Effects of Irradiation on Vicinal YBCO Thin Films

Tom D. Withnell, K. Robert Schöppl, John H. Durrell, and Harald W. Weber

***Abstract*—The achievable transport critical current densities in coated conductors are limited in part by low angle grain boundaries. Effects like vortex channeling found in these low angle boundaries at low fields can also be studied in vicinal thin films. The influence of neutron irradiation, a proven method for increasing magnetic and current carrying properties, on these effects was investigated in this work. An YBCO vicinal sample, grown on a $SrTiO_3$ substrate with the ab plane oriented at 6 degrees off parallel, was fabricated through pulsed layer deposition (PLD) and both transition temperature and transport current measurements were performed using a 2-axis probe. The sample was rotated at varying temperature in an applied magnetic field of up to 6 T. The angular dependence of the critical density was determined before and after an irradiation to a neutron fluence of 1×10^{21} m^{-2} in the TRIGA Mark II reactor in Vienna.**

***Index Terms*—Radiation effects, vicinal thin film, YBCO.**

I. Introduction

CRITICAL currents in type II superconductors are directly related to the effects of flux pinning within the material. For technical applications of high temperature superconductors (HTS) the behavior of the critical current in external magnetic fields is important. In addition, due to the anisotropy of $YBa_2Cu_3O_{7-\delta}$ (YBCO) there is an angular dependence between the current and applied field. Rotation of a sample within an applied field allows different states of the flux lattice to be investigated in a single experiment.

Below a critical temperature, T_{cr}, the two dimensional layered nature of the vortex state of YBCO must be taken into account. This temperature is when the Ginzburg-Landau (GL) coherence length in the c direction is $\xi_c(T) = \xi_{ab}(T)/\gamma = d/\sqrt{2}$, where ξ_c and ξ_{ab} are the GL coherence lengths in the c axis and ab plane respectively, γ is the anisotropy parameter, and d is the distance between superconducting planes. With θ being the angle between the applied field and the ab planes, as θ decreases the vortices become distorted, changing from rectilinear, three dimensional vortices to a two dimensional kinked vortex state, where pancake vortices along the ab planes are connected by Josephson strings between the ab planes. The angle where this transition begins, θ_1, is defined as $\tan(\theta_1) = d/\xi_{ab}$. At a second critical angle, θ_2, where $\tan(\theta_2) = 1/\gamma$ the transition is complete. For very low angles ($\theta \approx 0.2°$) the vortices enter a "locked" state, where the magnetic field aligns perfectly with the ab planes. At higher temperatures the vortex state remains as three dimensional anisotropic vortices with no kinked state or "lock-in" occurring.

As previously reported for YBCO $\gamma \approx 5$, $d \approx 1.2$ nm and $\xi_{ab}(0) \approx 1.6$ nm. This gives values at 0 K of $\theta_1 = 35°$, $\theta_2 = 11°$ and $T_{cr} = 80$ K [1].

In c axis grown films the applied current, J, is always parallel to the ab plane. In the force free configuration (J and B aligned) measurements performed on such films mean that this effect is superimposed on others such as intrinsic peaks. Use of a vicinal substrate, where the ab planes are tilted by some angle away from the surface, reduces the symmetry of the configuration and allows the effects of an applied magnetic field on the experimental geometry to be separated from those of the crystal axes [2]. In addition, channeling effects which are observed in vicinal films can be investigated [3]. Miscut $SrTiO_3$ has been found to be well-suited as a substrate for the growth of vicinal films due to the small crystal misfit, with the YBCO layer grown in a step-flow growth mode [4].

Neutron irradiation has been shown to increase the critical current, J_c, in single crystals by introducing well defined defects [5]. Therefore the purpose of this study was to investigate how the transport properties of a vicinal film sample are altered by neutron irradiation.

