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Transport Properties of a Josephson-Coupled Network in a Superconductive Ceramic of $YBa_2Cu_4O_8$

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Abstract. Ceramic $YBa_2Cu_4O_8$ samples composed of sub-micron size grains are considered as random Josephson-coupled networks of 0 and π 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 $YBa_2Cu_4O_8$ and $YBa_2Cu_3O_{7-\delta}$ samples, which are composed of homogeneous sub-micron-size grains, may be regarded as random Josephson-coupled networks that contain so-called π junctions. The circulation of a local loop-supercurrent is generated spontaneously in a zero field when there is an odd number of π junctions in a closed loop that consists of some Josephson junctions. Theoretically, the frustration effect due to the random distribution of π junctions should lead to the chiral-glass state.[1] In experimental studies, ceramic $YBa_2Cu_4O_8$ and $YBa_2Cu_3O_{7-\delta}$ 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 $YBa_2Cu_4O_8$ and $YBa_2Cu_3O_{7-\delta}$ 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

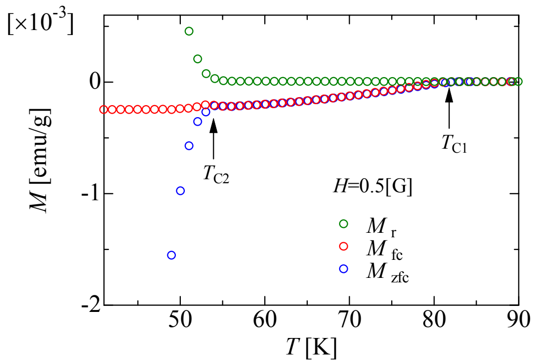

Figure 1. Temperature dependencies of zero-field-cooled magnetization (M_{zfc}), field-cooled-magnetization (M_{fc}), and thermoremanent magnetization (M_r).

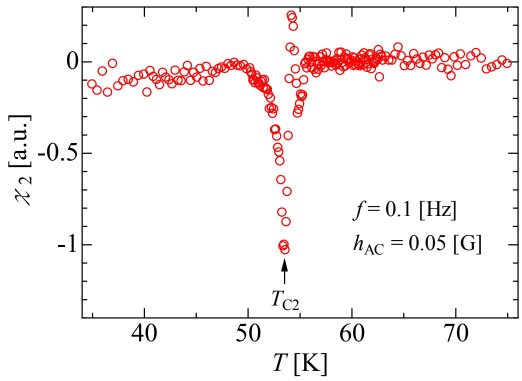

Figure 2. Temperature dependency of the nonlinear susceptibility χ_2.

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 $YBa_2Cu_4O_8$ 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 $YBa_2Cu_4O_8$ 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 µ-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 = 0.5G. The upper transition at T_{c1} = 83K 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} = 53.6K. 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} = 53.6K, at which temperature the ceramic $YBa_2Cu_4O_8$ 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.

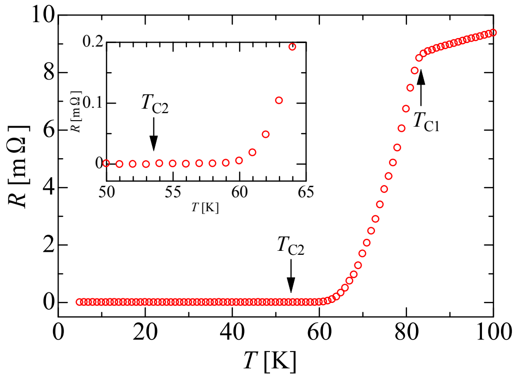

Figure 3. Temperature dependency of linear resistance $R = V/I$ at $I = 0.5$ mA.

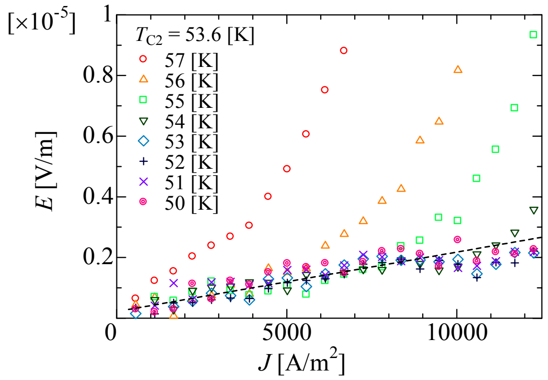

Figure 4. *E-J* characteristics at different temperatures near T_{c2}. The dashed line represents the boundary separating the upper temperature from the lower temperature at T_{c2}.

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 60 K.

