Artificially induced reduction of the dissipation anisotropy in high-temperature superconductors

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(Received 13 February 2002; accepted for publication 3 April 2002)

$Bi_2Sr_2CaCu_2O_8$, $RBa_2Cu_3O_7$ (R=Y, Eu) thin films and $RBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices have been fabricated by sputtering technique. The anisotropic dissipation was measured close to the critical temperatures with high applied magnetic fields rotating from parallel to perpendicular to the substrate. In multilayers, in a large magnetic field interval, the dissipation anisotropy is reduced as much as 60% in comparison with the most anisotropic system ($Bi_2Sr_2CaCu_2O_8$) and at least 50% at 30 kOe in comparison with 123 films. This strong anisotropy reduction is discussed taking into account the role played by the superlattice modulation lengths on magnetic matching effects and coupling between the superconducting layers.
[DOI: 10.1063/1.1482420]

Low critical current (J_c) values are one of the most important bottlenecks that preclude some of the technological applications of high temperature superconductors (HTS). One of the origins of these low J_c is related to grain boundaries.[1] This problem has been successfully addressed, in the 123 oxides, using two techniques, the so-called ion beam assisted deposition (IBAD)[2] and rolling assisted biaxial texturing substrates (RABiTS).[3] Another effect that limits J_c is the large anisotropy of HTS. For instance, taking as one example, the Bi family, these strong anisotropic compounds are transparent to magnetic fields applied parallel to the Cu–O planes, but keeping the same temperature and applied magnetic field, the sample begins to dissipate when the applied field is tilted at some angle off the Cu–O planes.

In this letter we address the anisotropy problem. We will show how to reduce its effect on the angular dependence of the dissipation when the magnetic field is varied from parallel to perpendicular to the Cu–O planes. The clue to reducing the dissipation anisotropy is to use multilayers with appropriate modulation lengths.

Five different types of superconducting oxides have been used in this work, Bi based (2212) films and Y or Eu based (123) films and superlattices. The 123 compounds were grown with two different orientations, the usual c-axis orientation (Cu–O planes parallel to the substrate) and a-axis orientation (Cu–O planes perpendicular to the substrates). The samples were grown on (001) $SrTiO_3$ (STO) substrates using two dc sputtering methods. $Bi_2Sr_2CaCu_2O_8$ (BSCCO) films[4] and c-axis oriented $YBa_2Cu_3O_7$ (YBCO) films and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (YBCO/PBCO) multilayers[5] were obtained using high pressure atmosphere (3 Torr) of pure oxygen. The a-axis $EuBa_2Cu_3O_7$ (EBCO) and $EuBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (EBCO/PBCO) samples were obtained with the sputtering atmosphere being a mixture of Ar and O_2 (94% Ar and 6% O_2 up to 300 mTorr total pressure).[6] The superconducting properties and structural characterization of the BSCCO and YBCO films and of the YBCO/PBCO and EBCO/PBCO superlattices are published elsewhere.[4–7] Measurements of the angular dependence resistivity, at different magnetic fields, were done using a commercial cryostat with a magnet up to 90 kOe and a computer controlled rotatable sample holder. The angle is measured with respect to the parallel direction of the Cu–O planes (perpendicular to the substrate in the a-axis oriented samples and parallel to the substrate in the c-axis oriented samples). Measurements were done at 0.99 T_c and at high magnetic fields to be sure that the vortices are in the liquid state. We define as the relevant anisotropic dissipation parameter $[R_H(\theta)-R_H(90)]/R_H(90)$, with $R_H(\theta)$ and R_H (90) being the resistance with applied magnetic field H at angle θ and perpendicular to the Cu–O planes, respectively.

Figure 1(a) shows the BSCCO film experimental data: there is no dissipation with H applied parallel to the Cu–O planes, even at temperatures of 0.99 T_c and $H=90$ kOe. This Bi-based HTS is a good example of the important effect of anisotropy on the dissipation mechanisms. This compound

