The Vortex State in YBa$_2$Cu$_3$O$_{7-x}$ System

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We have studied the vortex state problem systematically in YBa$_2$Cu$_3$O$_{7-x}$ system with twinned/untwinned single crystals. Different vortex states are observed on samples with different characteristics. Our detailed I-V characteristics measured in different magnetic fields, at temperature below where the resistive knee occurs, show that the dynamics of the vortex motion depends on the sample characteristics and field strength. Under an intermediate external field, vortex lattice phenomenon is observed in untwinned and some twinned single crystals. On the other hand, vortex glass (or solid) state is observed in twinned crystals with strong pinning effect. In high external magnetic field region, the low resistivity data fit nicely to giant flux-creep model, predicted by Tinkham.

I. INTRODUCTION

The problem of the vortex state in T SUPERCONDUCTING YBa$_2$Cu$_3$O$_{7-x}$ system has attracted great attention for the past few years. The large broadening of the resistive transition in field was first attributed to the giant flux-creep due to large thermal fluctuation effect. Tinkham gave, considering only single flux motion, a simple relation ([1]) which fit beautifully to the data reported by Iye et al. [2]. Detailed measurements on the single crystals of YBa$_2$Cu$_3$O$_{7-x}$ revealed that there are more complicated features at the transition regions in the high T$_c$ oxides. Early data indicated that the observed unusual vortex dynamic was possible the signature of a vortex glass \- vortex liquid transition as proposed by Fisher et al. [3] considering the presence of random pinning centers. Later, more careful results show that there exists, in addition to the large broadening of resistive transition, two distinct anomalies in the transition region. They were ascribed to either the first order vortex lattice melting or a second order glass transition depending on the field

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range [4]. Our recent results suggest that these two resistive anomalies are fundamentally different. One (occurs at higher temperature) is related to the dimensional crossover of the superconducting transition, while the other is related to the change in the vortex state.

In this paper, we report the detailed measurements of the low-resistivity transition region in a wide range of magnetic field. Our $R - T$ data obviously do not fit to the simple flux-creep model for fields $B \leq 17$ tesla. We find from the $I - V$ characteristics, samples with higher density of defects (including point defects, dislocations, twin planes and etc.) can be described by the vortex glass transition model [3]. These $I - V$ curves obey nicely the scaling relations at $T \approx T_g$,

$$E \propto J^\alpha \quad \text{at} \quad T = T_g$$

(1a)

$$Et^{-\gamma} = E_G(t^{-\beta}/K_B T) \quad \text{at} \quad T \neq T_g$$

(1b)

where $t = [1-T/T_g]$, $\alpha$, $\beta$, and $\gamma$ are critical exponents that satisfy $\gamma = \beta(\alpha - 1)$. On the other hand, $I - V$ characteristics of samples with fewer pinning centers suggest the direct vortex lattice to vortex liquid transition.

II. EXPERIMENT

Both twinned and untwinned YBCO crystals were used in this study. The twinned crystal is prepared by the conventional flux grown method [5]. Typical crystal dimension is $1 \times 1 \times 0.02 \text{ mm}^3$ with the shortest dimension along c-axis. The untwinned crystal is grown by quench and post-annealing method with typical dimension $1 \times 1 \times 0.1 \text{ mm}^3$. The electrical leads were made using Pt wires attached with silver-paste. After annealed in a flow oxygen at 500 °C for one hour, the contact resistances were less than 0.1 Ω. Using a special temperature sensor unit, the temperature resolution better than $1 \text{ mK}$ is achieved in $R - T$ measurement. In $I - V$ measurement, the temperature stability is about $\pm 20 \text{ mK}$. Low frequency, 37 Hz, AC transport measurements were carried out using lock-in technique. A Keithley 220 current source and a low noise nanovoltmeter are used for DC transport measurements. In order to reduce the Joule-heating and thermal voltage in $I - V$ measurements, we used a pulsed current. Magnetic field is applied in parallel to the c-axis of sample up to 17 Tesla.

III. RESULTS AND DISCUSSIONS

Typical $R - T$ curves for single crystal in magnetic fields are shown in Fig. 1. There are clearly two resistive knees observed. The high temperature knee is related to the dimension crossover of superconducting transition and is discussed in another paper [6]. The low temperature knee is closely related to the vortex phase transition. Our observations show that the temperature dependence of resistivity below the lower resistive knee behaves
FIG. 1. (a) $R$-$T$ curves of untwin crystal under 0, 1, 4, 8, 11, 15 tesla magnetic field. (b) $R$ - $T$ curves of twin crystal under 0, 0.12, 2.3, 3.5, 4.6, 5.8, 7, 8.1 tesla magnetic field.

differently depending on the sample characteristic. For untwinned crystal, the resistive tail is much broader, as shown in Fig. 1a, because of the lower effective pinning centers density. On the contrary, the resistive transition for twinned crystal is quite sharp, as shown in Fig. 1b, due to its stronger pinning effects.

