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Dependence of memory effects on the stop temperature and the probing field in a ceramic YBCO superconductor

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Abstract

The magnetic memory phenomena in a ceramic YBCO superconductor are studied by zero-field-cooled and thermoremanent magnetization after specific cooling protocols. The ceramic YBCO is considered as random Josephson-coupled networks of 0 and π junctions and shows successive phase transitions. The magnetic glass behavior, similar to those of spin-glasses, is observed below the lower transition temperature. The memory effect occurs strongly in an intermediate stop temperature and suppressed with an increased probing field. The results can be understood by the screening effect of the ceramic superconductor with a finite self-inductance.

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Keywords: memory effect; ceramic YBa₂Cu₄O₈; chiral glass; random Josephson-coupled network; *d*-wave superconductivity

1. Introduction

The ceramic YBa₂Cu₄O₈ composed of sub-micron size grains is considered to be made up of random Josephson-coupled networks of 0 and π junctions, and shows successive phase transitions under zero and weak fields. Theoretically, the frustration effect, due to the random distribution of π junctions, should lead to a chiral-glass state, as predicted by Kawamura and Li [1]. In ceramics, the first transition occurs inside each grain at T_{c1} and the second transition occurs in 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. Extensive measurements of the magnetic and transport properties in YBa₂Cu₄O₈ and YBa₂Cu₃O_{7- δ} ceramics have been performed, and the results are consistent with the chiral-glass picture [2,3]. Moreover, the magnetic memory phenomena, which were familiar in the field of spin glasses [4, 5], have been observed in YBa₂Cu₄O₈ ceramics [6] and Bi₂Sr₂CaCu₂O₈ samples [7-9].

The origin of such memory phenomena relates to the rugged energy landscape which appears due to disorder and frustration [10]. At high fields or high temperatures the roughness of the energy landscape does not play any crucial role and the system loses its memory. At low temperatures the role of the energy landscape becomes important in the spin glass system. However, in the case of ceramic superconductors at low temperatures, the external field is screened from the sample with a finite self-inductance of the Josephson junction network and it cannot probe the glass behavior such a memory effect [11]. In the present work, we investigated the stop temperature and the probing field dependence of the memory effects in order to clarify the off-equilibrium dynamics of the glass phase and the effect of screening of the magnetic field on the energy landscape.

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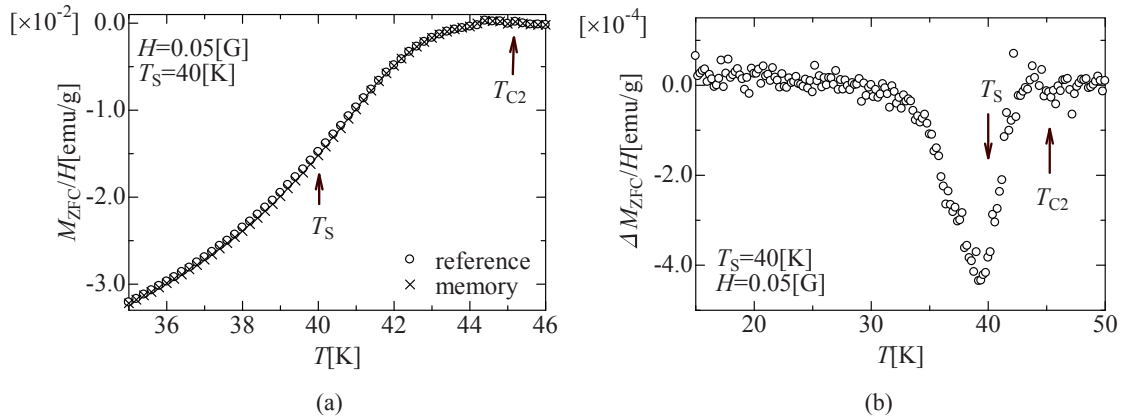


Fig. 1. (a) Temperature dependence of the ZFC magnetizations recorded on re-heating after direct cooling (reference) and a temperature stop of $t_w = 10000$ s at $T_s = 40$ K (memory); $H = 0.05$ G. (b) Difference plots of $\Delta M/H$ for the two magnetizations shown in Fig. 1 (a).

2. Sample and experiments

The sample was prepared using a citrate pyrolysis method [12]. The precursor was calcined for 140 h at 777 °C to yield a pure $\text{YBa}_2\text{Cu}_4\text{O}_8$ phase. This yield was sieved and pressed then sintered for 100 h at 778 °C. From SEM observation, the grain size has been estimated to be 200-500 nm. The magnetization was measured with a SQUID magnetometer (Quantum Design MPMS-5) with an ultra- low-field option.

