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Peak Effect and Enhancement of the Critical Current Density by γ- Irradiation in a $TlBa_2Ca_2Cu_3O_x$ Superconductor

Ihab M. Obaidat[a*], Borhan A. Albiss[b] and Khalid A. Al-Khaza'leh[c]

[a]*Department of Physics, United Arab Emirates University, Al-Ain 17551, United Arab Emirates Email: IObaidat@uaeu.ac.ae*
[b]*Department of Physics, Jordan University of Science and Technology, Irbid 22110, Jordan*
[c]*Department of Physics, Al al-Bayt University, Mafraq, Jordan*

Abstract

We have investigated the effect of γ-irradiation on the transport properties of a $TlBa_2Ca_2Cu_3O_x$ polycrystalline superconducting sample under several values of applied magnetic field using the resistivity measurements and I-V characteristics. The polycrystalline sample was prepared by the conventional solid state reaction method, and irradiated at room temperature by a ^{60}Co γ-ray source at a dose rate of 0.5 MR/h. The critical temperature and the critical current density at all applied fields were measured before and after irradiation. We found that the γ-irradiation has a minor effect on the critical temperature. We also found that γ-irradiation plays different roles on the critical current density depending on the applied magnetic field and on the temperature. The peak effect of the critical current density also was observed at 0.1 Tesla.

Keywords: $TlBa_2Ca_2Cu_3O_x$ polycrystal; γ-irradiation; vortex pinning forces, Peak effect.

Introduction

Increasing the critical current density, J_c, in high-critical temperature (high-T_c) superconductors is one of the important goals that allows for their use in practical applications, especially in those that require high magnetic fields. High-T_c superconductors in magnetic fields of strength higher than H_{c1} and smaller than H_{c2} are known to be in the mixed state, where magnetic field penetrates them in form of quantized magnetic vortices. H_{c1} is the first critical magnetic field, below which no

field penetrates the superconducting sample. H_{c2} is the second critical magnetic field above which the sample becomes normal. A transport current density **J** in the sample produces a Lorentz force on the vortices $\mathbf{F}_L = (1/c)\ \mathbf{J}\times\mathbf{\Phi}_o$ trying to move them, where $\mathbf{\Phi}_o$ is the quantized magnetic flux per vortex and c is the velocity of light. If the Lorentz force is not opposed, the vortices will move with velocity **v** in a transverse direction to both **J** and **B**, thus inducing an electric field, $\mathbf{E} = (-1/c)\ \mathbf{B}\times\mathbf{v}$. The resulting dissipation of energy causes a non-zero effective resistance to appear in the superconductor. If a pinning force on the vortices prevents Lorentz force from moving them, they will be fixed in the material and no resistance will appear. Vortex pinning results from spatial inhomogeneities of the material (arising from impurities, grain boundaries, voids, etc.), which produces local reductions of the free energy of a flux line, thus attracting and holding vortices to these locations. The pinning of vortices in high-T_c of superconductors is fairly weak, especially at high temperatures [1]. Hence there has been considerable interest in increasing the vortex pinning forces by various sample treatments, especially using various energetic radiations.

The effects of energetic radiations on solids have been under intensive study for a little more than one hundred years. The mass of accumulated information is enormous but the number of well-established principles is less impressive. Radiation effects are caused primarily by alteration in the structure of the lattice, and the study of radiation effects have been mainly an attempt to resolve these alterations into a moderate number of lattice defects, and to elucidate the properties of these defects.

The effect of different types of irradiation on high-T_c superconductors has been investigated since irradiation produces structural defects that act as effective pinning sites. Irradiation by neutrons, [2], protons, [3], electrons, [4], γ-rays, [5], and heavy ions [6] has been very successful in this respect. However, more detailed temperature dependence of vortex pinning before and after irradiation will provide more information.

Recent magnetic measurements on non-irradiated $YBa_2Cu_3O_7$ (YBCO) crystals [1] and on $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_{10}$ (BPSCCO) polycrystals [5] revealed that the detailed variation of the vortex pinning strength with temperature consists of two distinct components, one of which decreases very rapidly with increasing temperature at low temperature, while the other continues to diminish gradually as the temperature rises towards T_c. This behavior suggests that there are two different types of pinning sites which vortices face, localized defects and extended defects.

