Shift of the surface-barrier part of the irreversibility line due to columnar defects in Bi$_2$Sr$_2$CaCu$_2$O$_8$ thin films

Yu. Talanov
Zavoisky Physical-Technical Institute, 420029, Kazan, Russia

H. Adrian, M. Basset, G. Jakob
Johannes Gutenberg-Universität, Institut für Physik, D-55099 Mainz, Germany

G. Wirth
Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany

Abstract

In the present work we report the results of studying the influence of the uranium-ion irradiation of the Bi$_2$Sr$_2$CaCu$_2$O$_8$ thin films on the high-temperature part (close to $T_c$) of their irreversibility line. We studied irreversible properties of the films by measuring the hysteresis of nonresonant microwave absorption. The results have revealed the shift of irreversibility line towards low temperatures and magnetic fields. The effect is most significant for the films irradiated with large doses, $B_\Phi > 1$ T. This fact is in good agreement with the theoretical prediction by Koshelev and Vinokur of suppression of surface barrier by columnar defects.
I. INTRODUCTION

It is well known that in some high-T_c superconductors intrinsic (natural) pinning centers have rather little efficiency. They can not support undissipative current flow with large enough density. In crystals and films of Bi_{2}Sr_{2}CaCu_{2}O_{8} the critical current density is very low in a wide area of magnetic field and temperature, from \( \sim 0.5T_c \) to \( T_c \) (see for example [1, 2]). In this area the surface or edge barriers of different types can manifest themselves. They prevent the entry and exit of vortices and consequently provide for the magnetic flux trapping.

To increase pinning the various artificial pinning centers are created in a superconductor. The most effective among them are defects of columnar shape. They are generated by irradiating the material in a beam of heavy ions accelerated up to high energy, \( \sim 1 \text{ GeV} \) (see [8] and references therein). It has been shown in many publications that columnar defects (CD) have a large pinning potential and enlarge the critical current density (see for example [3, 4]). The creation of CD in the Bi_{2}Sr_{2}CaCu_{2}O_{8} crystals leads to the shift of irreversibility line (IL) towards high magnetic fields and temperatures (see for example [5, 6]).

However the effect of columnar defects is not always straightforward. Sometimes the inverse influence of CD on superconducting properties is observed. An example of such influence has been presented in the work by J.K.Gregory et al. [7]. They have found the decrease of the penetration field in Bi_{2}Sr_{2}CaCu_{2}O_{8} whiskers after electron and heavy ion irradiation. The authors had attributed this effect to the suppression of surface potential barriers due to the CD creation near the superconductor surface.

The theoretical discussion of the mechanism of the surface barrier reduction under the CD production was presented by A.E. Koshelev and V.M. Vinokur [8]. In accordance with this discussion, CD near a surface of superconductor change the interaction of pancake vortices with a shielding current and with their mirror images. Firstly, CD serve as obstacles for the shielding current and change its density. Secondly, additional vortex images are formed behind the column surface. Both these circumstances make vortex penetration easier and thereby reduce the surface barrier.

The studies of magnetization of the Bi_{2}Sr_{2}CaCu_{2}O_{8} whiskers irradiated by electron and Pb-ion beams with comparison with that of pristine samples [7] have shown the decrease of both the penetration field and the irreversible magnetization after irradiation. As in
accordance with previous studies the magnetic properties in Bi$_2$Sr$_2$CaCu$_2$O$_8$ whiskers are dominated by surface effects, the penetration field decrease was attributed to the suppression of surface barriers by CD. But after irradiation the bulk pinning becomes remarkable and contribute to a sample magnetization, which was measured in the work. It is impossible to separate contributions of surface barrier and bulk pinning in such type of measurements.

In our study we use another technique, namely, a registration of the hysteresis loop of microwave absorption (MWA). This method allows one to separate contributions of bulk pinning (BP) and of surface pinning (SP) by the shape of loop. The present study of the irreversibility line in the Bi$_2$Sr$_2$CaCu$_2$O$_8$ thin films irradiated with heavy ions confirms the suggestion of Ref.[7] and the theoretical estimates of suppression of surface barrier by columnar defects. The results of measurements of hysteretic microwave absorption have shown that in the films irradiated with $^{238}$U-ions the high temperature part of irreversibility line, which is due to surface barrier, shifts towards low temperature and magnetic field.

II. EXPERIMENTAL

The Bi$_2$Sr$_2$CaCu$_2$O$_8$ films were prepared on a LaAlO$_3$ substrate with sputtering technique as described in Ref.[10]. They are of 200 nm thickness and have the superconducting transition temperature near 85 K. They were irradiated with $^{238}$U ions in the accelerator facility of the Gesellschaft für Schwerionenforschung in Darmstadt. The irradiation doses, expressed in the dose-equivalent matching field $B_\Phi$, were varied from 0.3 to 3 T. The superconducting transition shifts towards low temperature and broadens after irradiation of the films. The shift increases with the irradiation dose. The transition temperature of the film irradiated with dose $B_\Phi = 2$ T equals 78 K.

