Effects of 200-MeV Ag-ion irradiation on magnetization in a $Bi_2Sr_2CaCu_2O_{8+y}$ single crystal

A. K. Pradhan, S. B. Roy, and P. Chaddah
Low Temperature Physics Group, Centre for Advanced Technology, Indore 452013, India

D. Kanjilal
Nuclear Science Centre, Aruna Asaf Ali Marg, Post Box 10502, New Delhi 110067, India

C. Chen and B. M. Wanklyn
Clarendon Laboratory, Department of Physics, Oxford University, Parks Road, Oxford OX1 3PU, United Kingdom
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We report a dramatic change in the magnetization double peak anomaly and irreversibility line of a $Bi_2Sr_2CaCu_2O_{8+y}$ [BSCCO(2212)] single crystal after irradiation with 200-MeV Ag ions. We found that the partial destruction and ineffectiveness of dislocation networks in the CuO_2 planes of the BSCCO crystal after irradiation are responsible for the disappearance of the double peak anomaly. Ag irradiation induces damage in the form of columnar defects which cause an enhancement of flux pinning and a shift in the irreversibility line towards higher temperatures.

Flux pinning in the superconducting state is of importance from the point of view of both theory and potential applications. Enhanced flux pinning in irradiated high-T_c superconductors (HTSC's) has been the topic of numerous recent studies. Particularly, aligned columnar defects in HTSC's produced by heavy ion irradiation (near the GeV range energy) pin magnetic vortices much more effectively than other kinds of defects, such as point defects.[1] These types of strong and highly directional pinning of magnetic vortices with long columnar defects are technologically very relevent, because they enhance the critical current density J_c by orders of magnitude and considerably expand the useful irreversible regime.[1–6] There remains a great deal of contradiction on the pinning-dependent nature of the irreversibility line[3–5] after irradiation. It is true that in contrast to the point defects and other similar types of defect structure where the core pinning is very weak, the Lorentz force acts over the entire length of the aligned columnar defects and the fraction of the vortex core pinning can approach unity.

For a highly anisotropic layered superconductor like $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO), where the interlayer distance between the CuO_2 layers is considerably large compared to the coherence length ξ_c, the idea of pancake vortices[7] assuming two-dimensional (2D) superconducting layers separated by insulating layers is very much appropriate. BSCCO crystals display very interesting low-field anomalous double peak magnetization behavior which is discussed in the framework of a signature of dimensional crossover from a 3D to a 2D state.[8–10] Yang *et al.*[10] have explicitly explained that matching of 2D pancake vortices with the in-plane dislocation networks causes pinning after a transition from a 3D flux lattice to a 2D pancake vortex regime. This low-field pinning is seen in the form of a double peak structure in magnetization.

In this paper, we present the dramatic disappearance of this double peak anomaly after heavy Ag-ion irradiation in BSCCO(2212) single crystals. We believe that the dislocation networks responsible for low-field pinning, and hence the double peak anomaly, become ineffective after ion irradiation. Furthermore, the shift of the irreversibility line to higher temperature after irradiation clearly demonstrates the enhanced pinning by columnar defects and the increase in the 3D to 2D crossover temperature.

Single crystals of BSCCO(2212) were grown by the self-flux method[11] and their detailed characterizations have been reported elsewhere.[9,12] The single crystals were chosen from the same growth batch. The pristine crystals were cleaved into dimensions of $\approx 1.5\times 1\times 0.02$ mm^3 and the same crystal was used throughout the measurements before and after irradiation. The crystals were irradiated with 200-MeV $^{107}Ag^{14+}$ ions from the 16 MV Tandem Pelletron Accelerator[13] at the Nuclear Science Centre facility in New Delhi, India. The fluences varied from 10^{11} ions/cm^2 to 10^{12} ions/cm^2, and the columnar defects were aligned ($5°\pm 1°$) away from the c axis of the crystal to avoid ion channeling. To avoid backscattering the sample holder was covered with an absorbing material except the beam path. All the samples were irradiated in a vacuum of 10^{-7} torr and at room temperature. The beam current was kept as low as 2 nA to avoid any warming effect during irradiation ($<$ 10 K). The fluence was estimated by collecting the charges falling on the sample kept in an electron-suppressed geometry. The charges were integrated by a current integrator and the corresponding pulses generated by the integrator were counted to measure the total fluence on each of the samples. The variation of electronic and nuclear stopping power with the energy of the Ag beam based on the calculation of the transport of ions into solids[14] (TRIM-95) is shown in Fig. 1. From this plot it is seen that the electronic stopping power due to inelastic ionizing collisions which produce the columnar defects starts peaking near 200 MeV energy. The nuclear stopping power due to elastic collisions is negligible at this energy.