II. Experimental

The film consisted of a 200 nm thick layer of $YBa_2Cu_3O_{7-\delta}$ grown by pulsed layer deposition (PLD) on a single crystal $SrTiO_3$ substrate miscut by an angle of 6° thereby giving a so-called vicinal film. The film had a low density of anti-phase boundaries and stacking faults [6]. Tracks of length 100 μm and cross section 10 μm$\times$200 nm were patterned using photo lithography and Ar-ion beam milling, with connecting pads to allow 4-point I-V measurements on each track. Each connecting pad had Au and Ag sputtered onto it to allow electrical connectivity. The tracks of interest for this study are those running perpendicular to the vicinal step direction (⊤ tracks), as shown in Fig. 1. Tracks running parallel to the vicinal step direction (L track) will show similar behavior to a c axis film and were not measured in this study.

Track characterization was performed using a two-axis goniometer in a liquid helium gas flow cryostat equipped with a 6 T split coil magnet. I-V curves were recorded as the sample was tilted through θ at various applied fields and temperatures. The rotation angle, φ, (see Fig. 1) was kept at 0°, giving a variable Lorentz force configuration. Each I-V curve was analyzed using a voltage criterion of 0.5×10^{-6} V.

Sample irradiation was performed in a TRIGA Mark II reactor to a neutron fluence of 1×10^{21} m^{-2} (E > 0.1 MeV). To

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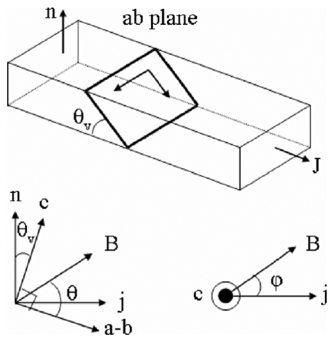

Fig. 1. Arrangement for measurement of a T-track. The vicinal miscut angle is θ_v. The lower section displays how the orientation of the applied magnetic field can be varied by angles θ and φ, with $\theta = 0$ corresponding to the applied field parallel to the a-b planes. The condition $\theta = \theta_v$ and $\varphi = 0$ gives the field aligned with the current.

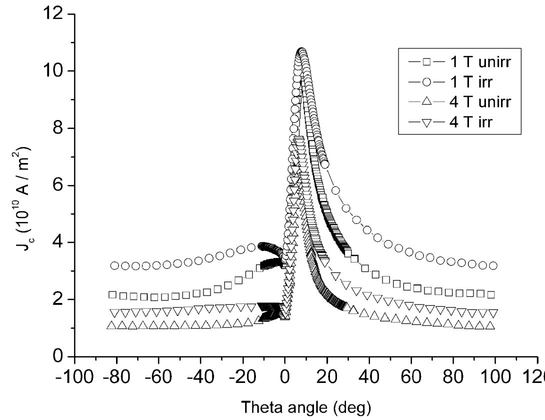

Fig. 2. Comparison of critical currents for sample at 50 K in applied fields of 1 T and 4 T in irradiated and unirradiated states.

protect the sample from moisture it was sealed in a quartz tube in a helium atmosphere. The variable Lorentz measurements described above were repeated.

III. Results and Discussion

A. Critical Temperature and Self-Field Current

The critical temperature, T_c is expected to decrease with neutron irradiation. This was observed as T_c was reduced from 90.45 K pre-irradiation to 90.25 K post-irradiation. The decrease reported in [5] is approximately 4 K per 10^{22} m^{-2}, which would imply a drop of 0.4 K for the present experiment, in reasonable agreement with this result of 0.2 K.

For the case of the self-field critical current, J_c, it reduced from 4.0×10^{10} A/m^2 to 3.5×10^{10} A/m^2 at 77 K after neutron irradiation. An effect like this has been reported previously, with the J_c showing an increase after irradiation only when external fields are applied [7]. However, the cause of this was found to be due to the lower current carrying capability of grain boundaries after irradiation. Although the sample in this study should not contain any grain boundaries the effect may be due to the overall degradation of the sample structure. As there is no applied field the additional defects from the irradiation process have minimal effect, thereby reducing the self-field J_c.