We studied irreversible properties of films by measuring the hysteresis of nonresonant microwave absorption. The detailed description of this method one can find in Refs.[11, 12]. This method is sufficiently sensitive to enable the investigation of magnetic irreversibility of very thin superconducting films. Moreover it allows one to separate contributions of bulk pinning and of surface pinning by the shape of the hysteresis loop. The measurements were performed in the high-temperature area, close to $T_c$, where the surface pinning contribution became remarkable.

The ESR-spectrometer BER-418s (Bruker) with the working frequency of 9.4 GHz (X-
band) was used to measure the microwave absorption of superconducting thin films. A sample was placed into the spectrometer cavity inside the helium gas-flow cryostat. Its orientation was as follows: the applied DC field $H_a$ was perpendicular to the film plate (parallel to c-axis), and the microwave field $h_1$ was in the film plane. A DC field was modulated with a frequency of 100 kHz and an amplitude from 0.1 to 10 Oe. To record the MWA hysteresis loop $H_a$ was swept with a velocity of $\sim 20 \div 40$ Oe/s from cooling field $H_i$ to $H_i + \Delta H$ and back ($\Delta H = 100 \div 5000$ Oe). To avoid the instrumental error of detected hysteresis the signal of electron spin resonance (ESR) of paramagnetic substance DPPH (diphenylpicrylhydrazyl) is recorded along with the MWA hysteresis loop. The points of the irreversibility line $H_{ir}(T)$ were obtained by registration of the field at which the MWA hysteresis collapsed.

III. RESULTS AND DISCUSSION

Previously we had found that both the shape of the MWA hysteresis loop and its dependence on modulation amplitude were governed by the vortex matter state and by the type of pinning: bulk or surface \[12\]. One can exploit these properties of the MWA loop to locate the phase diagram areas with predominance of bulk pinning or surface barrier. In Fig.1 the MWA hysteresis loops obtained on the pristine Bi$_2$Sr$_2$CaCu$_2$O$_8$ film B1711 at different temperatures are shown. At low temperatures ($T \leq 50$ K) the loop shape corresponds to bulk pinning only \[11, 12\]. At high temperatures, close to $T_c$, (Fig.1d) the loop has the shape, which is due to surface barrier \[12\]. Here the point of irreversibility line ($H_{ir}(72$ K) $\simeq 400$ Oe) is determined by surface pinning. At intermediate temperatures the mixture of these two types of the hysteresis is observed (Fig.1d). At $T = 60$ K the small addition of "surface loop" to the main loop, which is due to bulk pinning, occurs in low field. The hysteresis disappears at $H_a \simeq 5000$ Oe, and the boundary of irreversibility is determined by the bulk pinning. At $T = 65$ K (Fig.1d) the contributions of bulk pinning and surface one are approximately equal to each other.
FIG. 1: MWA hysteresis loops obtained on the pristine Bi$_2$Sr$_2$CaCu$_2$O$_8$ film B1711 at different temperatures: (a) $T = 25$ K, the loop shape is of purely "bulk pinning type"; (b) $T = 60$ K, the small addition of the loop of "surface pinning type" is seen in low fields, while in high fields "the bulk pinning loop" predominates and determines $H_{ir}(T)$; (c) $T = 65$ K, the contributions of BP and SP to the MWA hysteresis are compatible; (d) $T = 72$ K, the hysteresis is due to surface barrier only and $H_{ir} \simeq 400$ Oe. The ESR signal of a small piece of DPPH is seen on loops $H_{a} \simeq 3300$ Oe in the panels (b) and (c).

When both types of pinning contribute to a hysteresis we use the difference of their dependence on the field modulation amplitude in order to separate one contribution from another. In Fig. 2a it is shown the change of a loop shape with increasing the modulation amplitude $h_m$ from 0.4 to 8 Oe. At small $h_m$ SP contributes remarkably in the low field range ($H_a < 200$ Oe), and BP predominates in higher fields. At $h_m = 8$ Oe the BP contribution is fully eliminated. A shape of hysteresis loop is of "pure surface type" over whole field range from 0 to $H_{ir} \simeq 900$ Oe. So this field corresponds to the boundary of existing the surface
barrier, and the irreversibility field has to be denoted as $H_{ir}^{SP}$, that is due to surface pinning.

![Diagram](image)

**FIG. 2:** (a) The shape of the MWA hysteresis loop in the film B1712 irradiated with the dose $B_{\Phi} = 0.3$ T at two magnitudes of modulation amplitude, 0.4 Oe and 8 Oe, $T = 62$ K. Dashed vertical lines indicate fields, at which the dependence $L(h_m)$, shown below, is measured. The arrow points out the field at which the hysteresis disappears. (b) The dependence of hysteresis value on modulation amplitude obtained at two magnitudes of applied field, (■) – 100 Oe and (○) – 1000 Oe. Solid straight line and dashed exponential decay are drawn to illustrate the different character of the dependence in two cases discussed.

