APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 5 4 FEBRUARY 2002

Realization and properties of $YBa_2Cu_3O_{7-\delta}$ Josephson junctions by metal masked ion damage technique

D.-J. Kang,[a] G. Burnell, S. J. Lloyd, and R. S. Speaks
Department of Materials Science, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, United Kingdom

N. H. Peng, C. Jeynes, and R. Webb
SCRIBA, School of Electronics, Computing and Mathematics, University of Surrey, Guildford, GU2 7XH, United Kingdom

J. H. Yun, S. H. Moon, and B. Oh
LG Electronics Institute of Technology, Seoul 137-724, Korea

E. J. Tarte, D. F. Moore, and M. G. Blamire
Department of Materials Science and IRC in Superconductivity, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, United Kingdom

(Received 1 October 2001; accepted for publication 7 December 2001)

We have developed a simple process to fabricate high-T_C Josephson junctions by a combination of focused ion beam milling and 100 keV H_2^+ ion implantation. The resistively shunted junction-like current–voltage characteristics were observed in the temperature range of 48 to 4.2 K. The devices showed clear dc and ac Josephson effects. This technique is very promising in terms of simplicity and flexibility of fabrication and has potential for high-density integration. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1446998]

Josephson junctions play a key role in numerous superconducting electronic devices. In order to develop devices using high temperature superconductors (HTS), the fabrication of reliable and reproducible Josephson junctions is necessary. A number of different approaches have been developed to fabricate HTS Josephson junctions such as bicrystal grain boundary junctions, step-edge junctions, and ramp junctions.[1] Due to the inherent microstructural nonuniformity of the interfaces and barrier layers formed during the growth, the desired properties of the junctions have yet to be fully realized. The focused electron beam irradiation (FEBI) junctions developed in Cambridge and elsewhere[2,3] show good superconductor/normal/superconductor (SNS) junction behavior;[4] using electron irradiation, Josephson coupling can be realized via a damaged region by taking advantage of the extremely small spot size of the highly focused electron beam. However, the FEBI technique is limited to circuits consisting of fewer than 100 junctions due to the serial nature of the irradiation process and the long processing time and so alternative techniques will be required for large-scale circuit fabrication. Ion implantation, a well-established semiconductor process technology, can also be used to achieve chemical and structural alternations enabling local modification of the electrical properties of HTS thin films in a controllable manner.[5,6] HTS Josephson junction devices have been made using $YBa_2Cu_3O_{7-\delta}$ (YBCO) by direct focused ion beam (FIB) writing, or by ion implantation using masking techniques, although with limited success due to the difficulties in preparing viable mask structures.[7,8]

In this letter, we report a technique for fabricating YBCO Josephson junctions with a nanometer scale barrier formed by H_2^+ ion implantation through a 40 nm wide slit defined by direct milling with an FIB in a metal mask. These junctions show strong modulation of the critical current (I_c) with applied magnetic field, and Shapiro steps in the current–voltage ($I-V$) characteristics are seen under microwave irradiation at the expected biases. Junctions on the same chip show nearly identical properties.

The films for this study were high quality *c*-axis oriented 100 nm thick epitaxial YBCO grown on (100) $SrTiO_3$ substrates by pulsed laser ablation. 450 nm of Au was *ex situ* deposited on the YBCO by dc magnetron sputtering. Tracks with a width of 2 μm were then patterned by optical lithography and Ar ion milling at 500 eV on a water-cooled rotating stage. The T_C of these tracks was measured before and after processing and found to be unchanged at around 89 K. The Au masking layer was chosen to be sufficiently thick to absorb the implanted protons, but also thin enough that the slit which defines the junction barrier could be cut with sufficient accuracy. Simulations show that scattering in the vicinity of the mask aperture leads to an effective ion range in the sidewall of the aperture which is considerably larger than for the mask away from the aperture; this effect can be reduced by using a mask with a greater effective thickness.[9] Therefore, we used a 450 nm thick single Au layer mask.[10] To prepare these mask apertures, the patterned chip was mounted on a carrier to which electrical connection was made by Al wire bonds. This carrier was transferred to the FIB system (Philips Electron Optics/FEI Corporation 200 xP® FIB workstation) with a Ga source. Using 30 keV Ga ions, slots of single-scan linewidth were milled at 4 pA in the Au. Accurate control of the milling depth was achieved by *in situ* measurements of the track resistance during milling;[11] since the room temperature conductance of the YBCO is

