Nonlinear resistivity in a \( d \)-wave superconductor \( \text{YBa}_2\text{Cu}_4\text{O}_8 \) of sub-micron scale grains

H Deguchi\(^1\), T Shoho\(^1\), Y Kato\(^1\), T Ashida\(^1\), M Mito\(^1\), S Takagi\(^1\), M Hagiwara\(^2\) and K Koyama\(^3\)

\(^1\) Faculty of Engineering, Kyushu Institute of Technology, Kitakyushu 804-8550, Japan
\(^2\) Faculty of Engineering and Design, Kyoto Institute of Technology, Kyoto 606-8585, Japan
\(^3\) Faculty of Integrated Arts and Science, The University of Tokushima 770-8502, Japan

E-mail: deguchi@tobata.isc.kyutech.ac.jp

Abstract. The \( d \)-wave ceramic \( \text{YBa}_2\text{Cu}_4\text{O}_8 \) superconductor composed of sub-micron size grains is considered as random Josephson-coupled network of 0 and \( \pi \) junctions and shows successive phase transitions. The upper transition occurs inside each grain at \( T_{c1}=82 \) K and the lower transition occurs among the grains at \( T_{c2}=66 \) K. We measured the temperature dependence of the current-voltage characteristics of the ceramic \( \text{YBa}_2\text{Cu}_4\text{O}_8 \) and derived the linear and nonlinear resistivity. The nonlinear resistivity \( \rho_2 \) and \( \rho_4 \) have finite values between \( T_{c1} \) and \( T_{c2} \) and have the peak at the same temperature \( T_p=70 \) K above \( T_{c2} \). The result agrees with the theoretical one obtained by Li and Domínguez. They interpreted \( T_p \) as the crossover temperature from the normal state phase to a chiral paramagnetic one.

1. Introduction

Ceramic high-\( T_c \) superconductors, depending on the relative orientation of the \( d \)-wave superconductor 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. The frustration effect due to the random distribution of \( \pi \) junctions should lead to a novel glass state. Kawamura and Li investigated the novel glass phase of ceramic high-\( T_c \) superconductors using Monte Carlo simulations.[1] They proposed that the chiral glass phase characterized by a broken time-reversal symmetry may occur in zero external magnetic field. Evidence for the transition to chiral glass has been seen from experimental studies of nonlinear ac magnetic susceptibility, dynamic scaling analysis and of ac resistivity in the \( d \)-wave ceramic \( \text{YBa}_2\text{Cu}_4\text{O}_8 \) and \( \text{YBa}_2\text{Cu}_3\text{O}_{7-\delta} \) superconductors.[2-6] The two ceramic samples are weak-link coupled systems and show successive phase transitions. 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 appears at below \( T_{c2} \), and negative divergence of nonlinear susceptibility is observed at
Figure 1. Temperature dependence of zero-field-cooled magnetization ($M_{zfc}$), field-cooled-magnetization ($M_{fcc}$), and thermoremanent magnetization ($M_r$).

Figure 2. Temperature dependence of the nonlinear susceptibility.

$T_{c2}$, which reflect a chiral-glass transition.

Yamao et al. [7] measured the ac linear resistivity $\rho_0$ and nonlinear resistivity $\rho_2$ of the ceramic YBa$_2$Cu$_4$O$_8$. Since $\rho_0$ does not vanish at the peak position of $\rho_2$, they identify the transition at the peak position of $\rho_2$ as a transition to the chiral-glass phase. Li and Dominguez [8] calculated the linear and nonlinear resistivity by a Langevin dynamics simulation. They found that $\rho_2$ has a peak at $T_p$ above $T_{c2}$ and interpreted $T_p$ as the crossover temperature from the normal-state phase to a chiral paramagnet. In order to probe the existence of the crossover point $T_p$ and chiral glass transition $T_{c2}$ we have measured the current-voltage characteristics of the ceramic YBa$_2$Cu$_4$O$_8$ composed of sub-micron size grains and derived the linear and nonlinear resistivity with magnetic measurements.

