Transport Properties of a Josephson-Coupled Network in a Superconductive Ceramic of YBa$_2$Cu$_4$O$_8$

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Abstract. Ceramic YBa$_2$Cu$_4$O$_8$ samples composed of sub-micron size grains are considered as random Josephson-coupled networks of 0 and $\pi$ junctions, and they show successive phase transitions. The first transition occurs inside each grain at $T_{c1}$ and the second transition occurs among the grains at $T_{c2}$ ($< T_{c1}$), where a negative divergence of nonlinear susceptibility is found. This critical phenomenon at $T_{c2}$ suggests the onset of the chiral-glass phase, as predicted by Kawamura and Li. We measured the temperature dependencies of the current-voltage characteristics of the samples and derived the linear and nonlinear resistivities. With decreases in temperature, linear resistivity decreased monotonously and remained at a finite value at temperatures less than $T_{c2}$, while nonlinear resistivity diminished continuously for temperatures moving towards $T_{c2}$. These results are consistent with the theoretical predictions.

1. Introduction
Ceramic YBa$_2$Cu$_4$O$_8$ and YBa$_2$Cu$_3$O$_{7-\delta}$ samples, which are composed of homogeneous sub-micron-size grains, may be regarded as random Josephson-coupled networks that contain so-called $\pi$ junctions. The circulation of a local loop-supercurrent is generated spontaneously in a zero field when there is an odd number of $\pi$ junctions in a closed loop that consists of some Josephson junctions. Theoretically, the frustration effect due to the random distribution of $\pi$ junctions should lead to the chiral-glass state.[1] In experimental studies, ceramic YBa$_2$Cu$_4$O$_8$ and YBa$_2$Cu$_3$O$_{7-\delta}$ samples have shown successive phase transitions under the zero and small fields.[2,3] With decreases in temperature, the first transition occurs inside each grain at $T_{c1}$ and the second transition occurs among the grains at $T_{c2}$. The discrepancy between the field-cooled and zero-field-cooled magnetization levels appears at below $T_{c2}$, and negative divergence of nonlinear susceptibility is observed at $T_{c2}$, which may reflect a chiral-glass transition.[4] Further experimental measurements of ac-susceptibility for dynamic scaling analysis[5] and of ac-resistivity[6] in the ceramic YBa$_2$Cu$_4$O$_8$ and YBa$_2$Cu$_3$O$_{7-\delta}$ samples have been carried out, and the results are consistent with chiral-glass transitions. Kawamura and Li investigated the chiral-glass phase of ceramic high-$T_c$ superconductors using Monte Carlo simulations.[7] They
studied numerically the transport property of a high-$T_c$ ceramic. In these simulations, the chiral-glass state is not a true superconductor but exhibits Ohmic behavior with a low linear resistance below $T_{c2}$. The purposes of the present paper were to investigate the transport property of ceramic YBa$_2$Cu$_4$O$_8$ and to determine whether the linear resistance exists at temperatures below the chiral-glass transition temperature $T_{c2}$.

2. Experimental

The sample was prepared using the citrate pyrolysis method. [8] The precursor was calcined for 120 h at 777°C to yield the pure YBa$_2$Cu$_4$O$_8$ phase, which was sieved and pressed, and then sintered for 50 h at 778°C. The dc magnetization and the ac susceptibility were measured with a SQUID magnetometer (Quantum Design MPMS-5) using the ultra-low-field option. The sample space in the magnetometer was shielded with $\mu$-metal. As a result, the residual field was reduced to less than 10 mG. The nonlinear susceptibility was derived from the harmonics in-phase Fourier component for the ac field response. The $E$-$J$ characteristics and dc-resistivity were measured by low-level pulsed electrical characterization with a current source (KEITHLEY 6221) and nanovoltmeter (KEITHLEY 2182A) combination. The delta method for low-voltage measurements was used to eliminate the constant thermoelectric voltage and to minimize the amount of power dissipated in the sample.

3. Results and Discussion

We measured the temperature dependencies of the dc magnetization and ac susceptibility, to determine the transition temperatures $T_{c1}$ and $T_{c2}$. Figure 1 shows the temperature dependencies of the zero-field-cooled, field-cooled, and thermoremanent magnetizations at $H = 0.5$G. The upper transition at $T_{c1} = 83$K was identified as the intragrain superconducting ordering, in which the small diamagnetism due to the Meissner effect appears in the zero-field-cooled and field-cooled magnetizations. The discrepancy between the field-cooled and zero-field-cooled dc magnetizations appeared at $T_{c2} = 53.6$K. The nonlinear susceptibility estimated from the first three terms of the series of in-phase odd-harmonic responses in the frequency of 0.1 Hz with ac field amplitude of 0.1G is shown in Figure 2. Negative divergence of nonlinear susceptibility was observed at $T_{c2} = 53.6$K, at which temperature the ceramic YBa$_2$Cu$_4$O$_8$ underwent a chiral-glass transition.

