Magnetic Field Sensitivity of Variable Thickness Microbridges in TBCCO, BSCCO, and YBCO

Bruce A. Davidson, Ronald D. Redwing, Tuong Nguyen, *Student Member, IEEE,* Juan O'Callaghan, Farshid Raissi, Ji Ung Lee, Joseph P. Burke, Gert K. G. Hohenwarter, James E. Nordman, *Member, IEEE,* James B. Beyer, *Senior Member IEEE,* S. H. Liou, James Eckstein, Michael P. Siegal, S. Y. Hou, and Julia M. Phillips

***Abstract*—We describe results of a study comparing the magnetic field sensitivities of variable thickness bridge (VTB) arrays fabricated in TBCCO, BSCCO, and YBCO thin films. Identical structures were patterned in a variety of films, and the bridges were thinned by four different methods. Analysis of the data yields experimental evidence as to the suitability of these types of films for devices such as the superconducting flux flow transistor (SFFT) which is based on this geometry. The volt-ampere characteristics of the arrays were measured in low uniform magnetic fields ($\leq$ 130 G) and in nonuniform fields ($\leq$ 5 G) produced by a nearby control line. For these films in this geometry, no measurable effect of the control line magnetic field was observed. Large values of transresistance and current gain could only be attained through a thermal mechanism when the control line was driven normal. Upper bounds for (magnetically generated) transresistance ($\leq$ 5 mΩ) and current gains ($\leq$ 0.005) have been inferred from the uniform field data assuming a standard best-case device geometry. All volt-ampere curves followed closely a power law relationship ($V \sim I^n$), with exponent n $\sim$ 1.2–10. We suggest materials considerations that may yield improved device performance.**

I. Introduction

FLUX flow in high temperature superconductors (HTS) thin films has been assumed to be the mechanism responsible for the interesting behavior of the superconducting flux flow transistor (SFFT) [1], [2]. The SFFT is based on a superconducting thin film region which has a critical current that is very sensitive to magnetic field (a $\Delta I_c/\Delta B$ of the order of 1 mA/G) and an output resistance (defined as $\Delta V/\Delta I$) in the range of ohms, out to voltages of order 10 mV. Furthermore, early devices were made using films that were poorly characterized and not easily reproduced [1], [2], and it is likely that these films were polycrystalline. It appears that most recent attempts to realize suitable device characteristics with well-characterized films have failed. Because of the variety of microstructures that can exist in HTS films grown by different methods in different laboratories, and the sensitivity of the films to various processing techniques (most importantly the thinning of the bridge structure used in this device), it is difficult to compare results among different laboratories. To address these concerns, and to identify the necessary film properties which may yield useful and reproducible SFFT devices, a comparative study of VTB's was made by collecting a variety of characteristic films, processing them in the same way, and then systematically testing them for magnetic field sensitivity.

Typical high-T_c films have high J_c (i.e., high pinning). This suggests that for a flux flow device, low-pinned films (at best approaching the bulk single crystal limit) would be required. However, because of the very large B_{c2} (several tesla) in these materials, flux flow resistivity values implied by the Bardeen–Stephen model [$\rho_{ff} = \rho_n(B/B_{c2})$] may be too small in low magnetic fields to yield practical device impedance levels. It has been suggested [3] that in highly anisotropic superconductors, near T_c the irreversible field B_{irr} may replace B_{c2} as the important characteristic field; since B_{irr} can be of order tesla, one might expect in theory an order of magnitude improvement in flux flow resistance values but still not into the practical range. An alternative approach would be the intentional use of granular films with transport characteristics that are dominated by an array of high-angle grain boundaries which follow highly damped resistively shunted junction (RSJ) behavior. It has been shown that such junctions are extremely sensitive to magnetic fields of order gauss [4]. In this limit, step-edge or bi-epitaxial techniques would allow for single junction devices similar to the low-T_c vortex flow transistor (VFT) [5] and

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B. A. Davidson, R. D. Redwing, T. Nguyen, J. O'Callaghan, F. Raissi, J. U. Lee, J. P. Burke, J. E. Nordman, and J. B. Beyer are with the Department of ECE, University of Wisconsin-Madison, Madison, WI 53706.

