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Irradiation effect on the pinning potential of YBCO single crystal

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ABSTRACT

The results of the magnetization measurements of single crystal of $YBa_2Cu_3O_y$ with Tc = 91 K are adduced. The temperature, field and time dependencies of the remnant magnetization $M_r(T, B, t)$ were obtained using VSM method for the temperature range from 4.2 K to 75 K for H||c configuration. The single crystal has been irradiated by the fast electrons (E = 4 MeV) with fluences up to $2 \cdot 10^{18}$ cm^{-2}. The relaxation of $M_r(t)$ obeys to the logarithmic law for the time interval t = 1 h for whole temperature range except the ~ 30 – 50 K interval for starting and irradiated states. After irradiation the J_c decrease despite the flux creep reduction. The irradiation become less effective at high temperatures. The results are discussed in frame of conventional flux creep theory and of the interaction model of radiation defects with the background ones.

Keywords: the high-T_c superconductivity, $YBa_2Cu_3O_y$ single crystal, the magnetization relaxation, the pinning potential, irradiation.

1. INTRODUCTION

The introduction of radiation defects has proved to be a very useful method changing of the critical current density J_c in high-T_c superconductors. Besides J_c, the flux creep in high-T_c superconducting materials is very important with respect to potential applications. It is known that these superconductors are characterized by rather weak flux pinning by lattice defects and, ergo, by the strong relaxation rate of remnant magnetization even at low temperatures due to the flux motion across low energy pinning barrier U_{eff}. To use irradiation experiments permit to introduce the defects in a controlled manner. In our earlier work[1] we studied the isothermal magnetization at different temperatures in $YBa_2Cu_3O_y$ single crystal including the irradiated state. It was shown that at the temperatures above ~ 20 K the single crystal displayed nonmonotonous change of the difference $\Delta M(B)$ between rising and decreasing magnetization values in an external magnetic field. This so-called fishtail effect disappears at temperatures above ~ 70 K. The origin of this phenomenon is not yet clear[2] (and also the references therein). The investigation on the flux creep process, no doubt, can be complete our understanding of such anomalous behavior of $YBa_2Cu_3O_y$ single crystal. The purpose of the present work is determine the relaxation rate of the magnetization and, ergo, the pinning potential U_{eff} in $YBa_2Cu_3O_y$ single crystal in a wide temperature region before and after irradiation.

2. EXPERIMENTAL

The single crystal of $YBa_2Cu_3O_y$ was grown from flux melt.[3] The value of T_c is equal to 91 K and ΔT_c ~ 1 K determined from ac magnetic susceptibility at ZFC with B = 5 G. Magnetic hysteresis loops were obtained using automated vibrational magnetometer at external magnetic fields up to 6 T over temperature range from 4.2 K to ~ 75 K. All measurements have been performed with the magnetic field oriented parallel to c-axis to avoid the strong intrinsic flux pinning existing for the experimental geometry when the magnetic field is parallel CuO layers (H⊥c) as was shown by us for thick films of $YBa_2Cu_3O_y$.[4] For each measurement run the crystal was heated to ≈ 100 K, and prior to cooling was held in zero field. for some minutes. The magnetic field was increased up to the necessary value, then the field was switched on and the relaxation of remnant magnetization $M_r(t)$ has been recorded for t ≈ 1 h after the field reached zero. The time dependence of remnant magnetization was analyzed according to next relation[5]:

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$$dM/d\ln t = -kT/(M_r U_{eff}), \quad (1)$$

where U_{eff} is the activation energy of the flux creep or the pinning potential, which can be found from the slopes of curves M/M_r versus lnt.

Then the single crystal was irradiated by the fast electrons with energy 4 MeV and fluences up to $\sim 2 \cdot 10^{18}$ cm^{-2} at room temperature; afterwards, the hysteresis loops and magnetization decay under irradiation were re-measured.

3. RESULTS AND DISCUSSION

Since the width of the magnetization curve is proportional to the critical current density J_c (Bean model), this quantity was calculated using the standard expression $J_c = 30\ \Delta M/d$, where d is the average width size of sample. The J_c values are $\sim 10^6$ A $\cdot$ cm^{-2} at 4.2 K for B = 0.5 T. With rising magnetic field J_c monotonously decreases and J_c (4.2 K, 5 T) amounts to $3 \cdot 10^5$ A $\cdot$ cm^{-2}. But at higher temperatures (≥20 K) the pronounced additional peak H_p appears in the high field range and J_c (70 K) value, for example, at 1.5 T is three times larger than that at ~ 0.5 T. The values of J_c at fixed temperatures (20 ÷ 70 K) reach to maximum at Hp = 4 ÷ 1.5 T.

