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The Low-Field Ac Impedance of $YBa_2Cu_3O_{7-\delta}$ Superconducting Slab

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Using results of surface impedance measurements, the penetration of ac field into a melt-textured $YBa_2Cu_3O_{7-\delta}$ slab was investigated. We obtained a linear correlation between the surface impedance and ac frequency. The impedance curve shifts towards higher temperatures — 0.9 K per decade of the frequency increase, for dc magnetic field $\mu_0 H_{\mathrm{dc}} \leq 8 \times 10^{-3}$ T. This is an evidence of thermally activated flux creep. A plateau in the temperature dependence of the real impedance part was observed at approximately 88 K.

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1. Introduction

Surface impedance measurement is one of the simplest methods to study ac field penetration in a medium. In normal metal, surface impedance is calculated in a simple linear conductivity model [1]. For superconducting materials in the flux creep regime surface impedance cannot be described in frames of the conductivity model, because of the nonlinear correlation between current density and electric field. This case is typical of ac impedance measurements of high temperature ceramics below irreversibility line [2]. In this case one can observe the generation of odd and even harmonics [3, 4]. This behavior can be understood in frames of macroscopic critical state model [3–7]. In this model there are two critical current regimes: the Bean regime — for low magnetic field magnitude [5–7], and the Kim–Anderson regime — for high magnetic field magnitude [4]. For these two regimes, measurements and simulations were carried out both for granular [4–6] and for melt-textured [3, 5, 7] ceramic bulk samples. It was shown that in the case of high temperature ceramics the measured critical current density is affected

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by thermal activation [2, 7, 8]. Thermal activation of the vortices over an energy barrier, $U_0(H,T)$, is modulated by the Lorentz force, and leads to the reduction of the measured critical current density below its value $j_{c0}(T,H)$ [8]:

$$j_c(T,H,f) = j_{c0}(T,H)\left[1 - \frac{kT}{U_0(H,T)}\ln(f_0/f)\right], \tag{1}$$

where $j_{c0}(T,H)$ is the critical current density in the absence of thermal activation, T is the temperature, H is the external magnetic field, f_0 is the characteristic attempt frequency, and f is the measurement frequency. In conventional superconductors the thermal activation term, in Eq. (1), introduces negligible correction to the critical current density [2, 8]. However, in high-temperature superconductors, where the temperature, T, may be of an order of magnitude higher than in conventional superconductors and where activation energy U_0 is usually lower [2, 8], this term may be significant. It was shown that for a $YBa_2Cu_3O_{7-\delta}$ single crystal the thermal activation term, $(kT/U_0)\ln(f_0/f)$, approaches 1 [2]. Thus, critical current measurements and ac surface impedance measurements may be strongly affected by thermally activated flux creep.

2. Experiment

Our $YBa_2Cu_3O_{7-\delta}$ sample was prepared by the method of texturization of grains (MTG), by heating the ceramics to the melting point. In this technological process ceramics acquires a "brickwork" structure [9]. The sample has a form of a slab with dimensions $15 \times 3.5 \times 2$ mm^3 and 2 mm thickness. Its superconducting critical temperature $T_c = 91.5$ K. The slab was placed in a pick-up coil, which had 150 turns of copper wire. Impedance measurements were carried out by a high precision RLC meter (Agilent Technologies, model 4284A). Ac magnetic field was parallel to *ab*-planes. The amplitude of the ac magnetic field in the coil was estimated to be not higher than $\mu_0 h_{ac} \approx 4 \times 10^{-4}$ T. The frequency of the ac magnetic field was changed from 10 kHz to 1 MHz. The measurements were performed in constant dc magnetic field, $\mu_0 H_{dc} \leq 8 \times 10^{-3}$ T, that was parallel to *c*-axis of the ceramics and perpendicular to ac magnetic field. The temperature was varied from 77 K to 95 K and was controlled by a thermocouple, which was placed at the sample surface.

3. Results and discussion

In Fig. 1 we present experimental data of the real impedance part, R_{exp}, as a function of temperature for different frequencies, changed from 50 kHz to 1 MHz. In Fig. 2 we plot the absorption in maximum versus frequency. One can see linear dependence of the absorption on frequency. This behavior is typical of the impedance calculated in frames of the critical state model. We will present main equations for the impedance in the critical state model. We assume that the critical current density does not depend on ac field magnitude ($j_c(|\boldsymbol{H}|) = j_c(|\boldsymbol{H}_{dc} + \boldsymbol{h}_{ac}|) \approx j_c(|\boldsymbol{H}_{dc}|)$ for the case $|\boldsymbol{H}_{dc}| \gg |\boldsymbol{h}_{ac}|$) and depends on frequency

