Angular dependence of the high-frequency vortex response in YBa$_2$Cu$_3$O$_{7-x}$ thin film with self-assembled BaZrO$_3$ nanorods

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ABSTRACT

We present a microwave study of the angular dependence of the flux-flow resistivity ρ_{ff} and of the pinning constant k_p in YBCO thin films containing BZO nanorods. We find that BZO nanorods are very efficient pinning centers, even in tilted fields. We find that ρ_{ff} is a scaling function of a reduced field $H/f(\theta)$. We extend a model for the anisotropic motion of vortices in uniaxially anisotropic superconductor, able to describe the experimental $f(\theta)$ on the basis of only the intrinsic anisotropy of YBCO. The pinning constant k_p, by contrast, exhibits different field dependences in different angular ranges, consistent with pinning by BZO at angles as large as 60°, and with pinning along the a,b planes as originating from the same mechanism as in pure YBCO with the field along the c axis.

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1. Introduction and model

Enhanced pinning by artificial defects, such as those originated by BaZrO$_3$ (BZO) inclusions within YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) films, has been extensively studied in the last years due to the potential impact on applications, with substantially increased critical currents and irreversibility fields [1–3]. Issues connected to the directional nature of the pinning efficiency have been under careful scrutiny, since BZO defects self-assemble typically in linear structures roughly parallel to the c axis, thus competing with intrinsic pinning due to the layered structure itself. As a consequence, the angular dependence of critical current density j_c is heavily affected by BZO defects [1,4], with a maximum of j_c along the c axis. Whether this behavior competes or coexists with the intrinsic anisotropy of YBCO is difficult to ascertain with a dc technique, where the pinning potential is probed at high current densities, that is when the flux lines can be extracted from the pinning potential wells and moved apart.

We present in this paper a microwave study of the angular dependence of the vortex motion resistivity in a YBZO/BZO film, where we disentangle the effects of directional pinning from the intrinsic anisotropic resistivity, exploiting the peculiarities of the microwave complex response. At microwave frequencies the flux lines oscillate over distances of less than ~1 nm [5], thus probing only the bottom (i.e., the steepness) of the pinning potential. Interestingly, we observed previously a strong increase of pinning as measured at ~50 GHz in YBCO/BZO films with different BZO

content [6], thus showing that BZO induces very steep pinning wells. The short-distance oscillations allow in most cases the application of mean-field theories developed for the vortex motion resistivity ρ_{vm} [7–9]. Comparison with the data is made easier by the fact that those theories can be described by a unified formulation [10]:

$$\rho_{vm} = \rho_{vm,1} + i\rho_{vm,2} = \rho_{ff} \frac{\varepsilon + i(\nu/\bar{\nu})}{1 + i(\nu/\bar{\nu})} \tag{1}$$

where the resistivity ρ_{ff} represents the genuine flux flow resistivity (only viscous drag), reached at high frequency instead of at high currents, $\bar{\nu}$ is a characteristic frequency and the dimensionless parameter $0 \leqslant \varepsilon \leqslant 1$ is a measure of thermal activation phenomena. When ε is small, the model reduces to the well-known Gittleman–Rosenblum model [7] and $\bar{\nu} \to k_p \rho_{ff}/\Phi_0 B$. A complete discussion on the extraction of the vortex parameters k_p (pinning constant) and ρ_{ff}, together with the assessment of the validity limits, has been given in [10]. In the measurements of the angular and field dependence of ρ_{ff} and k_p here reported, the systematic (not scattering) error is less than 20%.