As already known[5], the remnant magnetization value M_r, obtained in the limiting hysteresis loop regime in accordance with Bean model, is proportional to the critical current density in the sample. If the temperature dependence $M_r(T)$ is determined by the flux creep, the value of $M_r(T)$ decreases linearly as the temperature rises:

$$M_r(T)/M_r(0) \approx J_c/J_0 \approx 1 - (T/U_{eff})\ln(t/\tau), \quad (2)$$

where t is the time of the first measurement, τ is a microscopic attempt time of order 10^{-6} to 10^{-12} s.[6]

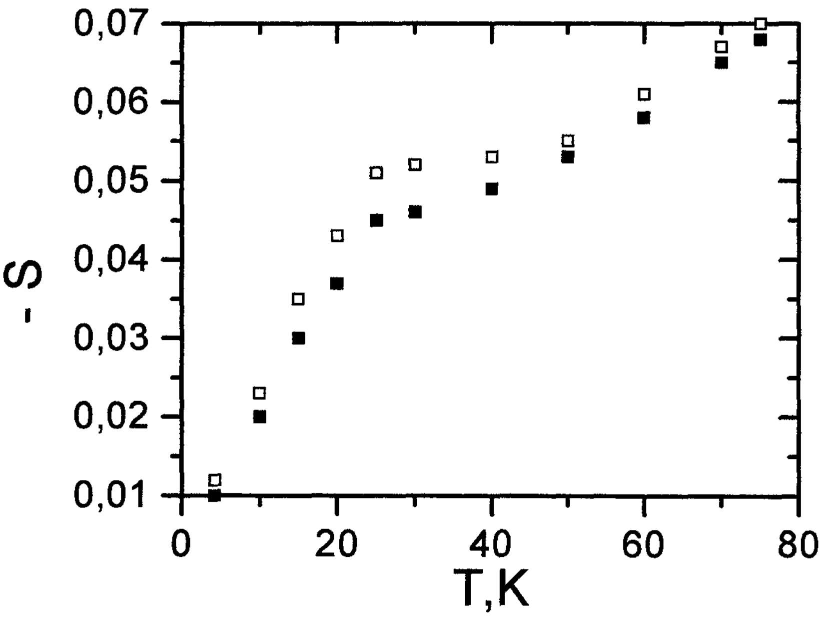

Fig. 1. The temperature dependence of the normalized magnetization relaxation rate for $YBa_2Cu_3O_y$ single crystal in starting (light symbols) and irradiated (dark symbols) states.

At low temperatures the magnetization was found to relax logarithmically with time (for t ≥ 10 s), indicating that the sample was in critical state. The normalized magnetization relaxation rate $S = (1/M_0)dM(t)/d\ln t \equiv T/U_{eff}$, where M_0 is the initial magnetization, is very important characteristic describing the creep process in high-T_c superconductors. Fig. 1 (light symbols) shows the temperature dependence for the normalized magnetization relaxation rate (–S) in single crystal before irradiation. The values of (–S) equal to ~ 0.012 at 4.2 K starts increasing with the temperature and reach ~ 0.051 at 25K, but the M(t) decay in time deviates from logarithmic law on the some plateau of –S(T) dependence at ~ 30K - 45 K, where the nearly constant value of (–S) is kept. The increasing of the relaxation rate is observed again at higher temperatures (fig. 1, light symbols). It is worth to note that nearly at such temperatures we have found an anomalous increase of hysteresis loops with field.[1]

The value of magnetization decay can be calculated from[5]:

$$S = (1/M)(dM/d\ln t)\,|_t = -1/[(U_{eff}/kT) - \ln(t/\tau)]. \qquad (3)$$

Assuming t = 60 s we found $-1/S + 18 \le U_{eff}/kT \le -1/S + 32$ depending on the choice of τ. The values of –S for $YBa_2Cu_3O_y$ single crystal are small, and $U_{eff}(T)$, ergo, is slightly depend of the choice of τ, at least, for low temperatures.

The Fig. 2 (light symbols) shows a temperature dependence of $U_{eff}(T)$ in starting state. As seen from our data, the U_{eff} barrier equal to ~ 30 meV at 4.2 K reaches to ~ 90 meV at 75 K.

