Critical current density and flux pinning dominated by neutron irradiation induced defects in $YBa_2Cu_3O_{7-x}$

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The functional dependence of critical current density (J_c) upon defect density is studied with neutron irradiation of $YBa_2Cu_3O_{7-x}$. Identical polycrystalline samples of $YBa_2Cu_3O_{7-x}$ have been irradiated with fast neutrons ($E > 0.1$ MeV) in eight steps between 0 and 2.1×10^{18} n/cm^2. Critical current densities are obtained from magnetic hysteresis measurements and correlated with defect density measurements obtained from transmission electron microscopy. We observe that despite the existence of a significant degree of hysteresis in the as grown material the hysteretic J_c in the irradiated samples appears to be dominated by a power law dependence on neutron fluence with an exponent of approximately 1/3 over a wide range of temperature, field and fluence.

I. INTRODUCTION

One of the most important issues pertinent to high temperature superconductors concerns the development of a fundamental understanding of the way in which defect pinning occurs and may be altered so as to produce high J_c materials at high temperatures. The study of flux vortices and critical currents in type II superconductors is in many respects a mature field with an extensive history of research[1] prior to the discovery of superconductivity above 30 K in La–Ba–Cu–O.[2] The question is how do concepts developed to explain the behavior of flux vortices in type II materials whose critical temperatures (T_c) are lower than 30 K extrapolate for the newer materials whose large anisotropies, short coherence lengths and higher critical temperatures change the directionality, size scale, and energy scale, respectively, associated with their electromagnetic properties.

Earlier experimental work indicated that defects introduced by neutron irradiation in single-crystal[3,4] and polycrystalline[5–7] $YBa_2Cu_3O_{7-x}$ were effective in increasing the hysteretically measured J_c while reducing J_c anisotropy and transition temperatures. More recent work on polycrystalline samples has shown several additional effects of neutron irradiation upon the electromagnetic properties of high temperature superconductors including the absence of saturation of magnetic hysteresis (J_c) at 5 K for fluences up to 2.1×10^{18} n/cm^2, whereas J_c is shown to saturate for a fluence of approximately 0.79×10^{18} n/cm^2 at 60 K and is nearly saturated at 0.44×10^{18} n/cm^2 at 77 K.[8] Additional novel features observed in this work are dramatic changes in the shape of magnetic hysteresis loops after irradiation including the evolution of pinning as defects are introduced into a sample which has a nearly ideal reversible type II magnetic behavior at 77 K prior to irradiation and the suppression of peak effects which have been attributed to oxygen inhomogeneity in unirradiated samples.[9] The temperature dependence of J_c has been measured and described using volume pinning force[10] and effective activation energy $U_{\rm eff}(B,J,T)$[8,11] points of view. Recent microstructural studies on irradiated versus unirradiated samples[5,12] have confirmed expectations that defects introduced by such radiation damage are homogeneously distributed and of a size comparable to the coherence length (defected regions 2–7 nm in size). In this paper we discuss the fluence dependence of J_c for polycrystalline $YBa_2Cu_3O_{7-x}$.

II. EXPERIMENT

Polycrystalline samples of $YBa_2Cu_3O_{7-x}$ were produced following the procedure detailed in Ref. 5. Optical microscopy indicates an average grain size of approximately 10 μm for this material. The samples were determined to have nearly identical T_c's and hysteresis curves prior to irradiation. Subsequent irradiation was performed on eight samples yielding a set with fast neutron ($E > 0.1$ MeV) fluences of 0, 0.06, 0.24, 0.44, 0.79, 1.3, 1.9, and 2.1×10^{18} n/cm^2, respectively (including the unirradiated sample). Neutron irradiation was performed isothermally (80 °C) at the Los Alamos National Laboratory Omega West reactor.[5] Magnetic measurements were made either using a PAR vibrating sample magnetometer or a Quantum Design superconducting quantum interference device (SQUID) magnetometer equipped with 9 and 5 T superconducting solenoids, respectively.

Hysteresis curves were obtained for field ramp rates of approximately 6 kOe/min. The temperature dependence of magnetization was measured by first expelling trapped flux from the solenoid by oscillating demagnetization at a temperature above T_c for the sample, cooling the sample in zero field, applying field and measuring the moment of the sample as temperature was increased above T_c and then cooled back to 5 K. At least a 5 min equilibration time was used between measurements for temperature dependence studies. All samples examined in this work had been allowed radioactive decay for several weeks prior

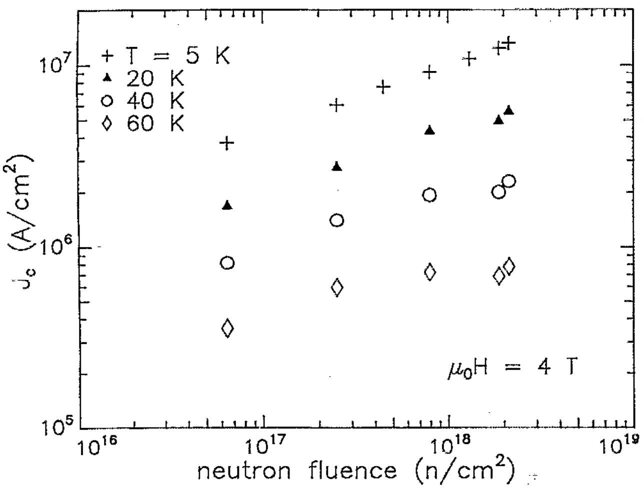

FIG. 1. Plots of hysteretically measured J_c vs fluence for temperatures from 5–60 K in an applied field of 4 T showing a fairly consistent 1/3 power law in this regime.