The magnetization measurements of both as-grown and irradiated crystals were carried out using a Quantum Design superconducting quantum interference device (SQUID)

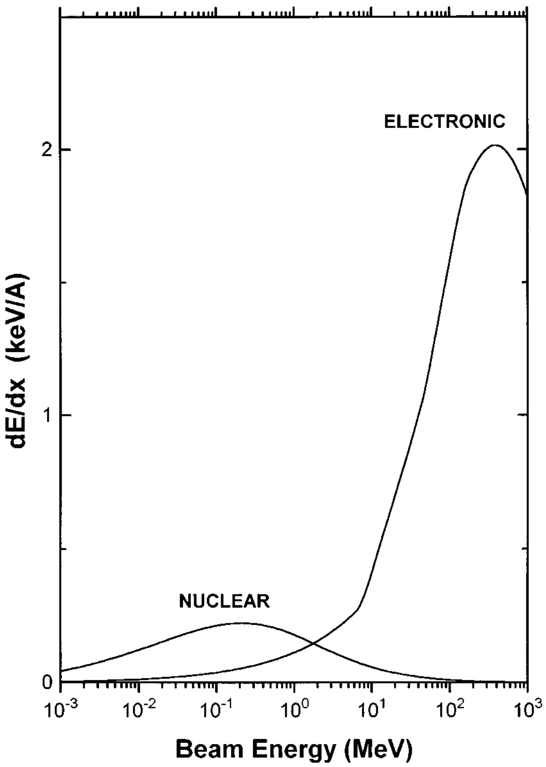

FIG. 1. Nuclear and electronic stopping power versus energy for ^{107}Ag beam in BSCCO.

(MPMS5) magnetometer with 4 cm scan length with H parallel to the c axis of the crystal. Isothermal magnetizations were measured and the irreversibility line (IL) was determined at various temperatures from the divergence of forward and return legs of the M-H curves.

Figure 2 shows the pronounced double peak anomaly observed in BSCCO(2212) as-grown single crystals at 25 K. This anomaly occurs in the magnetization loop at temperatures between 20 and 40 K in as-grown crystals. The temperature evolution of the anomaly is found in the literature for as-grown BSCCO crystals.[8–10] For the sake of clarity we have shown only one temperature. The present anomalous feature is much more pronounced than our earlier report,[9]

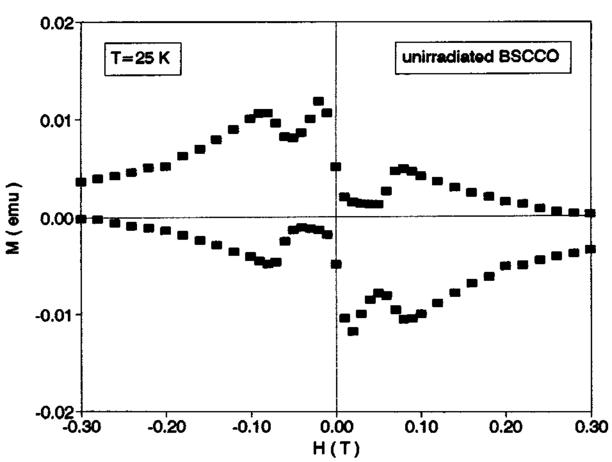

FIG. 2. Magnetization hysteresis loop of as-grown BSCCO single crystals at 25 K.

