Temperature dependence of critical current in YBa$_2$Cu$_3$O$_{7-\delta}$ films

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Abstract. Analysis of temperature behavior of the critical current in YBa$_2$Cu$_3$O$_{7-\delta}$ films is presented. We demonstrate that the overall current can be separated into two components caused by weak pinning on oxygen vacancies in CuO$_2$ planes and strong pinning on defects in volume of the superconductor. Temperature dependences of the components are obtained and discussed.

1. Introduction
A large variety of defects act as pinning centers in YBa$_2$Cu$_3$O$_{7-\delta}$ films, such as vacancies, twin boundaries, dislocations, segmentation faults, non-superconducting inclusions and so on [1]. Vacancies produce a weak pinning [2, 3] while other defects produce a strong pinning [2–4]. Parameters of pinning centers strongly affect value of the critical current density $J_c$ in superconducting state and its dependence on temperature and applied magnetic field. Any YBa$_2$Cu$_3$O$_{7-\delta}$ film contains oxygen vacancies but presence and concentration of other defects strongly depend on both technology and conditions of the film synthesis. Therefore different samples contain different sets of defects and as a sequence their critical current demonstrates different temperature and field behavior.

Roughly exponential decrease of the critical current at low and elevated temperatures has been observed for YBa$_2$Cu$_3$O$_{7-\delta}$ films in numerous experiments [5–12]. The dependence [5–8, 12]

$$J_c = J_c(0) \exp(-T/T_0)$$

was attributed to presence of pinning centers with small energies $T_0 = 17 – 32$ K. Such small pinning energy causes thermally activated depinning of vortices and rapid decay of the critical current with temperature [13]. This dependence produces rather well approximation for $J_c(T)$ in the range from about 10 to 50–60 K. The dependence

$$J_c = J_w \exp(-T/T_w) + J_s \exp[-3(T/T_s)^2]$$

was used to take into account the presence of both weak and strong pinning centers and the temperatures $T_w = 8–13$ K and $T_s = 78–93$ K were found [9–11]. Here $w$ and $s$ mark the current components produced by weak and strong pinning. For some samples this expression extends the higher range of the exponential approximation for $J_c(T)$ up to $T \lesssim 75$ K.
Figure 1. Color online. Temperature dependences of the critical current. The curves are shown in standard and semilogarithmic scales in order to bring out both low and high temperature behavior of \( J_c \). Symbols are experimental data. Lines are fits by dependences (1) — dashed, (2) — dash-dotted, as well as sum of dependences (4) and (5) — solid.

Exponential approximation cannot describe \( J_c(T) \) behavior at high temperatures since neither eq. (1) nor eq. (2) become zero in vicinity of the critical temperature \( T_c \). The power laws

\[
\begin{align*}
J_c &= J_c(0)(1 - T/T_c)^\alpha, \quad \text{(3a)} \\
J_c &= J_c(0)[1 - (T/T_c)^\beta]^\gamma, \quad \text{(3b)}
\end{align*}
\]

were found in this temperature range [14–19]. Values \( \alpha \approx 0.9–2 \) [14–16, 18] and \( \beta \approx 1.2–1.5 \) [17, 19] were obtained. The observed power law was explained by temperature dependence of the coherence length \( \xi \) and the penetration depth \( \lambda \).

As follows from this brief analysis an approach to describe \( J_c(T) \) behavior in the whole temperature range is still absent. In this paper we show that the critical current of YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) films can be separated into two components caused by weak and strong pinning, obtain their temperature dependences and precisely describe \( J_c(T) \) in the range from 4.21 K to \( T_c \).

2. Results and discussion

Thin epitaxial YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) films were prepared on (100) SrTiO\(_3\) substrates by pulsed laser deposition technique [20] using KrF laser. In resistivity measurements the films demonstrated sharp superconducting transitions at \( T_c = 90–91 \) K with transition width about 1 K. Temperature dependence of saturated remanent magnetic moment \( M \) of films was measured by means of original SQUID-magnetometry method described in [21, 22]. The critical current density was calculated from the moment as \( J = 24M/(\pi D^2d) \) (in SI units), where \( D \) and \( d \) are the film’s diameter (\( \sim 2 \) mm) and thickness (300–500 nm).

