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Quenching quantum vortex fluctuations in order to achieve higher critical current densities in $M\mathrm{Ba_2Cu_3O}_x$ coated conductors

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ABSTRACT

The relationship between the issue of obtaining higher critical current densities in textured $M\mathrm{Ba_2Cu_3O_7}$ films and the boundary between the electrically dissipation-less vortex solid state and the dissipative vortex liquid state is explored in the context of a recently developed phenomenological melting line expression. Based on an extension of the Lindemann melting theory of Blatter and Ivlev, the temperature-field $H{-}T$ dependence of this expression for $H_g(T)$ depends upon three parameters, a quantum fluctuation parameter Q, the Lindemann number c_L, and an exponent s, for which the value of each is relevant to understanding the problem of increasing the critical current density over an extended $H{-}T$ region. The importance of minimizing the value of the quantum parameter Q as a means of achieving higher critical current densities is demonstrated by examining the $H_g(T)$ lines of $\mathrm{YBa_2Cu_3O}_x$ with various levels of Pr, Ca, and oxygen doping.

1. Introduction

Soon after the discovery of superconductivity in the Ba–La–Cu–O system by Bednorz and Müller [1], examination of the material's magnetic properties revealed the presence of an intermediate region, characterized by a reversible magnetic response in $M(H)$, between the diamagnetic onset of superconductivity and a magnetically irreversible state [2]. This boundary between these two regions in the $H{-}T$ phase space has come to be known as the irreversibility line $H_{irr}(T)$. This boundary, which separates the electrically dissipation-less vortex solid state and the dissipative vortex liquid state, is also commonly referred to as the vortex-lattice melting line, $H_m(T)$, the vortex-glass melting line, $H_g(T)$, or the resistive upper critical field, $H_{c2}(T)$. There is a general consensus that all of the above "lines" represent the same phenomenon, and thus have come to be interchangable in meaning. We primarily refer to this line as the vortex-glass melting line $H_g(T)$; however when discussing results from other sources, we retain their nomenclature. From the perspective of recent work [3–7], the position of $H_g(T)$ in the $H{-}T$ phase diagram is inherently linked to the condensation energy density, $H_c^2(0)/2\mu_0$, the critical scaling properties of the superfluid density, and the nature of the electronic states within the vortex core. In turn, these same characteristic physical properties are at play in determining the critical current density, $j_c(H,T)$. The effectiveness of a defect to pin an individual vortex flux line is directly related to $H_c^2(0)/2\mu_0$, i.e., the pinning force density $F_p \propto H_c^2(0)/2\mu_0$ [8]. The nature of the defect, i.e., point like, columnar, magnetic, etc., is reflected in the critical exponent characterizing the scaling class of the superfluid density [4]. The extent to which quantum fluctuations play a role in displacing a pinned flux line is dependent upon the nature of the scattering of quasiparticles within the vortex core. In light of this connection between the effectiveness of pinning vortices and the physics which determines the location of the vortex-glass melting line $H_g(T)$, we compare trends found from the analysis of the $H_g(T)$ lines of $\mathrm{YBa_2Cu_3O}_x$ samples that are doped with various amounts of Pr, Ca, and oxygen. Based upon the results, we suggest possible methods by which higher critical current densities can be achieved over an extended $H{-}T$ region in $M\mathrm{Ba_2Cu_3O_7}$ (MBCO) coated conductors that is complimentary to the approach of focusing on introducing strong vortex pinning defects [9–12].

2. Pinning force density and the vortex-glass melting line

The goal of achieving larger critical current densities in high-T_c superconductors over an extended $H{-}T$ range can be approached from various perspectives. The most simple description of the problem is that we need to control the location of the $H_g(T)$ line in the $H{-}T$ phase diagram. By doing so we will have, of course, expanded the $H{-}T$ area capable of carrying a non-dissipative current, but perhaps more importantly the critical current density

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in the pre-expanded H—T region will be enhanced as well since the minimum value of the critical current density J_{cm}, as determined within the percolation model [13], depends directly upon $H_g(T)$, wherein [8,14],

$$J_{cm}B = AH_g(T)^{\zeta'}\left[\frac{B}{\mu_0 H_g(T)}\right]^{\gamma}\left[1-\frac{B}{\mu_0 H_g(T)}\right]^{\delta}, \quad (1)$$

where $B = \mu H$ is the magnetic induction, and where A, ζ', γ, and δ are pinning parameters characterizing the pinning mechanism. From a microscopic perspective, in order to increase J_c the bulk pinning force density F_p must be increased since $F_p = J_cB$. The macroscopic pinning force density F_p depends mostly upon the elementary pinning force per unit length f_p' (the elementary pinning force per flux line, f_p is given by Df_p', where D is the length of the flux line). Pinning mechanisms that can contribute to f_p' include magnetic interactions, elastic interactions, and the condensation energy interaction. The latter can be calculated from the energy of a single flux line which can be estimated as $f_p' \simeq 0.430\pi\xi\mu_0 H_c^2$, where ξ is the coherence length. A field dependent formula which is found to hold over a wide range of magnetic field is given by [8],

$$f_p' \simeq 0.430\pi\xi\mu_0 H_c^2\left(1-\frac{B}{\mu_0 H_{c2}}\right). \quad (2)$$

Since the H—T dependence of the condition where $f_p = 0$ determines the location of $H_g(T)$, we can see that there is a correlation between the vortex-glass melting line and the condensation energy density. Indeed, within the thermal-fluctuation model of Cooper et al. [15], they find experimentally for $YBa_2Cu_3O_x$ that $H^* \propto H_c^2$ where H^* is a characteristic field parameter that determines the magnitude of the irreversibility line $H_{irr}(T)(H_g(T))$. With the relationship between the critical current density J_c and the vortex-glass melting line $H_g(T)$ in mind, we discuss below some of the early investigations into the properties of the $H_{irr}(T)(H_g(T))$ boundary and highlight the recent development of an expression for $H_g(T)$ that has been demonstrated to accurately describe melting line data over a temperature range as large as $0.03 \leqslant T/T_c \leqslant 1$.