Magnetic measurements on similarly prepared (BPSCCO) polycrystal showed the same two-component behavior after γ-irradiation at room temperature by a ^{60}Co γ-ray source with a dose of 100 MR as before irradiation. This indicates that the primary effect of γ-irradiation is the enhancement of the low-temperature component which decays rapidly with increasing temperature. This suggests that γ-irradiation produces localized defects which are effective vortex pinning centers at low temperatures. More recent magnetic study on Pb-ion irradiated melt-textured $YBa_2Cu_3O_x$ crystals [7] showed that vortex pinning is greatly enhanced by the Pb-ion irradiation at all temperatures below T_c. This result implies that the Pb-ion irradiation creates extended structural defects, which are effective as pinning centers up to relatively high temperatures.

Revealing the influence of different types of crystal-lattice disorder on the properties of high-T_c superconductors is essential for a fundamental understanding of their nature. Typically, two types of crystal-lattice disorder in superconductors are investigated. The first type is microscopic associated with atomic scale defects such as vacancies and impurities. The second type of crystal-lattice disorder is macroscopic associated with structural inhomogeneities of the superconductors such as granular structure [8]. There are still some contradictions in our understanding of the influence of γ-irradiation on the properties of high-T_c superconductors, were it was reported that γ-irradiation might increase or decrease the critical temperature as well as the critical current density [9-12].

To understand the effect of γ-irradiation on the temperature dependence of the critical current density J_c, we have conducted transport measurements on a $TlBa_2Ca_2Cu_3O_x$ polycrystal before and after irradiation. Our study avoids structural discrepancies between samples since it has been done on the same sample. Since our interest in this $TlBa_2Ca_2Cu_3O_x$ superconductor is in increasing its vortex pinning force at elevated temperatures, this study was conducted in temperature range from 80 to 105 K. In section 2 of this paper, we present our experimental setup and the details procedures followed in obtaining the data. In section 3, we present our data and discuss these results by comparing them to the most recent reports on this topic. In section 4, we summarize and conclude our results.

Experimental details and procedures

Our sample with nominal composition $TlBa_2Ca_2Cu_3O_x$, was prepared using the solid-state reaction method. It was cut in a rectangular shape with dimensions 8×4×0.1 mm^3. The R-T curves and I-V characteristics were measured using the standard dc four-probe method with magnetic field applied parallel to the surface of the sample. I-V characteristics were investigated over temperature range of 80 -105 K in zero, 0.1 τ, and 0.2 τ applied magnetic fields (τ stands for Tesla). The critical current densities were determined using an electric field criterion of 1μV/cm. The temperature was measured with a calibrated platinum resistance sensor with an accuracy of ± 0.1 K. The probes were fixed with silver paste to the rectangular – shaped sample. In all measurements, the sample was first zero-field cooled down to 80 K. At zero applied magnetic field, the temperature was increased in steps of 5 K up to 105 K. At each of these temperature values, the I-V characteristics were measured. The sample was again zero-field cooled down to 80 K, and then a magnetic field of 0.1 τ was applied. The temperature then was raised in steps of 5 K up to 105 K, where the I-V characteristics were measured at each of these steps. The same procedure was repeated at 0.2 τ. After all the R-T and I-V measurements were made at all applied fields, γ-irradiation of the sample was done at room temperature by a ^{60}Co γ-ray source at a dose rate of 0.5 MR/h. All the measurements were repeated on the sample after irradiation.

Results and discussion

From the R-T measurements we have found that critical temperature T_c, at 0.0 τ, 0.1 τ, and 0.2 τ was 125 K, 120 K, and 115 K respectively. These values increased very slightly after γ-irradiation dose of 50 MR.

Fig. 1 summarizes our results of the effect of γ-irradiation of a dose of 50 MR on the critical current density as a function of temperature at all applied fields. The temperature dependence of current density J_c at all values of applied magnetic field before γ-irradiation is represented by solid lines in the figure. As expected, it is clear from this figure that J_c decreases with increasing temperature at all applied fields. From a log-log graph of J_c and $(1-T/T_c)$ we found that J_c is proportional with $(1-T/T_c)^{\beta}$ where $\beta = 6.5$ at 0.0 τ, and 2 at 0.1 τ through the whole temperature range. At 0.2 τ we can identify two-component behavior of J_c. At low temperatures ($T/T_c \leq 0.77$), J_c decreases very fast with increasing temperature with $\beta = 6$. At high temperatures ($T/T_c > 0.77$), J_c decreases slowly and linearly with increasing temperature with $\beta = 1$. The figure also shows that at 0.2 τ the values of J_c approach those at 0.0 τ, indicating that at high temperatures the magnetic field has almost no effect on the critical current density. From the figure we also can see that due to the very slow decrease of J_c at 0.1 τ, its values remain larger than those at 0.0 τ at high temperatures, which is not expected.

