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Microwave properties of DyBCO monodomain in the mixed state and comparison with other RE-BCO systems

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ABSTRACT

We report on microwave measurements on $DyBa_2Cu_3O_{7-\delta}$ monodomains grown by the top-seeded melt-textured technique. We measured the field increase of the surface resistance $R_s(H)$ in the a–b plane at 48.3 GHz. Measurements were performed at fixed temperatures in the range 70 K–T_c with a static magnetic field $\mu_0 H < 0.8$ T parallel to the c-axis. Low field steep increase of the dissipation, typical signature of the presence of weak links, is absent, thus indicating the single-domain behavior of the sample under study. The magnetic field dependence of $R_s(H)$ is ascribed to the dissipation caused by vortex motion. The analysis of $X_s(H)$ points to a free-flow regime, thus allowing to obtain the vortex viscosity as a function of temperature. We compare the results with those obtained on RE-BCO systems. In particular, we consider strongly pinned films of $YBa_2Cu_3O_{7-\delta}$ with nanometric $BaZrO_3$ inclusions.

1. Introduction

The microwave electrodynamic response in High-T_c Superconductors (HTCS) is a precious tool in the investigation of these materials. It provides a great deal of information concerning fundamental physics [1], as well as allowing to address essential issues in view of technological applications [2]. The microwave response determined at zero field has allowed to address many points such as the temperature dependence of the superfluid density [3–5], and the quasi-particles (QP) properties above and below the superconducting transition [4–6]. By applying a static magnetic field $H > H_{c1}$, HTCS are driven in the mixed state where the presence of vortices allows for the disclosure of additional physics [5,7]. Vortices, which are set in motion by the Lorentz force exerted by microwave currents, dissipate energy through the QP excitations located in and around their cores, in which the order parameter is depressed. Because of the nature of their cores, vortices can be considered as a window of "quasi-normal" state properties accessible below T_c, embedded in the superconducting condensate, and thus useful to probe "normal"-state-related properties, simultaneously with the superconducting gap issues (in particular, its symmetry).

From the point of view of fundamental physics, it is then interesting to investigate the vortex dissipation, dictated by the quasi-particle density of states (DOS) and relaxation time in the vortex cores.

At the same time, from a technological point of view, it is well known [2] that the power handling of HTCS, relevant to microwave devices, is limited by grain-boundaries contribution (dominant at low fields) as well as by vortex motion, the latter being the ultimate, unavoidable limitation. Within this scenario, the investigation of vortex pinning mechanisms is an essential task. Single crystals are ideal systems for the study of intrinsic properties, while epitaxial films are of interest for applications. On the other hand, monodomains, despite their technological interest, are rarely the subject of microwave studies. Therefore, in this paper we will present the microwave characterization and study of $DyBa_2Cu_3O_{7-\delta}$ (DyBCO) monodomains. A very few studies of DyBCO at microwaves in the mixed state exist [8], while the parent compound $YBa_2Cu_3O_{7-\delta}$ (YBCO) is widely studied. It will demonstrate particularly useful a comparison between data taken in DyBCO monodomains, in YBCO single crystals [9] and in YBCO epitaxial thin films with artificially enhanced pinning [10], as prototypical case for intrinsic and extrinsic behavior, respectively.

2. Experimental technique and data analysis

The main experimental quantity in microwave experiments is the effective surface impedance $Z_s = R_s + iX_s$. In this work, the surface impedance is measured by means of two cylindrical resonators, a silver-coated metal cavity [11] and a dielectric resonator

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[12], operating in the TE_{011} mode at approximately 48.3 GHz and 47.7 GHz, respectively. The surface perturbation method is used, with the sample under measurement replacing one of the cavity bases. The microwave currents flow parallel to the sample surface (along the $a-b$ planes for the c-axis oriented samples) on circular patterns. A solid/liquid nitrogen cryostat allows to reach temperatures T as low as 60 K, with temperature control within ±0.005 K. A conventional electromagnet generates magnetic fields $\mu_0 H \leqslant 0.8$ T, applied perpendicularly to the probed surface of the sample (i.e. parallel to the superconductor c-axis in c-axis oriented samples). The field-dependent cavity quality factor Q and resonant frequency ν are measured and they yield the corresponding surface impedance variations according to the following equations:

$$\Delta R_s(H,T) = R_s(H,T) - R_s(0,T) = G\left[\frac{1}{Q(H,T)} - \frac{1}{Q(0,T)}\right] \quad (1)$$

$$\Delta X_s(H,T) = X_s(H,T) - X_s(0,T) = -2G\frac{\nu(H,T)-\nu(0,T)}{\nu(0,T)} \quad (2)$$

where G is a geometric factor of the cavity which can be computed from the theoretically known distribution of the electromagnetic field. Here, $G \approx 10840\,\Omega$ and $G \approx 2000\,\Omega$, for the cavity and the dielectric resonator, respectively. Samples smaller than the base of the resonators are accommodated with the aid of an auxiliary thin metallic mask. In this case the geometric factor increases and sensitivity decreases.

Measurements are performed by quasi-statically sweeping the applied field intensity H at fixed temperature after zero field cooling. It is worth noting that by considering field-induced variations of Z_s, no calibration of the cavity response is needed since the latter is field independent.