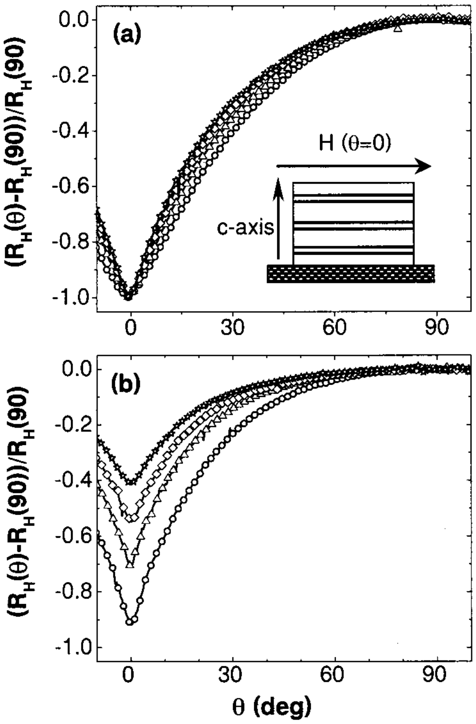

FIG. 1. (a) Dissipation anisotropy vs angle between the magnetic field applied and the Cu–O planes in BSCCO film at $0.99T_c$ ($T_c=84$ K). Applied magnetic fields of 30 (○), 50 (△), 70 (◇), and 90 kOe (☆). (b) Dissipation anisotropy vs angle between the magnetic field applied and the Cu–O planes in YBCO film at $0.99T_c$ ($T_c=90$ K). Applied magnetic fields of 30 (○), 50 (△), 70 (◇), and 90 kOe (☆). Anisotropy parameter: $\gamma=(H_{c2}^{\parallel}/H_{c2}^{\perp})\sim 7$, where $H_{c2}^{\parallel}(H_{c2}^{\perp})$ is upper critical field parallel (perpendicular) to the Cu–O planes. Inset: Sketch of the Cu–O planes in *c*-axis YBCO films.

shows a extreme anisotropic behavior, which follows purely two-dimensional (2D) behavior,[8] i.e., only the component of *H* perpendicular to the Cu–O planes matters. The well-known intrinsic pinning effect[9] produces magnetic field independent vanishing dissipation only when *H* is applied parallel to the Cu–O planes. Figure 1(b) shows a different picture: YBCO film follows three-dimensional (3D) anisotropic behavior and clear magnetic field dependent dissipation is observed. This behavior has been explained in terms of highly directional intrinsic pinning mechanisms in HTS, due to the very anisotropic structure of these oxides. Therefore, the crucial point is how to diminish the effect of the anisotropy and keep intrinsic pinning effective. Some promising results have been reported: for instance, the intercalation of Pb along the *c* axis in single crystals of 2212 Bi compounds has been claimed to reduce the anisotropy.[10]

In the following, we explore the effect on the dissipation anisotropy due to intercalation of nonsuperconducting layers in the growth direction. The nonsuperconducting spacers are very effective pinning centers: for instance, low-temperature multilayered (NbN/AlN) films show enhancement of J_c due to flux pinning in the nonsuperconducting (AlN) layers.[11] The same effect has been observed in HTS superlattices.[6] Superlattices *a* axis oriented [see Fig. 2(a)] are ideal tools with which to learn about the interplay between artificially induced pinning (PBCO layers) and natural intrinsic pinning (Cu–O planes) mechanisms,[12] because the two mechanisms are perpendicular to each other. Moreover, in these superlattices an additional matching effect has been reported.[13] The matching condition is $\Lambda=a_0$, Λ and a_0 being the superlattice modulation length and the lattice vortex spacing, respectively [assuming an Abrikosov lattice $a_0=(\Phi_0/H)^{1/2}$, Φ_0 being the flux quantum]. This effect smoothens the magnetic field dependence of the dissipation in a magnetic field interval around the matching field. The overlap of these two effects, pinning centers 90° off the Cu–O planes and the matching effect, makes *a*-axis multilayers promising candi-

