Direct observation of the depairing current with short current pulses in ultrathin high-temperature superconductor films

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Abstract. Resistivity measurements on ultrathin (36 and 42 nm thick) YBCO films were performed with a novel pulsed-current technique that allows for application of current densities up to several MA/cm\textsuperscript{2} with minimal self-heating even in the resistive state. Using current pulses as short as 50 ns we found that the onset of resistance in the \textit{I-V} curves takes place at substantially higher current densities as compared to results achieved with the commonly used d.c. technique. Both the temperature dependence and the absolute values for such critical current measurements indicate that indeed the depairing current has been probed. The results are in quantitative agreement with the predictions from Ginzburg-Landau theory. Thus, our measurements can determine the ultimate thermodynamic limit for dissipation-less current transport in a high-temperature superconductor that is more than an order of magnitude larger than previous d.c. technique results.

Together with the critical temperature $T_c$, the critical current density $j_c$ represents a key quantity for the design of superconductor applications. The value and temperature dependence of $j_c$ are governed by various mechanisms that limit the supercurrent, such as flux vortices motion, phase slip, junctions or fluctuations, but its maximum limit is set by the depairing current density $j_d$. Due to the short coherence length in high-temperature superconductors (HTSC), the depairing current density is considerably higher than in conventional superconductors. Applying high current densities on cuprates is however not an easy task, since the dissipated power density would attain the order of GWcm\textsuperscript{-3} in the normal state, for current densities of the order of MAcm\textsuperscript{-2}. Only few experiments have explored in HTSC the supercritical current region far above $j_c$ [1, 2, 3].

In this work we point out the importance of combining a pulsed current technique (pulses as short as 50 ns), with using very thin films (36 and 42 nm thickness in our experiments), as the only satisfying method to substantially reduce the self-heating in the high dissipation regime, with the aim of a correct estimate of the depairing current density in HTSC materials. We show that not only in the normal state, but even at the onset of the dissipative state, where the threshold voltage criterion is usually applied for assessing the critical current, the measure is altered through self-heating at d.c. current densities above $10^5$A/cm\textsuperscript{2}. The heating problem at high current densities can be however only partially solved by using short-duration pulsed currents. Even for a time scale of tens of nanoseconds pulse length, the main source of sample heating remains the phonon mismatch at the film-substrate interface [1], which produces a temperature drop between the apparent temperature $T_a$, measured at the sample holder,
and the actually higher sample temperature $T$, such as $T - T_a = p R_{\text{th}} \approx p d R_b$, where $p$ is the dissipated power density in the sample, $d$ the film thickness, $R_{\text{th}}$ is a thermal resistance that globally quantifies the heat conduction out from the sample and $R_b$ the thermal boundary resistance. It would be therefore highly desirable to investigate films with very small thickness, in order to favor as much as possible the heat transfer to the substrate.

We present for comparison resistivity data collected from three epitaxial YBCO thin films, of 330 nm and, respectively, 36 and 42 nm thickness, fabricated by pulsed-laser deposition on MgO substrates. The distance between voltage contacts was 300 $\mu$m and 600 $\mu$m, respectively, while the bridge width was 30 $\mu$m for the thicker sample and 300 $\mu$m for the thinner ones. The MgO substrate was preferred against the Al$_2$O$_3$ or LaAlO$_3$ ones because of its smaller thermal boundary resistance [4]. Figure 1a summarizes the results for the 330 nm thick film, when measurements are performed with the d.c. current method. One can clearly see that for current densities of the order of $10^5$ A/cm$^2$ the curves exhibit an almost parallel shift towards higher resistivity and lower apparent temperature, suggesting thus a self-heating effect.

Previous pulsed current investigations, with pulse lengths of the order of microseconds, turned out to be successful for current densities up to 1 MA/cm$^2$ on 100 nm thick YBCO films [1], provided the temperature rise during the pulses could be satisfactorily accounted for by the temperature correction procedure with a suitable $R_{\text{th}}$ value. In order to extend this kind of investigations to current densities higher than 1 MA/cm$^2$, we have developed the improved pulsed current installation, presented in detail in Ref. [3]. It was possible to detect voltage pulses in a four-probe arrangement as short as 50 ns, which is about 50 times faster than other previously reported pulse-current measurements [1, 2] performed on HTSC. Figure 1b shows resistivity measurements performed with this technique on the same 330 nm thick sample as in Fig. 1a. One can notice a broader transition than for the d.c. case, but the same qualitative picture, namely the parallel shifts towards higher resistivity and lower apparent temperature. This indicates that significant self-heating is still present, although strongly diminished with respect to the d.c. measurements, since comparable shifts are now produced by current densities about five times higher. This is a clear evidence that even at very low resistivity, where the

![Figure 1](image-url)
threshold voltage criterion is commonly applied in order to assess the critical current, the self-heating alters the d.c. measurements at high values of the current density. The inset in Fig. 1b illustrates an attempt to apply the temperature correction proposed in Ref. [1], with the aim to obtain the curve superposability in the normal state region. The procedure fails however for current densities higher than 1 MA/cm², since it leads to unphysical curve undercutting. This suggests that the temperature rise during the pulse has a more complex dependence on the dissipated power than a simple linear one.

A significant further improvement in reducing the self-heating is attained by using very thin films, in order to minimize the temperature drop at the film-substrate interface. A very small thickness is known however to bring about different kinds of imperfections, like structural defects and modifications of the local charge density which reduce the conductivity of the film at the interface. This defect-rich zone typically extends about 10 to 30 nm into the YBCO film and has been verified by resistivity measurements and transmission electron microscopy [5]. To account for this situation we introduce as parameter an "effective electrical thickness" of the YBCO film that corresponds to the thickness of the undistorted layer. Our model is supported by the fact that the resistivity vs. temperature characteristics is linear in the normal state and extrapolates to a very small residual resistance at $T = 0$, an indication that the current distribution is confined to sample regions with only moderate defect density in our ultra-thin films.