B. Effect of Irradiation on Rotational Measurements

The curves produced from measurements on the sample gave the basic features as reported previously [2]–[4], [6]. The sample exhibits a small component of c axis pinning, shown by the rise on left-hand side of Fig. 2 for the 1 T unirradiated case.

Outside of the kinked vortex regime (i.e. $|\theta| > \theta_1$) the curves can be normalized about a point away from the characteristic features, as demonstrated in [2]. In the kinked vortex regime the characteristic deformation due to channeling was observed. The overall shape of the curves in this regime did not depend strongly on the applied field. The curves exhibit a strong temperature dependence, whereby the channeling effect was greatest at lower temperatures, and disappeared at 80 K, as predicted by theory.

A comparison of the critical current, J_c, curves obtained at 50 K for the irradiated and unirradiated cases are shown in Fig. 2.

Measurements on the sample after irradiation produced curves similar to the unirradiated case, but no c axis pinning effects were visible as shown by the relatively constant J_c values on the left-hand side of Fig. 2 for the 1 T irradiated case. Away from the kinked vortex depinning region, J_c increased by between 20% and 50%, depending on the applied magnetic field. As expected this increase did not depend on the angle because the introduced pinning centers should not produce any angular dependence. This increase is reduced in the vortex cutting region, where pinning has less effect as the Lorentz force is low. The characteristic channeling dip was more pronounced.

As with the unirradiated data the temperature dependence was largely unchanged, the channeling effect having again disappeared at 80 K.

Figs. 3(a) and 3(b) show the angular behavior of the normalized J_c curves before and after irradiation at 50 K for a number of applied fields. The abscissa is set to show the kinked vortex depinning region in detail. This normalizing process allows the angular crossover between the three dimensional and layer regimes to be examined; in the case of isotropic pinning the curves will lie on each other in the three dimensional regime for all fields and temperatures.

It can be easily seen that there is greater field dependence with the unirradiated state, Fig. 3(a). It can be observed that the crossover from the three dimensional to layered regimes occurs at $\pm 45°$. This is greater than the $\pm 35°$ predicted for θ_1 by theory, but this effect is believed to be sample dependent. The spread of the scaled curves for the irradiated case, Fig. 3(b), is less pronounced. This is to be expected as neutron irradiation reduces anisotropy through the introduction of additional scattering centers.

C. Application of Model

The vortex deformation and breaking model developed by Pardo, Durrell *et al.* [8], [9] was used to compare the data. Results for the test run at 1 T and at 40 K before irradiation produced a pancake flux pinning force per unit length, $f_{\mathrm{p,pc}}$, of

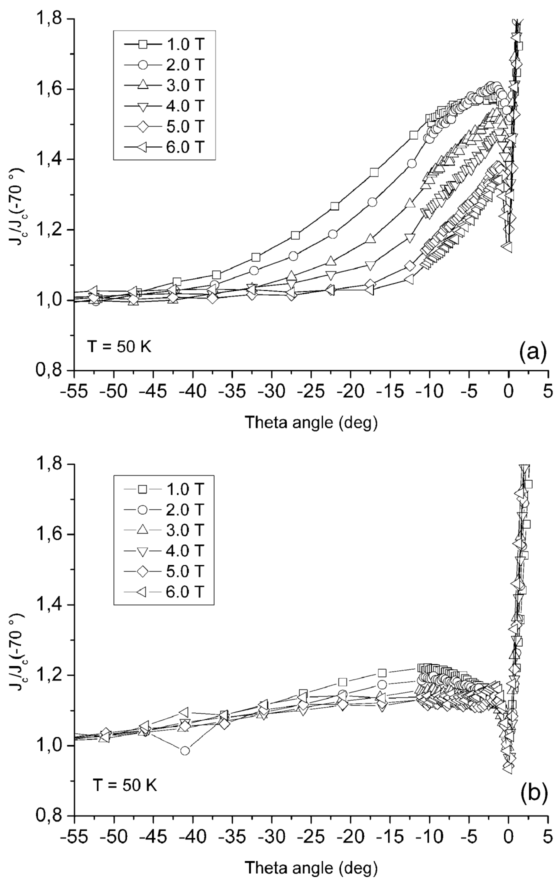

Fig. 3. Comparison of critical currents for sample in (a) pre-irradiated and (b) post-irradiated state for varying applied fields at 50 K. Currents are normalized and the figure is localized on the kinked vortex section. The effects of irradiation can be readily observed.