G. K. G. Hohenwarter is with Parkview R & D, Madison, WI 53711.

S. H. Liou is with the Department of Physics, University of Nebraska, Lincoln, NE 68588.

J. Eckstein is with Varian Research Center, Palo Alto, CA 94304.

M. P. Siegal is with Sandia National Laboratories, Albuquerque, NM 87185.

S. Y. Hou and J. M. Phillips are with AT & T–Bell Laboratories, Murray Hill, NJ 07974.

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SQUID amplifiers [6]. In this case, the vortex dynamics are described in the Josephson regime rather than the Abrikosov regime. As an intermediate case, vortices in a granular material with a grain size on the order of the penetration depth might exhibit a mixture of characteristics of both types. Devices based on these dissimilar flux flow mechanisms would be expected to show different limiting behaviors such as vortex velocity, gain-bandwidth product, and noise properties which would ultimately determine their usefulness as high-frequency devices.

The variable thickness bridge (VTB) geometry studied here consists of a parallel array of weakened links between two "banks" of good superconductor. The weakened links have a thickness d much less than their width w, length l, or the thickness of the banks. The magnetic field is applied normal to the film and the bias current is applied along their length. The Lorentz-like force exerted on the vortices by the bias current gives them a component of velocity across the width, developing a voltage across the banks. Likharev [7] has treated theoretically the case for a single link where d is less than the penetration depth λ, and analyzed the various volt-ampere characteristics expected when the width and length are either large or small with respect to λ and the coherence length ξ. High-T_c epitaxial films typically have their c-axis normal to the substrate surface and exhibit anisotropy between the a-b plane (CuO_2 planes) and the c-axis in such characteristic properties as penetration depth, normal state resistance, and coherence length. This anisotropy becomes more pronounced as the CuO_2 plane spacing increases, being the largest in the TBCCO 2223 phase. This anisotropy could complicate the description of c-axis oriented vortex motion across the links if Josephson coupling exists across the CuO_2 planes.

II. Film Characterization and Processing

Table I summarizes the films used in this study and typical characteristic properties. Films from four high-T_c materials systems were characterized, processed, and tested: YBCO 123, BSCCO 2212, TBCCO 2212, and 2223. Pulsed laser deposition (PLD) films of YBCO were grown in our laboratory, and are considered representative of high-J_c, highly pinned films that are grown in many laboratories. YBCO films from Hypres were obtained because films from this supplier were used for the original studies of SFFT's in YBCO [1]. These Hypres films were grown by an amorphous multilayer sputter deposition procedure followed by a high temperature postanneal, and a significant density of second phase precipitates was always present. For a similar motivation, optimized YBCO films grown by the BaF_2 technique at Bell Laboratories [8] were obtained because later reports on successful SFFT's [9] suggested that their lower pinning was responsible for improved results. High-quality epitaxial BSCCO 2212 films grown by *in situ* MBE were obtained from Varian [10]. High quality films of both phases of the TBCCO material were also obtained: TBCCO 2212 films were grown by MOCVD at ATM, and (thick) TBCCO 2223 films grown by a sputter/postanneal technique at the University of Nebraska [11]. The high temperature postanneal produced a rough surface morphology and a significant density of pinholes in the 2223 films which had to be avoided during processing.

All films were patterned with identical bridge structures so that the current versus voltage (I–V) curves could be directly compared. Depending on substrate size, each film was patterned with 4–12 arrays and (when space allowed) 1 or more adjacent control lines. Each array consisted of 4 parallel links with dimensions 5 μm wide by 10 μm long (5 μm separation between links); the control line was 8 μm wide and 7 μm from the nearest link. All voltage leads were placed within 10 μm of the links, to ensure that the voltages measured were developed across the links and did not include the adjacent banks. The circuit pattern was defined with AZ1350J-SF photoresist which was then ion-beam etched (IBE) using a 2.5 cm Kaufmann source while in good thermal contact with a water cooled Cu plate (at a typical beam voltage of 500 V and an ion current density of 0.3 mA/cm^2). Noble metal contacts (pad area 1 mm^2, typically 1000 Å thick) were made by a contact liftoff procedure (for Ag deposited by dc magnetron sputtering) or shadow masking (for thermally evaporated Au). The entire circuit, with the exception of the bridge structure and contacts, was protected with HR-100 photoresist for subsequent thinning of the bridges.

Thinning ("tuning") of the arrays was accomplished by four methods where appropriate: IBE, EDTA, Br, and HNO_3. Tuning by IBE was done as previously described for circuit etching but at lower current densities to enhance control of the process. The choices of etchants (both aqueous and nonaqueous) were based on [12]–[16] reporting the etching of surfaces with close-to-ideal stoichiometry and little degradation of the superconducting properties and surface resistance. Aqueous etchants used were ethylenediaminetetraacetic acid (EDTA, 1.7×10^{-3} M solution) and nitric acid ($\sim 0.003\%$ by volume); these solutions were continuously stirred during the etching process with N_2 bubbling ("de-gas") to reduce the equilibrium concentration of CO_2 in H_2O [12]. The samples were immersed for the desired time and quenched in isopropyl instead of DI water to minimize surface exposure to water. Since there was a concern for the reactivity of HTS with water [16], a nonaqueous etchant (1% Br in isopropyl) was also used. It was found that etch rates depended on the time the samples were exposed to air or water; it is believed that this is due to the formation of passivating layers.

