Journal of Alloys and Compounds 408–412 (2006) 212–214
www.elsevier.com/locate/jallcom

Vortex instability phase of $Bi_2Sr_2CaCu_2O_{8+y}$ single crystal

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Available online 27 June 2005

Abstract

Using single crystals of $Bi_2Sr_2CaCu_2O_{8+y}$, we performed detailed magnetization measurements in the low temperature region below the vortex solid-glass transition temperature, a region, which has not received any attention well to date. We observed that thermoremnant magnetization showed dramatic, random oscillations in both the real part and the imaginary part of the AC magnetic susceptibility at temperatures below approximately 20 K. The drastic change of AC susceptibility is usually observed in the magnetic phase transition, indicating the presence of a new magnetic state in the region below the vortex solid-glass transition temperature. We also measured the long-time relaxation effect of thermoremnant magnetization below and above the anomalous temperature. From the analysis of decay of thermoremnant magnetization based on weak collective pinning and vortex glass theory, activation energy of vortices has sharp decline at the temperature where the AC susceptibility anomaly occurs. From the result of AC susceptibility and decay of the thermoremnant state, we consider the boundary of vortex motion in $Bi_2Sr_2CaCu_2O_{8+y}$ at 20 K.

Keywords: Bi2212; Vortex matter; Pinning; Magnetization; Activation barrier

1. Introduction

Among high-T_C-superconductors, Bi-series has a high critical current in high magnetic field. The characteristics are most appropriate for superconducting wire of high field magnet at the present time. In order to fabricate the high-performance Bi-wire for high field magnet, much investigation for processing method is carried out. Concurrently, the basic researches for the characteristics are now ongoing.

The crucial problem for application use in Bi-wire is the behavior of magnetic vortex in the magnetic field, and therefore it is important to investigate the basic properties of vortices. Many studies are underway to resolve the "vortex matter", which is extremely susceptible to the thermal fluctuations due to their characteristics, such as high anisotropy and short coherence length, caused by the long blocking layers along *c*-axis. The vortices compose an Abrikosov lattice structure at low temperature, but at high temperature, the lattice melts and a liquid state of vortices occurs. This melting process is revealed as a first-order phase transition by the precise investigations [1–4]. Below the melting temperature, as mentioned above, it is supposed that the vortices form a triangular lattice in low field, which is the Bragg glass phase. Since the Bragg glass phase is rather ordered phase and thus stable, this region has not received much attention.

On the other hand, the characteristics of high critical current at high field of Bi-superconductors gradually fall above about 20 K, which is simply described by the thermal effect [5]. But the origin of degradation is still unclear. The motivation of this study is to extend the understanding of the performance degradation of Bi-superconductors above 20 K. In a series of our studies, the attention is mainly paid on the low temperature region below the transition and have observed anomalous dispersive behaviors in the AC susceptibility [6,7] and proposed the possibility of the existence of new phase [8]. In the present work, we present the result of decay of the thermoremnant magnetization, and the stability

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doi:10.1016/j.jallcom.2005.04.100

of the vortex and the activation energy anomaly for the vortex pinning are discussed.

2. Experimental

$Bi_2Sr_2CaCu_2O_{8+y}$ single crystals were grown using a floating zone method [9]. Crystallinity was checked by X-ray diffraction analysis with double-crystal diffractometry on an over-doped crystal with a $T_C = 86 \pm 0.3$ K. Magnetization measurements were carried out on a single crystal shaped into a platelet with a diameter of 2 mm and a thickness of 100 μm by cleaving. The magnetizations were measured using a commercial superconducting quantum interference device (SQUID) magnetometer with the magnetic field applied perpendicular to the *ab* plane. To fix the samples at the appropriate position in the magnetometer, Teflon tape and thin polymer straws were used. These materials have diamagnetizations, estimated to be 10^{-6} emu in our experimental conditions. We checked that the diamagnetization is almost independent of temperature. As a result, the diamagnetic signal by the polymers is negligible in this study when compared to the sample signal.

