Alternating transport-current flow in superconductive films: The role of a geometrical barrier to vortex motion

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$YBa_2Cu_3O_{7-\delta}$ films grown on both $SrTiO_3$ single-crystal and rolling-assisted biaxially textured (Ni) substrates (RABiTS) carry high critical current densities J_c. A geometrical barrier to vortex motion raises the apparent J_c, but also increases power loss associated with ac transport current through such tape above that expected from Norris's 1970 theory of hysteretic energy loss. Present theoretical estimates of the geometrical barrier have insufficient magnitude to account for our observations at low ac current levels. Evidence is reported that the ferromagnetic Ni substrate makes no significant contribution to the tape self-field loss. Loss is enhanced, and J_c modestly reduced by the presence of low-angle grain boundaries. Application of dc magnetic field further lowers J_c and raises loss in films. [S0163-1829(99)01833-0]

INTRODUCTION

Heavy transport current flow is clearly needed for industrial applications of high-T_c superconductive cable. Unfortunately the presently available materials have exceedingly limited current-carrying capacities in the liquid-nitrogen temperature range. One serious problem is sensitivity to magnetic fields. Tape consisting of Bi-2223 uniaxially textured, polycrystalline filament arrays distributed in Ag can carry loss-free engineering current densities of the order of 10^4 A/cm^2 at 77 K if shielded from magnetic field. A rapid falloff of this capacity in a field of a few tenths of a tesla effectively eliminates usage in motors and transformers, as well as for high-field generation.[1] Far weaker sensitivity to magnetic field makes single crystals or epitaxial films of $YBa_2Cu_3O_{7-\delta}$ (YBCO) attractive, but crystals or small chips are impractical for large-scale applications. Alignment of YBCO grains in possibly usable superconductive wire is a natural endeavor to minimize potential drops associated with current flow.[2–10] The technique[11] of cold rolling and annealing metallic Ni can form highly textured tape with crystallographic cube edges parallel to all surfaces. Epitaxial growth of an appropriate buffer layer followed by YBCO leads to a polycrystalline film structure with overall granular misorientations less than 10° and with grain-to-grain misorientations substantially less.[12] This high degree of alignment allows current densities of the order of 10^6 A/cm^2 in the YBCO with no magnetic field. As a result engineering current densities of 10^4 A/cm^2 are easily achieved in films with mechanically durable substrates. Field application lowers J_c modestly but far less than in composite Bi compounds.[4,11]

Magnetic hysteresis is a natural source of loss in or near material carrying alternating electrical current—even for current levels below the critical current I_c of the superconductive material. In an earlier study[13] our observations were compared with a theory developed by Norris[14] for a superconductor of elliptic cross section. This geometrical assumption conflicts with the rectangular cross sections of our thin-film strips. Norris's theoretical results for a rectangular conductor (with uniform critical current density) are distinctly inconsistent with our data. In this paper we consider various possibilities to explain the discrepancy with special attention to the geometrical barrier. A nonuniform distribution of both transport and shielding current in thin films has been discussed recently by Brandt and Indenbom[15] and by Zeldov *et al.*[16] These two references cover theoretical pictures of a number of differing magnetic-field and transport-current situations. Here we focus on the history applicable to our experimental procedure.

Recent studies[17–23] have found strong evidence of a geometrical barrier-to-vortex entry, which allows a sharp peak of the critical current density $J_c(x)$ at the film edge during half of each cycle. This peak leads to a natural discrepancy between the inherent critical current density and a total current measurement. In addition we show here that it may be responsible for the discrepancy between our data and the classical theory[14] of ac loss from hysteresis in the superconductor, which assumes a perfectively uniform critical current density J_c.

THEORETICAL BACKGROUND

Magnetic field is naturally excluded from the interior of superconductive material as best shielding currents can do so. It has long been known that this shielding is limited in a sample of thin rectangular cross section because of the need for infinite current densities at edges in order to perfectly cancel an applied field or the self-field of a conductor. Norris derived a distribution of transport-current density that would produce no magnetic field in a central ''core'' region and was limited to a uniform critical value J_c outside this core.

