

## Superconducting Current Relaxation in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Thin Films Deposited on the $\text{CaNdAlO}_4$ Substrates

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Decay of induced superconducting currents in  $\text{YBa}_2\text{Cu}_3\text{O}_7$  thin films deposited on the  $\text{CaNdAlO}_4$  substrates was measured by a vibrating sample magnetometer in magnetic fields up to  $\pm 2$  T and temperatures down to 4.2K. The experimental temperature dependence of the induced current density  $j_s$  is interpreted in terms of the interpolation formula combining effects of thermally assisted flux creep and macroscopic quantum creep. The analysis indicates importance of the macroscopic quantum tunnelling at temperatures below  $\approx 5$ K. Significant difference in the  $j_s(T)$  dependences obtained on thin films prepared by different techniques (dc-magnetron sputtering and laser ablation) was observed especially at temperatures  $T < 0.5T_c$ .

The induced superconducting current decay is governed at different temperature ranges by different activation processes: whereas in the relatively broad range of medium and high temperatures the thermally activated flux motion (TAFM) takes place, at low temperatures the macroscopic quantum creep (QC) becomes important [1]. For TAFM the probability of vortex hopping  $P_{\text{TA}}(j_s, T, B) \propto \exp[-U_e/kT]$ . Here  $U_e(j_s, T, B)$  is the activation energy,  $j_s$  is the superconducting current density,  $T$  is the temperature and  $B$  the external magnetic field. For the quantum tunneling process Caldeira and Leggett [2] derived the hopping probability  $P_{\text{QC}} \propto \exp[-A\eta(\Delta q)^2/\hbar]$ , where  $A$  is a constant,  $\Delta q$  is the tunneling distance through the barrier and  $\eta$  is the viscosity. In [3] the interpolation formula was proposed enabling us to combine these two processes in the whole temperature range including the crossover interval, in  $\text{YBa}_2\text{Cu}_3\text{O}_7$  typically 1-10K. Using the Caldeira-Leggett expression and assuming that the energy distribution is  $N(E) = \exp[-E/kT]/kT$  and the potential barrier is of parabolic shape with the height  $E(j)$  and bottom width  $x_0$ , the total probability for the vortex to overcome the pinning barrier is [3]

$$P = P_0 \frac{T^*}{T - T^*} \left[ e^{-U_e/kT} + e^{-U_e/kT^*} \right] + e^{-U_e/kT} \quad (1)$$

where  $P_0 \approx 1$  and  $T^* = \hbar E(j)/\eta x_0^2(j)$  is the parameter

characterising the crossover temperature between quantum tunneling and thermal relaxation.

In this paper we use the interpolation formula (1) to fit the experimental  $j_s(T)$  dependence inferred from magnetic hysteresis loops (MHL) measured on the  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  prepared by dc-magnetron sputtering (MS) and by laser ablation (LA) on the  $\text{CaNdAlO}_4$  substrates. The  $\text{CaNdAlO}_4$  substrate material has a tetragonal structure of the  $\text{K}_2\text{NiF}_4$  type with a lattice constants  $a=0.369\text{nm}$  and  $c=1.215\text{nm}$  [4]. It does not exhibit the phase transition leading to formation of twin boundaries in superconducting films. Both MS and LA thin films have nearly same thickness  $d=200\text{nm}$  and approximately the same area  $a_1 \times a_2 = 5 \times 6 \text{ mm}^2$ . The critical temperatures are 86.8K and 89.4K for the MS and LA film, respectively. The surface morphology of the films is shown in figure 1. It is evident that the MS film has surface quite smooth, whereas the LA film surface is covered by small crystallites of the mean size  $\approx 0.4\mu\text{m}$ .

