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IRRADIATION EFFECTS IN YBCO THIN FILMS

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Oxide superconductors are very sensitive to electron or ion beam irradiation/ implantation. In the past 19 years after high-T_c (HT_c) superconductivity was discovered in these materials, many aspects of interactions of accelerated particles with HT_c thin films were investigated. In this paper short review of most significant phenomena is given, especially of those important for electronic applications (controllable reducing of critical temperature and critical current density) and their applications for HT_c films patterning, fabrication of HT_c Josephson junctions and SQUIDs. Some new results in creating 3-d inhomogeneous regions in YBCO superconductors by ion irradiation/implantation and investigation of high harmonic generation in YBCO film modified by 100 keV oxygen ions are presented.

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1. Introduction

Ion implantation / irradiation is a key and very well established technology in the semiconductor industry today. Fabrication of modern integrated circuits use dozens of implantation steps for forming transistors, vias, resistors and capacitors. In the superconducting electronics, however, this powerful tool is seldom use. There are many reasons for this. Probably the most important one is that active elements of the low-T_c superconducting electronics – Josephson tunnel junctions based on Nb-AlO_x-Nb technology are so perfect, that it is not necessary to use anything else as a simple oxidation and photolithography. There is only one exception. In 1975 Harris [1] succeded in fabrication of low-T_c Josephson junctions by ion implantation. As stated already above these junctions could not compete with the existing tunnel junctions.

In the HT_c superconductors the situation is quite different. Until now, almost 19 years after the discovery of high-T_c superconductivity in oxide materials it is not possible to fabricate tunnel junctions from these materials. The reason are the poor interface properties of the complicated oxide superconducting material. Therefore already 1990 [2] we tried and succeeded in fabrication of Josephson junctions and SQUIDs from high-T_c YBCO films using accelerated electrons or oxygen ions. Since then continuous progress and improving of the ion modified HT_c electronic devices was made.

In this paper we briefly summarize the most significant irradiation effects in high-T_c superconductors. Some recently investigated phenomena are presented as well. However, chemical effects like "poisoning" of the oxide superconductors by the implanted ions [3] will be not considered here.

2. Irradiation effects in HT_c superconductors

Modification of high-T_c superconductors with accelerated particles influences practically all properties of these materials. For the superconducting electronics applications the most important

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are two phenomena: depressing of the superconducting transition temperatute T_c and reducing of the critical current density j_c. Both phenomena are significant for fabrication of Josephson junctions, where a “weak link” between the two superconducting electrodes should be created. In order to use irradiation effects in oxide superconductors, it is necessary to be able to calculate and predict first the critical temperature dependence on the irradiation parameters. Such dependence was found by Summers et all. [4] who noticed that practically for all irradiation species from electrons up to heavy ions, an universal curve exists for all oxide superconductors. The shift of the critical temperature caused by the irradiation is directly proportional to the nonionizing energy loss (NIEL) of the incident particles over a wide range of particles and energy. Fig. 1 shows this proportionality between $dT_c/d\Phi$ and NIEL. This result means that the particle induced depression of T_c is due to atomic displacements. The atomic displacements can be calculated, however, very reliable using one of the well known Monte-Carlo computer programs like TRIM (SRIM) [5]. By TRIM program and the link between $dT_c/d\Phi$ and NIEL we succeeded in prediction of T_c reducing for every kind of ion, energy and dose [6-7]. Fig. 2 shows an example of such calculation for three implantation steps with different energies and doses. The calculated critical temperature is in very good agreement with our experimental results.

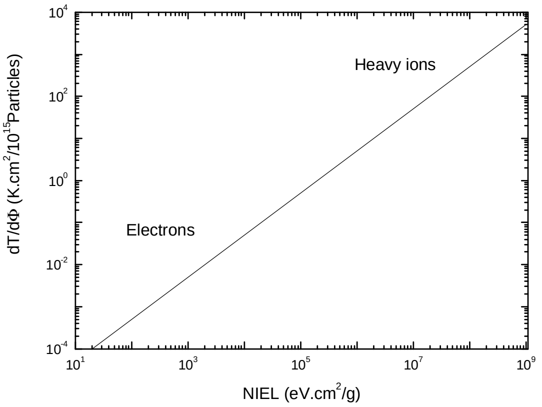


Fig. 1. Dependence between the critical temperature reduction and the nonionizing energy loss (NIEL) of the incident particles.