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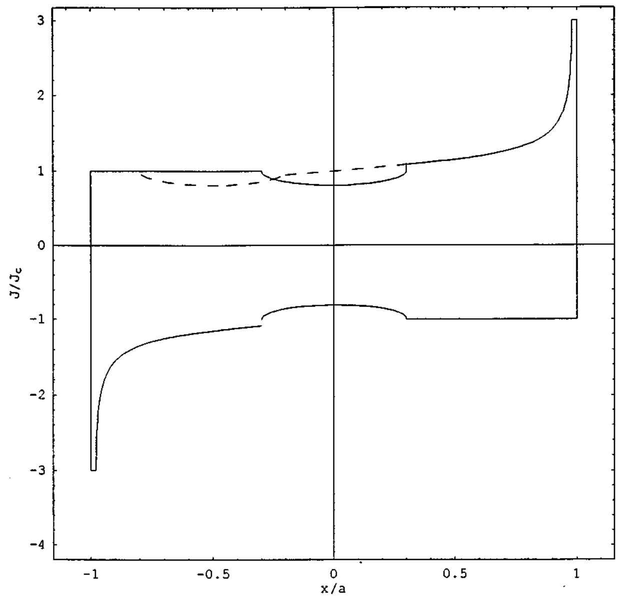

FIG. 1. Plot of electrical current density J versus distance x from the center line of a superconductive film strip of width $2a$. Initially a magnetic field applied perpendicular to the film induces shielding current density that is nearly a step function of x. J assumes the value $J_c\,\mathrm{sgn}(x)$ over the central region and is sharply peaked at the value $2\,\mathrm{sgn}(x)I_e/\pi a^{1/2}d^{3/2}\arctan\{[(a^2-e^2)/(e^2-x^2)]^{1/2}\}$ near the edges, $|x|\rightarrow e=a-d/2$. The dashed line shows the current distribution expected when transport current is subsequently supplied during the first half cycle. Positive transport current flows in the region $x<0$, where the induced shielding current was in the negative direction. $J(x)$ dips below J_c in the region $|x-a/2|<b=a(1-I_0^2/I_c^2)$, where there is no normal self-field, and it cannot exceed J_c except at the right edge, where the geometrical barrier to vortex entry allows it to peak sharply. The peak is shown much wider for clarity than is deduced from our results. The lower solid curve for maximum transport current in the opposite direction must peak for vortex entry past the barrier at the left edge. The upper solid curve occurs after subsequent increase of transport current to the positive maximum level, and is identical to the dashed line for $x>b$.

Within the core region, $|x|<b$, he found[14]

$$J=\frac{2J_c}{\pi}\arctan\left(\sqrt{\frac{a^2-b^2}{b^2-x^2}}\right). \tag{1}$$

In the self-field penetration region, $b<|x|<a$, Norris assumed $J=J_c$. Obviously, there is no current outside a current-carrying strip ($x>a$, see Fig. 1). Recent theoretical discussion[16] of the field-free region treats $J(x)$ as an ‘‘image current’’ that reflects the field induced by the uniform current density in the penetration region. This field perpendicular to the strip is zero for $|x|<b$ and

$$B=\frac{\mu_0 J_c}{2\pi}[\ln(a^2-x^2)-2\ln(a^2-b^2-\sqrt{x^2-b^2})]$$
$$\text{for } b<|x|<a. \tag{2}$$

The magnetic flux that enters the superconductive strip is[15]

$$\Phi=\frac{\mu_0 I_c}{2\pi}\left[\left(1+\frac{I}{I_c}\right)\ln\left(1+\frac{I}{I_c}\right)+\left(1-\frac{I}{I_c}\right)\ln\left(1-\frac{I}{I_c}\right)\right]$$
$$\approx\frac{\mu_0 I^2}{2\pi I_c}\quad\text{for small } I. \tag{3}$$

