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Magnetic irreversibility in $Bi_2Sr_2CaCu_2O_8$ fibers irradiated by neutrons

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We describe magnetic measurements on $Bi_2Sr_2CaCu_2O_8$ (BSCCO) fibers irradiated by neutrons up to a fluence of 2.2×10^{15} cm^{-2}. The irradiation effects are similar to those reported for BSCCO crystals irradiated by fast neutrons. In particular, the critical current J_C increases with the increase fluence of neutrons and the irreversibility line is shifted gradually with irradiation to higher fields and temperatures. Results obtained from relaxation measurements show only a slight increase of the effective barriers as a consequence of the irradiation.

I. INTRODUCTION

Attempts to fabricate high-temperature cuprate superconductor (HTS) fibers began almost immediately after their discovery. Fibers, with their small cross section, can serve as a model for studying HTS wire systems. Also, the shape of the fibers simplifies calculations of their properties by modeling them as an infinite cylinder. The best HTS fibers to date are the $Bi_2Sr_2CaCu_2O_8$ (BSCCO).[1,2] BSCCO is characterized by weak flux pinning reflected in its relatively low critical current, J_C, and low irreversibility fields, H_{irr}.[3] In order to make these compounds suitable for most of the expected applications, one has to enhance H_{irr} and J_C. One of the most common techniques used to achieving this goal is to induce defects by irradiation. These defects, which serve as pinning centers for flux lines, have been characterized by the type of particles used in the irradiation process and their energy. One of the promising irradiation sources has been neutrons which are accessible at nuclear reactors. Studies of their effects on crystals of BSCCO (Refs. 4–7) revealed a dramatic enhancement in J_C and H_{irr}, while their effect on BSCCO polycrystalline melt samples was very moderate.[6] The purpose of this work is to report, for the first time, investigation into the effect of neutron irradiation on BSCCO fibers.

II. EXPERIMENT

Fibers were grown by laser-heated pedestal growth (LHPG) methods.[8,9] This technique has some advantages over other methods. In particular, it allows precise control of the growth process through the control of the melt composition.[1] The fibers produced by this method are composed of stacks of thin platelike crystallites having a highly aligned morphology.[2] The c axis of the crystallites are oriented normal to the fiber axis, i.e., the a-b planes are along the longest dimension of the fibers.[2] This orientation ensures that currents, which transport parallel to the fiber axis, will flow only in the Cu-O planes and thus J_C is maximized.

In this work we present magnetic measurements on three samples which were cleaved from a BSCCO fiber. One sample ($5.25\times0.27\times0.11$ mm^3) serves as a reference. We refer to it as sample $F0$. The other two samples, $F1$ and $F2$ ($4.13\times0.46\times0.15$ mm^3 and $5.74\times0.45\times0.2$ mm^3, respectively), were cleaved from the same fiber and were irradiated in the Israeli reactor IRR 2. Total fluences of 3.6×10^{14} cm^{-2} ($F1$) and 2.2×10^{15} cm^{-2} ($F2$) were used. Due to the low cross section of these particles, the penetration is considered to be full and homogeneous. The critical temperature, T_C, of the three samples is 83 K; no change in T_C was observed after irradiation.

All the measurements were performed on an "Oxford Instruments" vibrating sample magnetometer (VSM) which allows rotation of the sample relative to the magnetic field. As mentioned above, the sample is composed of stacks of thin platelike crystallites having a highly aligned morphology. For the magnetic experiments described below, it is essential to determine the directions of the crystallites. For this purpose we mounted the sample with its longest axis (the fiber axis) perpendicular to the magnetic field and rotated the sample (with an accuracy of ±1°) around its longest axis (see inset of Fig. 1). We then cooled the sample in zero field to 20 K and measured the magnetization after applying a low magnetic field (typically 100 Oe, i.e., less than H_{C1}). The magnetization measured in this procedure exhibited a large anisotropic feature. The direction which showed the highest magnetic moment is identified as the direction parallel to the c axis. Consistent with this identification are the magnetization curves measured both parallel and perpendicular to the fiber long axis. The width, ΔM, of the hysteresis loop for fields parallel to the c direction is found to

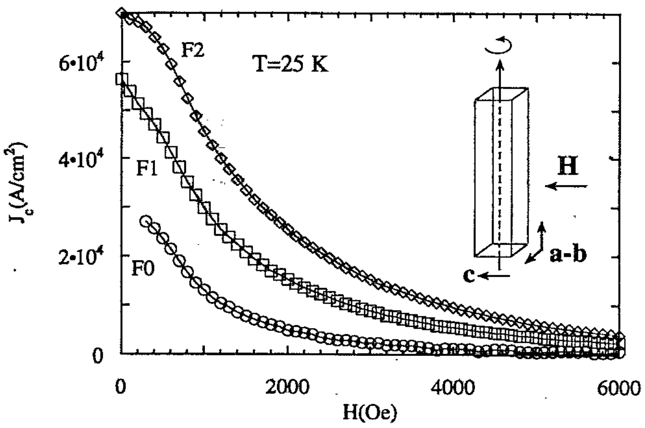

FIG. 1. The critical current density as a function of the applied magnetic field at $T=25$ K for $F0$ (unirradiated, open circles), $F1$ (3.6×10^{15} cm^{-2}, open squares), and $F2$ (2.2×10^{16} cm^{-2}, open diamonds). Inset: A schematic description of the sample orientation.

