Increase of the critical current in single-crystal $Bi_2Sr_2CaCu_2O_{8-\delta}$ with ion-induced flux-pinning sites

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Single crystals of $Bi_2Sr_2CaCu_2O_{8-\delta}$ were irradiated with 50-MeV $^{16}O^{+6}$ along the c axis. Using a single coil as a noncontact probe, the transition temperature and the critical current of the samples were measured *in situ* as a function of total beam fluence. We observe an increase and a subsequent decrease in the critical current at 60, 75, and 80 K with a peak corresponding to fluences of $\sim 1\times10^{13}$ ions/cm^2. Up to this fluence the transition temperature remained a constant. Higher fluences caused a decrease in both the transition temperature and the critical current. The results are discussed in terms of a simple model assuming the ion-induced defects cause flux pinning sites.

Critical currents and flux pinning in high-T_c superconductors are areas of much recent interest. Defects in high-T_c superconductors create pinning sites for magnetic flux lines allowing higher critical magnetic fields (H_c) and higher critical currents (J_c) than in better crystals. This is of technological interest in the aspiration toward making devices with these materials. Also there are a number of flux-pinning theories, collective pinning theory,[1] and pancake vortices[2] to name two, which should be tested in high-T_c superconductors.

Deliberate introduction of defects by ion irradiation has been shown to increase J_c in thin films of $YBa_2Cu_3O_{7-\delta}$ (Refs. 3 and 4) and more recently in crystals of the same material[5,6] and in $Bi_2Sr_2CaCu_2O_{8-\delta}$.[7] All of these experiments report a rise in critical current as a function of total beam fluence (ions/cm^2) followed by a decrease once the fluence is high enough to deteriorate the sample. It was also shown that heavier ions create much more damage than protons or neutrons,[6,7] as intuitively expected. In the present work we present *in situ* critical current and transition temperature data on single-crystal $Bi_2Sr_2Ca_1Cu_2O_{8-\delta}$ irradiated with 50-MeV $^{16}O^{+6}$ as a function of beam fluence. An elementary flux-pinning argument explains the features in our data.

The critical current (J_c) and transition temperature (T_c) were measured using a single-coil, noncontact method developed by Claassen, Reeves, and Soulen at the Naval Research Laboratory.[8] The T_c measurements were made by observing the small change in self-inductance of a coil on which the sample was placed, similar to susceptibility measurements.[9] To increase the sensitivity, we added a bridge circuit with a second coil at the same temperature as the sample, but without a sample placed on it. The difference in inductive signal between the two coils was measured with a lock-in amplifier. The critical temperature obtained by this procedure is quite accurately in agreement with four-probe resistivity measurements[10] (inset of Fig. 1). To measure J_c, we triple the frequency of the signal going to the coils and use this as a reference for the lock-in amplifier. We therefore measure the third-harmonic content of the signal as a function of drive current to the coils. A sudden onset of the third-harmonic component should occur once the induced current in the sample is above the critical current. We indeed observe this sudden onset and utilize it to measure the drive current required to induce the critical current in the sample (Fig. 1). Claassen, Reeves, and Soulen[8] showed that the drive current is proportional to the induced current in the sample with the propor-

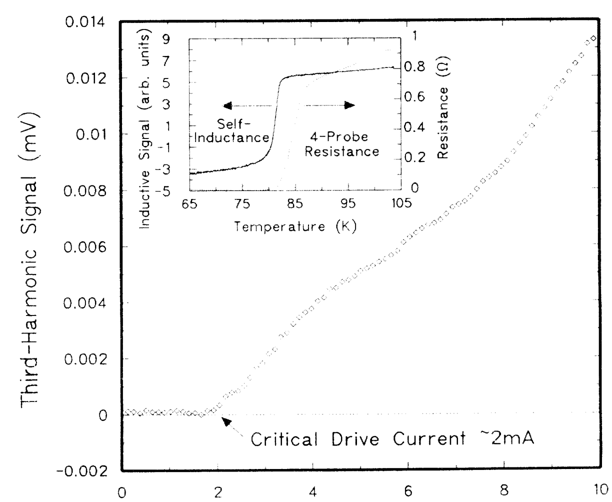

FIG. 1. Measurement of T_c and J_c. Main figure shows a typical measurement of the onset of third-harmonic component at the critical drive current. Inset compares a four-probe resistance measurement of T_c with the self-inductance measurement used in this study. The agreement is good.

tionality constant dependent only on the coil to sample distance and other geometrical factors. Thus any change we observe in the critical drive current is directly proportional to the change in J_c of the sample.

The samples were 1–3 mm^2 thinned single crystals of $Bi_2Sr_2Ca_1Cu_2O_{8-\delta}$ grown in our laboratory and heat treated in air using a process previously published.[11] The samples were placed on an approximately 200-turn coil and mounted on the cold finger of an APD Cryogenics Lt-3-110A Heli-Tran liquid transfer refrigerator. The temperature of the sample was measured and regulated by two Scientific Instruments diodes and an SI temperature controller. This refrigerator system was placed in the +30° beam line of the State University of New York at Stony Brook Nuclear Structure Laboratory's Tandem Van de Graaff accelerator.[12] A beam of $^{16}O^{+6}$ at 50 MeV was focused uniformly over the sample. The beam size was deliberately larger than the sample size to ensure the entire sample would be irradiated. Fixed beam currents, measured with a Faraday cup, of 2.5×10^{-13} A and higher were used to irradiate the sample variable amounts of time to obtain the fluences reported. The samples were maintained at 60 K during irradiations and all measurements were made *in situ* without warming the sample above 110 K.