Here $I=2adJ$. Norris derived a hysteretic energy loss per cycle, per unit volume of superconductive material, for a conductor of rectangular cross section of area $2ad$, carrying continuous ac current, $I_0\cos(\omega t)<I_c=2adJ_c$,

$$Q_N=\frac{I_c^2\mu_0}{2\pi ad}\left[\left(1-\frac{I_0}{I_c}\right)\ln\left(1-\frac{I_0}{I_c}\right)+\left(1+\frac{I_0}{I_c}\right)\ln\left(1+\frac{I_0}{I_c}\right)-\frac{I_0^2}{I_c^2}\right]$$
$$\approx\frac{\mu_0 I_0^4}{12\pi adI_c^2}\quad\text{for } I_0\ll I_c. \tag{4}$$

As a means to describe an intuitive picture of this hysteretic loss, Norris argued that as the supplied current I increases, the cross sectional area where $J=J_c$ increases. As I peaks and then decreases an edge region of reversed $J=-J_c$ forms and then increases its area. The central region with distributed $J<J_c$ continues to flow in the initial direction until the current densities over the entire penetration region have reversed.

Transport current effectively applies magnetic field to the film strip. References 17–22 argue that shielding current distributes itself to cancel a normal applied field. Also transport current peaks at the strip edge outside the core region with uniform J_c. This spatially varying peak current density, $J_e(x)=I_e/(ad^3)^{1/2}$ for $|x|>e=a-d/2$ and $J_e(x)=(2I_e/\pi\sqrt{ad^3})\arctan[\sqrt{(a^2-e^2)/(e^2-x^2)}]$ for $a-2I_e^2/\pi^2J_c^2ad^2<|x|<e$. Normal field is excluded from the latter region, but penetrates within $b<|x|<a-2I_e^2/\pi^2J_c^2ad^2$. Norris originally argued that work done moving magnetic flux into the strip is $Q/2=(2ad)^{-1}\int_{-I_0}^{I_0}I\,d\phi=(4/a)\int_b^a J_c\phi(x)dx=(4/a)\int_b^a J_c\int_b^x B(x')dx'dx$ as current increases from $-I_0$ to I_0. To include $J_e(x)$ we add this loss inside the core region, $|x|<x_0=a-2I_e^2/\pi^2J_c^2d^2a$, where $J_e(x_0)=J_c$, to the work required for flux entry and obtain

$$Q=(4/a)\left[\int_b^{a-2I_e^2/\pi^2J_c^2d^2a}J_c\int_b^x B(x')dx'dx+\int_{a-2I_e^2d/\pi^2J_c^2d^2a}^{a}J_e(x)\int_b^x B(x')dx'dx\right].$$

Since $J_e(x)$ produces no normal field within the film strip, $B(x)$ is given by Eq. (2),[24] and the extra loss due to vortex entry past the geometrical barrier is of order $\phi_0 I_e$. Note that once past this barrier flux will jump easily to the edge of the core region, where current density is limited to J_c. Carrying out the integrals gives a first term, $Q_C\approx Q_N(1-I_e/I_0)^4[1+6(I_e/\pi adJ_c)^2]$, and a second term, $\Phi I_e/2ad$, with the condition, $I_e<I_0\ll I_c=2adJ_c+I_e$. When $I_0<I_e$ vortices cannot enter, current density is $I_e/(ad^3)^{1/2}$, and magnetic field penetrates only within the narrow edge region $a-d/2=e<|x|<a$. This loss is negligible in comparison with that discussed in this paper. Reference 18 gives $I_e=2H_{cl}(ad)^{1/2}$, but more recent work[21] leads to a weaker

peak with $I_e = 1.24 H_{cl}(ad)^{1/2}$. Adding this estimate of the additional loss from the flux Φ entry to the loss of Eq. (4) gives

$$Q_{\rm tot} = Q_C + \Phi I_e / ad$$

$$\approx \frac{\mu_0}{\pi a d}\left[\frac{(I_0 - I_e)^4}{12(2adJ_c)^2}\left(1 + \frac{6I_e^2}{\pi^2 J_c^2 a^2 d^2}\right) + \frac{I_e I_0^2}{J_c a d}\right]. \quad (5)$$

