Characteristics of advanced $\text{YBa}_2\text{Cu}_3\text{O}_x/\text{PrBa}_2\text{Cu}_3\text{O}_x/\text{YBa}_2\text{Cu}_3\text{O}_x$ edge type junctions

J. Gao, Yu. Boguslavskij,^{a)} B. B. G. Klopman, D. Terpstra, G. J. Gerritsma, and H. Rogalla

Department of Applied Physics, University of Twente, P.O. Box. 217, 7500 AE Enschede, the Netherlands

(Received 13 August 1991; accepted for publication 19 September 1991)

This letter describes the scaling behavior and Josephson properties of improved YBCO/PBCO/YBCO edge-type junctions. The critical current, normal-state resistance, and $I_c R_n$ product scale with barrier thickness and junction area. The coherence length of the PBCO barrier is estimated to be between 5 and 8 nm. As unambiguous evidence of the Josephson behavior, the microwave response as a function of microwave power, as well as the current modulation with applied magnetic field, have been studied: well-developed Shapiro steps at 10 GHz have been observed, and the modulation of $I_c(H)$ shows Fraunhofer-like behavior with 95% I_c suppression.

We have previously reported the fabrication of high-quality epitaxial, all high- T_c edge-type $\text{YBa}_2\text{Cu}_3\text{O}_x$ (YBCO)/ $\text{PrBa}_2\text{Cu}_3\text{O}_x$ (PBCO)/YBCO Josephson junctions,^{1,2} prepared with our modified off-axis sputtering technique.^{3,4} These junctions have shown Josephson behavior up to rather high temperatures, and dc SQUIDS with such junctions are promising for practical applications. However, the physical properties of these junctions are far from clear. For fabrication of really controllable and uniform junctions, these properties must be studied. The scaling behavior, intrinsic parameters, and magnetic field modulation, as well as the microwave response of our edge junctions, are presented here.

Our junctions show good uniformity in the scaling of the critical current and the inverse normal resistance with the junction area, defined as $A = w \times d / \sin \vartheta$ (w is the junction width, d is the thickness of the base electrode, and ϑ is the angle of the junction edge). This is shown in Fig. 1 for junctions with the same barrier thickness. The values for the smallest junctions may be somewhat too low due to the larger influence of the damaged edge by ion etching. At any rate, Fig. 1 demonstrates uniform behavior with different junction areas.

A strong dependence of the critical current density J_c on the PBCO barrier thickness L has been observed. A plot of $\ln J_c$ as a function of L at 4.2 K is shown in Fig. 2. It indicates that, to a good approximation, J_c decreases exponentially as L increases. Such exponential scaling is also predicted, by theory, for large superconductor/normal-metal/superconductor (SNS) junctions.⁵ From the equation $\ln J_c \approx \ln J_{c0} - L/\xi_n$ (J_{c0} is the critical current density of the electrodes) we have estimated the effective normal metal-coherence length ξ_n of the PBCO layer at 4.2 K to be 5 to 8 nm. For $L \leq 6$ nm, J_c is found to be higher than predicted by the exponential dependence. There are several possible reasons. First, when $L < \xi_n$, the Cooper coupling between base and counter electrode is stronger and described by another $J_c(L)$ dependence.⁵ Second, a junction with a very thin barrier is more sensitive to nonuniformities, or the existence of small pinholes in the barrier. Third,

the intrinsic nature of the PBCO might play a role.

The dependence of J_c on the $R_n A$ product has been investigated as well. The data shown in Fig. 3 are distributed along the line $J_c \sim (R_n A)^{-m}$, with $m = 1.2$. For SNS structures with $L \ll \xi_n$, one would expect $J_c \sim (R_n A)^{-2}$, whereas for superconductor/insulator/normal-metal/superconductor (SINS) structures $J_c \sim (R_n A)^{-1}$ (Refs. 5 and 6). The observed dependence differs from the prediction for SNS structures and more closely resembles that for SINS structures. On the other hand, the temperature dependence of the critical-current density, $J_c(T) \sim (1 - T/T_c)^2$, is in good agreement with the SNS type model, as we reported earlier.¹ This discrepancy may be attributed to the interface resistance between the base electrode and PBCO barrier, and the influence of the specific resistance of PBCO, which may be different for $L > \xi_n$ or $L < \xi_n$.