Prior to thinning the links, bulk etch rates on the various films were measured. During tuning, it was found that on some of the films tested, the critical current decreased an order of magnitude faster as a function of etch time than was expected from a simple reduction of the cross section. We take this as an indication that, in these films, the critical current was determined by grain boundaries which were attacked by the wet chemistry faster than the bulk of the grains. This was particularly

TABLE I
SUMMARY OF TYPICAL PROPERTIES OF FILMS TESTED

Film/Subst	Supplier	Growth	No. films	thickness (Å)	T_c (K)	Jc @ 77K (A/cm^2)
YBCO / LAO	UWisc	PLD	4	1000	89	mid 10^6
YBCO / LAO	Hypres	Post-anneal	6	3000	86	low 10^5
YBCO/sapphire	Hypres	Post-anneal	1	3000	83	mid 10^4
YBCO / LAO	Bell Labs	BaF/Post-anneal	3	900	89	1 x 10^6
BSCCO 2212/STO	Varian	MBE	1	1200	80	low 10^5 (@ 70K)
TBCCO 2212/LAO	ATM	MOCVD	3	5000	95	low 10^5
TBCCO 2223/LAO	UNeb	Post-anneal	4	30000	105	mid 10^5

true for the Hypres YBCO samples, which correlates with their low J_c.

III. Testing of Magnetic Field Sensitivity

The bridges were thinned incrementally from their original I_c (2–150 mA) to 50–200 μA, and testing was done immersed in LN_2; the dc applied external field was either a variable uniform magnetic field (0–130 G, produced by a wire-wound solenoid) or the nonuniform field produced by an adjacent control line (0–5 G maximum). All testing was done with the sample inside a sealed box purged with dry nitrogen gas. Electrical measurements of the bridges were made using a standard four-point technique. The test fixture had a spring-loaded pin arrangement which was designed for easy alignment with the contact pads; contact resistances of 1–10 Ω were typically obtained (lower if the samples were annealed at 450°C in pure O_2 for 30 min).

In the films with J_c in the 10^5 A/cm^2 range or lower, the 8-μm-wide control line often had a critical current of a few mA or less after processing. In this case, the field produced by the control line at the first link is less than 1 G, which limits the range of nonuniform fields which could be applied to the links (see discussion below). The films with higher J_c had control lines with significantly higher critical currents (10–30 mA), but the same reason for the higher critical current (i.e., pinning) was expected to render the films insensitive to flux flow.

Current versus voltage curves were taken after each thinning step to measure the reduction in I_c and to observe any change in the curve due to the applied field. Typical I–V curves as the links were thinned are shown (Fig. 1) for YBCO on LAO from Bell Labs, etched in EDTA. A typical volt-ampere curve for a sample which showed sensitivity to 130 G field is shown in Fig. 2. This Varian MBE-grown BSCCO was measured at two temperatures near T_c ($\sim$ 80K). Note the different current scales and the common voltage axis.

IV. Results

Two device parameters of practical importance were inferred from dc I–V curves: the transresistance ($r_m = \partial V_{out}/\partial I_{in}$) and the (dynamic) output resistance ($r_0 = \partial V_{out}/\partial I_{out}$), with the current gain β given by their ratio. For an actual device, the input current I_{in} is the current applied to the control line, and V_{out} and I_{out} are the bias voltage and current of the microbridge array. Since any change in the I–V curve due to a control line supercurrent was below the sensitivity of the measurement equipment used (see discussion below), transresistances and current gains reported here were extrapolated from the uniform field data assuming the existence of a control line which could generate 1 G per mA of input current. A linear field response was assumed over the range of magnetic fields applied (0–130 G); this was consistent with I–V curves measured at fields between these limits. As summarized in Table II, the largest values extrapolated for r_m (typically calculated as a bias voltage of 1 mV) were ≤ 5 mΩ for TBCCO 2223 devices, with $\beta \leq 0.005$.

Typical plots of the (extrapolated) transresistance and current gain for a TBCCO 2223 device, as a function of bias current, are shown in Figs. 3 and 4. The T_c had been reduced to $\sim$ 80K during processing. Since the I–V curves were not linear, r_m and β vary as a function of bias current. The BSCCO 2212 film showed similar values, and all YBCO values were one to two orders of magnitude lower. It was observed that thinning had no appreciable effect on the measured ΔV of the VTB under applied field (and hence had no effect on r_m), while the reduction of the cross section of the links increased r_0 and hence decreased β.