While Eq. (5) is relevant to understanding the data reported here, we note that our numerical evaluations of Q_e rise substantially above $\phi_0 I_e$ when $I_0 > 0.6 I_c$.

An applied magnetic field makes serious changes in this hysteretic picture of ac current flow. The study by Zeldov, Clem, McElfresh, and Darwin[16] treats a sizable list of current histories. They apply the expected shielding current distribution[15,25] of

$$J(x) = -\frac{2J_C}{\pi}\arctan\left(\frac{x}{a}\sqrt{\frac{a^2 - b^2}{b^2 - x^2}}\right) \quad (6)$$

for $x < b$ and $J(x) = J_c$ for $b < x < a$. Note that in the case of response to high-field application, this spatial dependence approaches a step function of $x[J(x) = J_c\,\mathrm{sgn}(x)]$, and for a thin film a "high" field is not of large magnitude. As discussed in Ref. 18, the geometrical barrier allows this shielding current density to peak at the film's edge as for the transport current. Field penetrates roughly when the applied field exceeds $H_{cl}(d/a)^{1/2}$. For a truly thin film, $d \ll a$, the shielding current is ineffective, allowing internal fields nearly equal to the perpendicular applied field $H_\perp$ except within the extremely narrow field-free region, $|x| < b \ll a$. All current primarily curves vortices within the superconductive film. Strong pinning naturally makes the transport-current distribution $J(x)$ similar to what is described above in zero applied field. We argue that the primary effect of a high density of vortices is a reduction of J_c. Its effect upon I_e is not at all clear, but our data fits discussed below suggest that $H_\perp$ changes I_e little.

Since current density is limited to J_c over most of the film, a supply of transport current shrinks the region where $|J(x)| < J_c$ and widens the region where $|J(x)| = J_c$ in the direction of the transport current (the latter is analogous to the flux penetration region when no external magnetic field is applied). As discussed in Refs. 15 and 16, the field-invariant region [where $J(x) < J_c$] initially is restricted to the side of the center line where shielding current flows opposite to the direction of the transport current. Note that since transport current applies the Lorenz force, $\mathbf{J} \times \mathbf{B}$, moving vortices right to left in Fig. 1, the geometrical barrier requires current density to peak at J_e at the right edge in order to permit vortex entry into the film strip. After the supplied current peaks and begins to decline, $J(x)$ initially declines very near the edge, $a - x \ll a$ without changing the normal flux distribution. However, after that edge peak falls to J_c transport current flows in the opposite direction near both edges of the conductive strip. Further reduction of current drives vortices near the edges to move left to right, and $J(x)$ peaks sharply to $-J_e$ at the left edge. The absence of any significant barrier to vortex exit allows it to be limited to J_c at the right edge while the current decreases. The central region becomes a new field-invariant region for the remainder of the cycle. The current distribution within this new field-invariant region must reflect the magnetic field induced by the changing total $J(x)$. Reference 16 discusses the calculation of this image current. We add an edge current to the uniform J_c used to get Eqs. (57) and (58) of Ref. 16. As supplied current increases, its density must peak at the right edge but not at the left edge. Flux entry during subsequent half cycles will require half the work of $I_e \Phi / ad$. This gives a revised Eq. (5):

