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Enhancement of Critical Current Density j_{cm} and Pinning Energy U in Melt Textured $Bi_2Sr_2CaCu_2O_{8+\delta}$ on Ag-Tape by Heavy Ion Irradiation

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Abstract

Irradiation experiments using 502 MeV ^{127}I ions were performed on 2212 BSCCO melt textured layers on Ag-tape to create well defined columnar amorphous tracks (diameter: 5–10 nm). These tracks should act as very effective pinning centers, especially if they are aligned in parallel to the magnetic field. Magnetization measurements resulted in an enhancement of the magnetization current density j_{cm} within the whole temperature range of 4.2 K up to 60 K. Enhancement factors up to 10^3 were obtained in a magnetic field of 2 T at 30 K after irradiation. We investigated our samples at magnetic inductions up to 12 T; the j_{cm} results will be compared with critical current densities j_{ct} derived from transport measurements revealing a pronounced lower j_c-enhancement due to irradiation. The evaluation of $E(j)$ curves gives evidence that granularity can be neglected in unirradiated samples, on the other hand, obvious limits for the intergrain currents exist after irradiation. According to relaxation measurements of the magnetic moment before and after irradiation with different doses of 502 MeV ^{127}I the activation energy U could only be increased from about 30 meV to 70 meV at 10 K and 0.1 T. The small increase of pinning energies is explained within the pancake vortex model and is consistent with recent results found on $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals.

1.Introduction

The use of high-T_c superconductors for applications in power engineering at 77 K could be very attractive because of the economic and simple nitrogen cooling. BSCCO based superconductors can be processed by conventional manufacturing techniques into long length, which is an absolutely necessary requirement for conductor materials. We investigated the $Bi_2Sr_2CaCu_2O_{8+\delta}$ compound, where flux line pinning is dominated by thermal activation at elevated temperatures. One possibility to achieve improvement, is to generate additional and probably more effective pinning sites by heavy ion irradiation, which has already been proved for single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ [1,2] and for thin epitaxial films of $YBa_2Cu_3O_{7-\delta}$ [3,4]. In this paper we present the influence of 502 MeV iodine irradiation on j_c and U in melt textured 2212 BSCCO [5]. The effects on the intragrain currents will be compared to the intergrain currents measured by transport critical current measurements and to earlier experiments on single crystals [1].

2.Experimental

Preparation of the polycrystalline samples was performed using a melt texturing process on Ag-tape. The 2212 BSCCO superconducting layer and the Ag-tape had a thickness of about 12 μm and 50 μm, respectively. A detailed description of the preparation technique was already given in a previous paper [5]. Before and after irradiation we characterized one part of our samples by magnetization measurements, using a commercial Vibrating Sample Magnetometer from Oxford Instruments having a resolution of as high as 8×10^{-9} Am^2 at 12 T and 4.2 K. The size of the samples was about 2.4 mm×2.4 mm×12 μm. Measurements were carried out in a temperature range of 4.2 K up to 77 K and in magnetic inductions up to 12 T. j_{ct} was measured on a second part of samples prepared from the same batch in magnetic fields up to 8 T at different temperatures. The irradiation experiments were performed at a low-temperature facility of VICKSI at the Hahn-Meitner-Institut in Berlin at a temperature of approximately 77 K. After irradiation the samples

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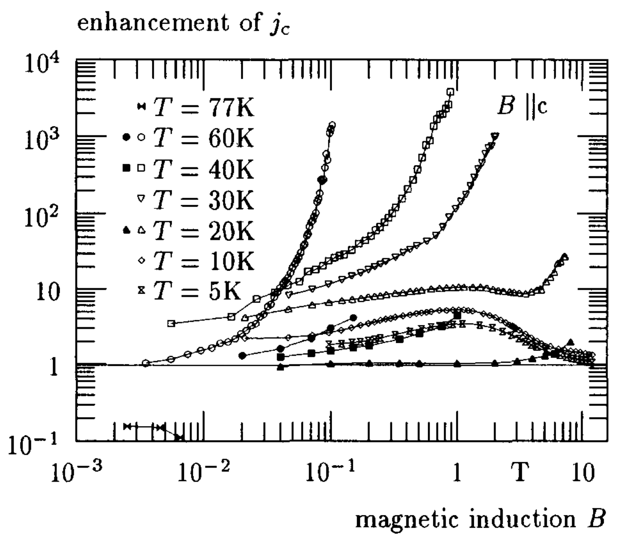

Figure 1: Enhancement of critical current density after irradiation with $2.5 \times 10^{11}/cm^2$ iodine ions. Results from magnetization measurements j_{cm} (open symbols) and transport measurements j_{ct} (closed symbols).