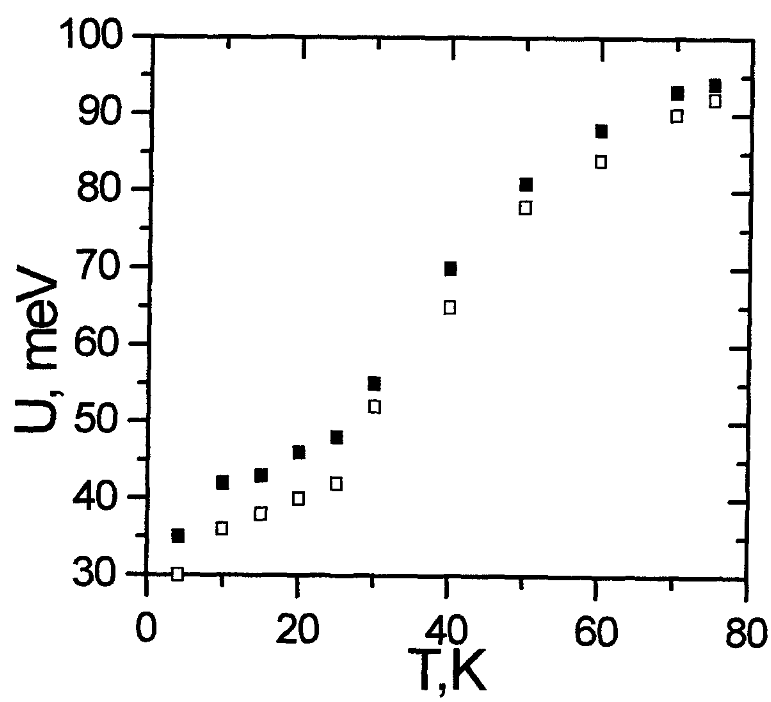

Fig. 2. The temperature dependence of the pinning potential for $YBa_2Cu_3O_y$ single crystal in starting (light symbols) and irradiated (dark symbols) states.

After electron irradiation with fluences up to ~ $2 \cdot 10^{18}$ cm^{-2} the critical temperature of the sample has decreased by ~ 1 K. This T_c deterioration is attributed mainly to displacement in the oxygen sublattice[1, 4]. The J_c decrease was observed in irradiated sample and J_c (4.2 K, 0.5 T) become $8 \cdot 10^5$ A $\cdot$ cm^{-2}. After irradiation the fishtail features display less noticeable (for the same temperature interval above ~ 20 K), at the time no fishtail was observed at low temperatures. Remarkably that in irradiated single crystal the reduction of the flux creep was observed in spite of a J_c decrease (Fig. 1, dark symbols). The flux creep rate is reduced at any temperature up to ~ 75 K, but this reduction of (–S) is more effective at temperatures below

~ 30 K than at higher temperatures. Correspondingly, the activation energy U_{eff} increases after irradiation, especially at low temperatures, and the values of U_{eff} enhance up to ~ 35 meV at 4.2 K and ~ 93 meV at 70 K (Fig. 2, dark symbols).

In work[2] it was proposed that the anomalous magnetization behavior in high-T_c superconductor $YBa_2Cu_3O_y$ was resulted from the existence of two kinds of pinning centers with different T_c. The fishtail effect can be due to the flux pinning by the ordered oxygen-deficient domains in the sample with T_c and H_{c2} lower than the matrix. When the field and temperature pass over the critical parameters of such domain, the superconducting domain becomes normal and it pinning forces (and ergo J_c) rise with field. At higher fields the J_c values decrease because of the possible weakening of the pinning forces with rising field. But besides this „static" origin there is a „dynamic" cause[5] of fishtail effect connected with change of the magnetization relaxation rate. Note that the fishtail effect in $YBa_2Cu_3O_y$ single crystal starts at temperatures ≥25 K when the „plateau" of the magnetization relaxation rate is displayed.

As seen from present study, after irradiation the J_c decrease in the sample is combined with the noticeable reduction of flux creep (especially at low temperatures). In other words, corresponding enhancement of the pinning potential in irradiated state (fig. 2) can not be absolute cause of the J_c rise. It should be mention the obtained values of the pinning potentials consist of the certain pinning potentials connected with the different sorts of pinning centers, therefore there is the effective pinning potential. The increase of J_c might be due to rise of the number pinning centers or to arise of the new pinning centers with not certainly deep potential barriers. In works[7, 8], for example, obtained results for $YBa_2Cu_3O_y$ single crystals and epitaxial films after neutron irradiation were explained within the conventional flux creep theory,[5] namely, $J_c \sim U/(N \cdot l \cdot b)$, where N is the number of vortices in a flux bundle, b and U are the main width and depth of potential, respectively, and l is the average distance between pinning sites. The decrease of J_c in $YBa_2Cu_3O_y$ single crystal along with the reduction of flux creep rate observed by us after electron irradiation may be attributed to the possible increase of b as was shown in [8] for neutron irradiated $YBa_2Cu_3O_y$ single crystal. The increase of U_{eff} after irradiation can be due to introduce more strong pinning centers than the background defects which are already effective before the irradiation. The weakening of the fishtail effect in irradiated state as compared to the initial state is assumed to be connected with defects including oxygen vacancies with vortices at the boundaries of two phases.[1]

4. CONCLUSION

The measurements of remnant magnetization relaxation in single crystal of $YBa_2Cu_3O_y$ with T_c = 91 K have been performed at 4.2 – 75 K. The M_r decay is found to decrease logarithmically with time except of the domain 30 ÷ 45 K. After irradiation by fast electrons with E = 4 MeV with fluences up to $2 \cdot 10^{18}$ cm^{-2} the relaxation rate reduced in spite of J_c decrease. The results can be explained in terms of the flux creep theory with taking into account the interaction radiation defects and background ones.

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