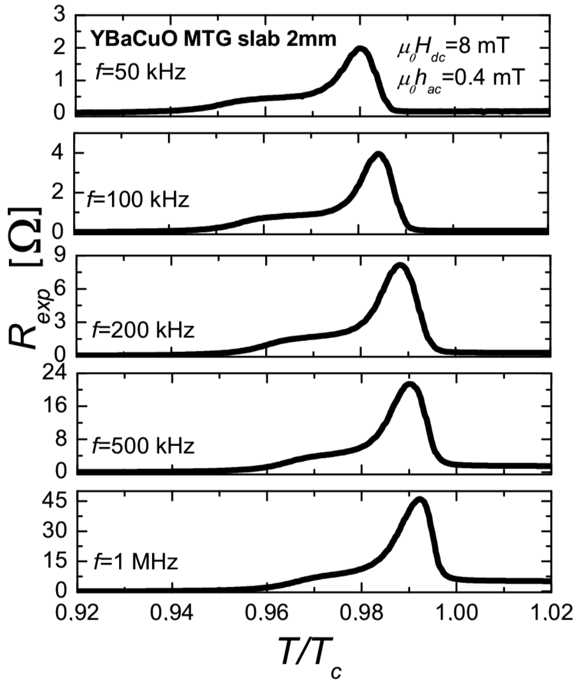

Fig. 1. Real impedance part as a function of normalized temperature measured in constant dc magnetic field, $\mu_0 H_{\mathrm{dc}} \leq 8 \times 10^{-3}$ T ($T_{\mathrm{c}} = 91.5$ K).

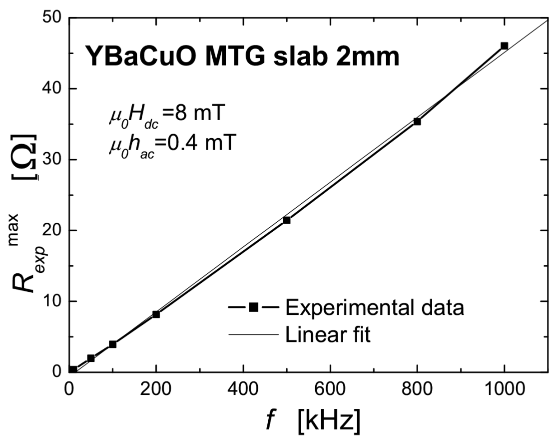

Fig. 2. Line plus symbol — experimental data of absorption in maximum, plotted as a function of ac frequency. Solid line — linear fit to experimental data.

according to the Kim–Anderson creep model [2, 8]. In the critical state model, the real part of the impedance of superconducting infinite slab, with the thickness $2d$, $R = \mathrm{Re}(Z)$, is given by the following equations [5, 6]:

$$R = \frac{2\mu_0 \omega h_{\mathrm{ac}}}{3\pi j_{\mathrm{c}}} \quad \text{for} \quad \frac{h_{\mathrm{ac}}}{j_{\mathrm{c}} d} < 1, \tag{2}$$

$$R = \frac{\mu_0 \omega d}{3\pi} \left[6\frac{j_{\mathrm{c}} d}{h_{\mathrm{ac}}} - 4 \left(\frac{j_{\mathrm{c}} d}{h_{\mathrm{ac}}} \right)^2 \right] \quad \text{for} \quad \frac{h_{\mathrm{ac}}}{j_{\mathrm{c}} d} > 1, \tag{3}$$

where ω — circular frequency ($f = \omega/(2\pi)$), $j_{\mathrm{c}} = j_{\mathrm{c}}(T, |\boldsymbol{H}|, f)$ — measured critical current density, according to Eq. (1). Analyzing Eq. (3) one can find a maximum at $h_{\mathrm{ac}}/j_{\mathrm{c}} d = 4/3$. The maximum value of the surface absorption of the infinite slab is given by the formula [6]:

$$R_{\max}(\omega) = \frac{3\mu_0 \omega d}{4\pi}. \tag{4}$$

Let us note that the absorption in maximum, following Eq. (4), does not depend on the critical current density and ac magnetic field amplitude. In Fig. 3 we plotted a normalized real impedance part, $R_{\mathrm{exp}}/(2\pi f)$, as a function of temperature. One can see a displacement of the impedance curve towards higher temperatures with increasing frequency. This is an evidence of the influence of thermally activated flux creep on the measured critical current density [2, 8]. For our sample, the shift of the impedance curve is equal to 0.9 K per decade of the frequency increase, with an experimental error of 0.2 K for the applied dc magnetic field $\mu_0 H_{\mathrm{dc}} \le 8\times10^{-3}$ T. The shift of the impedance curve is reduced with increasing dc magnetic field [7]. For example, in $\mathrm{YBa_2Cu_3O_{7-\delta}}$ ceramics the shift is equal to 0.7 K per decade of the frequency increase for the field of a few hundreds oersteds [10] and 0.4 K for the field of 0.6 T [8].