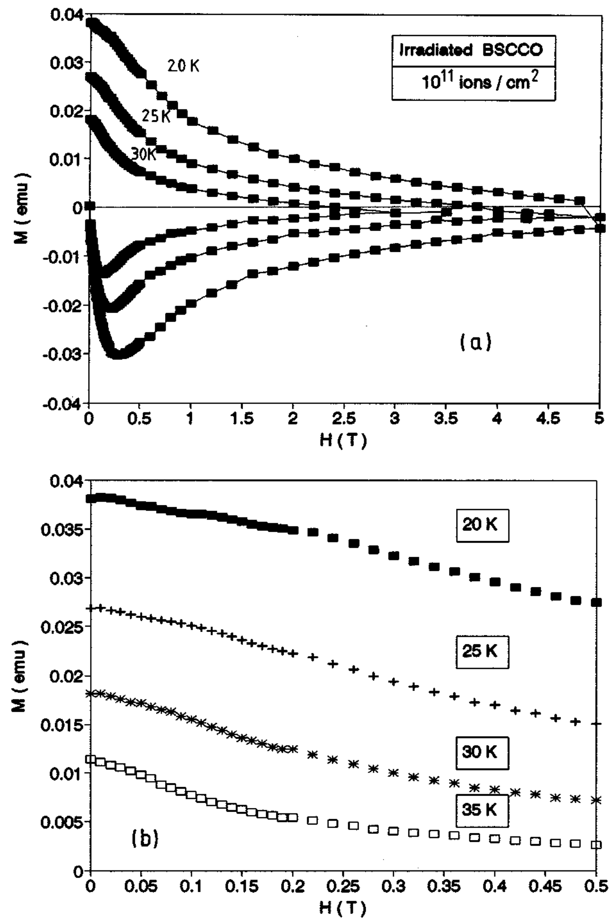

FIG. 3. (a) Magnetization hysteresis loops of irradiated single crystals of BSCCO at various temperatures. The virgin and return legs of the curves are shown. (b) Expanded portion of the return leg of the hysteresis loop is shown for various temperatures.

however, more like that observed in Ref. 10. The field at which the maxima occurs is almost independent of temperature. This peak is very different from the anomalous "fishtail" magnetization in YBaCuO crystals[15] where spatial variations of oxygen vacancies are effective flux pinning centers and recently in (YPr)BaCuO crystals[16] as well. In both the YBaCuO-based materials, the field at which the anomaly occurs decreases with increasing temperature. This suggests that the anomaly in BSCCO has a different origin from that in YBaCuO.

Figure 3(a) shows the M-H curves of BSCCO(2212) single crystals after Ag-ion irradiation (10^{11} ions/cm^2) at various temperatures. In Fig. 3(b), an expanded portion of the return leg of this curve in the field region 0–0.5 T is shown. In contrast to Fig. 2, these curves do not exhibit any double peak anomalous magnetic behavior. While the magnitude of features observed in the hysteresis loop can depend on the time scale of the measurement due to rapid flux creep,[17] we note that our measurements before and after irradiation were made with the same rate of field change and our comparisons are for the same time scale of measurement. We have shown the curves in a temperature range between 20 and 35 K where the anomaly was observed in as-grown crystals. Figure 3 shows a large enhancement of the hysteresis loop (only the virgin and the return leg of the magneti-

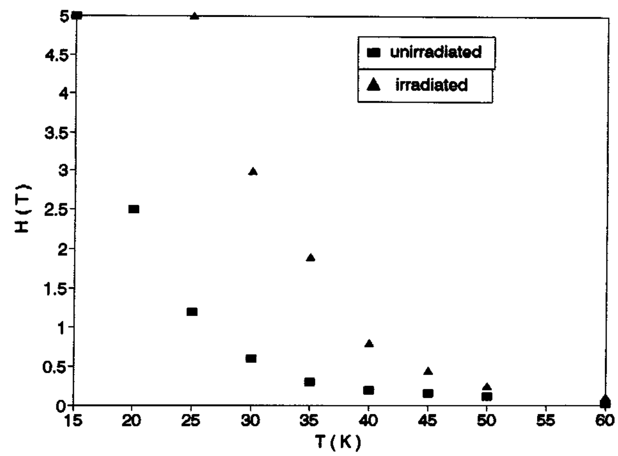

FIG. 4. Irreversibility lines of both as-grown and irradiated (10^{11} ions/cm^2) BSCCO single crystals.

zation of the field cycle 0–5 T–0 is shown) after irradiation. The remanent magnetization at 25 K is increased by a factor of 5, indicating a significant increase in flux pinning and J_c. It may be noted that neither visible damage on the surface of the crystal nor any dramatic change in T_c was observed after irradiation.

We first compare the IL or $H_R(T)$ determined magnetically [more details of the determination of $H_R(T)$ have been given in Ref. 9] for the unirradiated crystal with that observed after irradiation. In Fig. 4, it is seen that $H_R(T)$ is shifted to higher temperature over the whole magnetic field domain under consideration. Several BSCCO crystals were irradiated with different fluences, $\phi t = 1\times10^{11}$, 2.5×10^{11}, 5×10^{11}, and 1×10^{12} ions/cm^2. The dose-equivalent magnetic field values $B_\phi = \phi_0 \phi t$ (ϕ_0 is the elementary flux quantum) correspond to 2.1, 5.2, 10.4, and 20.8 T, respectively. If we compare various doses, it becomes clear that this effect is rather strong close to B_ϕ and diminishes at B with values away from B_ϕ. The details of various fluences of irradiation on the irreversibility line will be discussed elsewhere.[18] The most pronounced anomalous magnetization was observed at 25 K in as-grown crystals where the $H_R(T)$ line grows very sharply. A similar effect might have been expected at around 35 K after irradiation as the $H_R(T)$ line shifted about 10–12 K towards higher temperature. However, surprisingly, we could not notice any such anomaly in the temperature regime 10–60 K.