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 ρ_0 and nonlinear resistivity ρ_2 are defined as the coefficients of the first and third power term of E (J), respectively, expanded in a power series of J.[6] Figure 5 and 6 show the temperature dependencies of the linear resistivity ρ_0 and nonlinear resistivity ρ_2 estimated from *E-J* curves around T_{c2}, respectively. In Figure 5, ρ_0 remains finite below T_{c2} and has the low value of ≈ 0.02 μΩ·cm, which is consistent with the theoretical estimation of chiral-glass ordering.[7] Above T_{c2}, linear resistivity ρ_0 increases gradually and continuously with increasing temperature. As shown in Figure 6, the nonlinear resistivity ρ_2 decreases gradually around T_{c2} as the temperature decreases, and is negligible at about T_{c2}. The behavior of ρ_2 differs from that shown by ac resistivity measurements, in which divergence of ρ_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_v; and (2) the motion of the chiral domain walls, E_κ. Thus, the linear resistivity ρ_0 can be expressed as the sum of the two near-independent contributions $\rho_{0,v}$ and $\rho_{0,\kappa}$. At and near the chiral-glass transition temperature, $\rho_{0,v}$ remains finite, while $\rho_{0,\kappa} \approx 0$ below T_{c2} and $\rho_{0,\kappa} \approx c'(T-T_{c2})^{(z-1)\nu}$ above T_{c2}. Since the dynamic chiral-glass exponent $(z\text{-}1)\nu \approx 6.9$ is a large positive number, $\rho_{0,\kappa}$ above T_{c2} diminishes rapidly toward T_{c2}, and the behavior of ρ_0 is dominated by the term $\rho_{0,v}$. The theoretical analysis is consistent with the temperature dependency of the linear resistivity ρ_0 (Fig. 5). In addition, the nonlinear resistivity ρ_2 can be expressed as the sum of the two near-independent contributions $\rho_{2,v}$ and $\rho_{2,\kappa}$. Near the chiral-glass transition temperature, $\rho_{2,v}$ is essentially a regular term, while $\rho_{2,\kappa} \approx 0$ below T_{c2} and $\rho_{0,\kappa} \approx c''(T-T_{c2})^{(z-5)\nu}$ above

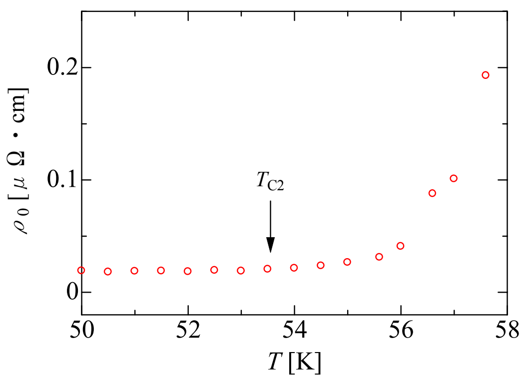

Figure 5. Temperature dependency of the linear resistivity ρ_0.

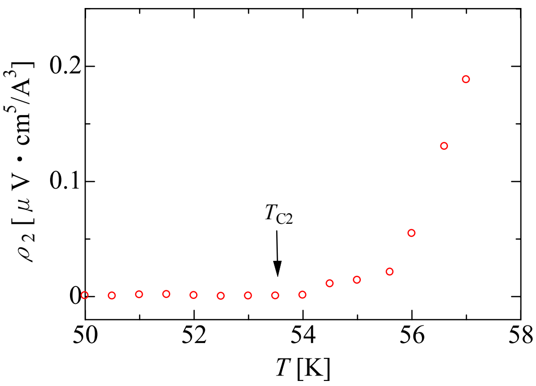

Figure 6. Temperature dependency of the nonlinear resistivity ρ_2.

T_{c2}. Thus, the nonlinear resistivity ρ_2 shows a greater anomaly than the linear resistivity ρ_0. If the chiral-glass exponent z is less than 5, the nonlinear resistivity ρ_2 exhibits positive divergence at T_{c2}. The ac nonlinear resistivity ρ_2 obtained by Yamao *et al.* [6] is consistent with the case of $z < 5$. For $z > 5$, with decreasing temperature, ρ_2 should diminish continuously approaching T_{c2}. The temperature dependency of the nonlinear resistivity ρ_2 is shown in Figure 6. The behavior of ρ_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 ρ_0 remains finite below T_{c2} and has the low value of $\approx 0.02\ \mu\ \Omega\cdot$cm. The nonlinear resistivity ρ_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 $YBa_2Cu_4O_8$.

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