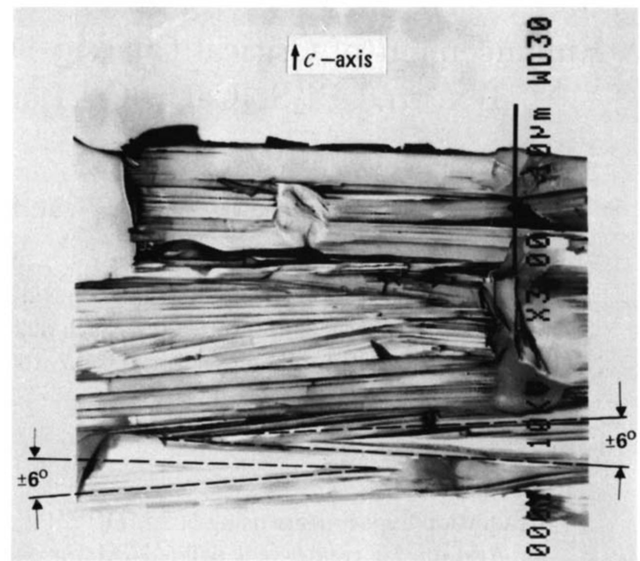

Figure 2: SEM micrograph of the fractured 2212 BSCCO layer on Ag-tape (longitudinal cross section).

were warmed up to room temperature. The 502 MeV ^{127}I ions have a projected range of about 27 μm in $Bi_2Sr_2CaCu_2O_{8+\delta}$, which is more than twice as large as the thickness of our samples. Therefore, a homogeneous damage distribution was obtained and any implantation avoided.

3.Results and Discussion

The projectiles of ^{127}I create well defined columnar defects as already proven for 2212 BSCCO single crystals [1] using TEM analysis. Because the electronic energy loss of the projectiles always exceeds a value of 2keV/Å along the path of the ions, the projectiles produce continuous amorphous tracks of 5–10 nm in diameter. Critical current densities were magnetically determined from the width of the irreversible magnetization loop ΔM using the Bean model [6]: $j_{cm} = 3\Delta M/\mu_0 D$, where D is the effective diameter of the samples ($D = 2\sqrt{A/\pi}$ and $A = 2.4 \times 2.4$ mm^2). The magnetic field was applied parallel to the c-axis and parallel to the tracks. The magnetization measurements result in an appreciable enhancement of j_{cm} after irradiation in a temperature region between 4.2 K and 60 K as shown in figure 1. At 77 K, however, j_{cm} is significantly lowered due to the irradiation induced reduction of T_c which is depressed from the initial $T_{c0} = 87$ K to $T_{c0} = 79$ K after a dose Φ of 2.5×10^{11} ions/cm^2. Compared to results from irradiated 2212 BSCCO single crystals, j_{cm} of melt textured samples is about one order of magnitude smaller after irradiation. Melt textured samples are composed of stacks of well aligned plate-like grains [5] as shown in figure 2. In this way the current transport might be limited by grain-grain connections within the polycrystalline samples.

Compared to j_{cm}, the enhancement of j_{ct} remains much smaller as evident from figure 1. Generally, j_{cm} is larger than j_{ct} after irradiation, especially at temperatures above 20 K as plotted in figure 3. These results are supported by the evaluation of $E(j)$ curves derived from our magnetization measurements and their comparison to the corresponding j_{ct}-curves. Figure 4 comprises $E(j)$ curves both from magnetization measurements, extracted from the magnetic flux change using $E = D/2 \times dM/d\ln t$ [7], and from transport data which fit very well before irradiation. The $E(j)$ curves could be described by a power law $E = E_0 \times (j/j_0)^p$ which is related to a logarithmic dependence of the activation energy on current. A detailed analysis is given in ref. 8. The $E(j)$ curves clearly demonstrate that granularity is no limiting factor in the unirradiated 2212 BSCCO samples. But, irradiation leads to a large difference between the $E(j)$ curves derived from transport and magnetization measurements. In the case of magnetization currents, we get a drastic enhancement of intragrain j_{cm} by the introduction of additional defects. Furthermore, the activation energy U is also increased as shown by the steeper slope of the E(j) curves. These results are in agreement with previous investigations on $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals [1].