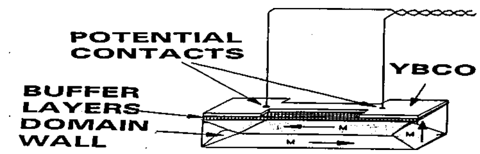

FIG. 2. Diagram of sample with four electrical contacts to the superconductive film and leads used to measure ac voltages. Domains of magnetization **M** are shown within the Ni RABiTS.

$$Q_{\rm tot} = Q_C + \Phi I_e / 2ad$$

$$\approx \frac{\mu_0}{\pi a d}\left[\frac{(I_0 - I_e)^4}{12(2adJ_c)^2}\left(1 + \frac{6I_e^2}{\pi^2 J_c^2 a^2 d^2}\right) + \frac{I_e I_0^2}{2J_c a d}\right]. \quad (7)$$

We emphasize that the very high demagnetization factor of a thin film in a perpendicular field makes Eq. (7), rather than Eq. (5), appropriate to the vast majority of situations.

EXPERIMENTAL TECHNIQUES

Cold rolling followed by primary recrystallization naturally textures polycrystalline fcc metals (here Ni) to $\langle 100 \rangle$ axes both perpendicular to the tape and in the rolling direction.[11] Epitaxial buffer layers of 0.5 μm ceria and 0.5 μm yttrium-stabilized zirconia (YSZ) make a useful substrate. Superconductive YBCO can then be grown epitaxially by several techniques including pulsed-laser ablation,[4] magnetron sputtering, or coevaporation.[26] The film is patterned to the structure shown in Fig. 2 in order to force electrical current flow through a relatively narrow (0.2–1-mm wide) bridge between two current-contact areas (approximately 3×3 mm). Several YBCO film strips grown on RABiTS and a similar YBCO film grown from precursor components deposited on a $SrTiO_3$ single crystal[27] were characterized by making four-terminal electrical measurements. Current was supplied through indium or Hg-In alloy pressed between copper blocks and Ag-coated contact areas. Spring contacts for voltage terminals extended about 3 mm perpendicular from the superconductive strip, sufficiently far[28] that voltage leads can sense magnetic hysteresis as assumed by Norris.[14]

Transport currents of up to 6 A at audio frequencies (22–256 Hz are presented in Fig. 3) were supplied. The sample voltage terminals were connected to the differential input of a lockin amplifier,[29] used in its tuned amplification mode to

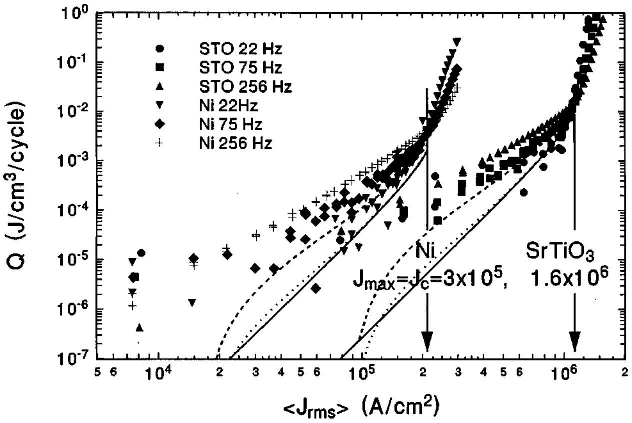

FIG. 3. Electrical energy loss Q per cycle per unit volume from the average ac current densities $\langle J_{\mathrm{rms}}\rangle = I_0/2^{3/2}ad$ through $YBa_2Cu_3O_{7-\delta}$ films on $SrTiO_3$ and RABiTS with no magnetic field applied. For currents below the critical value, theories give the continuous lines. The solid lines are based on Ref. 14; the dotted lines include edge currents that peak at $J_e = 2H_{cl}/d$; and the dashed lines include larger edge currents $I_e = 0.8$ A.

measure the loss voltage at the source frequency. (Phase accuracy is limited by instrument resolution of 0.1°.) In addition both the sample voltage, amplified by the lockin preamplifier stage in its flat mode, and the drop across a 0.5-Ω low-inductance standard series resistor were periodically recorded in a digital oscilloscope. The voltage drop across the sample was dominated by an inductive signal, 90° from the loss-signal phase. The lockin amplifier phase was frequently set to maximize the drop across the low-inductance standard. In order to analyze the oscilloscope-recorded voltage, the inductive component, proportional to time rate of change of current, was subtracted from the total digitized reading. The sample's inherent voltage-current characteristic could then be deduced from these oscilloscope records. Comparing loss calculations from both lockin and oscilloscope data provided a systematic check of the results.