2. Experimental
The sample was prepared using the citrate pyrolysis method.[9] The precursor was calcined for 140 h at 777 °C to yield the pure YBa$_2$Cu$_4$O$_8$ phase, which was sieved and pressed, and then sintered for 100 h at 778 °C, to become a pure YBa$_2$Cu$_4$O$_8$ ceramic of sub-micron size grains. 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 $E$-$J$ characteristics were measured by low-level pulsed electrical characterization with a current source (KEITHLEY 6221) and nanovoltmeter (KEITHLEY 2182A) combination.[6] 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
The temperature dependence of the dc magnetization and ac susceptibility were measured in order to determine the transition temperature $T_{c1}$ and $T_{c2}$. Figure 1 shows the temperature dependence of the zero-field-cooled, field-cooled, and thermoremanent magnetizations at $H = 0.1$ G. The upper transition at $T_{c1} = 82$ K was identified as the intragrain superconducting ordering, in which small diamagnetism due to the Meissner effect appears in zero-field-cooled and field-cooled-magnetizations. The irreversibility point in zero-field-cooled and field-cooled magnetizations occurs and the thermoremanent magnetization appears at temperatures lower than $T_{c2} = 66$ K. The nonlinear susceptibility estimated from the first term of the series of in-phase odd-harmonic responses in the frequency of 1 Hz with ac field amplitude of 0.1 G is shown in Figure 2. Negative divergence of
nonlinear susceptibility was observed at \( T_{c2} = 66 \) K, at which temperature the ceramic YBa\(_2\)Cu\(_4\)O\(_8\) underwent a chiral-glass transition. In order to investigate the transport property of the ceramic YBa\(_2\)Cu\(_4\)O\(_8\), we measured the \( E-J \) curves with zero-magnetic field in the temperature range between 5 and 90 K. Figure 3 shows the \( E-J \) curves near the chiral-glass transition temperature \( T_{c2} \). Below \( T_{c2} \), \( E \) increased almost linearly with \( J \). 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 \( \rho_2, \rho_4 \) are defined as the coefficients of the first, third and fifth power term of \( E(J) \) expanded in a power series of \( J \). Figure 4 shows the temperature dependence of the linear resistivity \( \rho_0 \) estimated from \( E-J \) curves. As the temperature was reduced, \( \rho_0 \) decreased rapidly at about \( T_{c1} = 82 \) K, and then decreased monotonously and almost disappears around a temperature of 70K. Below \( T_{c2}=66 \) K, \( \rho_0 \) remains finite and has the low value of about 0.01 \( \mu\Omega \cdot \text{cm} \), which is consistent with the theoretical estimation of chiral-glass ordering [10] and the experimental results.[6,7]

Figures 5 and 6 show the temperature dependence of the nonlinear resistivity \( \rho_2 \) and \( \rho_4 \) estimated from \( E-J \) curves, respectively. As shown in Fig.5, \( \rho_2 \) has a positive peak at \( T = 70 \) K, at which temperature the chiral-glass transition does not occur, and diminishes continuously toward \( T_{c2} \) with decreasing temperature. The behavior of \( \rho_2 \) differs from that obtained by Yamao et al.[7] The peak position of \( \rho_2 \) is concluded at \( T_{c2} \) by Yamao et al. but does not agree with \( T_{c2} \) in our result. \( T_{c2} \) is estimated by both the irreversibility point in the dc magnetization and the divergence point of nonlinear susceptibility in our study, however, Yamao et al. obtained \( T_{c2} \) by only the irreversibility point in the dc magnetization. Therefore, we confirm that the peak position of \( \rho_2 \) is higher than \( T_{c2} \). Kawamura studied the critical dynamic properties of the chiral-glass transition using Monte Carlo simulations.[11] He investigated transport property of ceramic high-\( T_c \) superconductors near the chiral-glass transition. The temperature dependence of \( \rho_2 \) in our experiment corresponds to the theoretical prediction by Kawamura with the case of the chiral-glass exponent \( z > 5 \).

The nonlinear resistivity \( \rho_4 \) has the finite value between \( T_{c2} \) and \( T_{c1} \) and has a negative peak at the same temperature \( T = 70 \) K as that for \( \rho_2 \). Thus, the nonlinear resistivity \( \rho_2 \) and \( \rho_4 \) show a great anomaly at \( T = 70 \) K above \( T_{c2} \). Li and Dominguez obtained theoretically \( \rho_2 \) of \( d \)-wave ceramic superconductor by solving the corresponding Langevin dynamical equations.[8] They found that \( \rho_2 \) has a peak at \( T_p \) above the chiral-glass transition temperature and interpreted \( T_p \) as the crossover temperature from the normal-state phase to a chiral paramagnet. They conclude that peak of \( \rho_2 \) has no
relation to the chiral-glass phase transition. Thus, \( T_p \) just separates the normal-sate phase from a chiral paramagnet where there are local chiral magnetic moments. At a lower temperature, collective phenomena due to the interactions among the chiral moments will start to be important, leading to the transition to the chiral-glass state. Similar theoretical results for nonlinear resistivity in \( d \)-wave granular superconductors obtained by Li et al.\cite{12}

Therefore, the temperature \( T = 70 \) K of the peak corresponds to the crossover temperature \( T_p \).

In conclusion, our experimental results for the linear and nonlinear resistivity are consistent with those of theoretical studies by Kawamura \cite{11} and Li et al.\cite{8,12} The linear resistivity \( \rho_0 \) remained at a finite value at temperature less than the chiral-glass transition \( T_{c2} \). The nonlinear resistivity \( \rho_2 \) and \( \rho_4 \) show a great anomaly at \( T_p = 70 \) K above \( T_{c2} \). The temperature \( T_p \) does not correspond to the chiral-glass transition but corresponds to the onset of the chiral paramagnet.

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![Figure 5](image5.png) **Figure 5.** Temperature dependence of the nonlinear resistivity \( \rho_2 \).

![Figure 6](image6.png) **Figure 6.** Temperature dependence of the nonlinear resistivity \( \rho_4 \).