Distribution of the critical current density and flux trapping in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ramp-edge Josephson junctions

A. Marx,^{a)} K.-D. Husemann, B. Mayer, T. Nissel, and R. Gross

Physikalisches Institut, Lehrstuhl Experimentalphysik II, University of Tübingen, Morgenstelle 14, 72076 Tübingen, Germany

M. A. J. Verhoeven and G. J. Gerritsma

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

(Received 2 August 1993; accepted for publication 29 October 1993)

We have studied the spatial distribution of the critical current density in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ramp edge Josephson junctions using low-temperature scanning electron microscopy. Applying this technique allows the imaging of the critical current density distribution with a spatial resolution of about $1\ \mu\text{m}$. Our measurements show that the geometry of the ramp-edge junction eases the trapping of magnetic flux quanta in the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer covering the ramp edge. These trapped flux quanta result in a spatially inhomogeneous magnetic field parallel to the barrier layer, which in turn results in a spatially modulated supercurrent density and an unusual magnetic field dependence of the critical current.

Since the discovery of high-temperature superconductivity a variety of approaches to achieve useful Josephson junctions have been developed. Beyond the different types of engineered grain boundary Josephson junctions (e.g., see Ref. 1) epitaxial multilayer junctions with artificial barriers²⁻⁵ seem to be satisfactory and promising for many electronic applications. The latter type may provide good control of the junction parameters such as the critical current density. Moreover, artificial barrier layer junctions using the ramp-edge geometry³⁻⁵ offer the use of *c*-axis oriented films providing the longer *ab*-plane coherence length parallel to the current flow.

Although the fabrication process and the superconducting transport properties of ramp-edge Josephson junctions have been studied intensively the physical nature of these junctions is not yet completely understood. In particular, there is little knowledge on the spatial homogeneity of the current density in these junctions. In this letter we report on the spatially resolved analysis of the current flow in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}/\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}/\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ramp-edge Josephson junctions using low-temperature scanning electron microscopy (LTSEM).^{6,7} By LTSEM we can show the influence of flux trapping in the top $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer covering the ramp region on the spatial distribution of the supercurrent density and its impact on the resulting magnetic field dependence of the critical current.

The investigated ramp-edge junctions were fabricated in a two-step process. A cross-sectional view of the junction is shown in Fig. 1. In the first step a 100-nm-thick *c*-axis oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) base electrode and a 150-nm-thick insulating $\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (PBCO) layer are deposited *in situ* on a SrTiO_3 (STO) substrate using off-axis magnetron sputtering. Then a ramp in the YBCO/PBCO bilayer is produced in an *ex situ* process using optical lithography and Ar ion beam etching. An incident angle of the ion beam of about 45° was used to obtain a ramp with a slope of about 20° . In

the next step the thin PBCO barrier layer with a thickness ranging between 8 and 30 nm and the YBCO top layer are deposited. Before depositing these layers the ramp is cleaned using a low energy Ar ion beam. The width W of the junctions investigated by LTSEM ranged between 5 and $25\ \mu\text{m}$. The critical temperature T_c of the base electrode typically was about 90 K, whereas that of the top electrode usually was slightly lower. The critical current density J_c and the product $\rho_n = R_n A$ of the normal resistance R_n and the junction area A depends on the barrier thickness. For the investigated sample we had $J_c \approx 1 \times 10^4\ \text{A}/\text{cm}^2$ and $\rho_n \approx 25\ \Omega\ \mu\text{m}^2$ at 4.2 K. The $I_c R_n$ product of the junctions typically was 2 mV at 4.2 K. The Josephson penetration depth λ_J estimated from the measured J_c values was about $5\ \mu\text{m}$ at 4.2 K, that is, the investigated junctions could be considered as narrow junctions ($W \leq 4\lambda_J$).⁸

For our LTSEM experiments the ramp-edge junctions are mounted on a temperature stabilized low-temperature stage⁹ in such way that they can be scanned directly by the focused electron beam of a scanning electron microscope. Details on the application of LTSEM to the study of high T_c thin film sample can be found in Ref. 7. The effect of the electron beam can be considered as a local heating effect resulting in an increase δT_0 of the sample temperature at the beam position. During the scanning process the sample is current biased at a value $I_b \geq I_c$ and the electron beam induced change $\delta V(x, y)$ of the sample voltage is recorded as a

FIG. 1. Sketch of the geometry of the investigated ramp-edge Josephson junctions.