Of course if the irradiation parameters are chosen correctly, one can even convert the irradiated area into a normal state, thus making film patterning without material removing. DC SQUIDS fabricated by this method were first fabricated by Koch et al. [8].

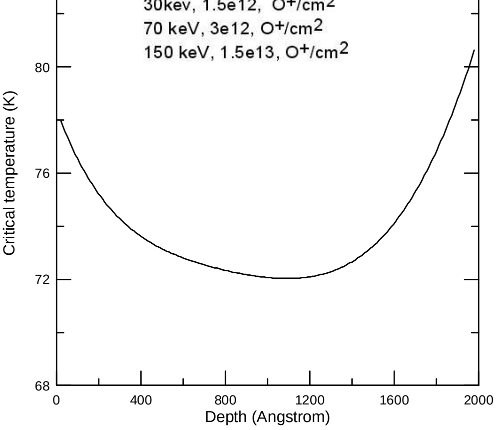


Fig. 2. Calculation by the TRIM program of the critical temperature for three implantation steps with different energies and doses.

Moreover linking the dependence between $dT_c/d\Phi$ and NIEL with the diffusion equation one can calculate the annealing effects, which are very important after every ion beam treatment. Fig. 3 shows for example one irradiation profile and its change after 20 min annealing at temperatures between 150 °C and 300 °C.

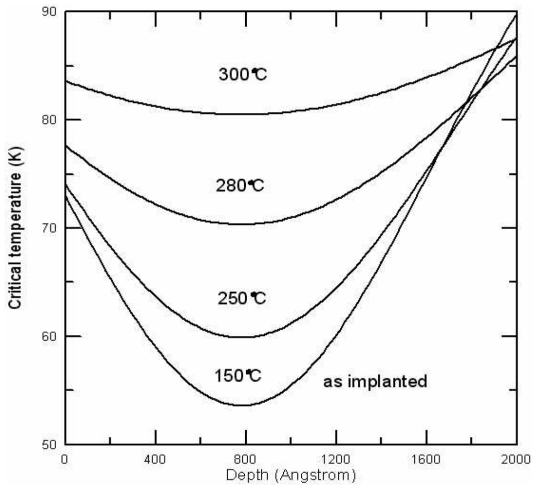


Fig. 3. Calculated critical temperature profile and its change after 20 min annealing at temperatures between 150 °C and 300 °C

Using oxygen ions we were successful in the fabrication of Josephson junctions and SQUIDs operating at liquid nitrogen temperature [9]. Other groups also applied this techniques using other kind of ions Ar, Ne or H [10-12]. Recently [13] a series ten-junctions arrays were made with 10-20 % spread of the junction parameters (I_c and R_N) over the chip. Although some problems, like long term stability of these junctions remain to be solved, one believe that ion modified HT_c Josephson junctions are good candidates to form large numbers of junctions in series arrays that can function at 77 K for quantum voltage standards and other applications.

3. High harmonic generation in inhomogeneous HT_c thin films

Using ion modification one can create not only 2-dimensional but also 3-d structures in HT_c materials. In such inhomogeneous structures, however, new phenomena are observed. Recently we observed peculiarities in high harmonic generation of YBCO thin films modified inhomogeneously by oxygen ions. While in homogeneous samples (Fig. 4a) high harmonics decrease monotonically with its increasing number, in inhomogeneous samples some harmonics rise and other are depressed (Fig. 4b,c). In order to explain this behavior let us consider a case when a thin superconducting strip is placed in perpendicular DC magnetic field. This is a typical geometry of many experiments with HT_c superconductors. If the magnetic flux is below so called lower critical field H_{c1}, the film is entirely superconducting and the field induces screening currents in the film. These screening currents flow in large loops, which are approximately parallel to the film edges (Fig. 5a).