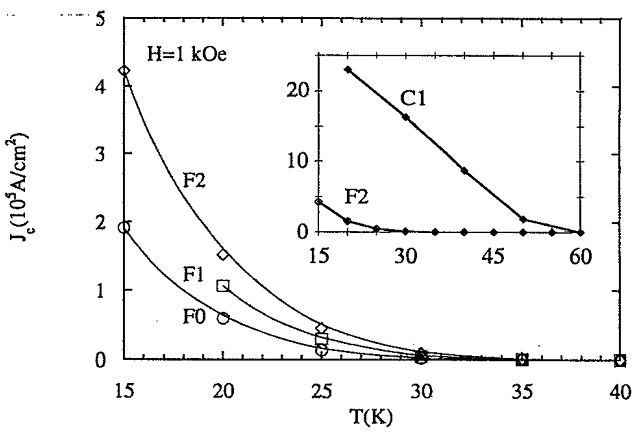

FIG. 2. The critical current density as a function of temperature at $H=1$ kOe for the three samples ($F0$, open circles; $F1$, open squares; and $F2$, open diamonds). Inset: The critical current for a single crystal, $C1$ (Pb fluence $=10^{11}$ cm^{-2}, solid diamonds). Also shown, for comparison, data points for $F2$.

be larger, by a factor ≈ 4, than for fields perpendicular to it. The difference in the width of the loops is consistent with previous reports[10] on the anisotropy between the c and a-b directions in the magnetic hysteresis loops of BSCCO crystals. It is important to emphasize that the ratio of the magnetization along c and along a-b is larger by a factor of 3 than that expected from demagnetization effects.

Once the directions of the crystallites were known, we performed two kinds of magnetic measurements on all three samples: (i) magnetization curves at various temperatures; (ii) magnetic relaxation of the remanent magnetization at the same temperatures as in (i). In all these measurements the magnetic field was parallel to the c direction.

III. RESULTS AND DISCUSSION

The critical current for fields along the c direction were estimated from the width of the magnetization curves, using the Bean model for samples with a rectangular cross section:[11] $J_C=20\Delta M/[d_1(1-d_1/3d_2)]$, where $d_1\leq d_2$ are the sides of the rectangle, and ΔM is the difference between the magnetization in the ascending and descending branches of the magnetization curves. The magnetization curves were measured in steps of 100 Oe, with waiting time of 4 sec at each field point. Figure 1 shows the critical current as a function of the magnetic field applied along the c direction at $T=25$ K, for the three samples under investigation. Apparently, the critical current was enhanced after the irradiation and the sample irradiated with the higher fluence ($F2$) exhibits higher critical current. The field dependence of the critical current is similar for all the samples.

Figure 2 shows the critical current of the samples as a function of temperature in a constant field, $H=1$ kOe. The decay of the critical current with temperature is very fast, even for the irradiated samples. At $T=40$ K the critical current drops to below our measurement resolution namely, 100 A/cm^2. This low critical current prevents any use of these fibers, even of the neutron-irradiated ones, for applications at liquid-nitrogen temperature.

For technical reasons we could not irradiate the fibers with other particles. Nevertheless, to obtain a rough estimation of the potential efficiency of irradiation with other particles, we compare, in the inset of Fig. 2, the present results with similar data of BSCCO crystal that we had irradiated with Pb ions (sample $C1$, fluence$=10^{11}$ cm^{-2}).[12] We note that J_C of the unirradiated crystal is of the same order of magnitude as that of the unirradiated fiber under investigation. The critical current of the Pb-irradiated crystal, in the temperature range 20–40 K, was enhanced by 2–3 orders of magnitude while J_C of sample $F2$ (neutron irradiated, 2.2×10^{15} cm^{-2}) was enhanced by only a factor of 2–5 in a similar temperature range.

Further increase of the critical current may be obtained by increasing the fluence of neutrons,[7] but even after irradiation by fluence of 6×10^{17} n/cm^2 the reported J_C is much less than J_C of the sample irradiated by heavy ions. For example, the critical current for the BSCCO crystal irradiated by fast neutrons[5] by fluence of 6×10^{17} n/cm^2 is approximately 2.5×10^2 A/cm^2 at $H=7.5$ kOe and $T=40$ K, while J_C of BSCCO crystal irradiated by Pb ions[13] by fluence of 2.5×10^{11} cm^{-2} at the same field and temperature is approximately 3×10^5 A/cm^2.