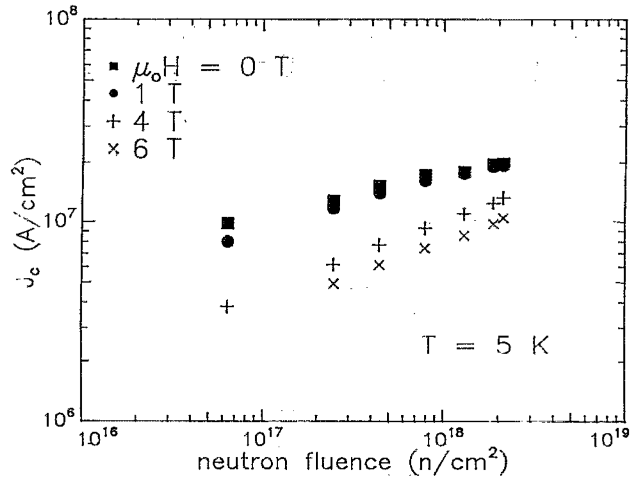

FIG. 2. Plots of hysteretically measured J_c vs fluence for fields from 0–6 T at a temperature of 5 K showing power law dependences with a range of exponent (0.2–0.33) depending on the applied field.

to measurement. Critical current densities were obtained by using the critical state model expression[13] $J_c \cong 15(M_+ - M_-)/R$ where M_+ and M_- are the magnetizations in emu/cm^3 on the decreasing and increasing field branches of the hysteresis loop, respectively, R is the average grain diameter of 10^{-3} cm as determined from optical and scanning electron microscopy studies of the material and J_c has units of A/cm^2.

III. RESULTS AND DISCUSSION

The main result of this paper is shown in Figs. 1 and 2 where several sets of hysteretically measured J_c are shown on a log–log plot versus fluence. In Fig. 1, we can see that J_c appears to follow a power law on fluence $J_c \approx (\text{fluence})^\alpha$ with $\alpha \cong 0.33$ over a wide range of temperature for $\mu_0 H = 4$ T without any special consideration of the mechanism responsible for hysteresis in the virgin material. There is no saturation except for deviations from the power law for temperatures at or above 60 K. If the simplest viewpoint may be applied, under the assumption that defect density is proportional to fluence, then this may be interpreted as J_c being inversely proportional to linear defect spacing in the material. In Fig. 2, J_c at 5 K is shown for $\mu_0 H = 0$, 1, 4, and 6 T. We see that the fluence dependence is still described well by similar power laws. The exponents fall within a range of $\alpha \cong 0.2$–0.33 with the lowest value corresponding to the lowest field and progressing systematically to larger exponents for the higher fields.

Despite the fact that the hysteresis at low temperatures in the unirradiated material is a significant fraction of that for the irradiated material,[8] the data of Fig. 1 is not fit well by introducing any significant initial defect density. Clearly the power laws must break down for lower fluences since the samples as grown have appreciable J_c's. Nevertheless, for temperatures below 60 K, the power law behavior appears to hold for the lowest fluences investigated. We interpret this to indicate a dominance of neutron irradiation induced defects over naturally occurring defects and any intrinsic pinning at least as far as J_c is concerned below 60 K and above the full penetration field.

Figure 3 shows the maximum T_c depression observed ($\mu_0 H = 2$ mT) for our sample with the highest fluence compared to the unirradiated sample. As can be seen in the vicinity of the transition, the depression of approximately 2 K in the transition temperature of the irradiated material is observed reproducibly for both zero-field-cooled (ZFC) and field-cooled (FC) magnetization. The relatively slight T_c depression would seem to indicate that the sample basically retains its intrinsic properties after irradiation to the highest fluence studied here. We take the full shielding of the unirradiated sample to indicate that grain coupled surface current effectively shielded the entire sample volume prior to irradiation whereas a significant degradation in shielding is observed after irradiation. The reduced mag-