When the external magnetic field exceeds the H_{c1}, the magnetic field begins to penetrate into the film starting from the film edges generating magnetic flux vortices (Fig. 5b). Each vortex consist of a normal core, surrounded by a circulating supercurrent. As the applied field increases, the vortices get closer and closer until they overlap at the upper critical field H_{c2}. The vortices density and the penetrating field *B* decreases lineary from the edge of the film, as illustrated in Fig. 6a.

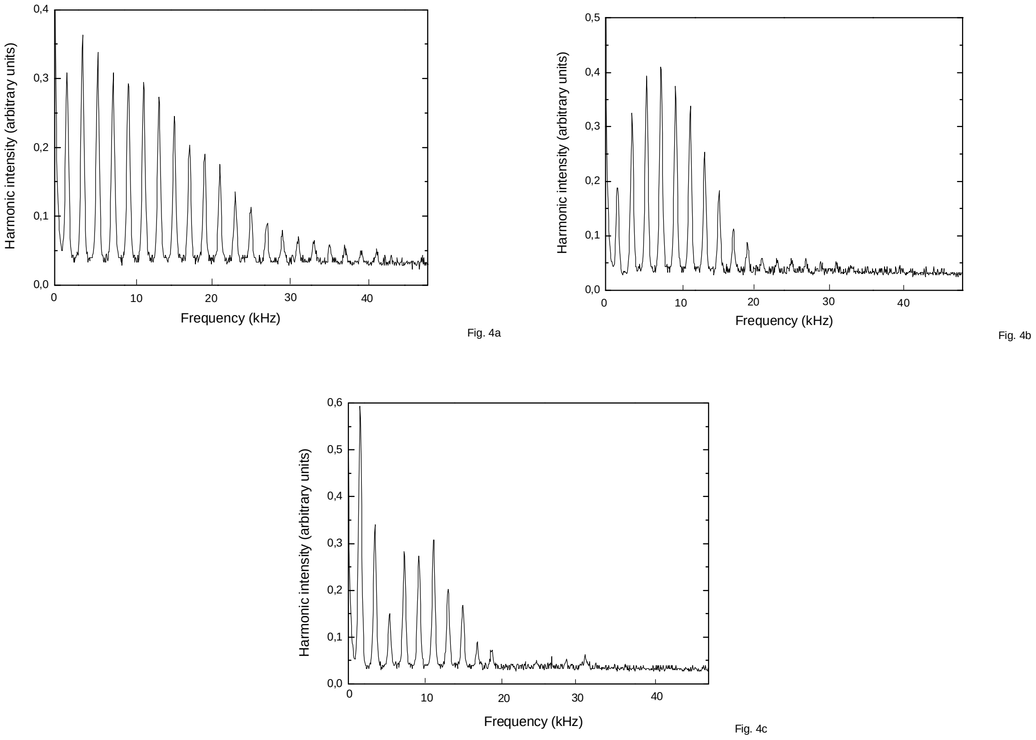


Fig. 4a

Fig. 4b

Fig. 4c

Fig. 4. Harmonic generation in homogeneous sample (a) and in the implanted (b) and virgin part (c) of the YBCO film.

