would be hardly visible in the $I - V$ characteristics. It can be shown that the temperature dependence of the curves is well described with thermally activated vortex motion according to $V \propto e^{-U/kT}$, where

the involved activation energy U is proportional to $1/I$ [14]. The position of the first kink is in good agreement with the theory of AL [3,4] if we allow for thermal activation of the vortices [14]. The other kink can be due to the appearance of additional paths along which the vortices start to move (See below).

Figure 2: Typical $I - V$ characteristic of an YBCO thin film microbridge with $w \sim 100$ nm and $l \sim 70$ nm at 4.2 K. The inset shows a numerically calculated characteristic, based on the theory of AL.

A typical $I - V$ characteristic of a bridge with $w \sim 100$ nm and $l \sim 70$ nm and $T_c=38$ K measured at 4.2 K is shown in Fig. 2. Very sharp features can be seen which indicates that thermal activation plays only a minor role. The shape of the lower part of the curve, showing clearly a sharp 'step' and two kinks, is in qualitative agreement with a calculated curve (Fig. 2-Simulation). Here we numerically simulated the motion of the vortices across a microbridge (with $\xi/w = 0.05$) in accordance with the theory of AL [3]. Thus, their motion is described with $F = \eta v$, where F is the force acting on each vortex, η is the viscosity coefficient of moving vortex [15] and v the vortex velocity. The force is calculated by summing the vortex-vortex interaction forces, the Lorentz force due to the transport current and the edge pinning force, as given by AL.

At higher currents typical steps are observed in the $I - V$ characteristic. They can be due to additional paths along which vortices start to move. Hence, the voltage becomes equal to a sum over several voltage drops in series, i.e. $V = \Phi_0 \sum_i 1/\tau_i$ where Φ_0 is an elementary flux quantum and τ_i is the period of the coherent vortex motion along the path with index i .

Furthermore, a dc-SQUID like structure was prepared, with two microbridges connected in parallel, and a hole size of $5 \times 5 \mu\text{m}$. w , l and d are of the order ~ 75 nm. The critical temperature of the structure was 37 K.

Upon applying a magnetic field B , a periodic modulation of the critical current I_c was observed (Fig. 3).

Figure 3: Critical current of a configuration with two microbridges in parallel and hole with an area $A = 5 \times 5 \mu\text{m}$. cf is an unknown calibration factor between approximately 0.7 and 1.3. The indicated Φ_0 is equal to $cf B A$.

The estimated period ΔB is within the experimental accuracy equal to $\Phi_0 A$, where A is the area of the pick-up loop. It can be shown that the observed critical current modulation is in good agreement with the relation which holds for all dc-SQUIDS with asymmetric weak links [16], i.e. $|I_{c,+}(\vec{B})| = |I_{c,-}(-\vec{B})|$, where the + and - subscripts indicate the critical currents for opposite current direction.

B. (105) oriented films

Recently first results have been reported concerning the tilted growth of YBCO on SrTiO_3 substrate with (305) orientation [10,11]. High Resolution Transmission Electron Microscopy, advanced X-ray diffraction analysis and Rutherford backscattering experiments provided conclusive evidence for the growth of almost single domain (105) oriented YBCO, with the c-axis tilted over approximately 31° from the surface normal and the b-axis parallel to substrate surface. These films offer nice possibilities to measure the anisotropy of the transport properties of untwinned YBCO films in the [010] and $[50\bar{1}]$ direction [10,11].

A relatively long microbridge was structured in such a film with $l \sim 150$ nm in the b direction and $w \sim 100$ nm (rough estimation) and a thickness $d \sim 70$ nm. A schematic view of the bridge and the expected tilted vortex motion across the bridge, is shown in Fig. 4a. T_c of the bridge is approximately 48 K. Fig. 4b shows the measured $V-I$ and $dV/dI-I$ characteristics. Clearly visible are constant dV/dI plateaus in the $dV/dI-I$ characteristics, with discrete jumps at currents I_j . The jumps apparently become smaller at higher currents. Below we will show that this behaviour is in agreement with some simple approximations.

