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Temperature and field dependence of critical currents, resistances and irreversibility fields of a $(Tl_{0.6}Pb_{0.24}Bi_{0.16})(Ba_{0.1}Sr_{0.9})_2Ca_2Cu_3O_y$ film on single-crystalline lanthanum aluminate

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Abstract

The temperature and magnetic field dependences of the ac resistance and the critical currents of a *c*-axis oriented, *ab* aligned $(Tl_{0.6}Pb_{0.24}Bi_{0.16})(Ba_{0.1}Sr_{0.9})_2Ca_2Cu_3O_y$ film on (100) single-crystalline lanthanum aluminate substrate were measured and analysed. The magnetic field and the temperature dependences of the width of the resistive transition to the superconducting state and of the irreversibility fields were analysed both within the flux-creep model and the superconducting liquid vortex state model. The temperature width of the resistive transition was explained on the basis of the superconducting Josephson weak links model of resistance and the barrier of vortex motion. The irreversibility field was described by an exponential formula. The temperature dependence of the critical current was described by a power law; the magnetic field dependence of the critical current was fitted to a Kim-type power law as well as to an exponential relation from the percolation model.

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1. Introduction

The vortex motion in high temperature superconductors (HTS) has been subject to intensive discussion since discovery of these materials. Initial approaches to this problem differed but finally led to a generally accepted relation for the temperature dependence of the irreversibility field [1–5]:

$$H_{\mathrm{irr}} = H_0\left(1 - \frac{T}{T_c}\right)^n \tag{1}$$

where H_0 is the irreversibility field at 0 K and T_c the critical temperature of the superconductor. The exponent n may be 1.5 or higher. In a theoretical paper based on thermodynamic melting of the vortex lattice a power coefficient $n = 2$ was predicted [6]. Some experimental data were in a good agreement with that prediction [7]. The temperature dependence of the irreversibility field for HTS close to T_c shows very frequently an upward curvature and the irreversibility line is usually described by Eq. (1).

Müller, Takashige and Bednorz [1] proposed a model based on superconducting grains, which were small compared to the London penetration depth. They assumed that the grains formed weakly coupled closed loops. This state was called a superconductive glassy state or vortex state. Some essential features of this model were the difference in field-cooled and zero-field-cooled responses, the existence of de Almeida–Thouless line separating meta-stable from stable regions and the non-exponential time dependence of magnetisation [2]. The line determined from Eq. (1) was called "irreversibility line".

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Yeshurun and Malozemoff developed the Thermally Activated Flux-Creep model (TAFC) considering strong anisotropic magnetic relaxation [3]. It was found that the flux activation energy U is in the order of several electron-volts for conventional second type superconductors while for HTS the authors obtained an activation energy of 0.15 eV. This low U-value and the much higher T_c in HTS compared to conventional superconductors led to the observed "Giant" Flux Creep. The authors obtained also the irreversibility line described by Eq. (1).

Tinkham [4] extended the TAFC model to account for the experimentally measured width as well as for the shape of the resistive transition in magnetic fields and developed the following equation:

$$\frac{R}{R_n} = \left[I_0\left(\frac{\gamma}{2}\right)\right]^{-2} \tag{2}$$

where I_0 is the modified Bessel function, usually given by some series, R is the resistance of the weak links, R_n is the resistance in the normal state at a given temperature and γ is a parameter connected with the activation energy of vortex motion. A similar formula was also obtained by Ambegaokar and Halperin [5] for superconducting Josephson weak links. The obtained γ parameter was in the form:

$$\gamma = \frac{U}{k_B T} = \frac{A(1-t)^{3/2}}{H} \tag{3}$$

where the coefficient A depends on the critical current at zero magnetic field, $t = T/T_c$ and H is the dc magnetic field. Including Eq. (3) into Eq. (2) and taking only the two first terms of the Bessel series the following equation may be derived:

$$\frac{R}{R_n} = \left[I_0\left(\frac{A(1-t)^{3/2}}{2H}\right)\right]^{-2} = \left[1 - \left(\frac{A(1-t)^{3/2}}{4H}\right)^2\right]^{-2} \tag{4}$$

for the dc magnetic field $H \neq 0$. Eq. (2) is valid for each value of $\frac{R}{R_n}$. If we consider $\frac{R}{R_n} = 0$, then a simple calculation yields the following result for the width of resistive transition:

$$\Delta T = 16 T_c \left(\frac{1}{A}\right)^{2/3} H^{2/3} = C H^{2/3} \tag{5}$$

For HTS the resistive transition is even for $H = 0$ relatively wide, so $\Delta T \neq 0$. Therefore, Eq. (5) should be rewritten to the following form [8]:

$$\Delta T = C H^n + \Delta T_0 \tag{6}$$

where $n = 2/3$ and ΔT_0 means the width of the resistive transition at zero dc applied magnetic field.

In HTS the transport critical current flows through the weakly coupled superconducting grains, which can be approximated by Josephson junctions. The critical current is determined by the weakest junction on the current percolative path. According to the Ginzburg–Landau strong-coupling limit approach, the critical current varies with temperature as given in the following equation [9]:

$$J_c = J_{c0}\left(1 - \frac{T}{T_{c0}}\right)^n \tag{7}$$

where T_{c0} is the temperature at which the whole sample stayed superconducting. That temperature depends on the dc applied magnetic field. J_{c0} is the critical current at 0 K and n is usually close to 1.5.

The dependence of the critical current on the magnetic field has been described by two critical state models. The first one is the Kim-type [10] critical state model in the power form:

$$J_c = J_{c0}\left[1 - \left(\frac{H}{H_k}\right)^{\alpha}\right]^{-1} \tag{8}$$

where J_{c0} is the critical current at zero magnetic field, H_k and α are the material parameters depending on the intrinsic sample properties.

The second critical state model is the exponential model derived from the percolation theory [11]. This percolation model yields, to good approximation, a universal equation of the form:

$$J = J_{c0}\left[\exp\left(-\frac{H}{H_e}\right) + \beta\right] \tag{9}$$

where J_{c0} is the critical current at zero magnetic field, H_e and β are phenomenological parameters connected with weak link network properties.

Eqs. (1) and (6)–(9) will be used to fit the experimental data obtained for a superconducting $(Tl_{0.6}Pb_{0.24}Bi_{0.16})$-$(Ba_{0.1}Sr_{0.9})_2Ca_2Cu_3O_y$ film on single-crystalline lanthanum aluminate in order to learn what theoretical approach accounts best for the experimental data.

2. Experimental

2.1. Preparation of the superconducting film

The preparation of Tl-1223 films with a nominal composition of $(Tl_{0.6}Pb_{0.24}Bi_{0.16})(Ba_{0.1}Sr_{0.9})_2Ca_2Cu_3O_y$ on (100) single-crystalline lanthanum aluminate substrate followed a published procedure [12]. Thallium-free precursors were made via the malic acid gel method. 2.294448 g PbO, 1.5967 g Bi_2O_3, 2.1881 g $Ba(CH_3COO)_2$, 11.3820 g $SrCO_3$, 8.5742 g $CaCO_3$ and 25.6546 g $Cu(CH_3COO)_2 \cdot H_2O$ were dissolved in 100 ml concentrated acetic acid. The mixture was kept at its boiling temperature for one hour. Following cooling of the solution, 100 ml distilled water and 10 ml ammonia solution were added. 4.3075 g malic acid was added and the solution carefully heated on a hot-plate until a gel was formed. The gel was dried at 115 °C in vacuum (20 mbar) and calcined at 800 °C for 50 h. The precursor powder was wet-milled in acetone using a centrifugal ball mill. The paste for screen-printing was obtained by adding