Single-crystal samples were mounted with the *c* axis approximately parallel to the beam direction in order to create defects in a column perpendicular to the plane of superconductivity (the *a*-*b* plane). This will make stronger pinning sites for fields in the *c* direction since a longer portion of the flux lines will be confined by columnar pinning sites as opposed to point pinning sites. This pinning geometry should therefore be the optimal configuration for enhancing J_c. We made no measurements confirming that the damage was columnar, however electron micrographs of samples irradiated with higher energy and higher mass ions show columnar defects.[6,7]

An estimation of the energy loss for a 50-MeV $^{16}O^{+6}$ ion in $Bi_2Sr_2CaCu_2O_{8-\delta}$ was made. This beam has an effective range of ~13.4 mg/cm^2, whereas the sample of 2212, a few micrometers thick corresponds to ~3 mg/cm^2. Thus the beam loses ~10.8 MeV in passing through the sample, but *will not stop in the sample.* Consequently, we are *not* adding oxygen, but creating crystal defects.

The summary of results for J_c measured at several temperatures and T_c measurements is shown in Fig. 2. In the lower panel of Fig. 2, T_c is observed to remain a constant for beam fluences of up to $\sim1\times10^{13}$ ions/cm^2. Further irradiation causes a reduction in the T_c. J_c was measured at 80, 75, and at 60 K and is in the upper panel of Fig. 2. In all cases the critical current remained approximately constant for beam fluences of up to $\sim1\times10^{12}$ ions/cm^2. This is followed by a rise in J_c up to a peak corresponding to fluences of $\sim1\times10^{13}$ ions/cm^2 in all three temperature measurements. For higher beam fluences, J_c decreased steadily, similarly to the decrease in T_c.

These results can be simply interpreted by assuming the ions create defects in the sample which act as flux pinning centers. Once the number of pinning centers introduced is significant, J_c will go up. This is because the

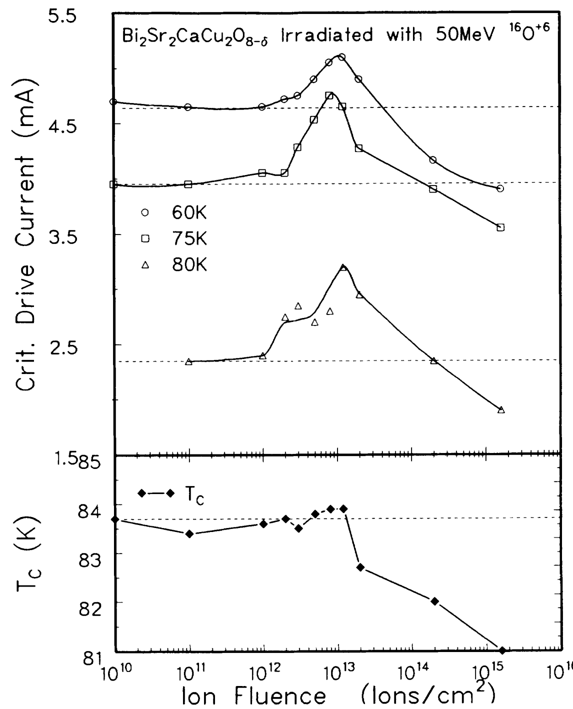

FIG. 2. Results of J_c and T_c as a function of ion fluence. The upper three curves show the critical current measured at 80, 75, and 60 K. All three show a rise followed by a fall in J_c. The lowest curve shows the T_c measurements made at the same time revealing that T_c is a constant while J_c increases, then decreases corresponding to the decrease in J_c.

magnetic field induced by supercurrents in the sample will be confined to more pinning sites, thus allowing for a higher magnetic flux, or equivalently a higher current before the flux lines move and the sample becomes resistive. The rest of the sample that is undamaged all around the new pinning sites remains superconducting with the same T_c. One theory that fits our results qualitatively is collective pinning theory.[13] The subsequent decrease in both J_c and T_c is phenomenologically explained by assuming the density of the defects becomes large enough to significantly affect the crystal properties, i.e., the sample begins to deteriorate. Thus measures of the crystal uniformity, such as T_c and J_c, will deteriorate as well. Assuming the ion damage is spread evenly and each ion creates one pinning channel, 1×10^{13} ion/cm^2 would produce pinning sites approximately 18 Å apart, or on the same order as the in-plane coherence length $\xi_{a,b}(0)$, estimated to be 9 Å (Ref. 14) to 22 Å.[15,16] Alternatively, the damage tracks due to the ions might begin to overlap at this distance resulting in a large portion of the crystal being in a disordered state. Thus it is sensible that the crystal properties will deteriorate for fluences above about 1×10^{13} ions/cm^2. Either explanation supports the assumption that the pinning sites produced under irradiation in our crystals are columnar.

In summary, we have observed an increase in J_c without a reduction in T_c in single-crystal $Bi_2Sr_2Ca_1Cu_2O_{8-\delta}$ irradiated with up to 1×10^{13} 50-MeV $^{16}O^{+6}$ ions/cm^2. Subsequent irradiation deteriorates the sample and T_c and J_c decrease.

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