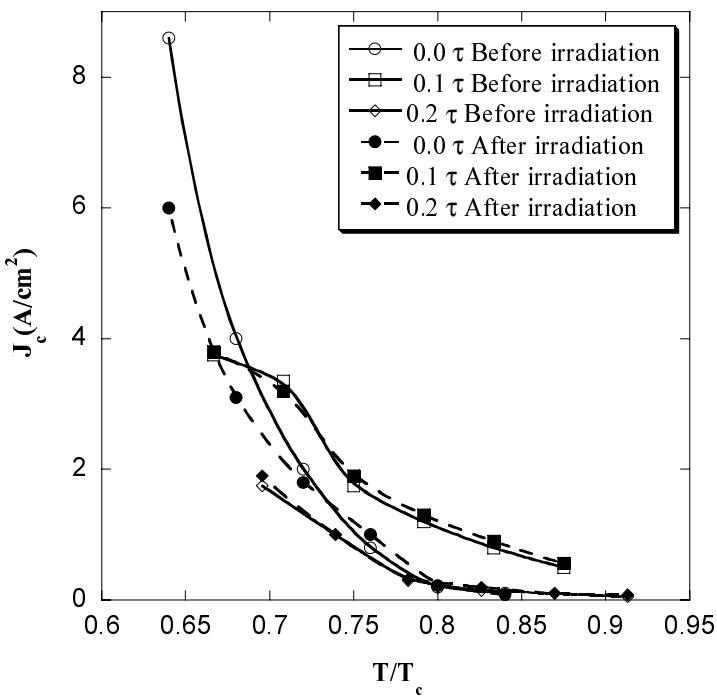

Figure 1. Temperature dependence of the current density J_c, at 0.0, 0.1, and 0.2 τ applied magnetic fields before and after 50 MR dose of γ-irradiation.

The behavior of J_c with temperature at all applied fields after γ-irradiation of a dose of 50 MR is represented by the dashed lines in the figure. It is clear that J_c behaves qualitatively similar to that before irradiation. We still see the one-component behavior at 0.0 τ and 0.1 τ with β = 6 and 1.5 respectively. At 0.2 τ, J_c has two components; One at low temperatures ($T/T_c \leq 0.77$), with β = 6 and the other at high temperatures ($T/T_c > 0.77$), with β = 1. The values of J_c at 0.2 τ are nearly equal to those at 0.0 τ, as was shown before irradiation. At high temperatures, the values of J_c at 0.1 τ become larger than those at 0.0 τ, which is similar to the situation before irradiation. The unexpected larger values of J_c at 0.1 τ compared to those at 0.0 τ before and after irradiation through most of the temperature range is a manifestation of the peak effect of the critical current density [13, 14], suggesting that 0.1 τ could be the matching field for our sample.

The influence of γ-irradiation at the dose of 50 MR on pinning the vortices in the sample can be more clarified by focusing on the J_c versus temperature curves before and after irradiation at each specific value of the applied magnetic field. From the figure, we see that the effect of γ-irradiation at 0.0 τ and 0.1 τ is to slow down the rate of decrease of J_c with increasing temperature. The effect of decreasing the values of J_c can be explained by saying that the grain boundaries in this granular high-T_c superconducting sample became more efficient in depressing J_c by this dose of γ-irradiation. The influence of these weak links is known to depress J_c strongly with increasing the applied field. But as shown in the figure, the slightly larger values of J_c after irradiation at 0.2 τ and at low temperatures could be a sign of point-like defects caused by the 50 MR dose of γ-irradiation. This result confirms our previous results on BPSCCO polycrystals [5].

Conclusion

We have measured the peak effect of the critical current density for this sample at the applied field 0.1 τ. We have found that at magnetic fields 0.0 τ and 0.1 τ, γ-irradiation at a dose of 50 MR suppressed the values of the critical current density through out the whole temperature range. However, the considerable effect of this dose of γ-irradiation at those fields was to slow down the rate of decrease of the critical current density as the temperature increases through out the whole temperature range. At the applied field of 0.2 τ, γ-irradiation at a dose of 50 MR was found to have a remarkable effect only at low temperatures where it slightly enhanced the values of the critical current density. These important effects suggest that γ-irradiation at a dose of 50 MR produced mostly localized point-like defect sites. These localized point-like defects are considered to be effective pinning sites only at low temperatures.