We assume that at each jump in dV/dI an additional path becomes 'active', along which vortices move

across the microbridge. Because the ab planes are tilted (Fig. 4a) and d and w are approximately equal, we make no distinction between them and simply put $d = w = \sqrt{A}$, where A is the cross-sectional area of the bridge.

Figure 4: a: Schematic picture of a microbridge and its cross section with $w \sim 100$ nm and $l \sim 150$ nm, which has been structured in a (105) oriented YBCO film. b: $V-I$ and $dV/dI-I$ characteristics of this bridge at 4.2 K. c: Observed jump in dV/dI as a function of $1/I_j^{3/4}$ where I_j is the current at the jump.

We can estimate each jump in the differential resistance dV/dI in accordance with the theory of AL [3]. It follows that for currents $I - I_j \gg I_j \sqrt{\xi}/w$, the differential resistance is approximately constant and given by $dV/dI \sim \Phi_0^2 / \pi \eta \sqrt{2\xi} A^{3/4}$. The current at each jump can be estimated from $I_j \sim J_c A$, where J_c is the critical current density at which the Lorentz force acting on the vortices just balances the forces which keep the vortices pinned at the edge of the bridge. Hence, $\Delta(dV/dI)|_{I_j} \sim \Phi_0^2 J_c^{3/4} / \pi \eta \sqrt{2\xi} I_j^{3/4}$, which is in agreement with the ob-

served linear dependence $\Delta(dV/dI) \propto 1/I_j^{3/4}$ (Fig. 4c). Thus, we can estimate η from the slope α in Fig. 4c according to $\eta \sim \Phi_0^2 J_c^{3/4} / \pi \sqrt{2\xi} \alpha$. Upon substituting $J_c \sim I_j/A \sim 35 \mu\text{A} / (75 \text{ nm})^2 \approx 6 \times 10^9 \text{ Am}^{-2}$, $\xi \approx 2.5 \text{ nm}$ and $\alpha \approx 0.0823 \text{ VA}^{-1/4}$, we obtain $\eta \sim 5 \times 10^{-18} \text{ VAs}^2\text{m}^{-2}$.

This value can be compared with the jump $\Delta(V)$ in the $V-I$ characteristics. From the theory of AL we derive $\Delta(V)/I_j \sim 4\Phi_0^2/\pi^2 A\eta$. Upon substituting typical values $A \sim (75 \text{ nm})^2$, $\Delta(V) = 0.8 \text{ mV}$ and $I_j = 35 \mu\text{A}$, we find $\eta \sim 1 \times 10^{-17} \text{ VAs}^2\text{m}^{-2}$, which is in approximate agreement with the value derived above.

However, comparison with the theoretical approximation [15] $\eta = \Phi_0^2 l / 2\pi \xi^2 \rho_n$, where l is length of the vortex and ρ_n is the normal state resistivity, fails. By substituting typical values $l \sim 70 \text{ nm}$ and $\rho_n = 50 \mu\Omega\text{cm}$, we obtain $\eta \sim 2 \times 10^{-14} \text{ VAs}^2\text{m}^{-2}$ which is about three orders of magnitude larger than the value estimated from the measurements. The large deviation might indicate that the effective ρ_n is much higher, caused by e.g. grain boundaries in the film along which the vortices are moving.

IV. CONCLUSION

Preparation of YBCO thin film microbridges with dimensions down to $\sim 100 \text{ nm}$ is possible. However, for widths below $\sim 350 \text{ nm}$ a decrease of the critical temperature is observed. Other etching procedures, e.g. reactively etching in a chlorine plasma or with an ion beam, might improve the results.

The resistive behaviour of the microbridges shows effects which can be attributed to discrete coherent vortex motion. At low temperature both kinks, which are consistent with the model of AL, and steps, which can be attributed to the appearance of additional vortex paths across the microbridge, are observed. At elevated temperatures the current voltage characteristics are dominated by the effect of thermally activated vortex motion.

A very small viscosity coefficient η is estimated from the measurements. Indications of SQUID modulation of the critical current have been observed in a structure with two microbridges in parallel.

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