The flux-flow resistivity, as an intrinsic property of superconductors, is a model-dependent function [11–13] of the reduced field $h = H/H_{c2}$ (in the London approximation, where $B \simeq \mu_0 H$), $\rho_{ff} = \rho_n F(h)$, where ρ_n is the normal state resistivity. The Bardeen–Stephen (BS) model [13] predicts linearity with the field, $\rho_{ff} = \rho_n h$. When H is tilted by an angle θ from the c axis, H_{c2} acquires an angular dependence: $H_{c2}(\theta) = H_{c2}(0)\varepsilon(\theta)$, with $\epsilon(\theta) = [\cos^2\theta + \gamma^{-2}\sin^2\theta]^{1/2}$ in the anisotropic 3D Ginzburg–Landau model, with $\gamma = H_{c2}(0°)/H_{c2}(90°) \simeq 5$–8 in YBCO. The resulting flux flow resistivity becomes

$$\rho_{ff}(H,\theta) = \rho_n H/H_{c2}(0°)\varepsilon(\theta) \tag{2}$$

In dc, Eq. (2) holds for the genuine flux flow resistivity, and when the force acting on flux lines does not change with the angle: this is typically the case when pinning is irrelevant or isotropic (e.g. in the crossover region between the flux-flow and fluctuation regimes [14]) and the Lorentz force on flux lines is constant. When directional pinning plays a role, the scaling hypothesis for the measured resistivity breaks down: a scaling (ρ_{ff}) and a non-scaling (pinning force) quantities mix to give the observed total vortex motion resistivity $\rho_{vm} \neq \rho_{ff}$, so that a comprehensive description of the experiments becomes difficult.

A second issue, relevant to this paper, comes when the angle between H and the current is varied. In this case the driving force changes with the angle. On a theoretical ground, this is far from being a trivial problem, and a general expression for ρ_{ff} can be written only under restrictive assumptions. Using a time-dependent Ginzburg Landau approach, Hao, Hu and Ting (HHT) [15] have obtained an expression for the flux flow resistivity in anisotropic superconductors. In spherical coordinates, where $c\|z$, θ is the angle of H with z and ϕ is the angle between x and the in-plane projection of H, in a uniaxial superconductor with $J\|x$ we reduce the HHT expression to:

$$\rho_{ff}(\theta,\phi) = \rho_{ab}(\theta)\frac{\rho_{ab}(\theta)\sin^2\theta\sin^2\phi + \rho_c(\theta)\cos^2\theta}{\rho_{ab}(\theta)\sin^2\theta + \rho_c(\theta)\cos^2\theta} \tag{3}$$

where ρ_{ab}, ρ_c are the intrinsic a, b plane and c axis flux flow resistivity,[1] and ρ_{ff} stands for the experimentally measured, in-plane flux flow resistivity. When (i) the anisotropic scaling applies, (ii) the flux flow resistivities are linear with the field (BS model), and (iii) $\rho_{c,n}/\rho_{ab,n} \simeq \gamma^2$, we obtain

$$\rho_{ff}(\theta,\phi) = \rho_{ab}(\theta=0)\frac{\gamma^{-2}\sin^2\theta\sin^2\phi + \cos^2\theta}{(\gamma^{-2}\sin^2\theta + \cos^2\theta)^{1/2}} \tag{4}$$

Eq. (4) is obtained under strong restrictions (in particular, (iii) is only approximate, even if the order of magnitude is correct [17,18]). Nonetheless, in nearly optimally doped or overdoped YBCO we do not expect significant deviations from the assumptions (i–iii). In Section 3 we will compare an extension of Eq. (4) to our anisotropic data for ρ_{ff}.

2. Experimental section

We hereby analyze a YBCO/BZO sample grown by PLD from targets containing BaZrO$_3$ (BZO) powders at 5% mol. (details are extensively given in [19]). The BZO inclusions generated columnar-like defects, approximately perpendicular to the film plane, as observed with transverse TEM images [20]. The directionality of the defects is consistent with the angular dependence of the critical current density [4].

The complex microwave effective surface impedance has been measured by a sapphire cylindrical dielectric resonator operating at ~48 GHz, extensively described elsewhere [21], so that we report here only the results. For the discussion of the data, it is important to stress that the microwave currents J_{mw} flow parallel to the film plane (i.e. parallel to the a, b planes) on a circular fashion (see inset of Fig. 1). A dc magnetic field $\mu_0H \leqslant 0.8$ T was applied at the angle θ with the c axis. Field sweeps were performed at different angles. We verified that the angular response was symmetric with respect to the a, b planes. The raw data yielded $\Delta\rho(H)/d = [\rho(H) - \rho(0)]/d = [\Delta\rho_1 + i\Delta\rho_2]/d$, where $\rho = \rho_1 + i\rho_2$ is