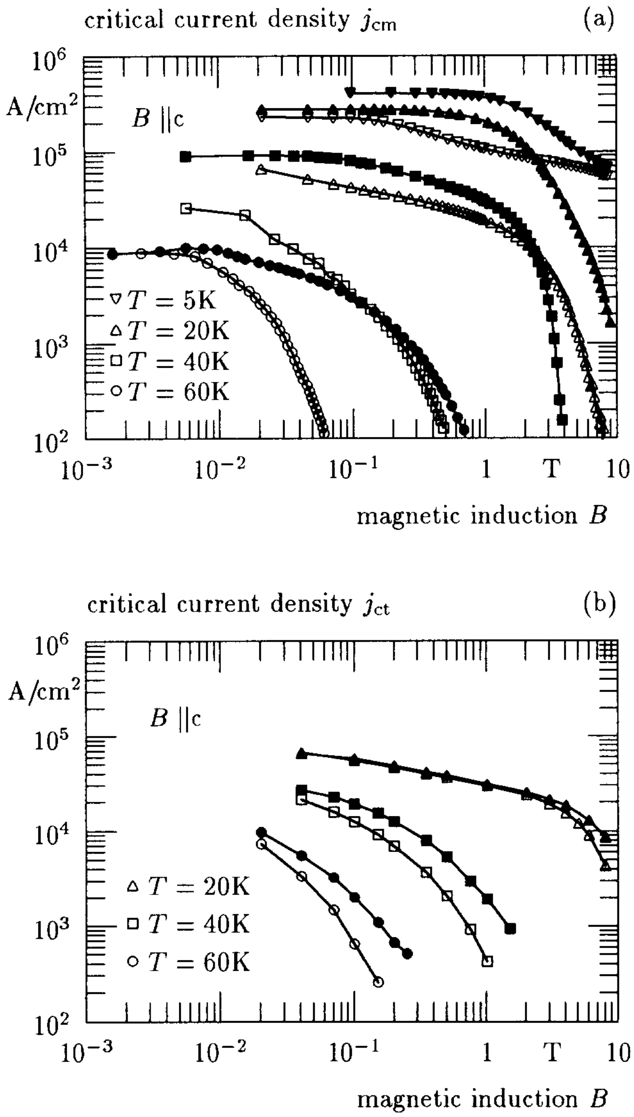

Figure 3: Critical current densities before (open symbols) and after (closed symbols) irradiation. j_{cm} from magnetization measurements (a) and j_{ct} from transport measurements with a voltage criterion of 1 μV/cm (b).

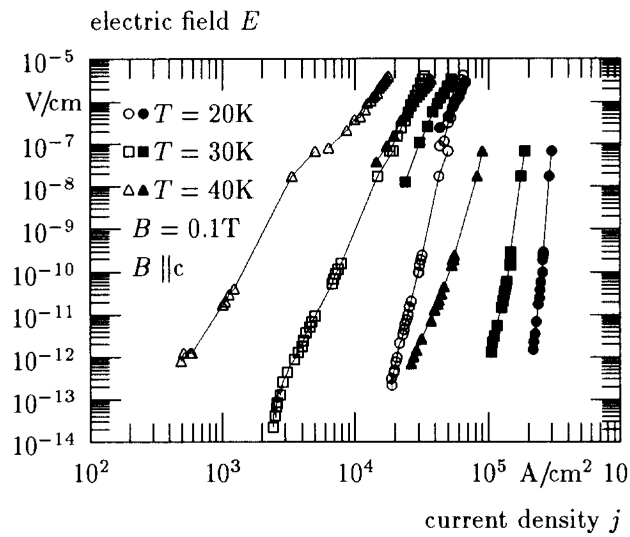

Figure 4: Voltage current curves obtained from transport measurements (10^{-7}-10^{-5} V/cm) and magnetization decay (10^{-14}-10^{-7} V/cm) before (open) and after irradiation (closed) with $2.5 \times 10^{11}/\mathrm{cm}^2$ ^{127}I.

Comparing transport and magnetic data in figure 4, there seems to be a limiting level for the enhancement of intergrain j_{ct} at a value of several 10^4A/cm^2 after a dose of $2.5 \times 10^{11}/\mathrm{cm}^2$, which is nearly independent on temperature. In the unirradiated samples the pinning within the plate-like grains is relatively weak comparable to results found in single crystals [1]. When increasing the number of defects by irradiation, j_{ct}-limiting mechanisms became effective. Further magnetic and microstructural investigations are still required to investigate the nature of these mechanisms.