In addition, the $I_c R_n$ products have been found to scale nearly linearly with L , ranging from 0.8 to 5 mV. The highest values obtained were 8 mV. The damage of the edge surface due to our *ex situ* process could also detri-

FIG. 1. Scaling of the critical current I_c and resistance R_n with the junction area A for junctions with the same barrier thickness.

^{a)} On leave from Institute of Metal Physics, Kiev 252142, USSR.

FIG. 2. Dependence of the critical-current density J_c on the PBCO barrier thickness, L .

mentally affect the $I_c R_n$ product.⁶ However, the presented results demonstrate good uniformity of the critical parameters of the YBCO/PBCO/YBCO edge junctions. The fabrication process is indeed *controllable and well reproducible*. Therefore, these junctions are favorable for applications.

A rough estimate of the resistivity at low temperatures of c -axis PBCO in our structures yields a lower limit of $10^4 \Omega \text{ cm}$. Normally, we use a thick ($> 250 \text{ nm}$) PBCO layer to insulate the base electrode from the counter electrode. Recent results reported by the *Bellcore* group on all a -axis oriented junctions demonstrated that a -axis PBCO layers as thick as 150 nm can be used as a barrier.⁷ Although PBCO is an anisotropic material and its resistivity, like other $\text{ReBa}_2\text{Cu}_3\text{O}_x$ compounds (Re: rare-earth element), is supposed to differ in c and a - b directions by some orders of magnitude, we have fabricated some junctions with a layer of SrTiO_3 instead of PBCO to ensure that our c -axis

FIG. 3. Critical current density J_c as a function of the product $R_n A$ at $T = 4.2 \text{ K}$.

FIG. 4. The I - V characteristics at various temperatures for a $20\text{-}\mu\text{m}$ -wide junction with a SrTiO_3 insulating layer. At low temperature the hysteresis can be observed.

PBCO layer can effectively insulate the YBCO base and counter layer. The normal state resistance and the shape of the I - V curves are almost the same as for those junctions which used PBCO as an insulator. From this, we conclude that a 250 nm PBCO layer is sufficient to separate the two electrodes.

Most of our junctions showed nonhysteretical current-voltage (I - V) curves. However, at low J_c ($\sim 10^2 \text{ A/cm}^2$) hysteresis has been observed in some junctions, as shown in Fig. 4. We have estimated the capacitance C of the YBCO/PBCO/YBCO junctions using the resistively shunted junction (RSJ) model. At 4.2 K , I_c was equal to $11 \mu\text{A}$, and the value of hysteresis $\alpha = I/I_c$ was found to be 0.9 . For this α , the dimensionless parameter β_J [$\beta_J = 1/\omega_J R_n C = (\phi_0/2\pi I_c C R_n^2)^{1/2}$] is equal to 0.84 , according to the $\alpha(J)$ dependence shown in Ref. 8. Using $R_n = 130 \Omega$, C is estimated to be $2.5 \times 10^{-15} \text{ F}$. The capacitance per unit area C/A is then $5 \times 10^{-8} \text{ F/cm}^2$. This is a very low value in comparison with typical capacitances for tunnel junctions ($C/A \approx 5 \times 10^{-6} \text{ F/cm}^2$) (Ref. 6). Because of the large permittivity ϵ of SrTiO_3 , C is mainly determined by the overlap area with the SrTiO_3 insulating layer. For junctions with PBCO as an insulator and the same L , C would be significantly lower. Thus, the YBCO/PBCO/YBCO edge junctions combining low capacitance and sufficiently large R_n , are promising for applications in high-frequency circuits.

