

Sensitive Josephson magnetometry of flux quantization in a normal conducting hole in a narrow $\text{YBa}_2\text{Cu}_3\text{O}_7$ line

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(Received 14 April 2000; accepted for publication 10 July 2000)

A small $\text{YBa}_2\text{Cu}_3\text{O}_7$ Josephson junction on a 24° symmetric SrTiO_3 bicrystal is used as a sensitive magnetometer with micrometer spatial resolution in magnetic fields of up to 1 mT. The dependence of its critical current on the external magnetic flux is used to measure the local magnetic field. In the narrow line of $4 \mu\text{m}$ width leading to the Josephson junction we prepared a normal conducting area of about $2.5 \mu\text{m}$ diameter. This was achieved by heating the $\text{YBa}_2\text{Cu}_3\text{O}_7$ locally with a focused laser beam to lower the oxygen content and thus suppress superconductivity at 77 K. We investigate the flux quantization in this normal conducting “hole” by cooling the whole device in different magnetic fields, reducing this external field to zero, and measuring the resulting flux. This way, superconducting properties of a hole in a superconducting film have been determined, which are important for the operation of hole-patterned magnetometers based on direct current superconducting quantum interference devices in static magnetic fields. © 2000 American Institute of Physics. [S0003-6951(00)00536-2]

With local probes very sensitive measurements of the magnetization can be made, if the sensitive area of the sensor matches the sample size. This has been used to study the magnetization of persistent currents in a single loop in GaAs–GaAlAs heterostructures.¹ Superconducting quantum interference devices (SQUIDs) from niobium are employed to measure the magnetization of a two-dimensional electron gas in the quantum hall regime.² Very high resolution of the magnetization down to 10^{-14} J/T was achieved, due to the close proximity of the sample and the resulting high filling factor of the magnetometer. Conventional SQUID susceptometers achieve a resolution of 10^{-11} J/T, and cantilever magnetometers or vibrating sample magnetometers can be used with resolutions down to 10^{-13} J/T when operating in magnetic fields of several tesla.³

Here we show, that sensitive magnetometry with high spatial resolution can be achieved without using SQUIDs and instead employing single Josephson junctions. The general use of Josephson junctions from high-temperature superconductors (HTS) as low-noise magnetometer devices recently has been demonstrated for single junctions⁴ and for serial arrays.⁵

The investigation of a hole in a superconducting film is motivated by the use of such geometries in HTS–SQUID magnetometers to operate them in static magnetic fields of the order of the earth field.^{6,7} This is limited by the maximum field of operation for the Josephson junctions. Here we demonstrate, that fields in the millitesla range can be tolerated. Further, the normal conducting area under investigation is written by optical means without removal of material, a technique similar to ion implantation techniques.^{8,9} This is of advantage for multilayer devices, since metallic wiring can be integrated without further planarization process.

The Josephson junction was prepared on a (100) SrTiO_3

bicrystal with symmetric 24° grain boundary in our KrF-eximer laser deposition process, which has been described in detail elsewhere.¹⁰ The bicrystal substrate was supplied by CrysTec GmbH, Berlin, FRG. The Josephson junction is $4 \mu\text{m}$ wide with a film thickness of 100 nm and shows a critical current of $I_c(77 \text{ K}) = 70 \mu\text{A}$. The sample geometry is shown in Fig. 1(a). The corresponding optical micrograph is included in Fig. 1(b). In the narrow line containing the Josephson junction we patterned a hole of about $2.5 \mu\text{m}$ diameter with an area of approximately $5 \mu\text{m}^2$ by using a focused beam of an Argon-ion laser with $\lambda = 514 \text{ nm}$ and a power of 9.5 mW. The focus diameter of about $1 \mu\text{m}$ leads to a power density of $1 \times 10^9 \text{ mW/cm}^2$. In earlier measurements it has been shown that with this power density the oxygen content and thus the critical temperature in the illuminated area can be reduced so that the $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ remains normal con-

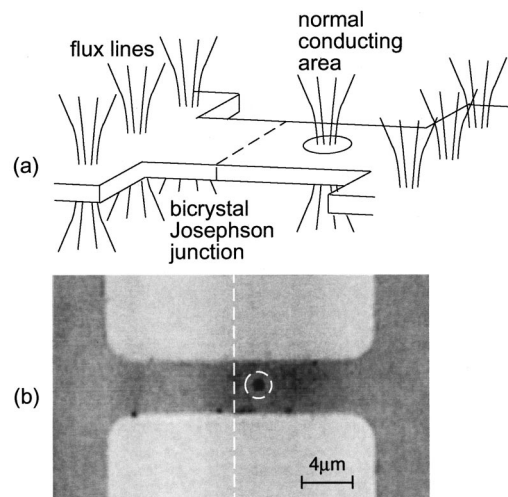


FIG. 1. (a) Scheme of the Josephson junction and (b) optical micrograph of the patterned Josephson junction. The figure displays an area of about $20 \times 35 \mu\text{m}^2$.