References

[1] Obaidat, I. M, Goeckner, H. P. Kouvel, J. S., "*Vortex pinning in a rotated $YBa_2Cu_3O_{7-\delta}$ crystal*", Physica C 291, (1997), pp. 8-16.

[2] Vlcek, B. M., Viswananthan, H. K., Frischherz, M. C., Fleshler, S., Vandervoort, K., Downey, J., Welp, U., Kirk, M. A., Crabtree, G. W., "*Role of point defects and their clusters for flux pinning as determined from irradiation and annealing experiments in $YBa_2Cu_3O_{7-\delta}$ single crystals*", Phys. Rev. B, 48, (1993), pp. 4067-4073.

[3] Civale, L., Marwick, A. D., McElfresh, M. W., Worthington, T. K., Malozemoff, A. P., Holtzberg, F. H., Kirk, M. A., "*Defect independence of the irreversibility line in proton-irradiated Y-Ba-Cu-O crystals*", Phys. Rev. Lett., 65, (1991), pp. 1164-1167.

[4] Giapintzakis, J., Lee, W. C., Rice, J. P., Ginsberg, D. M., Robertson, I. M., Kirk, M. A., Wheeler, R., "*Production and identification of flux-pinning defects by electron irradiation in $YBa_2Cu_3O_{7-x}$ single crystals*", Phys. Rev. B, 45, (1992), pp. 10677-10683.

[5] Hasan, M. K., Albiss, B. A., Obaidat, I. M., Park, S. J., Kouvel, J. S., "*Temperature dependence of the vortex pinning enhancement by γ irradiation of $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_{10}$ polycrystals*", Physica C, 336, (2000), pp. 75-79.

[6] Xu, M., Ostenson, J.E., Finnemore, D. K., Kramer, M. J., Fendrich, J. A., Hettinger, J. D., Welp, U., Crabtree, G. W., Dabrowski, B., Zhang, K., "*Comparison of superconducting flux pinning due to ion irradiation and fishtail effects*", Phys. Rev. B, 53, (1996), pp. 5815-5817.

[7] Goeckner, H. P., Olson, R. J., Kwok, W. K., Claus, H., Kouvel, J. S., "*Effects of Pb-ion irradiation on the vortex pinning in melt-textured $YBa_2Cu_3O_x$*", Physica C, 390, (2003) pp. 291-295.

[8] Belevtsev, B.I., "*Superconductivity and localization of electrons in disordered two-dimensional metal systems*", Sov. Phys. Usp., 33, (1990), pp. 36-38.

[9] Kato T. et. al, "*Radiation Effect of $YBa_2Cu_3O_{7-y}$ Irradiated by γ –Rays and 14 MeV Neutrons*", Jap. J. Appl. Phys, 27, (1988), pp. L2097-L2099.

[10] Kutsukake T. et. al, "*Gamma-Irradiation Effect on High-T_c Superconductor $YBa_2Cu_3O_{7-x}$*", Jap. J. Appl. Phys, 28, (1989), pp. L1393-L1394.

[11] Ozkan H. et. al, "*Effect of gamma irradiation and silver doping on YBCO superconductor*", J. Supercond., 7, (1994), pp. 885-888.

[12] Belevtsev, B. I., Volchok, I. V., Dalakova, N. V., Dotsenko, V. I., Ivanchenko, L. G., Kusnichenko, A. V. and Logvinov, I. I., "*Effect of γ-irradiation on superconducting transition temperature and resistive transition in polycrystalline $YBa_2Cu_3O_{(7-\delta)}$*", Physica C 341-348, (2000), pp. 2015-2016.

[13] Smith, A. W., Jaeger, H. M., Rosenbaum, T. F., Kwok, W. K., and Crabtree, G. W., "*Bose glass melting and the transverse Meissner effect in $YBa_2Cu_3O_{7-\delta}$ single crystals*", Phys. Rev. B, 63, (2001), pp. 064514-064522.

[14] Creffield, C. E. and Rodriguez, J. P., "*Optimum pinning of the vortex lattice in extremely type-II layered superconductors*", Phys. Rev. B, 67, (2003), pp. 144510-144515.