The lower part of Fig. 2 shows the dependence of the hysteresis magnitude $L$ on the modulation amplitude $h_m$ for two values of applied field: a low field $H_a = 100$ Oe, where the SP contribution is considerable at any $h_m$, and a higher field $H_a = 1000$ Oe, where the BP prevails at small $h_m$. It is seen that at $h_m > 0.3$ Oe the surface contribution increases almost linearly. In order to emphasize this fact the straight line is drawn along the points
of $H_a = 100$ Oe. However, the bulk pinning contribution drastically reduces with increasing modulation amplitude. The curve of exponential decay is added for comparison. Thus if one applies the modulation amplitude $h_m \sim 10$ Oe, it is possible to exclude the bulk pinning contribution and to investigate the dependence of $H^{SP}_{ir}$ on temperature and the irradiation dose.

FIG. 3: (a) The temperature dependence of the irreversibility field due to surface pinning $H^{SP}_{ir}(T)$ for three samples: (■) – pristine film, (◊) – film irradiated with small dose ($B_\Phi = 0.3$ T), (○) – film irradiated with large dose ($B_\Phi = 2$ T). (b) The dependence of the irreversibility field on reduced temperature for the pristine film (■) and film irradiated with dose $B_\Phi = 2$ T (○).

The points of irreversibility line $H^{SP}_{ir}(T)$ are shown in Fig. 3 for three films, one is pristine and two films ion-irradiated with various doses, 0.3 T and 2 T. It is clearly seen that IL shifts toward lower magnetic fields after irradiation. The effect is more pronounced in the
film with large irradiation dose.

To take into account the shift of the superconducting transition temperature $T_c$ after the ion irradiation the IL points of two samples are plotted versus reduced temperature $T/T_c$ in Fig. 3b. The shift of the IL of irradiated film looks not so considerable with this axis as in Fig. 3a, but it is unambiguous.

The shift of the "surface" irreversibility line towards the area of low temperatures and magnetic fields indicates that the surface barrier is weakened upon the creation of columnar defects under the heavy-ion irradiation. This fact is in qualitative agreement with the theoretical prediction [8]. Unfortunately, it is impossible to make quantitative comparison of our experimental data with the theoretical calculation since only the changes of the penetration field were estimated in paper [8], but not the irreversibility field. To estimate the decrease of the surface potential barrier under the CD generation quantitatively the comparison of the theoretically calculated IL shift with the experimental results is needed. This might be a subject of future publication.

IV. CONCLUSION

Thus, using the method of hysteretic microwave absorption measurements and its dependence on the applied magnetic field modulation we could isolate the contribution of surface pinning and watch the changes of the irreversibility line with increasing the dose of irradiation of the Bi$_2$Sr$_2$CaCu$_2$O$_8$ thin films with uranium ions. In agreement with the theoretical prediction [8], the suppression of surface barrier by columnar defects has been found. It manifests itself as the shift of irreversibility line towards low temperature and magnetic field. The effect is most significant for the films irradiated with large doses, $B_\Phi \geq 1$ T.

Acknowledgements

This work was performed in the frame of Joint Program for scientific collaboration between Russian Academy of Science and Deutsche Forschungsgemeinschaft. The work was partially supported by the Russian Ministry of Industry and Science under State Contract No. 40.012.1.1.1356, Russian Foundation for Basic Research (grant No. 03-02-96230) and
the NIOKR Fund of the Academy of Sciences of Tatarstan through grant No. 06-6.2-234 (Yu.T.).

[1] L. Klein, E. R. Yacoby, Y. Yeshurun, M. Konczykowski, K. Kishio, Phys. Rev. B 48 (1993) 3523.
[2] P. Wagner, F. Hillmer, U. Frey, H. Adrian, Phys. Rev. B 49 (1994) 13184.
[3] L. Civale, Supercond. Sci. Technol. 10 (1997) A11.
[4] Y. Kazumata, H. Kumakura, K. Togano, Phys. Rev. B 54 (1996) 16206.
[5] Konczykowski M., Chikumoto N., Vinokur V.M., Feigelman M.V., Phys. Rev. B. 51 (1995) 3957.
[6] Zech D., Lee S.L., Keller H., Blatter G., Janossy B., Kes P.H., Li T.W., Monovsky A.A., Phys. Rev. B 52 (1995) 6913.
[7] J. K. Gregory, M. S. James, S. J. Bending, C. J. v. d. Beek, M. Konczykowski, Phys. Rev. B 64 (2001) 134517.
[8] A. E. Koshelev and V. M. Vinokur, Phys. Rev. B 64 (2001) 134518.
[9] S. Aukkaravittayapun and P. J. King and K. A. Benedict and Y. I. Latyshev and I. G. Gorlova and S. Zybtsev and A. Campbell and R. A. Doyle and J. Johnson and W. S. Seow, Physica C 270 (1996) 123.
[10] P. Wagner, F. Hillmer, U. Frey, H. Adrian, T. Steinborn, L. Ranno, A. Elschner, I. Heyvaert, Y. Bruynseraede Physica C 215 (1993) 123.
[11] Shaposhnikova T., Vashakidze Yu., Khasanov R., Talanov Yu., Physica C 300 (1998) 239.
[12] Shaposhnikova T., Talanov Yu., Vashakidze Yu., Physica C 385 (2003) 383.