It is important to note that these links were 10 μm in length, and that perhaps a more significant figure for purposes of comparison is the voltage developed in an applied field (ΔV), scaled to the length of the link ($\Delta V/l$), that is, the voltage developed when a certain electric field is sustained across the links. This is suggested by the Kim–Stephen model [17] which gives the voltage as $V = n v_L \phi_0 l$ where n is the number of vortices per unit area, v_L is the vortex velocity, ϕ_0 is the flux quantum, and l is the length of the link. Measurements on links of varying lengths showed a monotonic increase in ΔV as the length increases, but not linear as expected from the simple model. Clearly, using links of arbitrarily long lengths can increase the ΔV developed, but this will have a detrimental impact on overall device performance: the input inductance increases as the device length increases, which reduces the upper operating frequency of the device. One

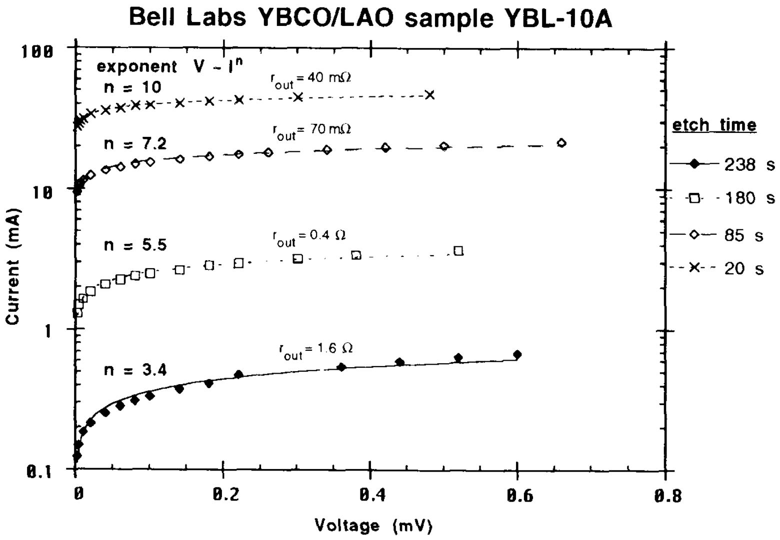

Fig. 1. Zero field I–V curves for YBCO/LAO as a function of EDTA etch time, with exponent and output resistance (measured at 0.3 mV).

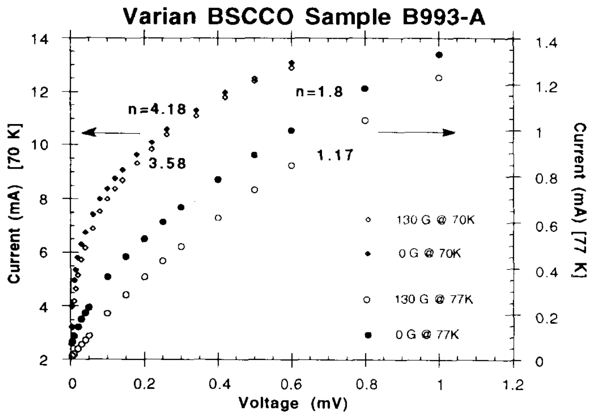

Fig. 2. I–V curves for BSCCO VTB in 0 and 130 G field, at 70 and 77K.

can estimate the voltage developed across a link due to an applied field using the above equation. If a vortex velocity of 10^3 m/s is assumed, then for a link length of 10 μm and an applied field of 100 G, the voltage developed along the link is of order 100 μV, which is consistent with our measured ΔV values.