[1] While $\rho_{ab}(\theta)$ can be directly measured when $\phi = 0$, see Eq. (3), $\rho_c(\theta)$ can be derived (see [15] for extensive discussion) only with a multiterminal technique (such as, e.g., in [16]).
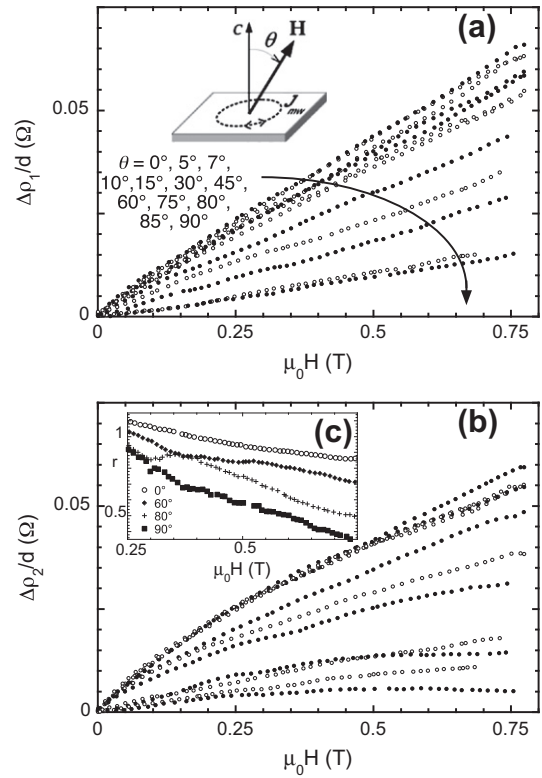
Fig. 1. Field induced variation of the real (a) and imaginary (b) microwave resistivity at $T = 81$ K and different angles θ between the dc field and the c axis. For the sake of readability, only a subset of the data are reported. The inset of panel (a) sketches the microwave current pattern and the definition of the angle θ. (c) Field dependence of $r = \Delta\rho_2/\Delta\rho_1$ at selected angles and expanded field scale.

the complex resistivity and d is the film thickness. When T is sufficiently below T_c one can neglect the field-induced pair-breaking. Thus, the subtraction of the zero-field value allows one to identify $\Delta\rho$ with ρ_{vm}. Taking into account this requirement and the disappearance of the signal in the noise as $\theta \to 90°$ at low T, measurements were performed at $T = 81$ K as a compromise to obtain a reasonable signal for all orientations.

Fig. 1 reports the field dependence of $\Delta\rho_1/d$ and $\Delta\rho_2/d$ for several angles θ. As expected, $\Delta\rho(H)$ decreases with increasing angle, due to the intrinsic anisotropy of YBCO and to the reduced effect of the Lorentz force on flux lines (when $\theta = 0$, $H \perp J_{mw}$, while when $\theta = 90°$ only part of the current lines are perpendicular to the field, thus reducing the net effective Lorentz force). The ratio $r = \Delta\rho_2/\Delta\rho_1$ expresses an experimental measure of the balance between reactive and dissipative contributions to the response. Roughly speaking, $r > 1$ indicates strong pinning. Fig. 1c shows that the overall response becomes progressively dominated by the dissipative contribution with $\theta \to 90°$. This interesting feature, that might suggest peculiar angular dependence of pinning and of ρ_{ff}, requires the explicit dependence of the vortex parameters for a quantitative discussion.

3. Discussion

We first discuss ρ_{ff}. In Fig. 2a we report ρ_{ff} at selected angles as derived from the data [10]. As a matter of fact, we are able to collapse all the curves (angular scaling) with an empirical angular scaling function $f(\theta)$. We report in Fig. 2b the collapsed curves of ρ_{ff} vs. $H/f(\theta)$ and the scaling function $f(\theta)$. As it can be seen, the anisotropy $f(90°)/f(0°) = 12$ is significantly larger than the commonly accepted values for the intrinsic anisotropy $\gamma = 5$–8.