RESULTS

Our results for transport-current loss per cycle in zero applied field, shown in Fig. 3, contrast sharply with the recent results obtained by Y. Iijima *et al.*[30] on a similar strip of YBCO film. Their data for a 1-cm-wide film strip fit the theory of Norris, Eq. (4) above, while our data (for narrower strips) clearly show more loss in the regime $I \ll I_c$. Note that in both cases, Norris's theory[14] fits the data very well when the supplied ac current peaks at the strip's critical current. Although it was noted in Ref. 13 that our data agreed reasonably with Norris's theory for a conductor of elliptic cross section, here we emphasize that the scatter was predominately on the higher-loss side. Norris's expression of loss proportional to $I_0{}^3$ for a thin strip applies only for $I_0 < BI_cd/2a$, well beyond the range we studied.

Figure 3 shows both curves generated by Eqs. (4) and (7). Note that use of Q_{tot} clearly improves agreement with the rather widely scattered observations. Although the scatter prevents unambiguous confirmation, the present theory falls within data while $I_0 > I_e$; in contrast, Norris's theory for a strip of rectangular cross section falls faster with decreasing ac current and is well below the data when $I \ll I_c$.

Application of a strong field perpendicular to the film reduces the bulk J_c, ultimately bringing predominance of the geometrical barrier. Figure 4 shows a collection of data with