On the samples where the control line remained superconducting after processing (all the YBCO films tested), no effect of the magnetic field due to a control lines supercurrent (as verified by a simultaneous four-point measurement) was observable ($\Delta V < 2$ μV). The transresistance in this case could then be at most about 0.5 mΩ for the Hypres films, and less for the higher J_c films. Even though the magnetic field thus produced is nonuniform, i.e., a gradient exists across the width of the link, the magnitude is always smaller than the uniform field attainable by the solenoid. At the nearest link (a distance of ~ 5 μm), a straightforward electrodynamics calculation shows the field of a control line in our geometry is less than 1 G at I_c for a critical current density of 10^5 A/cm^2, perhaps 5 G for 10^6 A/cm^2. An argument can be made that the voltage developed along a link in a nonuniform field could show an increase of order 2 as compared to in a uniform field, in the regime where the applied field is small compared to the link's self-field. In this case, the nonuniform field can add to the self-field vortex density without subtracting from the antivortex density, whereas the uniform field adds as much to the vortex density as it subtracts from the antivortex density. In the regime where the magnitude of the applied field is large compared to the self-field, by the same argument no significant difference between the two would be expected. In this model, reversing the direction of the nonuniform field with respect to the self-field could then decrease the voltage developed across the link (i.e., this effect is not symmetrical in the first and third quadrants of the I–V curve). A uniform field would be expected to retain symmetry between these quadrants. This symmetrical response between quadrants in uniform field was routinely observed experimentally, whereas any asymmetrical response from a nonuniform field was below our sensitivity, as mentioned.

Significant changes in the I–V curve could be realized by driving the control line normal (i.e., thermal effect). A typical I–V curve is shown for a Hypres film (Fig. 5). At control line currents well above $I_{c,\text{control}}$, transresistances upwards of 20 Ω and current gains greater than 10 were readily attainable. These results were independent of thinning of the links. Naturally, this thermal response is limited by phonon transit times (time required to remove the heat, returning the device below T_c), and as such is

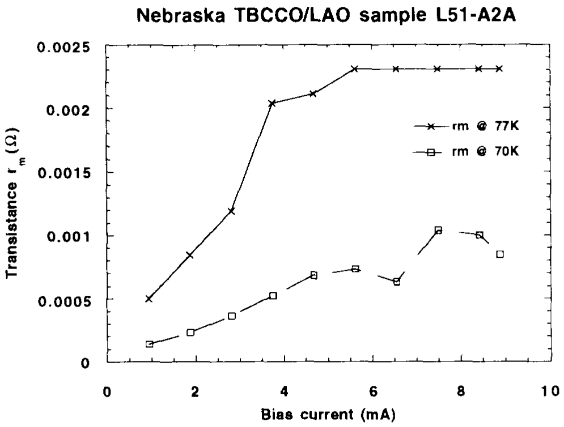

Fig. 3. Transresistance for TBCCO 2223 VTB as a function of bias current, at 70 and 77K, assuming a linear magnetic field response (see the text).

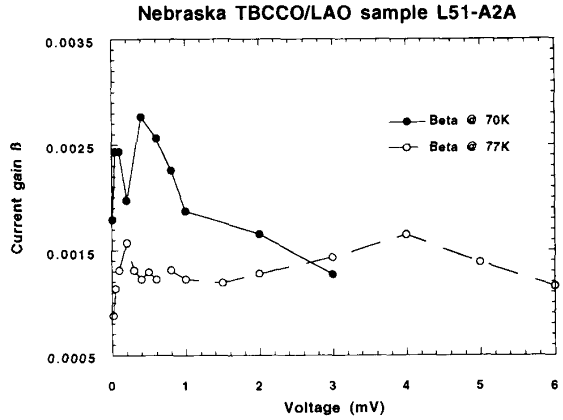

Fig. 4. Current gain as a function of bias voltage for TBCCO/LAO at 70 and 77K, assuming a linear magnetic field response.

TABLE II
SUMMARY OF TYPICAL DEVICE PARAMETERS FOR VTB'S TESTED

Film/Subst	Supplier	Growth	No. VTBs	typical r_m (Ω)	typical ß
YBCO / LAO	UWisc	PLD	22	$< 10^{-4}$	< 0.0001
YBCO / LAO	Hypres	Post-anneal	31	10^{-4}	< 0.0005
YBCO/sapphire	Hypres	Post-anneal	1	10^{-3}	0.0005
YBCO / LAO	Bell Labs	BaF/Post-anneal	18	10^{-4}	< 0.001
BSCCO 2212/STO	Varian	MBE	1	10^{-3}	0.001
TBCCO 2212/LAO	ATM	MOCVD	26	10^{-3}	0.001
TBCCO 2223/LAO	UNeb	Post-anneal	3	10^{-3}	0.003

expected to be limited to frequencies at most of order hundred(s) of MHz with noisy operation. On top of this thermal modulation, the (small) effect of the uniform 130 G field remained unchanged (not visible on the scale of Fig. 5). The thermal effect gave a symmetrical response in the I–V curve, independent of the direction of the control line current. The effect of the magnetic field of the control line (i.e., any asymmetry between the first and third quadrants) was not measurable.