A set of data analogous to those of Fig. 1b are presented in Fig. 2a for the 36 nm thick film. The corresponding data for the 42 nm film look similar and are not shown. An appealing way to estimate the effective thickness is to use a fit to the measured paraconductivity at very low currents, where the heating effects are negligible. We choose for the fluctuation conductivity the expression given by the Lawrence-Doniach (LD) model for layered superconductors, performed in the Hartree approximation and with inclusion of the UV cut-off of the superconducting fluctuating modes [3, 6]. The resulting fit is shown in the inset of Fig. 2a and uses the following parameters, common for YBCO: the interlayer distance $s = 1.17$ nm, the in-plane and out-of-plane coherence lengths, extrapolated at $T = 0$, $\xi_0 = 1.2$ nm and $\xi_{0c} = 0.14$ nm, respectively, and the Ginzburg-Landau (GL) parameter $\kappa = 70$. The best fit is obtained when the scaling factor to the measured resistance corresponds to an effective thickness $d_{eff} = 12$ nm. For the 42 nm thick film, this effective thickness was found to be 19 nm.

The curves in Fig. 2a, except the lowest one, which was recorded while injecting 1 pA d.c. current, were measured with the pulsed current technique. The picture is essentially different from those of Figs. 1a and 1b, since the transition region clearly exhibits now the fan-shape broadening without the temperature shift caused by self-heating.

According to the GL theory, the depairing current density writes [7] $j_d^{GL}(T) = \Phi_0 / 3 \pi \mu_0 \lambda^2 (T) \xi (T)$, with $\Phi_0$ the flux quantum, $\mu_0$ the vacuum permeability, $\lambda(T)$ and $\xi(T)$ the penetration and the coherence lengths, respectively. Empirically, the two characteristic lengths depends on temperature as $\lambda(T) = \lambda(0) / \sqrt{1 - t^2}$ and $\xi(T) = \xi(0) \sqrt{(1 + t^2) / (1 - t^2)}$ with $t = T/T_c$ [7], so that near $T_c$ the depairing current density scales like $j_d(T) \approx 4 j_d(0) (1 - t)^{3/2}$.

In Fig. 2b, the GL scaling relation is tested for our data. One can see that the d.c. measurements on the 330 nm thick film give an estimate for $j_d(0)$ more than one order of magnitude lower than that provided by the pulsed current measurements on the ultrathin films. An intermediate value is obtained from the pulsed measurements on the thicker film, but as we have seen before, these data are also significantly altered by self-heating. The theoretical estimate of the zero-temperature GL depairing current density writes $j_d^{GL}(0) = 2.98 \times 10^8$ A/cm², if one takes $\xi(0) = 1.2$ nm and $\lambda(0) = 2 \kappa \xi(0) = 168$ nm, in accordance to the parameter values from the fit in the inset of Fig. 2a. The values $j_d(0) = 2.42 \times 10^8$ A/cm² and $j_d(0) = 3.32 \times 10^8$ A/cm² obtained from the pulsed measurements on the ultrathin films of 36 and, respectively, 42 nm thickness, turn out to be in very good agreement to the theoretical estimate.
Figure 2. (a) Resistivity measured with the pulsed current technique on a 36 nm thick YBCO epitaxial film, corresponding to an effective thickness of 12 nm, inferred by fitting the lowest current curve according to the LD model, as shown in the inset. The linear extrapolation of the normal state resistivity above 150 K was used (dotted line).

(b) Scale relation between current density $j$ and critical temperature $T_c(j)$ for the pulsed measurements on the two thin films (open symbols) and for the d.c. and pulsed measurements on the thick one (filled symbols). The depairing current densities extracted from the scaling fits are given, as well as the criterion used to define the critical current.

In summary, we have investigated the superconducting transition at high current densities on optimally doped YBCO thin films, with the aid of an improved pulsed current technique in a four-probe arrangement. The very short pulse length (down to 50 ns), together with the small film thickness (36 or 42 nm) allow to minimize the sample self-heating and make possible injecting current densities up to 7.2 MA/cm$^2$ even deep in the normal state region (up to 160 K). The importance of using pulsed measurements and ultrathin films was evidenced by showing that in an ordinary thin film of 330 nm thickness investigated with the d.c. technique, the self-heating at high electric fields is important enough to alter the estimated depairing current by more than an order of magnitude.

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References
[1] Kunchur M N 1995 Mod. Phys. Lett. B 9 399
[2] Kunchur M N, Ilev B I, Christen D K and Philips J M 2000 Phys. Rev. Lett. 84 5204
[3] Puica I, Lang W, Peruzzi M, v Lemmermann K, Pedarnig J D and Bäuerle D 2004 Supercond. Sci. Technol. 17 S543
[4] Sergeev A V, Semenov A D, Kouminov P, Trifonov V, Goghidze I G, Karasik B S, Gol’tsman G N and Gershenzon E M 1994 Phys. Rev. B 49 9091
[5] Pedarnig J D, Rössler R, Delamare M P, Lang W, Bäuerle D, Köhler A and Zandbergen H W 2002 Appl. Phys. Lett. 81 2587
[6] Puica I and Lang W 2003 Phys. Rev. B 68 054517
[7] Tinkham M 1996 Introduction to Superconductivity (New York: McGraw-Hill)