---

[a] Electronic mail: djk1003@cam.ac.uk

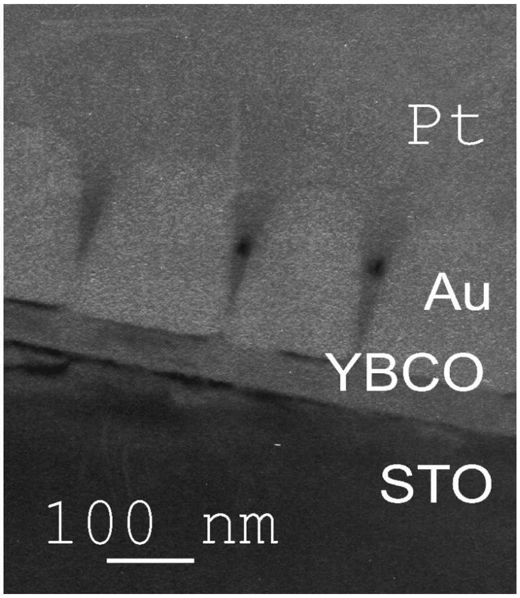

FIG. 1. Transmission electron microscope image of the cut made in the slots; Pt was deposited to prevent top-surface damage during sample preparation.

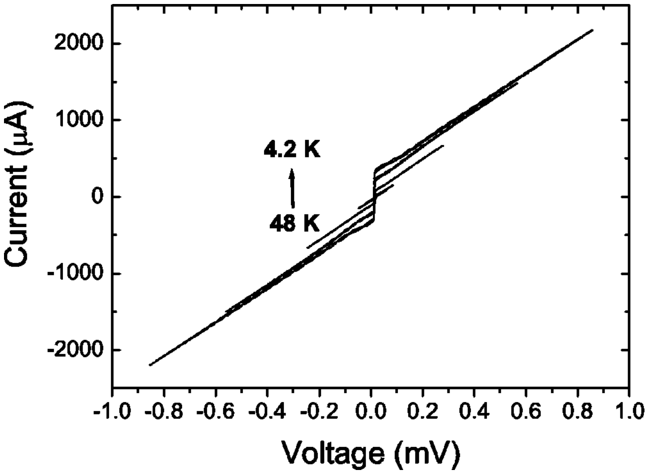

FIG. 2. $I-V$ characteristic of a 2 μm wide metal masked ion damage junction between 48 and 4.2 K.

negligible compared with that of the Au, the resistance increase during the milling is easily measured. Earlier transport measurements showed that Ga implantation of the YBCO caused severe suppression and time-dependent degradation of the superconducting properties and therefore should be avoided.[12]

As shown in Fig. 1, transmission electron microscopy indicates that the aspect ratio that can be achieved using direct milling was limited to less than 5 due to redeposition effects, which result in a very sharp cusp-like edge profile when the aspect ratio is larger than 5. It is postulated that such a slit shape could lead to increased sidewall scattering and therefore widening of the junction barrier. Furthermore, deep FIB milling results in Ga ion contamination below the bottom of the slit, resulting in disruption to the top surface of the YBCO, leading to further degradation in the superconducting properties. Thus, to minimize the sidewall scattering while maintaining rectangular shaped slit profiles and avoiding Ga contamination of the YBCO, we cut only the top 200 nm of the 450 nm Au mask layer.