Our first junctions had a large overlap area,¹ which caused difficulties in the microwave measurement. Having reduced this area and the shunting capacitance of the junctions, clear Shapiro steps have been observed in the presence of 10 GHz microwave irradiation, between 4.2 and 60 K . The magnitude of the current steps as a function of the normalized microwave current is plotted in Fig. 5. At higher temperatures, the Shapiro steps become rounded, but the critical current I_c still exhibits an oscillatory dependence clearly revealing Josephson behavior. To examine the applicability of the RSJ model, we simulated the I - V curves for different microwave currents by solving the appropriate differential equation using a standard fourth-

FIG. 5. Magnitude of the current steps vs the normalized microwave current.

order Runge-Kutta method. The measured data are in good agreement with the calculated values (Fig. 5).

The critical current depends very strongly on the magnetic field. Many junctions showed diffraction patterns approximating the expected Fraunhofer behavior, with a strong central peak and periodic I_c modulation with a depth of more than 95% up to 80 K. Figure 6 shows the $I_c(H)$ modulation at 60 K for one of these junctions. The field was applied parallel to the film and the junction, as shown in the inset. For $J_c = 5 \times 10^2$ A/cm² at 60 K, the

FIG. 6. Modulation of the critical current vs parallel magnetic field as seen in the inset.

Josephson penetration depth $\lambda_J = 15$ μ m is larger than the width of the junction ($w = 10$ μ m), which means that the junction can be treated as "small." For the "in-plane" direction of the magnetic field, the period H_0 of the $I_c(H)$ dependence is between 90 and 100 Oe, which is of the same order of the value calculated with $H_0 = \phi_0(2\lambda_L d/\sin \vartheta)$. A characteristic feature of many of our junctions is the presence of an additional periodical structure for all directions of the applied field. For the junction presented in Fig. 6, the small period H_0^s is 7 Oe at 60 K, increasing gradually to $H_0^s = 8$ Oe at 4.2 K. It is of the same order of what is expected if the field is applied perpendicular to the junction: $H_0^1 = 5$ Oe. The increase of H_0^s at lower temperatures correlates with the change of $H_0^1(T)$ due to the London penetration depth $\lambda_L(T) = \lambda_L(0)/[1 - (T/T_c)^4]^{1/2}$. A possible explanation of the observed "interference" picture may be the complex distribution of both the induced Meissner current and Josephson current over the junction area. It would lead to an induced magnetic field at the surface of the superconducting electrodes, and a complication of the $I_c(H)$ dependence.^{9,10}

In summary, we have demonstrated that YBCO/PBCO/YBCO edge junctions are very uniform and controllable for different barrier thicknesses and junction areas. Periodical modulation of the critical current in applied magnetic field and microwave power, as well as our earlier results in SQUID application, are clear evidences of the Josephson behavior. Because of the low capacitance and the good uniformity, our edge junctions are promising for practical application in high-speed electronics.

The authors wish to thank R. P. J. IJsselsteijn and F. J. G. Roesthuis for assistance in the experiments. This work was supported by the Dutch National Research Program in High- T_c Superconductivity.

¹J. Gao, W. A. M. Aarnink, G. J. Gerritsma, and H. Rogalla, *Physica C* **171**, 126 (1990).

²J. Gao, W. A. M. Aarnink, G. J. Gerritsma, D. Veldhuis, and H. Rogalla, *IEEE Trans. Magn.* **27**, 3062 (1991).

³J. Gao, B. Hauser, and H. Rogalla, *J. Appl. Phys.* **67**, 2512 (1990).

⁴J. Gao, W. A. M. Aarnink, G. J. Gerritsma, and H. Rogalla, *Physica C* **177**, 384 (1991).

⁵K. K. Likharev, *Rev. Mod. Phys.* **51**, 116 (1979).

⁶M. Yu. Kupriyanov and K. K. Likharev, *IEEE Trans. Magn.* **27**, 2460 (1991).

⁷J. B. Barner, C. T. Rogers, A. Inam, R. Ramesh, and S. Bersey, *Appl. Phys. Lett.* **59**, 742 (1991).

⁸W. J. Johnson and A. Barone, *J. Appl. Phys.* **41**, 2958 (1970).

⁹S. L. Miller, Kesin R. Biagi, J. R. Clem, and D. K. Finnemore, *Phys. Rev. B* **31**, 2684 (1985).

¹⁰A. Berone and C. Paterno, *Physics and Application of the Josephson Effect* (Wiley, New York, 1982).