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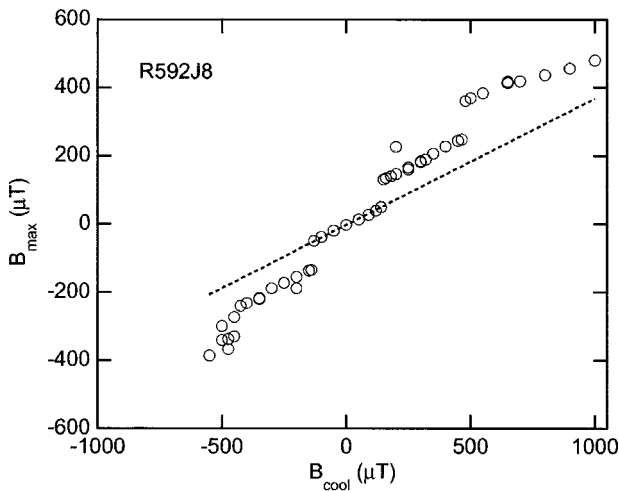


FIG. 2. Magnetic field where the maximum critical current is found in dependence of the cooling fields. Each data point corresponds to one cooling and measurement cycle. The dashed line shows the linear background caused by vortices in the film electrodes.

ducting at 77 K.^{11,12} The optical patterning has been completed in 10 min.

To determine the local magnetic field induced by the flux quantization in the normal conducting hole we cool the Josephson junction from 100 to 77 K in different static magnetic fields. At 77 K we slowly decrease the cooling field to zero, inducing a screening current around the hole. Now we apply a homogeneous measuring field which is superimposed to the stray field of the shielding current around the hole and measure the magnetic field dependence of the Josephson junction (Fraunhofer pattern). The magnetic measuring field where the maximum critical current is found is depicted in Fig. 2 in dependence on the different cooling fields. In this figure clearly the discontinuities in the measured magnetic field due to a change in the number of flux quanta in the hole can be seen.

The measurement is limited in our experiment to two flux quanta in the hole for both magnetic field directions due to the critical current of the 500 nm wide edge at the smaller side of the hole. We can consider the hole with a diameter of 2.5 μm as an inductance of a planar coil with one winding and find a value of about 4 pH. With two flux quanta in the hole a current of 1.4 mA flows around it when the external field is zero. Since for magnetic cooling fields above 500 μT flux quantization is not observable anymore, the smaller width of the YBa₂Cu₃O₇ stripe beside the hole exhibits a critical current of same order. With the film thickness of 100 nm this corresponds to a critical current density of $j_c(77\text{ K}) = 2 \times 10^6 \text{ A/cm}^2$. This can be compared to a micro-bridge on the same chip close to the Josephson junction, which shows a critical current density of $j_c(77\text{ K}) = 1.4 \times 10^6 \text{ A/cm}^2$. This clearly explains the cooling field limit found in the measurement.

The linear background seen in Fig. 2 is due to condensation of vortices in the film parts of the device during cool down, as sketched in Fig. 1(a). Thus, the contributing density of vortices depends linearly on the cooling field. In Fig. 3 this linear background of $H_{\text{offset}}/H_{\text{cooling}} = 0.37 \text{ μT/μT}$ has been subtracted from the data in Fig. 2.

A detailed analysis reveals an increasing step height of

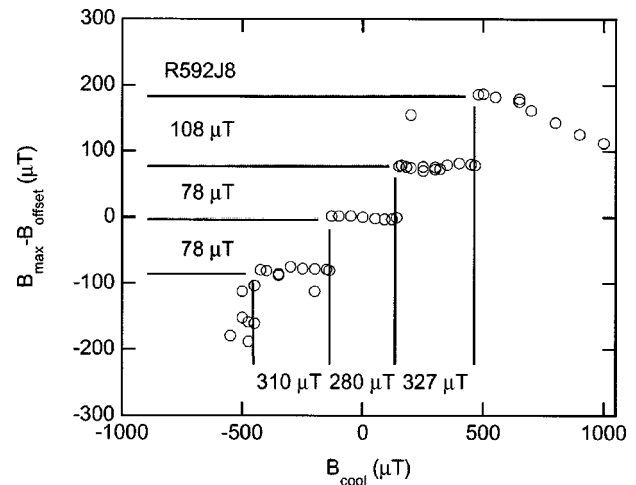


FIG. 3. Magnetic field where the maximum critical current is found in dependence of the different cooling fields after subtraction of the linear background contribution of vortices in the film areas.

78–108 μT between adjacent flux quanta for increasing number of flux quanta. This is caused by a change of the current distribution around the hole towards higher number of flux quanta in the hole. Since the distance of the Josephson junction from the area of quantized flux is of the order of the London penetration depth at 77 K, the flux in the hole remains periodic with Φ_0 only if the change in area is taken into account. The change in the current distribution is depicted in Fig. 4. We also find an increasing width of the plateau from 280 to 327 μT or 310 μT with increasing number of flux quanta for positive cooling fields or negative cooling fields, respectively. This is due to the decrease of flux concentration in higher fields due to the vortices which are pinned in the thin film electrodes. The observed values for the maximum cooling field in both magnetic field directions are different. This is caused by the superposition of the bias current and the screening current which in the negative field direction add for the edge of the hole with the smaller critical current. Since the hole is not exactly in the middle of the superconducting area, one of the paths at the edge has a smaller critical current.