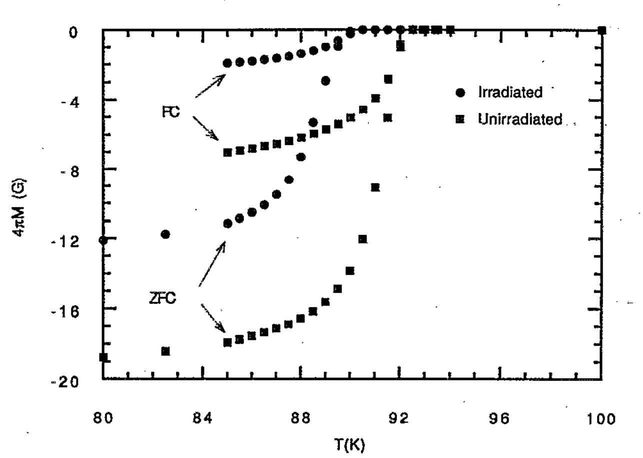

FIG. 3. Temperature dependence of zero-field-cooled (ZFC) and field-cooled (FC) magnetization for unirradiated and most irradiated (2.1 × 10^{18} n/cm^2) sample.

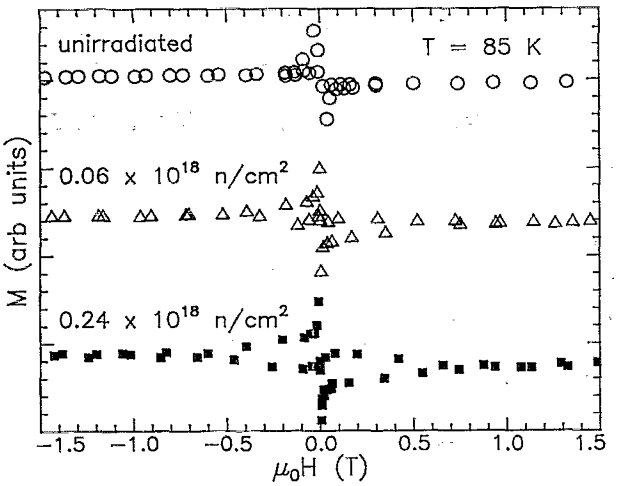

FIG. 4. Enhancements in magnetic hysteresis observed at low fields and low fluence at 85 K.

netic expulsion for the FC data in the irradiated sample also attests to the increased pinning for that sample.

The influence of n irradiation on reversibility is most dramatic near T_c. Figure 4 shows a series of hysteresis loops at 85 K before and after low fluence irradiations showing the hysteresis evolution as pinning sites are incrementally added. J_c enhancements are similar to those reported at 77 K[8] except that one observes the hysteresis increases only at lower fields and the improvements saturate at lower fluence.

IV. CONCLUSIONS

The dependence of hysteretically measured intragranular critical current density upon neutron fluence has been examined in polycrystalline $YBa_2Cu_3O_{7-x}$. It is found that the critical current density obeys a power law in fluence with an exponent in the range of 0.2–0.33. The fluence at which critical current density deviates from this power law and saturates appears to increase at lower temperatures.

[1] A. M. Campbell and J. E. Evetts, Adv. Phys. **21**, 199 (1972).
[2] J. G. Bednorz and K. A. Muller, Z. Phys. B **64**, 18 (1986).
[3] A. Umezawa, G. W. Crabtree, J. Z. Liu, H. W. Weber, W. K. Kwok, L. H. Nunez, T. J. Moran, C. H. Sowers, and H. Claus, Phys. Rev. B **36**, 7157 (1987).
[4] R. B. VanDover, E. M. Gyorgy, L. F. Schneemeyer, J. W. Mitchell, K. V. Rao, R. Puzniak, and J. V. Waszczak, Nature **342**, 55 (1989).
[5] J. O. Willis, J. R. Cost, R. D. Brown, J. D. Thompson, and D. E. Peterson, Mat. Res. Soc. Proc. **99**, 391 (1988).
[6] H. Kupfer, I. Apfelstadt, W. Schauer, R. Flukiger, R. Meier-Hirmer, H. Wuhl, and H. Scheurer, Z. Phys. B **69**, 167 (1987).
[7] A. Wisniewski, M. Baran, P. Przyslupski, H. Szymczak, A. Pajaczkowska, B. Pytel, and K. Pytel, Solid State Commun. **65**, 577 (1988).
[8] H. S. Lessure, S. Simizu, B. A. Baumert, S. G. Sankar, M. E. McHenry, M. P. Maley, J. R. Cost, and J. O. Willis, IEEE Trans. Mag. **27**, 1043 (1991).
[9] M. Daeumling, J. M. Seuntjens, and D. C. Larbalastier, Nature **346**, 332 (1990).
[10] F. M. Sauerzopf, H. P. Wiesinger, W. Kritscha, H. W. Weber, G. W. Crabtree, and J. Z. Liu, Phys. Rev. B **43**, 3091 (1991).
[11] M. P. Maley, J. O. Willis, H. Lessure, and M. E. McHenry, Phys. Rev. B **42**, 2639 (1990).
[12] M. A. Kirk, M. C. Frischherz, J. Z. Liu, L. R. Greenwood, and H. W. Weber, Philos. Mag. Lett. **62**, 41 (1990).
[13] W. A. Feitz and W. W. Webb, Phys. Rev. **178**, 657 (1969).