Magnetic measurements were performed with the vibrating sample magnetometer PAR 155. Magnetization loops were run up to  $B_e = \pm 2$ T at various temperatures ranging from 4.2K to 90K. Two sweep rates,  $dB_e/dt = 88 \text{ mT/s}$  and  $0.88 \text{ mT/s}$ , were used. The MHL size  $\Delta M$  was analysed at the fields  $B_e = +1$  and  $-1$ T and the mean value  $M_2(1T) = [\Delta M(-1T) + \Delta M(+1T)]/4$  was then used to calculate the current density  $j_s(1T)$  defined

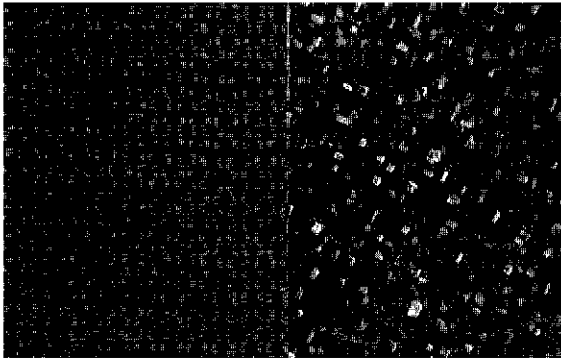


Figure 1. Scanning electron microscope images of the MS film (left) and LA film (right). Magnification is in both cases same, 3000 $\times$ .

according to the extended Bean model as  $j_s(T) = M_a(T) / [a_1^2(a_2 - a_1/3)d/4]$ .

Experimental MHLs measured on these samples were influenced by a significant paramagnetic component arising from the  $\text{CaNdAlO}_4$  substrate. This component can be easily separated as it has different field dependence from that caused by the induced superconducting currents. The necessity to correct results for the paramagnetic susceptibility  $\chi_p$  was highly compensated by the fact that  $\chi_p$  is strongly temperature-dependent quantity in the temperature range 1K-100K and can be therefore used as a sensitive thermometer in direct contact with the measured thin film.

The experimental  $j_s(T)$  obtained from the size of MHLs measured at different temperatures on the MS and the LA films are shown in figure 2. The theoretical curves calculated for the thermally activated relaxation process do not fit the experiments well at low temperatures (the dotted lines). Application of the interpolation formula (1) with  $T^* = 5$  and 5.8K for the MS and LA film, respectively (the full curves on the figure) gives on the other hand nearly perfect fit in the whole temperature range.

It should be emphasized that while at  $T > 0.5T_c$   $j_s(T)$  for both the MS and LA film is nearly the same, at lower temperatures the current density of the LA is film significantly reduced in comparison to that of the MS film. In spite of that  $T_c$  of the LA film is by  $\approx 3\text{K}$  higher than  $T_c$  of the MS film. On the other hand, figure 1. shows that the MS film is more compact than the LA film.

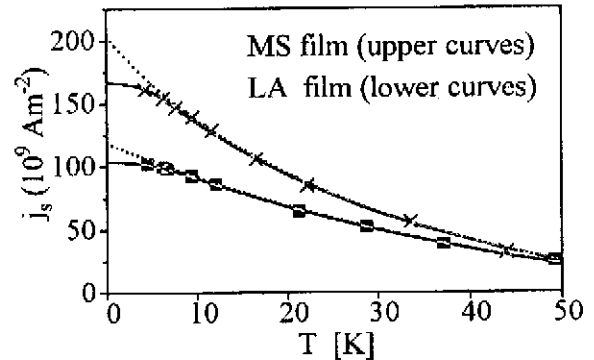


Figure 2. Temperature dependences of the superconducting current density ( $\times$  for the MS film,  $\square$  for the LA film) and their fits with taking into account only the thermal activation (dotted curves) and the combined quantum tunneling and thermal activation according eq.(1) (full curves).

In conclusion, the current density determined from the MHL experiments can be in a wide temperature range well described by interpolation formula (1) combining thermally activated and quantum tunneling relaxation process. Temperature dependences of the superconducting currents induced in MS and LA film differ at temperatures  $T < T_c$  which seems to be connected with the better film quality in the case of magnetron sputtering technique.

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