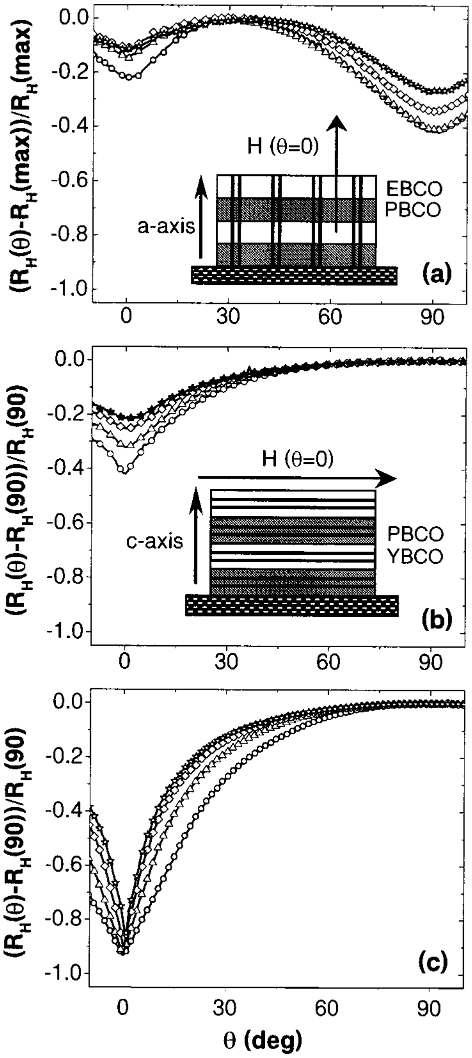

FIG. 2. (a) Dissipation anisotropy vs angle between the magnetic field applied and the Cu–O planes in an a-axis oriented EBCO/PBCO superlattice at $0.99T_c$ ($T_c=64$ K). Applied magnetic fields of 30 (○), 50 (△), 70 (◇), and 90 kOe (☆). Modulation length: 50 unit cells EBCO/5 unit cells PBCO (22 nm). Inset: Sketch of the Cu–O planes and multilayered structure in an a-axis oriented superlattice. Anisotropy parameter: $\gamma=(H_{c2}^{\parallel}/H_{c2}^{\perp})\sim 5$. (b) Dissipation anisotropy vs angle between the magnetic field applied and the Cu–O planes in a *c*-axis oriented YBCO/PBCO superlattice at $0.99T_c$ ($T_c=90$ K). Magnetic fields applied: 30 (○), 50 (△), 70 (◇), and 90 kOe (☆). Modulation length: 17 unit cells YBCO/2 unit cells PBCO (22.8 nm). Inset: Sketch of the Cu–O planes and multilayered structure in a *c*-axis oriented superlattice. Anisotropy parameter: $\gamma=(H_{c2}^{\parallel}/H_{c2}^{\perp})\sim 5$. (c) Dissipation anisotropy vs angle between the magnetic field applied and the Cu–O planes in a *c*-axis oriented YBCO/PBCO superlattice at $0.99T_c$ ($T_c=85$ K). Magnetic fields applied: 30 (○), 50 (△), 70 (◇), and 90 kOe (☆). Modulation length: 8 unit cells YBCO/5 unit cells PBCO (15.6 nm). Anisotropy parameter: $\gamma=(H_{c2}^{\parallel}/H_{c2}^{\perp})\sim 7$.

dates for the study of the possible role of these effects on the dissipation anisotropy. An *a*-axis EBCO/PBCO multilayer was fabricated with matching field of 50 kOe. Figure 2(a) shows the experimental data. As expected, two minima appear, one at 0° related to natural pinning (Cu–O planes) and the other at 90° related to artificially induced pinning (PBCO layers). (In this case, the experimental data are normalized to the maximum dissipation values keeping the same criterion as that in Fig. 1.) The most remarkable effect is that the dissipation anisotropy is reduced in the whole angular range. Therefore, once we have shown the effective role that multilayered structures and matching effects play in decreasing dissipation, the next step is to test it on *c*-axis superlattices. A *c*-axis YBCO/PBCO multilayer was fabricated with the same matching field (50 kOe). Figure 2(b) shows a strong reduction of the dissipation anisotropy. This effect is remarkable in comparison with YBCO film behavior; see Fig. 1(b).

Finally, we try to determine which is the crucial effect that rules the decrease in the dissipation anisotropy. The *c*- and *a*-axis oriented superlattices are in the strong coupling regime[14,15] (the superconducting layers are coupled) and the superlattice modulation length matches the vortex separation (matching effect). The role that could be played by the coupling regime of the superlattices is less clear than the matching field effect. One way to clarify the role of coupling is to modify the modulation length in order to move the system to a weaker coupling regime, keeping the sample T_c as high as possible and the matching field in the accessible experimental range (90 kOe). Figure 2(c) shows the experimental results obtained for a YBCO (8 unit cells)/PBCO (5 unit cells) multilayer. These experiment data show that, in spite of some remaining matching effect, the strong reduction of the dissipation anisotropy has vanished. Therefore coupling of the layers seems to play a crucial role.

In summary, appropriate superlattice modulation length values lead to a magnetic matching effect and, most important, to superconducting layer coupling, which yield a strong reduction of the dissipation anisotropy. Therefore, artificially layered HTS, obtained by intercalation of nonsuperconducting layers, could be used to reduce the dissipation anisotropy in a broad applied magnetic field range at temperatures close to T_c.

The authors want to thank the Spanish CICYT (MAT99-0724 and MAT2000-1468), U.S. DOE, COLCIENCIAS, New Del Amo Program, and the ESF Vortex program. One of the authors (J.E.V.) thanks the Comunidad de Madrid for a fellowship.

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