We also examined the temperature dependency of the linear resistivity at zero-field magnetization. Figure 3 shows the temperature dependency of linear resistance $R$ at dc excitation current $I = 0.5$ mA.
As the temperature was reduced, the linear resistance $R$ decreased rapidly at about $T_{c1} = 83K$, and then decreased monotonously and almost disappears around a temperature of $60K$.

In order to investigate the transport property near the chiral-glass transition temperature $T_{c2}$, we measured the $E$-$J$ curves with zero-magnetic field. Figure 4 shows the $E$-$J$ curves at temperatures between 50K and 57K. Below $T_{c2}$, $E$ increased almost linearly with $J$ and the value of $E$ appeared to be independent of temperature. Thus, the linear resistivity remained below $T_{c2}$. At temperatures greater than $T_{c2}$, rapid increases in $E$ were observed as $J$ increased, perhaps due to the nonlinear resistivity.

Linear resistivity $\rho_0$ and nonlinear resistivity $\rho_2$ are defined as the coefficients of the first and third power terms of $E$ ($J$), respectively, expanded in a power series of $J$.[6] Figure 5 and 6 show the temperature dependencies of the linear resistivity $\rho_0$ and nonlinear resistivity $\rho_2$ estimated from $E$-$J$ curves around $T_{c2}$, respectively. In Figure 5, $\rho_0$ remains finite below $T_{c2}$ and has the low value of $\approx 0.02 \ \mu \Omega \cdot cm$, which is consistent with the theoretical estimation of chiral-glass ordering.[7] Above $T_{c2}$, linear resistivity $\rho_0$ increases gradually and continuously with increasing temperature. As shown in Figure 6, the nonlinear resistivity $\rho_2$ decreases gradually around $T_{c2}$ as the temperature decreases, and is negligible at about $T_{c2}$. The behavior of $\rho_2$ differs from that shown by ac resistivity measurements, in which divergence of $\rho_2$ is concluded at $T_{c2}$.[6]

Kawamura studied the critical dynamic properties of the chiral-glass transition using Monte Carlo simulations.[9] He investigated the transport property of ceramic high-$T_c$ superconductors near the chiral-glass transition and suggested that the electric field $E$ is derived from the two near-independent sources: (1) the motion of the integer vortex lines, $E_z$; and (2) the motion of the chiral domain walls, $E_{\chi}$. Thus, the linear resistivity $\rho_0$ can be expressed as the sum of the two near-independent contributions $\rho_{0,v}$ and $\rho_{0,\chi}$. At and near the chiral-glass transition temperature, $\rho_{0,v}$ remains finite, while $\rho_{0,\chi} \approx 0$ below $T_{c2}$ and $\rho_{0,\chi} \approx c(\nu(T_{c2}))^{z-1} \approx 6.9$ is a large positive number, $\rho_{0,\chi}$ above $T_{c2}$ diminishes rapidly toward $T_{c2}$, and the behavior of $\rho_0$ is dominated by the term $\rho_{0,v}$. The theoretical analysis is consistent with the temperature dependency of the linear resistivity $\rho_0$ (Fig. 5). In addition, the nonlinear resistivity $\rho_2$ can be expressed as the sum of the two near-independent contributions $\rho_{2,v}$ and $\rho_{2,\chi}$. Near the chiral-glass transition temperature, $\rho_{2,v}$ is essentially a regular term, while $\rho_{2,\chi} \approx 0$ below $T_{c2}$ and $\rho_{2,\chi} \approx c^{1.5}(\nu(T_{c2}))^{2.5} \approx 0$ above

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**Figure 3.** Temperature dependency of linear resistance $R = V/I$ at $I = 0.5$ mA.

**Figure 4.** $E$-$J$ characteristics at different temperatures near $T_{c2}$. The dashed line represents the boundary separating the upper temperature from the lower temperature at $T_{c2}$.
Temperature dependency of the linear resistivity $\rho_0$. The ac nonlinear resistivity $\rho_2$ obtained by Yamao et al. [6] is consistent with the case of $z < 5$. For $z > 5$, with decreasing temperature, $\rho_2$ should diminish continuously approaching $T_{c2}$. The temperature dependency of the nonlinear resistivity $\rho_2$ is shown in Figure 6. The behavior of $\rho_2$ corresponds to the case of $z > 5$.

In conclusion, we measured the temperature dependency of the current-voltage characteristics of the sample and estimated the linear and nonlinear resistivities at temperatures close to $T_{c2}$. The linear resistivity $\rho_0$ remains finite below $T_{c2}$ and has the low value of $\approx 0.02$ $\mu\Omega \cdot \text{cm}$. The nonlinear resistivity $\rho_2$ diminishes continuously toward $T_{c2}$ with decreasing temperature. These experimental results are in good agreement with the theoretical analysis and suggest that chiral-glass ordering occurs at $T_{c2}$ in the ceramic YBa$_2$Cu$_4$O$_8$.

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