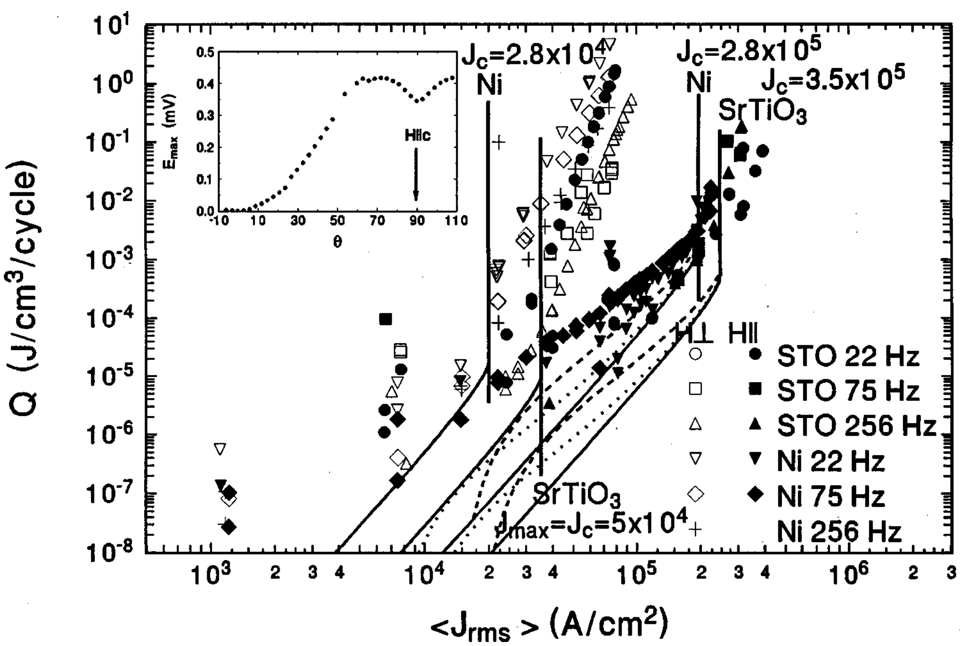

FIG. 4. Electrical energy loss Q per cycle per unit volume from average ac current densities $\langle J_{\mathrm{rms}}\rangle$ through $YBa_2Cu_3O_{7-\delta}$ films on $SrTiO_3$ and RABiTS with a magnetic field of 2 T applied both parallel and perpendicular to the film surface. In the inset the electrical potential observed with 2 A of current flow is plotted versus the sample angular orientation with respect to the applied field. For currents below the critical value, theories give the continuous lines. The solid lines are based on Ref. 14; the dotted lines include edge currents that peak at $J_e = 2H_{cl}/d$; and the dashed lines include larger edge currents $I_e = 0.8$ A.

a magnetic field of 2 T applied (which would reduce the conductivity of composite BSCCO tape to that of the Ag matrix). The inset electric-field dependence upon magnetic-field orientation indicates the importance of both intrinsic pinning by insulating *ab* planes and pinning by extended defects[31] parallel to the crystalline *c* direction. The stronger, intrinsic pinning by *ab* planes permits strong bulk current flow. The smaller critical current density for magnetic field perpendicular to the film surface leads to larger loss. In both cases the data are more lossy than predicted by Norris's theory, and some of the data strongly suggest $Q \propto \langle J_{\rm rms} \rangle^2$. Fitting these data indicates that the geometrical barrier allows more loss-free dc current flow than does bulk pinning over a wide range of supplied current less than the critical value I_c. The parameter $I_e = a^{1/2} d^{3/2} J_e = 0.8$ A is used for all the curves marked "$J_e = 2H_{cl}/d$" in both Figs. 3 and 4. Only the **H**‖ data (for magnetic field parallel to the surface and perpendicular to the crystalline *c* direction) are frequency independent for small $\langle J_{\rm rms} \rangle \ll J_c$. The higher-current data $\langle J_{\rm rms} \rangle > J_c$ obtained in zero applied magnetic field decrease with increasing frequency, qualitatively as expected for conduction in Ohmic material. Application of a perpendicular field produces such a frequency dependence over the whole range of ac currents.

Efforts to image magnetic domains within the Ni substrate (with no applied field) showed only magnetization parallel to the broad tape surface in spite of odd directions of ⟨111⟩ the preferred Ni magnetization axis.[32] Apparently the energy of magnetic fields outside the Ni led to confinement of magnet field within the ferromagnetic substrate. Magnetization measurements showed classic hysteretic behavior when a field was applied parallel to the tape surface and negligible effects of Ni presence when substantial applied field was perpendicular to the tape. Hysteresis is expected to arise from the required motion of walls between magnetization domains. The requirement of continuous magnetic induction *B* makes the presence of a thin slice of any magnetic material difficult to sense in a perpendicular field. The magnetic response gets more complex when fields smaller than one millitesla (10 G) are applied, and that situation has not been investigated thoroughly. As discussed above, the current density in the strips of superconductive film distributes itself to generate magnetic field parallel to the film and Ni surfaces, perpendicular to the direction of current flow along the tape length. The geometry of the ferromagnetic material favors two domains magnetized parallel and antiparallel to the long tape direction as shown in Fig. 2. The field induced by the transport current is perpendicular to this magnetization and cannot cause hysteresis in the ferromagnetic material. The absence of ferromagnetic hysteresis explains the agreement of loss observed in film strips deposited on $SrTiO_3$ with that for strips deposited on Ni.