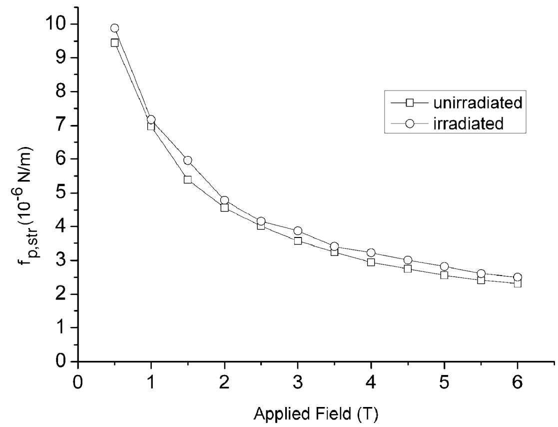

Fig. 4. Comparison of $f_{\mathrm{p,str}}$ calculated using model from data at 50 K for unirradiated and irradiated case.

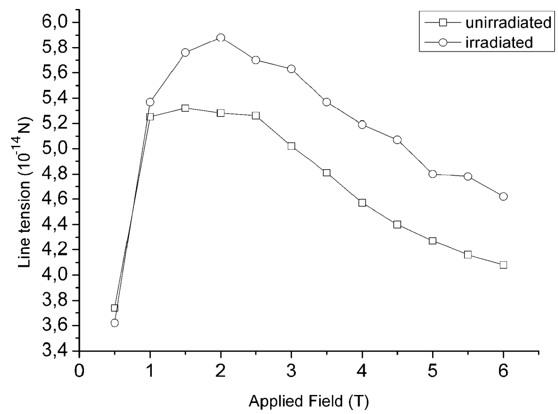

Fig. 5. Comparison of line tension, ε_l, calculated using model from data of unirradiated and irradiated case at 50 K.

$1.2 \times 10^{-4}\ \mathrm{Nm}^{-1}$, a string pinning force per unit length, $f_{\mathrm{p,str}}$, of $8.6 \times 10^{-6}\ \mathrm{Nm}^{-1}$, and a line tension, ε_1, of 5.8×10^{-14} N. These agree well with data published previously [2], [9], [10], only ε_1 is about four times larger than in [2]. The values for the irradiated sample at the same track and temperature are not available as the track under test broke.

Comparison of the data at 50 K between the unirradiated and irradiated case showed an increase in the values of $f_{\mathrm{p,pc}}$ and $f_{\mathrm{p,str}}$, the results of the latter are shown in Fig. 4, showing the increase after irradiation. The average increase was 15% and 7% for $f_{\mathrm{p,pc}}$ and $f_{\mathrm{p,str}}$ respectively.

If the pinning mechanism is unchanged a possible explanation for this behavior is that each string and pancake vortex is the same. As pancakes are pinned by vortex core pinning, the defects introduced by the irradiation will be more effective for them, as seen by their increase.

Fig. 5 shows the data calculated for the line tension, ε_1. At fields above 1.5 T there is again an increase after irradiation (average of 12%), but a reduction at lower fields; at 0.5 T the line tension is reduced by 5%.

This effect may be attributed to a decrease in anisotropy caused by the irradiation (as $\varepsilon_{1,\mathrm{ab}}$ is inversely proportional to the material anisotropy factor), although the magnitude of the changes are not sufficiently significant to draw any firm conclusion. Irradiation to higher fluences is clearly desirable, and currently under way.