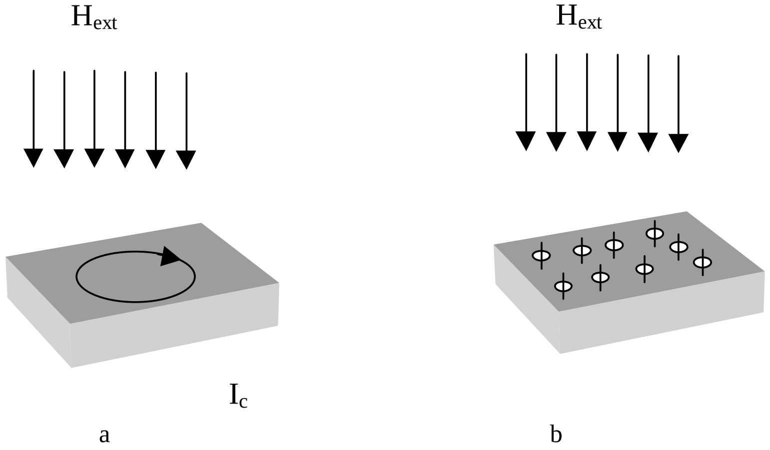


Fig. 5. The screnning currents (a) and the magnetic flux vortices (b) in a superconducting film placed in perpendicular DC magnetic field.

Let us consider what happens if a field is increased and then removed. This situation is illustrated in Fig 6 a,b with sets of profiles of the magnetic field at different stages of applied filed. Obviously, a hysteresis appears similar to the one showed in Fig. 6c. Actually we described the situation in a similar way as Bean did it [14] in 1964 for magnetization of hard (type 2) superconductors. However, the Bean's critical model was developed for a slab or cylinder in a field parallel to its surface. In our case (field is perpendicular) because of the great demagnetizing factor, the field H* when the magnetic field starts to penetrate the film is very low:

$$H^* = H_{c1}(1-D) \tag{1}$$

where *D* is the demagnetizing factor. Therefore the hysteresis loop is similar to the Bean's loop, but very tall. If the external magnetic flux is sinusoidal, one can easily calculate the harmonic spectra using the Fourier transformation and the simplest model of the magnetic flux changes with nearly square wave character. Although simple, this model is very close to the real magnetization and gives adequate harmonic content, similar to the measured one. This model, however, is applicable only for relatively low fields. For larger external fields the distortion of the magnetization are too big and should be described by more sophisticated models.

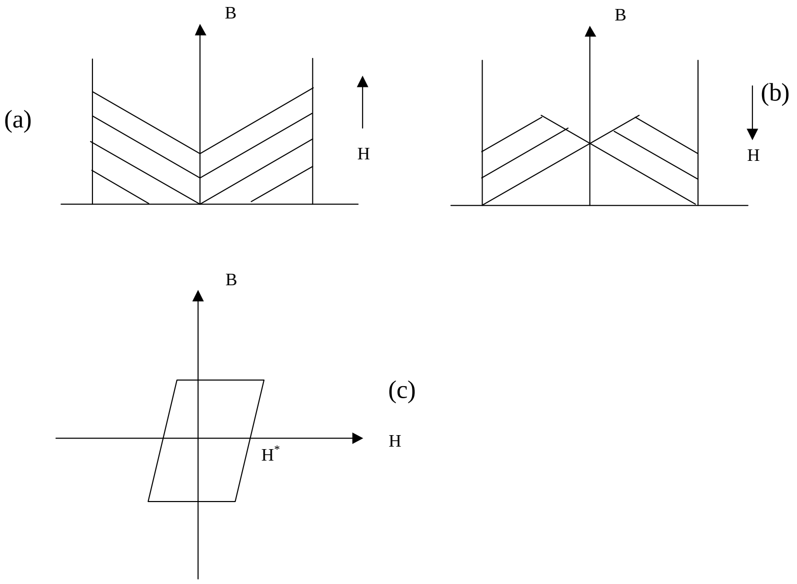
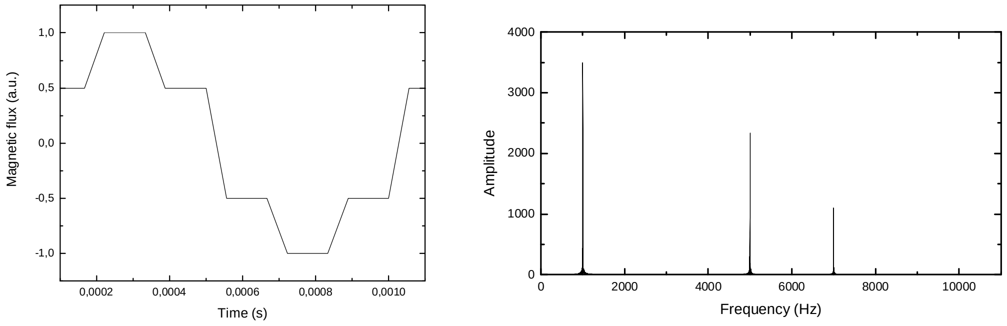


Fig. 6. Magnetic field changes if a field is increased (a) and then removed (b). In (c) the described hysteresis cycle is shown schematically.