Typical temperature dependences of the critical current obtained for two samples are shown in Figure 1. As seen, experimental data are rather well approximated by the dependence (1) in the range from 10 to 50–60 K though curvatures of experimental and approximating curves slightly differ in the range from 20 to 40 K. The dependence (2) provides a better approximation and extends the higher limit of the range up to 75 or 68 K for samples Y1 and Y3. The obtained characteristic temperatures \( T_0 = 24 \) and 37 K, \( T_w = 12 \) K, \( T_s = 84 \) and 90 K well agree with published data.
High temperature behavior is shown in Figure 2 where $J_c$ is plotted in logarithmic scales versus $1 - \frac{T}{T_c}$ and $1 - \left(\frac{T}{T_c}\right)^2$. Note that $T_c$ = 90 and 90.5 K for samples Y1 and Y3. In a wide temperature range the power law (3a) well approximates experimental data for sample Y3. More rapid decrease of the measured current is observed only at $T \gtrsim 72$ K ($1 - \frac{T}{T_c} \lesssim 0.2$). The dependence (3b) agree with $J_c(T)$ behavior at $T \gtrsim 35$ K [$1 - \left(\frac{T}{T_c}\right)^2 \lesssim 0.85$]. At lower temperatures the measured current rises more rapidly and at 4.21 K becomes twice more than the approximating $J_c$. More stronger deviation from the power laws (3) is observed for sample Y1 at both high and low temperatures.

Thermal fluctuations strongly affects superconductivity in YBa$_2$Cu$_3$O$_{7-\delta}$ at high temperatures. They destroy the critical state at the depinning temperature $T_{\text{dp}}$ which is lower than $T_c$ [2, 23–25]. Thus the critical current disappears at $T_{\text{dp}} < T_c$ and the power laws (3) cannot correctly describe $J_c$ suppression in vicinity of $T_{\text{dp}}$. We suppose that at high temperatures only strong pinning centers are effective and $J_c = J_2 = J_2(0)(1 - \frac{T}{T_{\text{dp}}})^\alpha$, (4)

where $J_2$ is the critical current produced by strong pinning. We fit the measured current by this dependence and obtained $J_2(0)$ = 7.8 and 8.8 MA/cm$^2$, $T_{\text{dp}}$ = 84 and 86.7 K, $\alpha$ = 1.16 and 1.33 for samples Y1 and Y3. As seen in Figure 2, for sample Y3 the measured current is well fitted by (4), however at low temperatures a small “excessive” increase of $J_c$ is observed. For sample Y1 such an increase at $T < 37$ K ($1 - \frac{T}{T_{\text{dp}}} \lesssim 0.55$) is distinctly seen.

Calculating the critical current of a layered superconductor, Ovchinnikov and Ivlev have shown that the overall current $J_c = J_1 + J_2$ consists of two components produced by pinning in superconducting planes, $J_1$, and pinning in superconductor volume, $J_2$ [4]. Following to Ovchinnikov and Ivlev we subtracted from the measured current the component $J_2$ described by (4) to separate the component $J_1$ produced by pinning on oxygen vacancies in superconducting CuO$_2$ planes. Obtained $J_1(T)$ dependence is presented in Figure 3. The component $J_1$ exists only at temperatures below 30–40 K. We found that it
is well described by the dependence

$$J_1 = \frac{J_1^*}{1 + \exp(T/T_1) / 2T_1}.$$  \hspace{1cm} (5)

where $J_1^*$ is a characteristic current and the parameter $T_1$ is in Kelvins in the exponent power and dimensionless in its divisor. The values $T_1 = 5.8$ K, $J_1^* = 8.6$ and 1.1 MA/cm$^2$ were obtained for samples Y1 and Y3. We attribute the quasi exponential dependence (5) to influence of flux creep which is strong because of low energy of pinning on oxygen vacancies. Fast relaxation of $J_c$ was observed at low temperatures [26].

Dependence $J_2(T)$ obtained in the whole temperature range via subtraction of $J_1(T)$ from the measured current is also presented in Figure 3. As seen, amplitudes of $J_1$ and $J_2$ components at low temperatures are equal each other for sample Y1, while for sample Y3 $J_2$ is eight times more than $J_1$.

Approximation of measured $J_c(T)$ by sum of dependences (4) and (5) is shown in Figure 1. Analysis of the separated current components $J_1$ and $J_2$ allows us to describe precisely $J_c(T)$ behavior in the whole temperature range.

Summing up we conclude that different ratio of $J_1$ and $J_2$ components in combination with different values of both the depinning temperature and the power $\alpha$ in samples with different set of defects provide a large variety of $J_c(T)$ dependences in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films.

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