3. The vortex-glass melting line

Both electron- and hole-doped cuprate-based superconductors share a common structural feature wherein the perovskite unit cell is comprised of Cu–O layers within the a—b plane separated in the c-direction by the remaining chemical constituents by varying distances, depending on the compound. This quasi-2D structure has been found to have consequences on the properties of vortices, vortex structures, and pinning of vortices. A common feature of the irreversibility line, found in the early investigations of different high-T$_c$ compounds [2], was a temperature dependence where $H_{irr} \sim (1-T/T_c)^{3/2}$. In more recent experimental investigations of the irreversibility line, $H_{irr}(T)$ (melting line $H_m(T)$), of both electron- and hole-doped cuprate superconductors an anomalous field-temperature dependence was observed as the magnetic field increased and the temperature decreased [17–20].

In particular, de Andrade et al. [19] found, for the electron-doped compound $Sm_{1.85}Ce_{0.15}CuO_{4-y}$ that, at temperatures $T \geqslant 0.6T_c$, $H_{irr}(T)$ follows a $(1-T/T_c)^m$ form with $m \approx 3/2$, however, the low temperature region follows the same analytic form, but with a larger value of the exponent m. A similar observation (see Fig. 1) was made by Almasan et al. [21] for a series of $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ samples, where the $H_{irr}(T)$ lines of each sample could be scaled in field and temperature onto a single curve where $H_{irr}(T) \propto (1-T/T_c)^{3/2}$ at $T \geqslant 0.6T_c$, and at lower temperatures $H_{irr}(T)$ increased much more rapidly with temperature (see also Fig. 2). Additionally, following the analysis of the irreversibility line of a $Bi_2Sr_2CaCu_2O_8$ single crystal by Schilling et al. [20], Almasan and Maple [22] found evidence for a crossover in dimensionality of the vortex ensemble from a low field 3D to high field 2D vortex regime in the $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ system at the characteristic temperature $T \geqslant 0.6T_c$. A universal expression for $H_{irr}(T)$ argues strongly for common underlying physics in spite of the many physical disparities of the high-T_c cuprate superconductors.

In contrast to the scenario of flux creep where independent motion of finite bundles of vortex segments are assumed [23,24], within the models of Brandt [25] and Fisher, Fisher, and Huse (FFH) [26–28], the irreversibility line delineates the transition

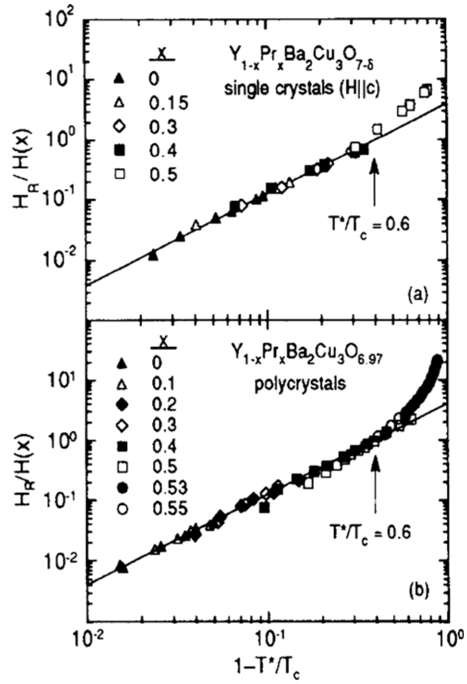

Fig. 1. The scaled irreversibility lines $H_R(T)$ of single crystal and polycrystalline $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ samples in magnetic fields up to 23 T. The figure is taken from Ref. [16].

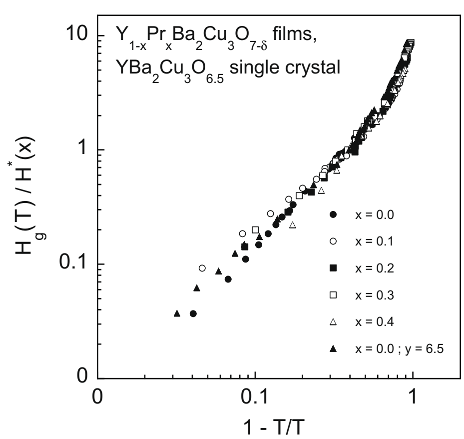

Fig. 2. The scaled vortex-glass melting lines $H_g(T)$ of $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ films and a $YBa_2Cu_3O_{6.5}$ single crystal in magnetic fields up to 45 T from Refs. [3,4], scaled according to the empirical from $H_g(T) \sim H^*(x)(1-T/T_c)^m$. The data are in agreement with earlier experiments on single crystal and polycrystalline $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ samples, shown in Fig. 1. However, as described in the text, a more complex expression for the vortex-glass melting line which is capable of accurately describing the entire range of $H_g(T)$ data has been deduced from a modification of the quantum-thermal vortex lattice melting model of Blatter and Ivlev [39].