As discussed often in the literature, in general it is difficult to explain any of the measured (nonlinear) I–V curves in terms of a simple flux flow model, instead relying on models such as thermally activated flux creep (e.g., [18]). For example, in zero applied field, it was possible to sustain voltage drops across thinned arrays of 30–200 mV for bias currents of 10–30 mA. In this case, the self-field could never exceed 100 G at the edges of a link with rectangular cross section [19]. The simple Kim–Stephen model equation above yields a voltage drop across the 10 μm link of 100 μV for a vortex velocity of 10^3 m/s. This is more than 2 orders of magnitude less than the measured 30 mV. It is not possible to use the above argument as a measure of the vortex velocity (for example, suggesting the vortex velocity is actually something like 10^5 m/s) since applying a uniform external field of 100 G to the link current biased at 30 mA should have a comparable effect on the voltage of the link as the self-field. As noted, this was not observed.

A study of the effect of deoxygenation on magnetic field sensitivity was performed on Hypres YBCO/LAO. Films were deoxygenated in an oven at 200°C in ambient, and the I_c was decreased a factor of 10 from the original value, at the rate of 4 mA/h. No change in the magnetic field sensitivity was observed.

V. ANALYSIS

In all bridges measured, the I–V curves followed a power law relationship extremely closely ($V \sim I^n$) in the region of the I–V curve most influenced by magnetic field [18]. The exponent n ranged between 1.2 and 10; and in the films that exhibited sensitivity to magnetic field, the exponent decreased in field. The I–V curve of the BSCCO device (Fig. 2) as a function of temperature indicates that both r_m and r_o increased as the temperature approaches T_c from below, while β decreased slightly (factor of 3). We note that this behavior applied only within 5–8K of T_c. The TBCCO 2223 also exhibited this trend in the same temperature range. In all YBCO and TBCCO 2212 devices, the values of r_m at a given temperature did not change measurably as the links were thinned.

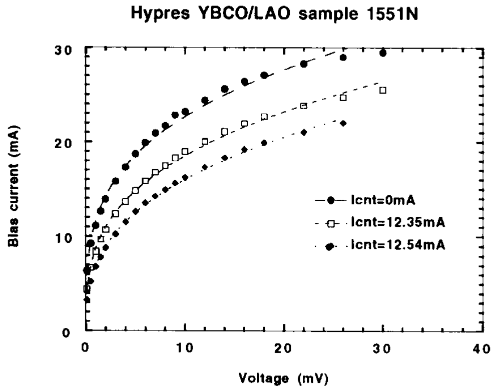

Fig. 5. I–V curves for YBCO/LAO when operating in thermal mode. I_c of the control line was 0.2 mA. The I–V curves were identical when the control line current was reversed.

If the I–V curve in the region of interest can be described accurately with a power law, then certain device analysis can be performed once the exponents have been experimentally determined as a function of applied field. One can write the power law in the form

$$V_{out} = V_c\left(\frac{I_{out}}{I_c}\right)^{n(B)} \tag{1}$$

where V_c and I_c are the intersection points of the power law fits to the I–V curves in different fields (replacing the critical current of the original Ambegoakar and Halprin notation for a Josephson junction [20]). It was found experimentally that V_c and I_c remained essentially constant in the range of fields tested, and the experimental I–V curves closely followed the power law fits to ~ 0.7 of V_c and I_c, which was the portion of the curves which showed the most sensitivity to field. Then $r_m = dV_{out}/dI_{in}$ and $r_o = dV_{out}/dI_{out}$ can be calculated with only two additional pieces of information. First, the relationship must be known between I_{in} (the control line current) and the resulting B at the links (an electrodynamic calculation); second, the functional dependence must be determined of the exponent on applied field, $n = n(B, T)$. For the former, we assume a (calculable) constant $c = dB/dI_{in}$ for simplicity, so that $r_m = c\,dV_{out}/dB$. For the latter, we found our data were fit well with the expression for $n(B)$ of Gupta [21]

$$n = 1 + \frac{n_o - 1}{1 + B/B_o} \tag{2}$$

where n_o is the exponent in zero field, and B_o is a parameter to be fit (which indicates the order of magnitude of fields in which the I–V curve will change exponent). The resulting expressions for r_m, r_o, and β are

$$r_m = cV_c\frac{\partial n}{\partial B}\left(\frac{I}{I_c}\right)^n \ln\left(\frac{I}{I_c}\right) \tag{3}$$

$$r_o = \frac{V_c}{I_c}n\left(\frac{I}{I_c}\right)^{n-1} \tag{4}$$

giving the current gain as

$$\beta = cI_c\frac{1}{n}\frac{\partial n}{\partial B}\left(\frac{I}{I_c}\right)\ln\left(\frac{I}{I_c}\right). \tag{5}$$

If (1) is substituted into (4), the current gain is given by

$$\beta = cI_c\left\{\frac{1 - n_o}{B_o(n_o + B/B_o)(1 + B/B_o)}\right\}\left(\frac{I}{I_c}\right)\ln\left(\frac{I}{I_c}\right). \tag{6}$$

This expression for β has a maximum at $B = 0$ and $x\ln(x) = 1/e$, and its highest order term depends inversely on B_o. It is relatively insensitive for zero-field exponent n_o, which varies between 2 and 10 experimentally.