The memory effects were observed in zero-field-cooled (ZFC) and thermoremanent (TR) magnetization. Temperature dependence was measured upon heating after the cooling process, with or without a stop (for a certain time t_w), at the stop temperature T_s below T_{c2} . For example, the effect of the ZFC magnetization has been measured as follows: First, we performed the reference experiment, where the sample is rapidly cooled in zero field from 90 K above T_{c1} to 30 K below T_{c2} , with a cooling rate of 3.5 K/min. Next, the ZFC magnetization is recorded during the reheating process at the constant rate of 0.14 K/min with a finite applied field. Finally, the specific cooling protocol was performed as follows: The sample was rapidly cooled with a cooling rate of 3.5 K/min under zero applied field from 90 K down to a temperature T_s below T_{c2} , at which a stop was made for the wait time, t_w . The cooling was then resumed down to 30 K with cooling rate of 3.5 K/min, and a weak magnetic field was applied. The ZFC magnetization was then recorded during the slow heating process with a heating rate of 0.14 K/min. A similar experimental process was adopted in the case of TR magnetization.

3. Results

We measured the temperature dependence of the dc magnetization and ac susceptibility, to determine the transition temperatures T_{c1} and T_{c2} . The upper transition at $T_{c1} = 82$ K was identified as the inter-grain superconducting ordering, at which temperature the small diamagnetism due to the Meissner effect appears in ZFC and field cooled (FC) magnetizations. The TR magnetization and the discrepancy between the FC and ZFC magnetizations appear at around 45 K. Negative divergence of nonlinear susceptibility was observed at $T_{c2} = 45.1$ K, at which temperature the ceramic $\text{YBa}_2\text{Cu}_4\text{O}_8$ underwent a glass transition [13].

Magnetic memory experiments have been performed using the temperature dependence of ZFC and TR magnetization [6]. First, we measured ZFC and TR magnetization with the fixed wait time of $t_w = 10000$ s, and with the fixed probing field of $H = 0.05$ G, and a stop temperature of $T_s = 40$ K. Figure 1(a) and Figure 2(a) show the results of the ZFC and TR magnetization recorded upon re-heating after direct cooling (reference) with a temperature stop of $t_w = 10000$ s at $T_s = 40$ K (memory). The ZFC plots with the stop around T_s lie slightly below the reference data measured with the same cooling and heating rates. The TR data with the stop around T_s lie slightly above the reference data. Figure 1(b) and Fig. 2(b) show the difference, $\Delta M/H = M/H$ (reference) - M/H (memory), in Fig. 1(a) and

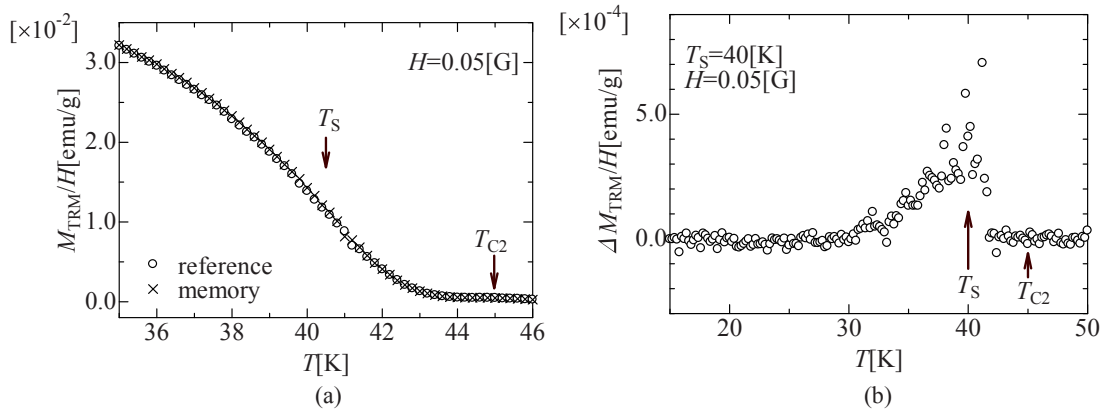


Fig. 2. (a) Temperature dependence of the TR magnetizations recorded on re-heating after direct cooling (reference) and a temperature stop of $t_w = 10000$ s at $T_s = 40$ K (memory); $H = 0.05$ G. (b) Difference plots of $\Delta M/H$ for the two magnetizations in Fig. 2 (a).

Fig. 2(a), respectively. In the case of both ZFC and TR, the influence of the stop is confined to a narrow temperature region near T_s , for the case of $T_s = 40$ K. The maximum of $|\Delta M/H|$ is small in magnitude (about 3 % of M/H), but well defined. The memory effects of the stop in the cooling process are observed in the magnetization during the re-heating process. When cooling from above T_{c2} , the stop at T_s below T_{c2} is made during the time t_w , allowing the system to relax towards its equilibrium state at T_s . The equilibrium state becomes frozen in for further cooling down to the lowest temperature, and is retrieved on re-heating.