Heavy ion irradiation is known to produce aligned columns of amorphized tracks of dimension 5–10 nm in diameter, randomly distributed in the plane normal to the beam line[19,20] which is parallel to the c axis of the crystal. The defects of continuous cylinders provide frequent core pinning sites for each flux line along the total length of the line for $H\|c$ axis of the crystal. Columnar defects produced by Ag irradiation are effective pinning centers and it has been shown that heavy ion irradiation shifts the IL towards the $H_{c2}(T)$ line.[1,2,6,7,17]

We now consider the absence of the double peak structure after irradiation. The mechanisms for the occurrence of the double peak anomaly available so far are (a) enhanced pinning due to matching effect of 2D pancake vortices with the dislocation network together with a 3D to 2D crossover[10] or (b) a signature due to dimensional crossover (3D to 2D).[8,9] In BSCCO crystals, the effective pinning centers at low temperature ($<$ 20 K) are believed to be mainly due to the oxygen vacancies in the CuO_2 layers; however, at high temperatures ($>$ 20 K), i.e., above the irreversibility line, the planar dislocation networks observed by transmission electron microscopic (TEM) studies[10] in single crystals of as-grown BSCCO become effective for pinning. As this happens above the irreversibility line, the decoupled 2D pancake vortices interact strongly with the extended dislocation network, and their spatial matching causes pinning in the low-field region. It has been shown that after vacuum annealing an as-grown crystal above 673 K, the anomalous magnetization and the dislocation networks disappear.[10]

The dislocation network takes place within a single plane and matching of the 3D flux lattice to such dislocation networks is not possible as there is no correlation between dislocation networks on different planes. However, it is true that the columnar defects are known to pin 3D flux lattices. Therefore, it is speculated that the dislocation networks present in the as-grown crystal become ineffective after ion irradiation by columnar tracks. Though there are 2D pancake vortices formed just above the IL after a crossover from a 3D to a 2D state, they are not pinned due to lack of pinning centers. The huge increase in magnetization in the post irradiated crystal in the same field range of the anomaly clearly reveals the domination of columnar defects over the dislocation networks. It is a fact that heavy ion irradiation does not produce any point defects. Therefore, it is believed that 3D flux lattice pinning after heavy ion irradiation is only done by the localized columnar defects. Once columnar defects of the right dimension are produced, pinning due to other defects like point defects and dislocation networks becomes very negligible. Let us compare the magnitude of magnetization near the peak value (i.e., between 0.08 and 0.1 T) of the anomaly in as-grown crystals to that of the irradiated crystal. We find that $dM/dH = +1.17\times10^{-4}$ emu/mT in the as-grown crystal and $= -1.61\times10^{-5}$ emu/mT after irradiation. It seems, therefore, that the anomaly due to dislocation networks is subdued after irradiation. It is possible that the dislocation network is broken or partially destroyed after irradiation. However, detailed microstructural studies are necessary to bring this out. It can be argued from the peak position that the dislocation networks are present in the field of 0.1 T. However, our minimum dose of irradiation corresponds to a fluence of 10^{11} ions/cm^2 and corresponding magnetic field of more than 2 T. Therefore, the density of columnar defects after irradiation is high enough to accommodate all the vortices, resulting in strong pinning, and renders the dislocation networks ineffective.

It has already been reported[21] that heavy ion irradiation significantly reduces the effects of material anisotropy of BSCCO and increases the interlayer couplings. Moreover, vortex dynamics is consistently described by the Bose-glass theory for vortex line pinning by columnar defects.[22] Hence, we suggest that due to drastic reduction of anisotropy in our BSCCO crystal, enhanced interplaner correlation, and strong columnar pinning after heavy ion irradiation the dislocation networks in planes are partialy destroyed and significantly negligible to cause the low-field double peak anomaly in magnetization hysteresis. We also rule out the possibility of vacuum annealing of the crystal as precautions were taken to avoid warming effects during irradiation.

In conclusion, we have observed the disappearance of the double peak low-field anomaly in the magnetization hysteresis loop in BSCCO(2212) single crystals after heavy ion irradiation. We believe that the partial destruction and ineffectiveness of dislocation networks by columnar defects after irradiation is mainly responsible for the disappearance of magnetization double peak anomaly in BSCCO crystal. The correlated columnar pinning of 3D flux lattices by heavy ion irradiation dominates over the dislocation networks and point defects as well. The shift of irreversibility line to higher temperature predicts that not only is flux pinning the origin of this line but also columnar defects enhance flux pinning with an increase in the 3D to 2D crossover temperature in BSCCO crystals.

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