The irreversibility field, H_{irr}, was determined from the magnetization curves with a criterion of $\Delta M\propto J_C<100$ A/cm^2. Figure 3 shows the irreversibility field as a function of temperature for the three samples under investigation. The irreversibility field, both before and after irradiation, decays exponentially as the temperature increases: $H_{\text{irr}}\propto\exp(-T/T_0)$, where $T_0\approx 9$ K for all samples. It is apparent from this figure that after irradiation, the irreversibility line shifts to higher fields and temperatures, and as the fluence increases the shift becomes more

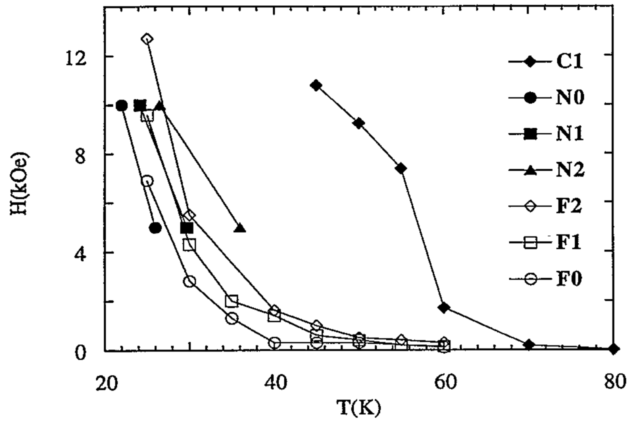

FIG. 3. The irreversibility field H_{irr} as a function of temperature for various samples. Three fibers: *F*0, open circles; *F*1, open squares; and *F*2, open diamonds. Pb-irradiated crystal: *C*1, solid diamonds and three crystals: *N*0, unirradiated, solid circles; *N*1, neutrons irradiated (fluence$=5\times10^{16}$ cm^{-2}); solid squares; and *N*2, neutrons irradiated (2.5×10^{17} cm^{-2}), solid triangles.

pronounced. In order to obtain an impression concerning the effect of increasing the fluence of neutrons and of heavy-ion irradiation, we add to Fig. 3 data for BSCCO crystals irradiated with Pb ions (*C*1, fluence$=10^{11}$ cm^{-2}, solid diamonds), and data from Ref. 7 for BSCCO single crystals before (*N*0, open triangles) and after fast neutron irradiation [fluences of 5×10^{16} cm^{-2} (*N*1, solid squares) and 2.5×10^{17} cm^{-2} (*N*2, solid triangles)]. The shift of the IRL's of the single crystals exposed to fast neutrons is similar to the shift of the fibers. On the other hand, the IRL of the Pb-irradiated sample shows an apparent different shift, both in the shape of the IRL and in the impulse of the line to higher fields and temperatures.

In the relaxation measurements, the sample was cooled in the presence of a field of 15 kOe. The field was then turned off and the relaxation measured for 1800 sec. The results should be treated with caution due to the possible effect of self-fields in this procedure. At low temperatures, the relaxation of the irradiated samples in the experimental time window are logarithmic with time. We thus neglect corrections of the interpolation formula and extract the effective barrier, U_{eff}, by using $U=kT/S$, where $S=[1/M(t=100)]\times[dM/d\ln t]$. We observed two main features: (1) a decrease in the relaxation rate of the irradiated sample relative to the unirradiated one. The effective barriers, at 15 K, that were extracted from these relaxation rates increased slightly after irradiation—from 0.0105 eV before irradiation to 0.013 eV afterwards. In comparison, after irradiation by 10^{11} cm^{-2} Pb ions U_{eff} (at $T=20$ K) increased from 0.0065 to 0.056 eV.[14] (2) The two irradiated samples exhibit almost identical relaxation rates at all temperatures up to 40 K. A similar result was obtained for BSCCO single crystals irradiated with different fluences.[14,15] The fluence-independent relaxation rates was interpreted as an indication that the intervortex interactions are not important and thus the effective barrier would reflect only the effective barrier for the depinning of a single vortex from the defect.[15]

IV. SUMMARY AND CONCLUSIONS

The general impression from our experiments is that the magnetic behavior of BSCCO fibers and crystals is quite similar; in particular, the anisotropic moment between the *a*-*b* plans and the *c* axis, the critical currents, and the IRL. These similarities indicate that the fiber fabricated by the LHPG method had good crystalline quality. Clear improvement of the magnetic properties was achieved after irradiation of the samples with neutrons. The critical current was enhanced and the irreversibility lines shifted to higher fields and temperatures as the fluence of neutrons was increased. Yet, even after irradiation, J_C drops quite quickly with temperature, hence preventing their use in any application requiring liquid-nitrogen temperatures. Results[7] obtained for BSCCO single crystals irradiated by fast neutrons indicate that further improvements of the critical current for the fiber may be achieved for a much higher fluence of irradiation. The relaxation rates decrease only slightly as a result of the irradiation and they are independent of the fluence of irradiation at least at low temperatures.

ACKNOWLEDGMENT

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