3. Result and discussion

Firstly, we show the AC susceptibility of thermoremnant state in the $Bi_2Sr_2CaCu_2O_{8+y}$ single crystal after field cooling at 0.1 T in Fig. 1. The dispersive AC susceptibilities in both real and imaginary part are observed below 20 K. The AC susceptibilities fall into stable values above 20 K. Note that the amplitude of dispersion is not small compared to the signal on T_C. This anomalous dispersion of AC susceptibility is observed only in very low AC frequency, which is less than 0.1 Hz. The drastic change of AC susceptibility at 20 K shows the existence of some boundary for the magnetic state. For the anomalous AC susceptibility measurement

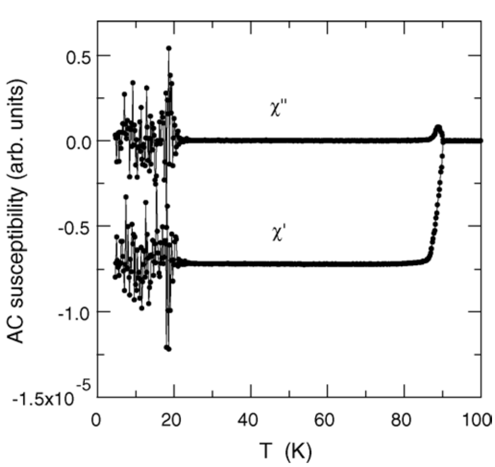

Fig. 1. Temperature dependence of AC susceptibility of thermoremnant magnetization at $H_{AC} = 10^{-6}$ T and $f = 1$ Hz. Solid lines are guide to eye.

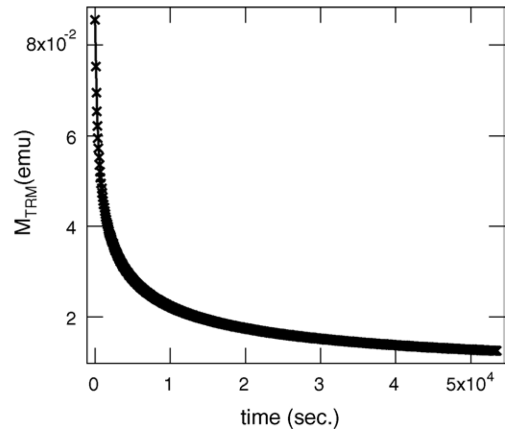

Fig. 2. A typical example of the decay of thermoremnant magnetization at $T = 17$ K. The solid line represents the theoretical fitting.

was reported elsewhere in detail [6,7]. We have thought that the unusual behavior of AC susceptibility was caused by the vortex instability. To check our scenario, we performed the measurements on the decay of thermoremnant magnetization in the temperature range between 9 and 40 K. The decay of the magnetization was measured as following manner. Single crystal is cooled down to the temperature from room temperature in a magnetic field of 0.1 T perpendicular to the *ab* plane, and then the field was reduced to zero. The DC magnetizations were measured at intervals of 60 s for 14 h. A typical result of time decay measurement is shown in Fig. 2. The thermoremnant magnetization decreases significantly up to 0.5×10^4 s. The initial decreasing of remnant magnetization is steeper around 20 K. In order to explain the data for time decay, we employed the equation [10] based on the flux creep model [11]. The creep motion governs the behavior of vortices, and accordingly yields thermal activation and quantum tunneling effects. The pinning in a type-II superconductor generates a vortex gradient and causes the flow of a diamagnetic screening current density j through the Maxwell equation of $\partial j/\partial t = c/4\pi \times \partial^2/\partial x^2(vB)$. Using a postulation by Anderson [12] together with the Maxwell equations, the activation barrier is obtained by logarithmic approximation:

$$U(j(t)) \simeq k_B T \ \ln\left(1 + \frac{t}{t_0}\right), \tag{1}$$

where t_0 is a scaling factor defined as $t_0 = k_B T \tau_0 / j_c |\partial_j U|$. When j is much smaller than j_c, the weak collective pinning theory applies. Assuming the single-vortex pinning regime, current density can be expressed as:

$$j(t) \simeq j_c \left(1 + \frac{t}{t_0}\right)^{-k_B T/U_c}, \tag{2}$$

where activation energy has a logarithmic dependence on j, $U(j) = U_c \ln(j/j_c)$. By the assumption of the constant current density of the sample at a time t for thin flat samples, magnetization is proportional to the current density, $M(t) \sim (R/3c) j(t)$, where R is the radius of the sample [13]. A typical fitting result is shown in Fig. 2, where the experimental result is