^{a)}Present address: Dornier GmbH, Applied Research Division, Physics and System Department, D-88039 Friedrichshafen, Germany.

function of the beam coordinates. Since the spatial extension of the ramp-edge junction in the x direction (see Fig. 1) is less than the spatial resolution of our imaging technique ($\sim 1 \mu\text{m}$) we only will discuss $\delta V(y)$. In the following we consider a quasi-one-dimensional Josephson junction with a sinusoidal current-phase relation $J_s = J_c \sin \phi$ extending in the y direction with the barrier parallel to the yz plane. For small electron beam perturbations ($\delta T_0 \ll T_c - T_b$, where T_b is the sample temperature) the electron beam induced voltage signal at the beam position y_0 can be expressed as

$$\delta V(y_0) \propto \left. \frac{\partial V}{\partial I} \right|_{I=I_b} \delta I_s(y_0), \quad (1)$$

with $\delta I_s = \delta I_s^J + \delta I_s^\phi$
and¹⁰

$$\delta I_s^J(y_0) = L \int_0^W dy \sin \phi(y) \left. \frac{\partial J_c(y)}{\partial T} \right|_{T=T_b} \delta T(y_0, y), \quad (2)$$

$$\delta I_s^\phi(y_0) = L \int_0^W dy J_c(y) \frac{\partial \sin \phi(y)}{\partial \phi} \delta \phi(y_0, y). \quad (3)$$

Here, $\phi(y)$ is the phase difference function and L the spatial extension of the range-edge junction in y direction. There is both a local (δI_s^J) and a nonlocal signal contribution (δI_s^ϕ).^{10,11} For the case of narrow Josephson junctions ($W \ll 4\lambda_J$) and small perturbation applying to our experiments, the latter contribution usually can be neglected.¹⁰ The integral in Eq. (2) can be approximated by $\delta J_c(y_0) \sin \phi(y_0) \Lambda$, where $\Lambda \sim 1 \mu\text{m}$ is the width of the region perturbed by the electron beam. Since in good approximation $\delta J_c(y_0) \propto J_c(y_0)$, the electron beam induced signal is obtained to

$$\delta V(y_0) \propto L \Lambda \left. \frac{\partial V}{\partial I} \right|_{I=I_b} J_c(y_0) \sin \phi(y_0), \quad (4)$$

that is, the electron beam induced signal is proportional to $J_c(y_0) \sin \phi(y_0)$. Hence, for $J_c(y_0) \approx \text{const}$ we have $\delta V(y_0) \propto \sin \phi(y_0)$.

For narrow Josephson junctions shielding effects can be neglected and an external magnetic field H applied in z direction penetrates the junction homogeneously. This causes a linear increase of the phase difference $\phi(y) = qy$ along the y direction, where $q = (2ed_m/\hbar c)H$ and $d_m = 2\lambda_L + \text{barrier thickness}$ is the effective magnetic thickness of the junction. Then, for a junction with $J_c(y_0) = \text{const}$ we expect $\delta V(y_0) \propto \sin(qy_0)$, i.e., $\delta V(y_0)$ varies sinusoidally along the junction in agreement with recent experimental results.¹⁰ A spatially inhomogeneous critical current density will result in a spatial variation of the oscillation amplitude.