Next, we investigated the stop temperature dependence of the memory effects in the case of ZFC and TR magnetization. We measured ZFC and TR magnetization with a fixed wait time of $t_w = 10000$ s, and with the fixed probing field of $H = 0.05$ G, for four stop temperatures: $T_s = 30, 35, 40$ and 43 K. Figure 3 (a) shows the difference in $\Delta M/H$ for the case of ZFC magnetization. The difference plots of $\Delta M/H$ show a maximum around each T_s , however, the influence becomes broader and smaller in the case of $T_s = 35$ and 30 K. The maximum of $\Delta M/H$ in the case of $T_s = 40$ K, an intermediate T_s , is the largest of the four experiments. Similar stop temperature dependence of the memory effects was obtained for TR magnetization.

We also studied the probing field dependence of the memory effects. We have studied ZFC and TR experiments with a fixed wait time of $t_w = 10000$ s and with a fixed stop temperature of $T_s = 40$ K for three probing field strengths $H = 0.05, 0.10, 0.50$ G. Figure 3 (b) shows the difference in $\Delta M/H$ for the case of ZFC magnetization. The temperatures of the peaks in $\Delta M/H$ are almost the same for $T_s = 40$ K in the three cases. However, the peak of $\Delta M/H$ becomes smaller and broader with increasing field strength. Similar probing field dependence of the memory effect was also obtained for TR experiments.

4. Discussion and conclusions

The memory effect is present strongly in an intermediate temperature $T_s = 40$ K below T_{c2} and becomes broader and smaller in the cases of low temperature T_s . Also, it gets suppressed as the field increases. Similar dependences on temperature and field were observed in the aging effect in the ceramic superconductor $\text{Bi}_2\text{Sr}_2\text{CaCuO}_8$ [14]. Such as memory and aging are nonequilibrium phenomena and the origin relates to the rugged energy landscape which appears due to disorder and frustration. Jonason *et al.* [5] investigated memory effects in the $\text{CdCr}_{1.7}\text{In}_{0.3}\text{S}_4$ insulating spin glass with the glass temperature $T_g = 16.7$ K. The effect for $T_s = 9$ K is strong as well as that for $T_s = 12$ K, and does not depend on the stop temperatures. In the ceramic superconductors, the screening effect is taken into account on the off-equilibrium dynamical properties such as memory effect. The screening makes the energy landscape less rough and the external magnetic field is screened from the bulk [11].

We have studied the dependence of the memory effect on the stop temperature and the probing field in the ceramic YBCO superconductor. Our results suggest that screening effect has a strong influence on the off-equilibrium dynamical properties of the glass phase in the ceramic superconductor.

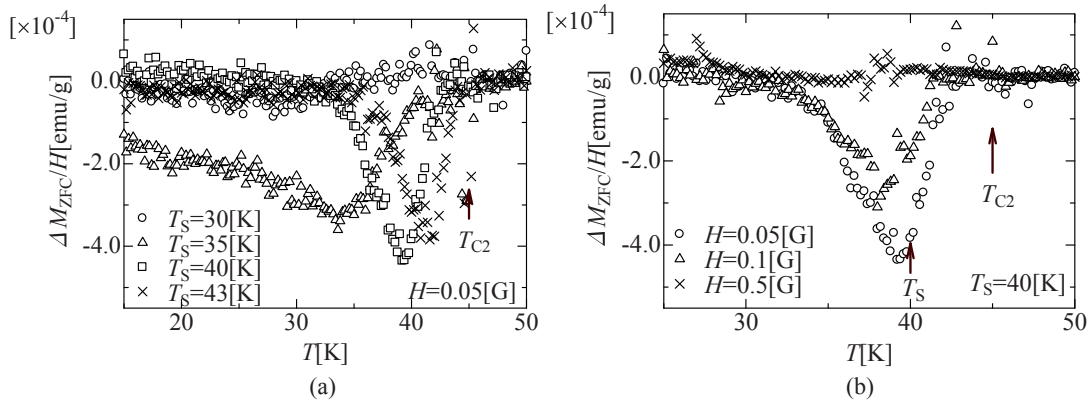


Fig. 3. (a) Difference plots of $\Delta M/H$ for ZFC magnetizations corresponding to a stop of 10000 s at $T_s = 30, 35, 40$ and 43 K; $H = 0.05$ G. (b) Difference plots of $\Delta M/H$ for ZFC magnetizations corresponding to a stop of 10000 s at $T_s = 40$ K for different probing field strengths; $H = 0.05, 0.10$ and 0.50 G.

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