DISCUSSION

While the present study generally confirms the concept of hysteretic ac loss in superconductive tape, it also identifies several limitations to the theoretical picture published in 1970 (Ref. 14). As expressed in Eq. (5) a geometrical barrier both increases the critical current, thereby reducing ac loss, and raises the power dissipated beyond that expected when the current density, has the uniform value J_c. Field exclusion naturally causes current density to peak with values greater than J_c at the edges, $x \approx \pm a$, of the superconductive strip. As expected, the geometrical barrier responsible for this peak adds loss that dominates over the wide intermediate range of $\langle J_{\rm rms} \rangle, I_e/2ad < I_0/2^{3/2}ad = \langle J_{\rm rms} \rangle < J_c$. The expectation that current $I < I_e$, the total peak current, can flow with extremely low loss was not clearly observed. Rather the data reported here shows a substantial random component when $I_0 < I_e$. The loss measurements in a perpendicular field for the film grown on RABiTS are especially widely scattered, and this regime is presently under further study.

The degree of sensitivity to magnetic field will be a central consideration in various possible applications. A magnetic field perpendicular to the film induces the "high-field" current distribution, $J(x) \approx [J_c + I_e \delta(|x| - a) \mathrm{sgn}(x)]$, where $I_e \delta(|x| - a)$ represents the narrowly peaked edge current density. The demagnetization geometry of a thin film makes the step function $J_c\,\mathrm{sgn}(x)$, applicable for very modest fields. The critical fields $H_c = J_c d/\pi$ of Ref. 15 are of the order of 10 mOe for these two samples. Much more important is a substantial reduction of I_c with the application of teslas. However, we emphasize that this reduction is small in comparison with that observed in sintered, polycrystalline materials. A magnetic field applied parallel to the film reduces I_c more modestly. Application parallel to the film grown on $SrTiO_3$ place the loss data close to the level $Q_e \approx \mu_0 I_0^2 I_e / 4\pi a^2 d^2 J_c$ over a wide range in spite of the fact that I_e appears to be less than half of adJ_c. We conclude that power loss in a tape of rectangular cross section cannot fall with reduction of current level as rapidly as previously expected.

Frequency dependence is unobservable in each sample when $I < I_c$, and shows up clearly when $I > I_c$. The observed frequency dependence shows the loss per cycle reduced by an increasing frequency as expected for a resistive material, although we emphasize that both the loss and its reduction with frequency are much less for these samples than for normal metals. Apparently dissipative flux motion plays an important role when $I > I_c$. This frequency-dependent loss also increases with increasing applied field. Consistent with this trend is our observation that the exponent in $E(J) \propto J^n$ is reduced with increasing field from a maximum $n \approx 20$ at very low field.

Biaxial grain alignment and introduction of crystalline defects clearly can increase the critical current density. However, a substantial portion of the total critical current of the narrow strips of thin YBCO films reported here appears to arise from sharply peaked current density at a strip edge. If this peak is indeed due to the geometrical barrier as argued in the theoretical background section, the edge current estimated in Ref. 18, $I_e \approx H_{cl}(ad)^{1/2} \approx 0.8$ A, is consistent with $H_{cl} \approx 400$ Oe, which is about twice the value deduced by Ossandon *et al.*[33] for single-crystal YBCO. This peak current density is flowing within a distance of the order of $2H_{cl}^2/J_c^2 d \sim 10$–$100\ \mu$m, a small portion of our 0.2- and 1-mm-wide strips. Although we have not identified a suitable microstructure, this high estimate for I_e might be due to strong pinning very near the strip edges (the authors of Ref. 17 purposely introduced such pinning). The entry barrier estimated in Ref. 21 is smaller, more clearly inconsistent with the interpretation discussed above. The true nature of the effective barrier to vortex entry is not clear at the present time.

Finally we address the question of possibly improving performance by making a more finely divided pattern of n film strips of width $2a/n$. We assume reproducing J_c and the total sample volume, supplying identical currents to all n strips, and arranging them so they cannot interact. Obviously the total critical current, $I_c = 2\Sigma a J_c/n + nI_e$, increases due to the increased number of film edges. Equation (4) implies that total losses decrease, $Q_N \propto n^{-1}$ and $Q_e \propto n^{-1/2}$, but not as fast as I_c increases.

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