Chips with completed mask structures were then transferred on sample mounts to an ion implanter equipped with a custom cryogenic stage and shielded to allow ion implantation of the device through a 2 mm aperture. While monitoring the barrier resistance *in situ*, the chips were then exposed to a 100 keV H_2^+ ion beam with a nominal dose of up to 1×10^{16} ions/cm^2 at 50 K, which is just above the intended maximum operating temperature of the completed devices. Most of the low energy defects appear to anneal out by bringing the sample up to room temperature as T_C between during the implantation and T_C after room temperature annealing was found to be different by more than 15 K. The samples were tilted at an angle of 15° along the slit length between the incident beam and the sample normal to eliminate ion channeling effects.[12] After the removal from the implanter and a storage period of 48 h at room temperature, the $I-V$ characteristics of the junctions were measured over a range of temperatures in a dip probe. Microwaves and magnetic field were applied to assess the quality of the junctions. Figure 2 shows the $I-V$ characteristic of a junction at temperatures between 48 and 4.2 K. The junction exhibits a typical resistively shunted junction (RSJ)-type $I-V$ curve with a maximum I_c of 400 μA at 4.2 K. The I_cR_n product of the junction at 4.2 K is estimated to be ≈0.2 mV. In Fig. 3, temperature dependence of I_c and R_n of the junctions is shown. The R_n was nearly temperature independent between 48 and 4.2 K and was about 0.47 Ω at 45 K. The temperature dependency of the I_c and R_n gives evidence for SNS nature of the junctions. These characteristics resemble those of junctions created by FEBI with heavy doses.[13] No significant change in the junction properties was observed over 2 months and a number of thermal cycles. Figure 4 shows the magnetic modulation of the I_c of a junction at 43 K. Deviation from the ideal Fraunhofer diffraction at a higher magnetic field in the experimental data implies that some inhomogeneities exist in local areas of the junction. However, Fig. 4 clearly indicates that our barrier shows a good Josephson junction behavior. The incomplete suppression of the I_c is largely an artifact arising from the use of a fixed finite voltage criterion used to assess the I_c. The asymmetry and hysteresis of the I_c modulation upon magnetic field curve might be explained by asymmetrical current distribution[14,15] possibly due to expected unevenness in the cut made in the

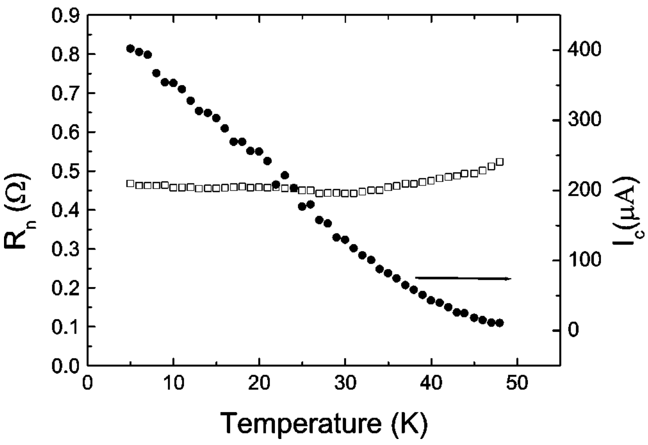

FIG. 3. Temperature dependence of I_c and R_n of a junction.

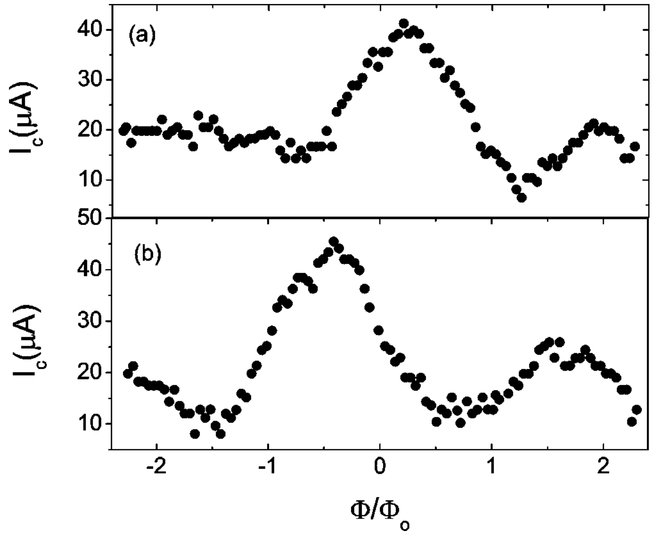

FIG. 4. Magnetic field dependence of the critical current of a junction; (a) increasing field (b) decreasing field.

slot or frozen flux motion during the long measurement times. Shapiro steps were also observed at the expected biases despite the low normal resistance of the junction due to screening by the thick Au mask layer. It is also likely that such a thick Au mask layer (450 nm) on the top of the junction barrier will attenuate the interaction between the junction and microwave radiation. At the frequency ($\approx$12 GHz), the skin depth of Au is only around 680 nm, which is just 1.5 times thicker than the mask.