From the determination of the number of flux quanta in the hole we can determine the sensitivity of the setup. The field change in the Josephson junction due to the change of the flux state in the hole by the first flux quantum is 78 μT. In the Fraunhofer pattern a field change of 148 μT corresponds to one flux quantum in the Josephson contact, so one

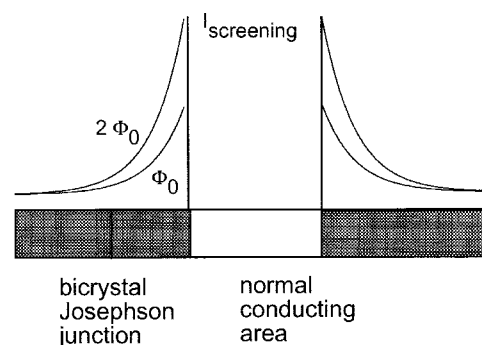


FIG. 4. Current distribution in the vicinity of the Josephson junction as analyzed from the Fraunhofer patterns.

flux quantum in the hole couples 0.53 flux quanta in the Josephson junction. From the inductance calculation of the hole we know that a screening current of about 0.7 mA corresponds to one flux quantum in the hole, corresponding to a screening current of 1.3 mA for one flux quantum in the Josephson junction. From this screening current we can determine the magnetic dipole moment of the hole as $m = I\pi(D/2)^2 = 6.4 \times 10^{-15}$ J/T. The determination of the maximum in the critical current is accurate to about $20 m\Phi_0$ per Φ_0 in the Josephson junction. This results in a resolution of our Josephson magnetometry of about 1.3×10^{-16} J/T in a background field of up to 1 mT. With the operation of the Josephson junction in a feedback loop only limited by the flux noise of the Josephson junction the sensitivity can be increased further significantly.

In conclusion, we have demonstrated that the HTS-Josephson junction operates after cooling in fields of up to 1 mT without distortion in the Fraunhofer pattern as would be expected for vortex trapping close to the Josephson junction. This opens interesting prospects for the flux-locked loop operation of SQUID magnetometers after cooling in high magnetic background fields. The optical patterning without material removal opens the possibility of planarized patterning of normal conducting holes in magnetometers for low-noise operation in static magnetic fields. The vortices pinned in the film contribute to a linear flux increase. This poses limitations on the linearity of SQUID magnetometers when large alternating current fields have to be compensated and due to the high screening currents in the superconducting pickup loops such moving vortices contribute to the flux noise. The flux focusing factor of the wider film areas depends on the

cooling field strength and thus limits the linearity of SQUID operation in higher fields. In this measurement we have shown that a single Josephson junction can be used as very sensitive local probe for magnetization measurements, if the linear background due to pinned vortices is taken into account.

This work was supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, Federal Republic of Germany under Contract No. 13N7323/8. The authors acknowledge financial support by the Deutsche Forschungsgemeinschaft in the Graduiertenkolleg ‘‘Physik nanostrukturierter Festkörper’’ and in the SFB 508.

- ¹D. Mailly, C. Chapelier, and A. Benoit, *Phys. Rev. Lett.* **70**, 2020 (1993).
- ²I. Meinel, D. Grundler, S. Bargstädt-Franke, Ch. Heyn, D. Heitmann, and B. David, *Appl. Phys. Lett.* **70**, 3305 (1997).
- ³I. Meinel, D. Grundler, S. Bargstädt-Franke, Ch. Heyn, and D. Heitmann, *Appl. Supercond.* **5**, 261 (1998).
- ⁴V. Martin, M. Lam Chok Sing, D. Bloyet, D. Robbes, C. Certenais, N. Quellec, and D. Crete, *IEEE Trans. Appl. Supercond.* **7**, 3079 (1997).
- ⁵S. Krey, O. Brüggemann, and M. Schilling, *Appl. Phys. Lett.* **74**, 293 (1999).
- ⁶E. Dantsker, S. Tanaka, and J. Clarke, *Appl. Phys. Lett.* **69**, 4099 (1996).
- ⁷S. Krey, H.-J. Barthelmess, and M. Schilling, *J. Appl. Phys.* **86**, 6602 (1999).
- ⁸Q. Y. Ma, *IEEE Trans. Appl. Supercond.* **7**, 2713 (1997).
- ⁹S.-G. Lee, Y. Huh, G.-S. Park, I.-S. Kim, Y. K. Park, and J.-C. Park, *IEEE Trans. Appl. Supercond.* **7**, 3347 (1997).
- ¹⁰J.-K. Heinsohn, D. Reimer, A. Richter, K.-O. Subke, and M. Schilling, *Physica C* **299**, 99 (1998).
- ¹¹A. Bock, R. Kürsten, M. Brühl, N. Dieckmann, and U. Merkt, *Phys. Rev. B* **54**, 4300 (1996).
- ¹²S. Krey, B. David, R. Eckart, and O. Dössel, *Appl. Phys. Lett.* **72**, 3205 (1998).