IV. Conclusions

In conclusion the transport characteristics on a T track of a 6° off-axis vicinal film YBCO sample have been measured both before and after a neutron irradiation to $1 \times 10^{21}\ \mathrm{m}^{-2}$. The self-field critical current, $\mathrm{J_c}$, at 77 K was reduced due to overall sample degradation. However, due to the increased pinning density, it was larger than before irradiation when an external magnetic field was applied. $\mathrm{T_c}$ decreased only slightly after irradiation.

The irradiation caused a possible decrease in sample anisotropy and reduced the field dependence. On applying the model of Pardo, Durrell, *et al.* the irradiation was found to increase by 5%–10% for the pinning forces of the string and pancake vortices, but increased the string tension only at higher fields.

Further studies can include a more detailed study of the temperature dependence.

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REFERENCES

[1] P. Berghuis, E. Di Bartolomeo, G. A. Wagner, and J. E. Evetts, "Intrinsic channeling of vortices along the ab plane in vicinal $\mathrm{YBa_2Cu_3O_{7-\delta}}$ films," *Physical Review Letters*, vol. 79, no. 12, pp. 2332–2335, Sept. 1997.

[2] J. H. Durrell, G. Burnell, Z. H. Barber, M. G. Blamire, and J. E. Evetts, "Critical currents in vicinal $\mathrm{YBa_2Cu_3O_{7-\delta}}$ films," *Physical Review B*, vol. 70, p. 214508, 2004.

[3] J. H. Durrell, G. Gibson, R. Rössler, and J. D. Pedarnig *et al.*, "Dependence of critical current on field angle in off-c-axis grown $\mathrm{Bi_2Sr_2CaCu_2O_8}$ film," *Applied Physics Letters*, vol. 77, no. 11, pp. 1686–1688, Sept. 2000.

[4] L. Méchin, P. Berghuis, and J. E. Evetts, "Properties of $\mathrm{YBa_2Cu_3O_{7-\delta}}$ thin films grown on vicinal $\mathrm{SrTiO_3}$ (001) substrates," *Physica C*, vol. 302, pp. 102–112, 1998.

[5] H. W. Weber, H. P. Wiesinger, G. W. Crabtree, and J. Z. Liu, "Critical currents in neutron irradiated YBCO and BiSCCO single crystals," *Supercond. Sci. Technol.*, vol. 4, pp. S103–S105, 1991.

[6] J. H. Durrell, S. H. Mennema, C. Jooss, G. Gibson, Z. H. Barber, H. W. Zandbergen, and J. E. Evetts, "Flux line lattice structure and behaviour in antiphase boundary free vicinal $\mathrm{YBa_2Cu_3O_{7-\delta}}$ thin films," *Journal of Applied Phys.*, vol. 93, no. 12, pp. 9869–9874, June 2003.

[7] A. Vostner, Y. F. Sun, H. W. Weber, Y. S. Cheng, A. Kuršumović, and J. E. Evetts, "Neutron irradiation studies on Y-123 thick films deposited by liquid phase epitaxy on single crystalline substrates," *Physica C*, vol. 399, pp. 120–128, 2003.

[8] J. H. Durrell and R. Herzog *et al.*, "Determination of pinning forces on vortex lines in $\mathrm{YBa_2Cu_3O_{7-\delta}}$," *Supercond. Sci. Technol.*, vol. 12, pp. 1090–1093, 1999.

[9] E. Pardo, J. H. Durrell, and M. G. Blamire, "Vortex deformation and breaking in superconductors: A microscopic description," *Philosophical Magazine*, vol. 87, no. 28, pp. 4359–4381, Oct. 2007.

[10] K. R. Schöppl, H. W. Weber, and J. H. Durrell, "Angular dependence of critical currents in $\mathrm{YBa_2Cu_3O_{7-\delta}}$ vicinal films," *Journal of Physics: Conference Series*, vol. 97, p. 012225, 2008.