As already anticipated in the previous section, the in-field surface impedance is determined by two main contributions: grain boundaries and vortex motion.

Grain boundaries, depending on the misalignment angle between adjacent grains, exhibit behaviors ranging from metallic to Josephson tunneling. In magnetic fields, they constitute preferential paths for the motion of vortices, yielding generally lower pinning forces along their direction: the actual nature of the vortices located in the GB depends again on the misalignment angle. With larger and larger misalignment angle, the nature of vortices changes from standard Abrikosov vortices to the so-called Abrikosov–Josephson (AJ) vortices, and finally to core-less Josephson vortices [13]. Many models have been developed in order to capture the GB behavior in the microwave regime [14–17]. Independently from the adopted model, the main signature of GB in the in-field microwave surface impedance consists in an abrupt, quasi-step-like increase of the surface resistance R_s with increasing field, followed by a flat plateau [14,18]. The field scale over which the step actually extends varies from a few mT [14,18] for weak-links and Josephson vortices up to 0.1 T or larger for AJ vortices [13,19].

Abrikosov vortex motion within intragrain regions is the ubiquitous phenomenon visible in surface impedance measurements in the mixed state. The mixed state microwave response, which includes vortex dynamics, is quite intricate, since it emerges from the interplay between the currents excited by the applied microwave fields and vortices set in motion by these currents. Many authors considered this issue, providing models which take into account various aspects [20–24]. Following Coffey–Clem (CC) approach [21], the whole complex resistivity $\tilde{\rho}$ can be written down as follows:

$$\tilde{\rho} = \frac{\rho_{vm} + i\omega\mu_0\lambda^2}{1 + i\frac{2\lambda^2}{\delta_{nf}^2}} \quad (3)$$

where $\omega = 2\pi\nu$ is the microwave angular frequency, ρ_{vm} is the complex resistivity due to Abrikosov vortex motion, and λ and δ_{nf} are the London and normal fluid penetration depths, respectively.

Vortex dynamics involves many mechanisms: the interaction with the superconducting condensate yields a viscous drag, described through a viscous drag coefficient (also commonly called vortex viscosity) η. The interaction between crystal defects and the fluxon system generates a pinning effect usually described through the pinning constant k_p, applicable in the limit of small vortex displacements from their equilibrium positions as determined by high frequency stimuli. Thermal fluctuations allow for thermally activated flux jumps between pinning sites, yielding the so-called creep.

One finds [25] that a large variety of different models can be formulated under the following very general expression for the vortex resistivity ρ_{vm}:

$$\rho_{vm} = \rho_{ff}\frac{\epsilon + i\frac{\omega}{\omega_0}}{1 + i\frac{\omega}{\omega_0}} \quad (4)$$

where $\rho_{ff} = \Phi_0 B/\eta$ is the flux flow resistivity, B the magnetic induction field, Φ_0 the flux quantum, ϵ a dimensionless creep factor, constrained in the range $0 \leqslant \epsilon \leqslant 1$. When creep can be neglected ($\epsilon = 0$), the above expression reverts to the well-known Gittleman–Rosenblum model [20].

The relation (in the local limit) between the superconductor complex resistivity $\tilde{\rho}$ and the measured surface impedance depends on the penetration depth of the e.m. field with respect to the superconducting sample thickness d: for bulk samples, i.e. $d \ll \min(\lambda, \delta_{nf})$, one has:

$$Z_s(H,T) = \sqrt{i\omega\mu_0\tilde{\rho}} \quad (5)$$

whereas in thin films, for which the $d \gg \min(\lambda, \delta_{nf})$ condition holds, it can be shown that [26]:

$$Z_s(H,T) = \frac{\tilde{\rho}}{d} \quad (6)$$

3. Measurements and discussion

3.1. DyBCO single domains

DyBCO single domains were prepared with precursor powders $DyBa_2Cu_3O_{7-\delta}$ and Dy_2BaCuO_5, produced by solid-state synthesis from Dy_2O_3, $BaCO_3$ and CuO powders. The powder mixture was pressed uni-axially to give cylindrical pellets of 10.8 mm diameter, which were melt-textured in atmospheric air conditions using a Nd-123 single-crystal seed. Large "quasi-single-crystals", mainly c-axis oriented, have been obtained, with $T_c \sim 88$–89 K. Two distinct pellets, (A) and (B), having similar $T_c \approx 88$ K, will be considered in the following.

From the first pellet (A), two samples of about the same thickness ~ 1 mm were cut: one (A2), approximately 2×2 mm^2 square, has been characterized by a magneto-optic (MO) study.

Magneto-optic images are reported in Fig. 1 (bright regions denote higher field intensity, black regions denote zero field): a static magnetic field is applied, perpendicularly to the sample surface, after a ZFC of the sample down to 73.5 K. In panel (a) the field is set to 15 μT: the sample is not threaded by magnetic flux, thus exhibiting a single domain behavior. At higher field values (90 μT, panel (b)), the magnetic flux penetrates in the sample: a few cracks, along which flux lines preferentially enter the sample are visible. Going back to zero field (panel (c)), remnant flux (indicative of significant pinning) is visible with slight dishomogeneities, apart from the cracks, along which flux lines easily exit from the sample volume.