Compared to our previous results,[10,12] a significant improvement in the junction performance has been obtained and these junctions resemble the behavior of high quality FEBI junctions. Firstly, RSJ-like behavior over a much wider temperature range (between 48 and 4.2 K) was observed; secondly, we show a greater stability of junction parameters over a longer period of time after the junction was first measured; thirdly, a temperature-independent resistance behavior over the whole temperature range was seen. All these observations suggest that we have a narrower barrier than others have reported[8] and we have totally suppressed the superconductivity in the barrier. The latter is consistent with the high dose we used, although the thick Au layer must have attenuated the actual dose. The improved performance of these junction characteristics compared to our previous results may be attributed to the optimized cut shape of the slots in the metal mask to avoid Ga poisoning into the YBCO. We have demonstrated the fabrication of high quality SNS HTS Josephson junctions working in the temperature range of 48 to 4.2 K by FIB milling and ion implantation. Given the results presented here, there is still scope for improvement with further development of the mask preparation and greater control of the annealing protocol. For instance, the introduction of a Ga diffusion barrier such as Si_3N_4, or polymer in the lower portion of the mask would allow us to reduce the thickness of the residual Au in the slit. We believe that this will result in less scattering, thus improving the definition of the barrier and the performance of the junctions.

This work was supported by the UK Engineering and Physical Sciences Research Council under the Grant No. GR/M84756. One of the authors (R.S.S.) is grateful to the US National Science Foundation for support. Three other authors (J.H.Y., S.H.M., and B.O.) are grateful to the Korean Ministry of Science and Technology under the National Research Laboratory project for support.

[1] R. Gross, L. Alff, A. Beck, O. M. Froehlich, D. Koelle, and A. Marx, IEEE Trans. Appl. Supercond. **7**, 2929 (1997).
[2] A. J. Pauza, W. E. Booij, K. Hermann, D. F. Moore, M. G. Blamire, D. A. Rudman, and L. R. Vale, J. Appl. Phys. **82**, 5612 (1997).
[3] B. Davidson, J. E. Norman, B. M. Hinaus, M. S. Rzchowski, K. Siangchaew, and M. Lebera, Appl. Phys. Lett. **68**, 3811 (1996).
[4] K. A. Delin and A. W. Kleinsasser, Supercond. Sci. Technol. **8**, 227 (1996).
[5] A. S. Katz, A. G. Sun, S. I. Woods, and R. C. Dynes, Appl. Phys. Lett. **72**, 2032 (1998).
[6] A. S. Katz, S. I. Woods, and R. C. Dynes, J. Appl. Phys. **87**, 2978 (2000).
[7] A. G. Sun, L. M. Paulius, D. A. Gajewski, M. B. Maple, and G. Zaharchuk, Appl. Phys. Lett. **59**, 3482 (1992).
[8] F. Kahlmann, A. Engelhardt, J. Schubert, W. Zander, C. Buchal, and J. Hollkott, Appl. Phys. Lett. **73**, 2354 (1998).
[9] N. H. Peng, I. Chakarov, C. Jeynes, R. Webb, W. Booij, M. Blamire, and M. Kelly, Nucl. Instrum. Methods Phys. Res. B **164**, 979 (2000).
[10] D. J. Kang, R. Speaks, N. H. Peng, R. Webb, C. Jeynes, W. E. Booij, E. J. Tarte, D. F. Moore, and M. G. Blamire, IEEE Trans. Appl. Supercond. **11**, 780 (2001).
[11] A. Latif, W. E. Booij, J. H. Durrel, and M. G. Blamire, J. Vac. Sci. Technol. B **18**, 761 (2000).
[12] W. E. Booij, C. A. Elwell, E. J. Tarte, P. F. McBrien, F. Kahlmann, D. F. Moore, M. G. Blamire, N. H. Peng, and C. Jeynes, IEEE Trans. Appl. Supercond. **9**, 2886 (1999).
[13] W. E. Booij, A. J. Panza, E. J. Tarte, D. F. Moore, and M. G. Blamire, Phys. Rev. B **55**, 14600 (1997).
[14] R. Li, Z. G. Ivanov, D. Winkler, M. Y. Zhang, H. Olin, P. Larsson, and T. Claeson, Appl. Phys. Lett. **65**, 1177 (1994).
[15] T. Ogawa and T. Yamashita, IEEE Trans. Appl. Supercond. **5**, 2204 (1995).