(a) (b)

Fig. 7. The model of magnetic flux changes during one AC cycle (a) and the Fourier transformation of this curve (b).

In an inhomogeneous superconductor another effect takes place. When the weaker part of the film is going in a normal state, the magnetic shielding currents will be switched to the other (stronger) part of the film. This effect is similar to what happens in so called "magnetic flux pump", where by converting a part of a superconductor into normal state it is possible to increase (pump) the field in an adjacent part of the superconductors. It is quite difficult to calculate changes in such systems during the flux jumps. However, in our simple geometry (a half of the probe is modified) one can estimate this effect remembering that because of the flux quantization, the magnetic flux in a superconducting ring is preserved. In our geometry after the switching, the inductance flowed by the supercurrent will be reduced approximately by 50%. One can expect the same amount of increased (pumped) flux in the virgin part of the film. Therefore we use the model of magnetic flux changes during one AC cycle shown in Fig. 7a. Fourier transformation of this curve give the spectrum (Fig. 7b), where some harmonics disappear and other rise, which can explain at least quantitatively our experimental results.

4. Conclusions

Particle irradiation/implantation can be used successfully for patterning of the HT_c superconducting films, as well as for fabrication of Josephson junction and SQUIDs. Two- and tree dimensional areas in HT_c superconductors can be created and new phenomena can be observed in such systems.

Acknowledgements

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References

[1] E. P. Harris, J. Vac. Sci. Technol. **12**, 1383 (1975).
[2] S. S. Tinchev, Supercond. Sci. Technol. **3**, 500 (1990).
[3] Q. Y. Ma, S. H. Honig, J. R. Miller, J. Z. Su, W. J. Gallagher, R. B. Laibowitz, Supercond. Sci. Technol. **9**, A92 (1996).
[4] G. P. Summers, E. A. Burke, D. B. Chrisey, M. Nastasi, J. R. Tesmer, Appl. Phys. Lett. **55**, 1469 (1989).
[5] J. Ziegler, P. Biersack, The stopping range of ions in solids, Pergamon Press, New York, (1985).
[6] S. S.Tinchev, J. Appl. Phys. **78**, 5851 (1995).
[7] S. S.Tinchev, J. Appl. Phys. **81**, 324 (1997).
[8] R. H. Koch, C. P. Umbach, G. J. Clark, P. Chaudhari, R. B, Laibowitz, Appl. Phys. Lett. **51**, 200 (1987).
[9] S. S. Tinchev, Microwave Physics and Techniques, NATO ASI Series 3/33, Dordrecht: Kluver Academic Publishers, 1996. p.173.
[10] J. Hollkott, C. Jaekel, B. Spangenberg, H. Kurz, F. Kahlmann, IEEE Trans. Appl. Supercond. **9**, 39 (1999).
[11] A. S. Katz, S. I. Woods, R. C. Dynes, J. Appl. Phys. **87**, 2978 (2000).
[12] D. -J. Kang, G. Burnell, S. J. Lioyd, R. S. Speaks, N.H. Peng, C. Jeynes, R. Webb, Y. H. Yun, S. H. Moon, B. Oh, E. J. Tarte, D. F. Moore, M. G. Blamire, Appl. Phys. Lett. **80**, 814 (2002).
[13] Ke Chen, Sh. A. Cybart, R. C. Dynes, Appl. Phys. Lett. **85**, 2863 (2004).
[14] C. P. Bean, Rev. Mod. Phys. **36,** 31 (1964).