Fitting the I–V curves allows an experimental determination of the values of n_o, B_o, and I_o of the different films. Further, using the assumption above for the field generated at the links [which determines the coefficient c in (5)], the curves generated with the above expressions for r_0, r_m, and β match well in shape and magnitude with our measured values. We should note that the I–V curves at 77K for the BSCCO film give $n_o = 1.8$ and $B_o = 35$ G. This value for B_o is surprisingly small with respect to the values referenced in the literature for other high-T_c materials. Pulsed laser deposited YBCO was reported to have $B_o \sim 1$ tesla at 80K [21], which is consistent with our measurements on PLD films, and BSCCO of an unknown fabrication method was reported to have a similarly large $B_o \sim 1$ tesla [22].

To achieve a current gain of unity ($\beta = 1$), if the characteristic current is 1 mA and the exponent n_o is constrained to be near 5, it is readily calculated that B_o must be of order 0.3 G or less, which is the order of magnitude of field sensitivity of a Josephson junction. It is for this reason that granular films may provide some promise. Of course, relevant properties of such a material (e.g., noise, Josephson plasma frequency limit, output impedance) must be adequately investigated.

VI. Conclusions

The results to date verify the expectation that conventional "good" high-J_c YBCO films are not suitable for active flux flow devices. A large number of VTB's in various films of YBCO, BSCCO, and TBCCO were fabricated and tested for sensitivity to small dc magnetic fields (≤ 130 G). Although greater in BSCCO and TBCCO than in YBCO, sensitivity to small magnetic fields at 77K was not sufficient in any bridge tested to allow production of a magnetic field controlled device with transresistance values greater than 5 mΩ or small signal current gains of 0.005. Both values, inferred from the volt-ampere characteristics of the VTB's tested, appear to be at least two orders of magnitude lower than necessary for use in a practical device. Suitable values could only be attained by raising control line currents until the line became normal. These values were, however, caused by a thermal, not magnetic, mechanism as evidenced by the symmetry of the

$I-V$ characteristics and the fact that an additional solenoidal magnetic field had little effect.

Since the required impedance levels are obtained by thinning the bridge, the film/substrate interface is quite important; it may not be characteristic of the film as a whole and it may be changed by the thinning process. The volt-ampere characteristics of all bridges tested followed a power law in the region of the $I-V$ curve that showed the most influence to magnetic field, with an exponent dependent on sample type, temperature, and magnetic field. Published volt-ampere characteristics of SFFT's appear to have more well-defined critical currents and more linear characteristics above this critical current. This suggests that successful devices may have operated in a Josephson rather than Abrikosov mode, implying granular material. Another important argument for a Josephson mode can be made on the basis of vortex velocities. If the mechanism is flux flow (or phase slip), the requirement for a large voltage at a given value of flux density (vortex density) is simply that the vortex velocity be large enough. Maximum velocities for Josephson vortices would appear to be orders of magnitude higher than those possible for Abrikosov vortices. With this in mind, studies with granular films are in progress. Since there remains some question of the similarity of the current Bell Laboratories BaF_2-process films to those films grown 2 years ago, we continue to study the Bell Laboratories YBCO films to further understand flux flow resistance in low pinned films.

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Bruce A. Davidson received the B.A. degree (with honors) in physics from Swarthmore College, Swarthmore, PA, in 1983.

He spent four years at AT & T-Bell Laboratories, Murray Hill, NJ, with Dr. Leonard Feldman studying surface science and thin film growth/characterization, primarily on group IV semiconductors and then-new high temperature superconductors. He is currently working toward the Ph.D. degree in electrical engineering at the University of Wisconsin-Madison under an AFOSR ASSERT fellowship studying devices in HTS thin films.

Ronald D. Redwing received the B.S. degree in physics from the University of Missouri-Rolla in 1986 and the M.S. degree in physics from Rensselaer Polytechnic Institute in 1988.

He is currently working toward the Ph.D. degree in physics at the University of Wisconsin–Madison in the area of HTS thin film grain boundary interfaces.