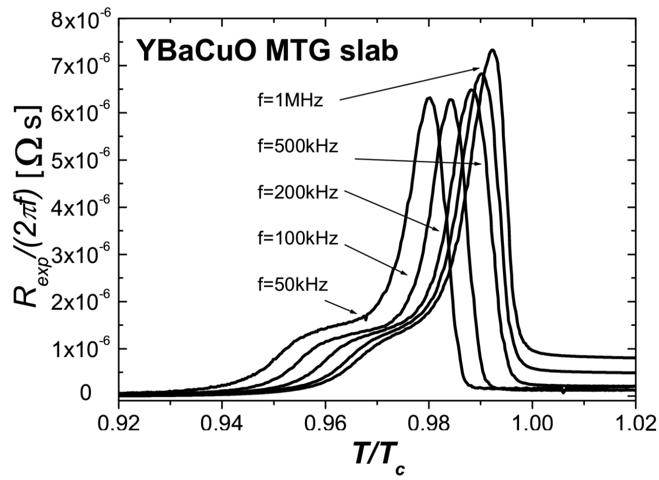

Fig. 3. Experimental data of normalized absorption $R/(2\pi f)$ as a function of normalized temperature for frequencies 50 kHz, 100 kHz, 200 kHz, 500 kHz, and 1 MHz. The anomaly in absorption for $T/T_{\mathrm{c}} = 0.97$ ($T = 88.7$ K) is seen.

Analyzing our experimental data in Fig. 1 and Fig. 3 one can find a plateau. This plateau is seen near 88 K in the temperature dependence of the real impedance part. This phenomenon can be connected with two transition peaks of the absorption, which form a plateau. It is known that in the case of high temperature ceramics, in dc field cooling regime, a flux droplet is formed in the central part of the ceramic sample [3, 11]. The measured ac susceptibility is determined by the interaction between the droplet and the Meissner current, and by the interaction between the droplet and bulk pinning centers [3]. At high temperatures the bulk pinning is weak, so the high temperature peak is due to magnetic hysteresis associated with the surface barrier [3]. According to the critical state model, the lower temperature peak is ascribed to the ac driven jumps of vortices between different bulk pinning centers, in the flux droplet inside the sample [11]. This peak, together with the high temperature one, creates a plateau. A similar plateau may also occur if the sample is not uniform. For example, it can contain different types of pinning centers, which did not disappear in the process of texturization. It is interesting to note that the anomaly near 88 K is also observed in the contact measurements of the critical current. As it was reported in Ref. [12], an anomalous bifurcation in the temperature dependence of the critical current density was observed in "dc coupled with the transient pulse" measurements.

4. The influence of the skin effect screening

At high frequencies ac surface impedance measurements may be affected by the skin effect screening [13]. It is known that for high frequencies there is a skin screening, and the ac magnetic field penetrates the sample volume only to the depth $\delta_\mathrm{n} = \sqrt{2/(\mu_0\omega\sigma_\mathrm{n})}$ (σ_n — normal state conductivity) [1]. The distribution of the magnetic field in a slab, with the thickness $2d$, in the normal state, is given by the formula: $h(x) = h_0[\cosh(kx)/\cosh(kd)]$, where $k = \sqrt{\mathrm{i}\mu_0\sigma_\mathrm{n}\omega}$. In order to fulfill the condition of the linear magnetic field distribution, according to the Bean model, $h_\mathrm{in} = h_0/\cosh(kd)$ must satisfy the inequality: $|(h_0 - h_\mathrm{in})/h_0| \ll 1$ (h_in is the magnetic field inside the slab, for $x = 0$). Using the above presented formulae, we calculated the value $|(h_0 - h_\mathrm{in})/h_0|$ for two frequencies: 200 kHz and 1 MHz, taking $\rho_\mathrm{n} = 1/\sigma_\mathrm{n} = 17$ mΩ cm (ρ_n was measured along the c-axis of a textured sample at T_c [14]). For 200 kHz we obtained $|(h_0 - h_\mathrm{in})/h_0| \approx 5 \times 10^{-3}$, $\delta_\mathrm{n} \approx 1.5 \times 10^{-2}$ m and for 1 MHz — $|(h_0 - h_\mathrm{in})/h_0| \approx 2.3 \times 10^{-2}$, $\delta_\mathrm{n} \approx 6.6 \times 10^{-3}$ m. Analyzing obtained results, we can see that even for the frequency of 1 MHz the value $|(h_0 - h_\mathrm{in})/h_0|$ is relatively small and the influence of the surface screening is negligibly small.

5. Conclusions

It was shown experimentally that the maximum of the absorption of the melt-textured $YBa_2Cu_3O_{7-\delta}$ sample depends linearly on frequency. There is a displacement of the impedance curve towards higher temperatures with increasing frequency — 0.9 K per decade in dc magnetic field $\mu_0 H_{\mathrm{dc}} \leq 8 \times 10^{-3}$ T. This behavior can be understood in frames of critical state model, taking into account thermally activated flux creep. A plateau in absorption was found near 88 K. This plateau shifts towards higher temperatures with increasing frequency.

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