Although the investigated ramp-edge junctions represent narrow junctions, here the situation is different. A magnetic field applied parallel to the z direction is not penetrating the barrier region homogeneously due to the upper YBCO layer covering the ramp region. As shown schematically in Fig. 1 the magnetic field is expected to pierce the top YBCO layer in form of Abrikosov vortices, if the applied field is larger than the lower critical field of this film. Within the Abrikosov

FIG. 2. Variation of the magnetic field H (a), the phase difference ϕ (b), and the normalized supercurrent density J_s/J_c [(c) and (d)] along the ramp-edge junction (y direction) in the presence of two vortices trapped at $y/W = 0.3$ and 0.8 as sketched in Fig. 1. For the calculation of the supercurrent distribution a starting phase $\phi_0 = 0$ (c) and $\phi_0 = \pi/6$ (d) was used.

vortices the field is confined to a tube of diameter $\sim 2\lambda_L$. Although the field is spreading out in y direction within the barrier region, a strongly inhomogeneous field distribution along the junction is obtained. The effect of the inhomogeneous field distribution on the supercurrent distribution and the LTSEM signal is shown in Fig. 2. Here, we have plotted the field distribution caused by two trapped vortices together with the resulting phase difference function and the expected LTSEM signal versus the normalized junction width. For the magnetic field generated by trapped Abrikosov vortices in the barrier region we have assumed Gaussian profiles. The different width of the assumed profiles shall reflect different distances of the trapping position from the junction area. The increase of the phase difference due to the field of a trapped vortex is 2π with the vortex containing a single flux quantum. Figures 2(c) and 2(d) show the resulting distribution of the Josephson current density $J_s(y) \propto \sin \phi(y)$ for different values of the starting phase $\phi_0 = \phi(y=0)$ assuming $J_c(y) = \text{const}$. The expected LTSEM voltage signal $\delta V(y_0) \propto \sin \phi(y_0)$ has the same dependence. Note that the correct value of the starting phase ϕ_0 is obtained by maximizing the total Josephson current $I_s = \int J_s(y) dy$. Figure 2 demonstrates that $J_s(y)$ and, hence $\delta V(y)$ strongly deviate from the sinusoidal dependence obtained for a spatially homogeneous field distribution.¹⁰ In particular, there are regimes of almost constant J_s , where the magnetic field is small, and regimes close to the trapped vortices, where J_s varies rapidly and changes sign.

FIG. 3. LTSEM voltage images showing the supercurrent distribution in a 25- μm -wide ramp-edge Josephson junction at $T=35$ K. Bright and dark regions correspond to sample regions yielding a positive and negative voltage signal, respectively. The two images (a) and (b) show the supercurrent distribution of the same junction with a different number of trapped vortices. On top of each voltage image we have plotted the LTSEM voltage signal for a single line scan along the y direction.

Figure 3 shows typical LTSEM voltage images of a 25- μm -wide ramp-edge junction recorded at $T=35$ K. No external magnetic field was applied during the recording of the images. The images are obtained by scanning the current biased junction and recording the electron beam induced change of the junction voltage as a function of the beam position. In Fig. 3 bright and dark regions correspond to sample regions yielding a positive and negative voltage signal, respectively. For clarity, on top of each LTSEM image we have plotted the voltage signal for a single line scan. The quasi-one-dimensional ramp-edge junction extends in the y direction (see Fig. 1). The extension of the junction in the x direction, i.e., the length of the ramp, cannot be derived from our measurements due to the limited spatial resolution of the LTSEM technique. Figure 3 shows that in x direction the signal is restricted to a width given by the spatial resolution of about $1\ \mu\text{m}$.

According to the above discussion the LTSEM images shown in Fig. 3 strongly suggest that the observed spatially modulated supercurrent density is caused by trapped vortices. The trapping position of the vortices is about equal to the position where the LTSEM signal is changing sign. Both LTSEM images are obtained for the same ramp-edge junction, however, with a different number of trapped vortices. The vortices are trapped during cooling down below T_c in a magnetic field of the order of the earth magnetic field, since no magnetically shielded sample holder was used. After warming up the sample above T_c and cooling down again, usually a different number of vortices, which also were trapped at different positions, was observed. In order to check whether the observed spatial modulation of the Jo-

sephson current density is indeed caused by trapped vortices we applied an external magnetic field and changed the bias current. Applying a small magnetic field in z direction hardly did change the voltage images. It is likely that the small applied magnetic fields are completely shielded by the YBCO film covering the ramp edge. Varying the bias current only changed the absolute magnitude of the electron beam induced voltage signal but not its spatial modulation.