The $I$-$V$ characteristic of untwinned crystal under 2 Tesla field are shown in Fig. 2. Clearly, the characteristics of $I$-$V$ curves change from non-linear to linear as temperature increases. The temperature ($T_m$) at which the change in $I$-$V$ characteristic is corresponding to the temperature at which lower resistive knee occurs. The non-linear $I$-$V$ characteristic below $T_m$ indicates that the existence of pinned vortex lattice state. As temperature increases, thermal fluctuation causes the pinned vortex to move (or creep) and eventually flow, as shown by the ohmic-like $I$-$V$ above $T_m$. This suggests that $T_m$ can be identified as the vortex lattice to vortex liquid transition temperature [7]. On the other hand, the $I$-$V$ characteristic for twinned crystal, as displayed in Fig. 3, shows the change from curvature downward to curvature upward passing through a linear characteristic as temperature increases. The temperature at which $I$-$V$ is linear is 81.3 K. This temperature ($T_g$) is also corresponding to the vortex state transition. The non-linear $I$-$V$ on both side of $T_g$ is consistent with the picture of vortex glass transition [3]. In the vortex glass state, most of the vortices are pinned by the random pinning centers and the collective pinning effect is strong. It results in sharp voltage drops as applied current decreases such that $I$-$V$ no longer follows simple power law. Consequently, there exists finite critical current at finite temperature. As the temperature raises to above the transition temperature, a highly viscous vortex liquid state forms because the pinning effect still drags the vortices. It shows up as an upward $I$-$V$ curve at temperature higher than $T_g$. As predicted by the theory of vortex glass transition, near the transition temperature $T_g$, $I$-$V$ curves can be
**FIG. 2.** $I-V$ curves of untwin crystal under 2 tesla external field. The temperature range is from 86 K to 87.1 K per 0.1 K a step. The vortex lattice melting temperature is 86.8 K.

**FIG. 3.** $E-J$ curves of twin crystal under 6T external field. The temperature range is from 76.4 K to 83 K and the vortex glass transition temperature is 81.3 K.

can be scaled with Eq. (1). As shown in Fig. 4, $I-V$ curves collect beautifully to two universal curves. The best fit critical exponents are $\alpha = 2.21$, $\beta = 0.6$, and $\gamma = 0.75$ for this particular crystal sample under 6 Tesla. The scaling law, $\gamma = \beta(\alpha - 1)$ [3], is well satisfied. Our results show that this scaling law is also universal and is independent of the applied magnetic field and the sample. However, the respective critical exponent $\alpha$, $\beta$ and $\gamma$ is field and sample dependent [8].

In the case of high external field, one has to take into account of the vortex-vortex interaction because vortices are close to each other. One would then expect the efficiency
of pinning effect become worse. Even in the presence of a small Lorentz force, the vortices would creep easily and results in ohmic-like $I-V$ even at low temperature. It would also reflect in $R-T$ as that due to giant flux creep. Indeed, Fig. 5 shows the $R-T$ data of untwinned crystal under high magnetic field and fit with Tinkham's formula [1]. The data fit nicely except the low resistance data at magnetic field, $B < 13$ T in this sample. The deviation originates from the pinning effect at low temperature. From the fitting parameters, the intrinsic current density of $6.25 \times 10^6$ A/cm$^2$ is obtained. The onset transition

$$R(T) = \frac{R_0}{(1-T/T_c)^{3/2}/2B}.$$

Solid lines fitting curves and open circles are experimental data.
temperatures are 76.8 K and 78.0 K for 15 T and 13 T field, respectively. These “$T_c$'s” are, close to the temperature of the higher temperature resistive $\kappa$ 

IV. SUMMARY

In summary, different vortex states are observed on YBa$_2$Cu$_3$O$_{7-y}$ samples with different material characteristics. Vortex lattice state exists in untwinned and some twinned crystal under intermediate external magnetic field. The resistance is ohmic above the vortex lattice melting temperature. Below the transition, $I=V$ characteristic becomes non-linear resulting from the presence of Abrikosov lattice with collective pinning effect. We also observe the existence of vortex glass state in twinned crystal samples that have high density effective pinning centers. The data fit very well with the scaling law predicted by the vortex glass phase transition theory. When magnetic field becomes very high, the vortex-vortex interaction must take into account and the $R-T$ data obey the giant flux creep model.

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