Tuong Nguyen (M'86–S'88) received the B.S.E.E. and M.S.E.E. degrees in electrical engineering from the University of Wisconsin-Madison in 1985 and 1991.

From 1986 to 1988 he was with Loral Corporation (Goodyear, AZ) working on the design and development of antennas and microwave circuits. Since 1988 he has been with the Department of Electrical and Computer Engineering, University of Wisconsin-Madison. He is currently working toward the Ph.D. degree in electrical engineering on HTS microwave superconducting devices.

Juan O'Callaghan, photograph and biography not available at the time of publication.

Farshid Raissi, photograph and biography not available at the time of publication.

Ji Ung Lee received the B.S.E.E. and M.S.E.E. degrees in electrical and computer engineering from the University of Wisconsin-Madison in 1989 and 1991, respectively.

He is currently working as a Research Assistant working toward the Ph.D. degree in EE in UW-Madison studying devices using highly anisotropic HTS materials.

Joseph P. Burke, photograph and biography not available at the time of publication.

Gert K. G. Hohenwarter received the Dipl.-Ing. degree in electrical engineering from the Technische Universitaet Braunschweig in 1978, and the M.S. and Ph.D. degrees in electrical engineering from the University of Wisconsin-Madison in 1979 and 1988, respectively.

From 1984 to 1987 he was responsible for the development of high-frequency interfaces and cooling systems for the superconducting instrumentation at Hypres, Inc. He has been involved in the development of low- and high-T_c superconductive electronic devices since 1987. Until 1989 he held a dual appointment as a Senior Staff Engineer at Hypres and a Research Associate at the University of Wisconsin-Madison. He recently joined Parkview Works, Inc. to continue exploration of novel devices and instrumentation in cooperation with the team at the University of Wisconsin.

James E. Nordman (S'61–M'63) received the B.S.E.E. degree in electrical engineering from Marquette University in 1957, and the M.S. and Ph.D. degrees in electrical engineering from the University of Wisconsin-Madison in 1959 and 1962, respectively.

In 1962 he was appointed to the Faculty of the Department of Electrical and Computer Engineering at the University of Wisconsin-Madison, where he is currently a Professor. His research and teaching have been primarily in the areas of electronic devices, semiconductors, superconductors, and thin film materials. In 1967–1968 he fabricated some of the first successful thin film niobium-lead Josephson junctions while on leave at RCA's Davids Sarnoff Research Laboratory in Princeton, NJ. During a second leave of absence in 1972–1973 he conducted research at l'Air Liquide, Sassenage, France, on various aspects of superconductive Josephson junctions using semiconductor and oxide tunneling barriers. His present research interests include materials and interface properties of low- and high-T_c superconductor thin films and electronic device mechanisms using superconductors.

James B. Beyer (S'61–SM'79) received the B.S.E.E., M.S., and Ph.D. degrees in electrical engineering from the University of Wisconsin-Madison in 1957, 1959, and 1961, respectively.

He served in the U.S. Navy during the Korean War. He has taught courses in the area of electromagnetic theory, microwaves, antennas, and electronics since his appointment to the faculty in 1961. From 1968 to 1969 he was a Fullbright Professor at the Technical University in Braunschweig, Germany. In 1984 and again in 1985 he served as a Consultant in India for the U.N. He is presently engaged in research on microwave circuits, antennas, and superconducting electronics.

Dr. Beyer is a member of Eta Kappa Nu and Sigma Xi.

S. H. Liou, photograph and biography not available at the time of publication.

James Eckstein, photograph and biography not available at the time of publication.

Michael P. Siegal, photograph and biography not available at the time of publication.

S. Y. Hou received the B.S. degree in metallurgical and materials engineering from the National Cheng Kung University, Taiwan, in 1984, and the M.S. and Ph.D. degrees in materials science and engineering from State University of New York–Stony Brook in 1989 and 1993, respectively.

His Ph.D. research involved growth and characterization of high-T_c thin films using the BaF_2 and postannealing method. He is currently doing postdoctoral research at AT & T–Bell Laboratories in Murray Hill, NJ. His research interests include oxide thin film growth using various techniques including electron-beam coevaporation and sputtering, and thin film materials characterization.

Julia M. Phillips received the B.S. degree in physics from the College of William and Mary, Williamsburg, VA, in 1976, and the Ph.D. degree in applied physics from Yale University, New Haven, CT, in 1981.

In 1981 she joined AT & T–Bell Laboratories as a Member of Technical Staff. In 1988 she became Supervisor of the thin film research group. Her interests include the growth and properties of epitaxial thin films and the relationships between film structure and other properties. She has authored or coauthored over 80 publications.