To investigate the pinning mechanism the pinning energy U was determined by relaxation measurements. The evaluation of the effective activation energy for different magnetic fields and irradiation doses was done according $U = k_B T[S^{-1} + \ln(t_b/\tau)]$ [9], where $S = [1/M(t_b)] \times dM(t)/d\ln t$ is the logarithmic slope of the $M(t)$ curve. The analysis within this model is reasonable, when applied at low temperatures [1]. t_b is the time of the first measurement after field settlement ($t_b \approx 10$ s) and $\tau = 10^{-10}$ s is a suitable relaxation time. U for melt textured and single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$ is shown in figure 5 for various magnetic inductions B at $T = 10$ K. As each incident ion produces a line defect it is useful to express the irradiation dose as a dose equivalent field $B_\Phi = \phi_0 \times \Phi$, where ϕ_0 is the elementary flux quantum. $\Phi = 2.5 \times 10^{11}/\mathrm{cm}^2$ corresponds to B_Φ=5.2T. The irradiation induced defects could rise the pinning energy from initially about 30 meV to only 70 meV at 10 K and 0.1 T for melt textured 2212 BSCCO which is in accordance to results on single crystalline material [1]. Compared to single crystals twice the dose is necessary for melt textured samples to reach the same U values, which is still unexplained; uncertainties in the dose measurements are excluded. The enhancement of U is large if there are more defects than flux lines in the sample. In case of $B > B_\Phi$ there are more flux lines than introduced defects in the sample and the enhancement of the activation energy remains quite small (figure 5). In this case the flux creep is controlled by the unbound vortices. These flux lines only can interact with the less effective

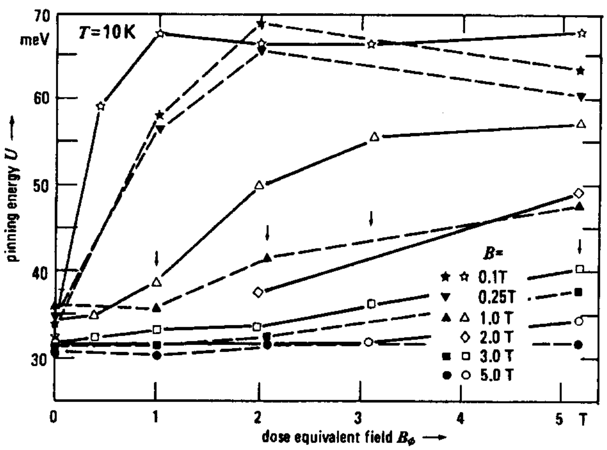

Figure 5: Pinning energy U versus the dose equivalent field B_Φ at various magnetic inductions B for single crystals (full lines) and polycrystalline melt textured layers (dashed lines). The arrows indicate the doses where $B = B_\Phi$.

intrinsic defects in the superconducting compound.

The small pinning energies obtained after irradiation and at low temperatures confirm Clem's pancake vortex model [10,11]. The reason for the existence of individual pancake vortices is the high superconducting anisotropy in $Bi_2Sr_2CaCu_2O_{8+\delta}$ [12] caused by the large distance between the CuO_2 layers compared to ξ_c. In the 2D-layered $Bi_2Sr_2CaCu_2O_{8+\delta}$ compound the essential pinning mechanism is determined by the individual interaction of weakly coupled pancake vortices with the defects.

4. Conclusions

Columnar defects introduced by heavy ion irradiation lead to a marked enhancement of j_{cm} and a smaller one of the pinning energy in 2212 BSCCO. The analysis of $E(j)$ curves supports the interpretation that there is no granularity in the samples before irradiation. Irradiation mainly improves the intragrain pinning properties, but j_{ct} is limited to a value of several $10^4 A/cm^2$. The two dimensional behaviour of 2212 BSCCO leads to the existence of pancake vortices which is confirmed by the small increase of U in melt textured and in single crystalline material after irradiation. Consistent to these results are previous irradiation experiments using 400 MeV ^{16}O-ions [13], where the prevailing small defects did not change U. In this way 2212 BSCCO is largely controlled by thermal activated depinning of individual pancake vortices at elevated temperatures. Therefore, the 2212 BSCCO compound is no longer considered for technical conductors operated at 77 K.

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