In Fig. 3(a) the number of trapped flux quanta is small. Here, the LTSEM signal $\delta V(y_0)$ shows a plateau in the junction regions between the vortices in agreement with the above model calculations. However, the LTSEM signal is not varying smoothly along the junction as the calculated dependences shown in Fig. 2. This is caused by the spatially inhomogeneous critical current density of the ramp-edge junction. Note that without trapped vortices [$\phi(y_0 = \text{const})$] one has $\delta V(y_0) \propto J_c(y_0)$. In this case the spatial variation of $J_c(y_0)$ can be measured directly. Unfortunately, due to the magnetically unshielded sample environment we could not obtain a situation with no trapped vortices. Nevertheless, our measurements allow us to estimate that the spatial variation of the critical current density of the investigated ramp-edge junctions is less than a factor of 2. This variation is much better than that usually observed for YBCO step-edge grain boundary junction.¹² However, more samples have to be studied in a magnetically shielded environment to confirm this preliminary result.

In summary, we have measured the spatial distribution of the supercurrent density in YBCO ramp-edge junctions using LTSEM. The observed spatial modulation of the supercurrent density could be attributed to the presence of Abrikosov vortices which are trapped in the YBCO layer covering the ramp edge. The problem of flux trapping should be taken into account in future designs of this junction type.

The authors thank W. Ludwig, U. Fath, and R. P. Huebener for stimulating discussions. Financial support by the European Community (ESPRIT Basic Research Project 7100 and 6677) is gratefully acknowledged.

- ¹ R. Gross, in *Interfaces in Superconducting Systems*, edited by S. L. Shinde and D. Rudman (Springer, New York, 1992), Chap. 6.
- ² C. T. Rogers, A. Inam, M. S. Hedge, B. Dutta, X. D. Wu, and T. Venkatesan, *Appl. Phys. Lett.* **55**, 2032 (1989).
- ³ J. Gao, W. A. M. Aarnink, G. J. Gerritsma, and H. Rogalla, *J. Appl. Phys.* **72**, 575 (1992); see also *Physica C* **171**, 126 (1990); *IEEE Trans. Magn.* **27**, 3062 (1991).
- ⁴ D. K. Chin and T. van Duzer, *J. Appl. Phys.* **58**, 753 (1991).
- ⁵ B. D. Hunt, M. C. Foote, and L. J. Bajuk, *J. Appl. Phys.* **59**, 982 (1991).
- ⁶ R. P. Huebener, *Rep. Prog. Phys.* **47**, 175 (1984).
- ⁷ R. Gross, K. Hipler, J. Mannhart, R. P. Huebener, P. Chaudhari, D. Dimos, C. C. Tsuei, J. Schubert, and U. Poppe, *IEEE Trans. Magn.* **25**, 2250 (1989); *Z. Phys. B* **75**, 423 (1989); *Physica B* **169**, 415 (1991); *Appl. Phys. Lett.* **62**, 2871 (1993).
- ⁸ A. Barone and G. Paterno, *Physics and Applications of the Josephson Effect* (Wiley, New York, 1982).
- ⁹ R. Gross, J. Bosch, H.-G. Wener, J. Fischer, and R. P. Huebener, *Cryogenics* **29**, 716 (1988).
- ¹⁰ J. Bosch, R. Gross, M. Koyanagi, and R. P. Huebener, *J. Low Temp. Phys.* **68**, 245 (1987); see also *Phys. Rev. Lett.* **54**, 1448 (1985).
- ¹¹ J. J. Chang, C. H. Ho, and D. J. Scalapino, *Phys. Rev. B* **31**, 5826 (1985).
- ¹² F. Schmidl, L. Alff, R. Gross, K.-D. Husemann, H. Schneidewind, and P. Seidel, *IEEE Trans. Appl. Supercond.* **3**, 2349 (1993).