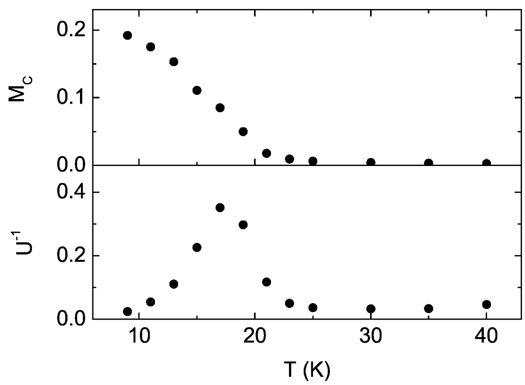

Fig. 3. Temperature variation of initial magnetization and inverse activation energy of flux pinning in over-doped Bi2212.

well reproduced. From the systematic analysis in the temperature range up to 40 K, the temperature variation for the activation energy U is obtained as shown in Fig. 3. The activation energy decreases around 17 K, which is close to the anomalous temperature of AC susceptibility. In Fig. 3, the temperature dependence of M_c, which indicates initial value of the thermoremnant magnetization, is also illustrated. The M_c decreases rapidly with increasing temperature, and become rather small above 20 K. In addition, M_c is almost independent to the temperature above 20 K. These results for the time decay of the thermoremnant magnetization support the existence of the boundary of the vortex stability around 20 K.

A significant decrease of the activation energy at around 17 K allows the penetration of magnetic vortices to keep the high critical current density at the higher temperatures. Next, we discuss the origin of the unusual behavior for the vortex activation energy, microscopically. Within the framework of weak collective pinning theory, the activation energy has an approximate logarithmic dependence on the macroscopic diamagnetic screening current density, j. For small j, the dependency of activation energy remains small in the low temperature region; nevertheless the activation energy is expected to be close to a constant as shown in Eq. (1). This indicates the increasing of elastic interaction of vortices. We suggest the concept of variable-range hopping to explain this unusual behavior [1,14,15]. In the scheme of weak collective pinning theory, it is possible to migrate between vortex segments or colligate over the vortices far apart. This idea easily leads to the growing of the elasticity of vortices with decreasing current density j. This concept is supported by the experimental result of Chang et al., where the monotonic increasing of the longitudinal sound velocity was observed with decreasing temperature without phonon softening [16,17]. In the hopping region, the individual pancake vortices can move independently. Therefore, in the themoremnant state, it is possible that the small *transition* of the moving vortices takes place in the system. The metastable state, which is the randomness in the energies, also causes a fluctuation in the vortex density. In the region, the dispersive behavior of physical quantity for the entropy might be observable. The entropy change is observable in the magnetization measurement; therefore it is possible to put the origin of the anomalous dispersive behavior in AC susceptibility on the hopping of vortices. We also notice that it is considerably difficult to explain the amplitude of the dispersion by the above-mentioned mechanism. This point is left for future study.

We measured the decay of the thermoremnant magnetization in over-doped Bi2212 single crystals. The time stability of thermoremnent magnetization was reproduced by the analysis based on the weak collective pinning theory. The systematic study for the decay extracted the temperature dependence of the activation energy of vortices, where an anomaly was observed at around 20 K. From the result of the decay measurements we hypothesized the hopping of the vortices in the metastable state.

Acknowledgements

We thank T. Mochiku for providing the samples, and M. Uehara for fruitful discussions.

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