

Planar thin film $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Josephson junction pairs and arrays via nanolithography and ion damage

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We have fabricated in-plane high- T_c Josephson junction pairs and series arrays using our established nanolithography and ion damage process. Junctions in a pair showed nearly identical electrical properties. The ten-junction array exhibited current-voltage characteristics that can be described by the resistively shunted junction model at 78 K. Flat giant Shapiro steps were observed in both cases. We believe that the ion-damaged high- T_c superconducting Josephson junction is a good candidate to form large numbers of junctions in series arrays that can function above 77 K for quantum voltage standards and other applications. © 2004 American Institute of Physics.

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Josephson junction arrays, especially series arrays, have been suggested as the core devices for many rf applications such as quantum voltage standards,¹ wave form generators,² microwave oscillators,³ etc. These applications require hundreds or even thousands of Josephson junctions in series, phase-locked to an applied microwave signal, or in some cases to each other. All of the junctions in the array should have very similar parameters i.e., I_c and R_n in the resistively shunted junction (RSJ) model to achieve this goal. It is usually desirable to make the array a lumped element. Therefore, the total length of the array is confined to be less than $\lambda/4$, where λ is the wavelength of the microwave associated with the application.⁴ To this end, spaces between adjacent junctions in the array must be less than $\lambda/4N$, where N is the number of junctions in the array. High- T_c superconductors (e.g., $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$) undergo a superconductor-insulator transition that can be modified by point defect disorder brought about by high-energy ion damage.⁵ This property has been used to fabricate planar thin film $SS'S$ $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Josephson junctions,⁶⁻⁸ where S' denotes a reduced T_c superconductor. Without a definite interface between the superconductor and the reduced T_c superconducting barrier, planar thin film ion-damaged junctions could be superior to competing technologies (e.g., grain boundary and ramp-type junctions) in terms of junction parameters' controllability, flexible configurations, and compactness. Tuning the ion damage dose and the mask trench width, allows critical current (I_c), normal resistance (R_n), and the working temperature of the Josephson junction to be changed over a broad region. Junctions can be located anywhere on a chip and in any orientation. The minimum distance between adjacent junctions can be 150 nm or smaller.

In this letter, we report our efforts to fabricate uniform ion-damaged $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Josephson junctions and series arrays. Earlier work^{8,9} has shown Josephson junctions with excellent properties can be made by our nanolithography and ion damage process combined with photolithography. The spread of the junction parameters (I_c and R_n) over a chip was estimated to be 10%–20%.¹⁰ This conclusion was based on data from junctions located on the same chip but on different bridges spaced at approximately 1 mm. We believe the uni-

formity of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film itself could have great impact on the junction uniformity. To reduce nonuniformity from the starting material, we have chosen commercial $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films¹¹ that were thermally co-evaporated on 2 in. sapphire wafers and buffered by cerium oxide. The $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film is guaranteed by the manufacturer to have T_c higher than 85 K, rms roughness of 6–10 nm, and critical current density variation less than 5% over the wafer.

Photolithography and ion-milling were used to pattern 4 μm bridges, and then a trilayer mask, consisting of 800 nm of Shipley S1808 photoresist, 25 nm of thermally evaporated germanium, and 180 nm of PMMA was placed on the sample. E-beam lithography was followed by reactive ion etching to pattern the mask. The detailed process has been reported in our previous work.⁸ A SEM picture of the top view of a Josephson junction pair immediately prior to ion damage is shown in Fig. 1(a). A patterned cross-shaped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film is covered by the ion damage hard mask. The width of the mask on top of the bridge is 2 μm . The two slits in the middle of the picture are where ion-damaged junctions were intended. We have made several samples of different slit widths and slit distances. In this picture, the slit widths are both 70 nm and slit center-to-center distance is 150 nm. Samples of this nature were loaded into a commercial implanter to be damaged by 200 keV Ne^+ . Several doses were used from 0.5 to $2 \times 10^{13}/\text{cm}^2$. After ion damaging, the mask was removed by an ultrasonic bath of warm acetone.

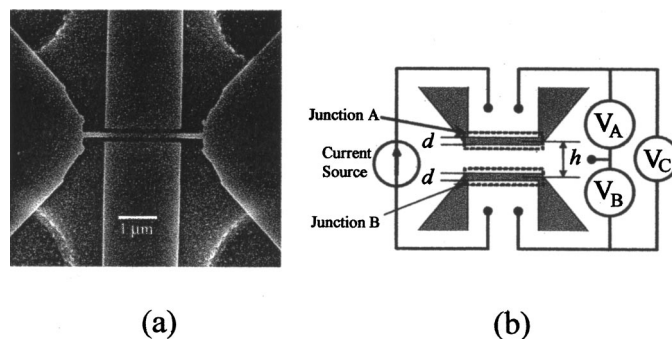


FIG. 1. (a) Top view of a junction pair prior to ion damage. A patterned cross-shaped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film covered with the implant mask. (b) Schematic drawing of the junction pair and measurement configuration.

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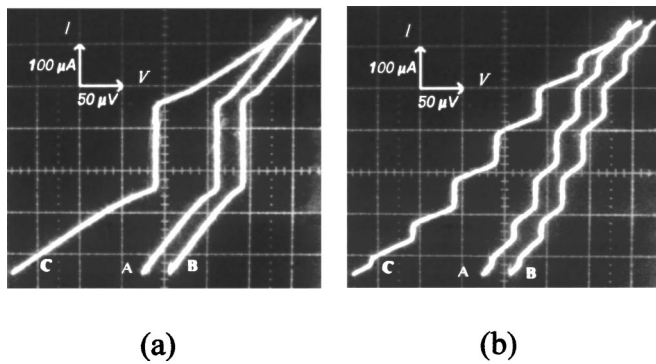


FIG. 2. Scope pictures of the current-voltage characteristics of junction 1 (curve A), junction 2 (curve B), and the junction pair (curve C) at 63 K without (a) and with (b) 12 GHz microwave radiation.

The sample was ultrasonically wire bonded and measured as diagrammed in Fig. 1(b) with current and voltage leads such that we can probe each individual junction as well as the series junction pair. The shaded and white area represent damaged and undamaged parts of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film, respectively. To investigate the current-voltage characteristics of each individual junction and the junction pair simultaneously, the current was biased through the junctions in series. Three preamplifiers were connected to the electrode pads as indicated (V_A , V_B , and V_C) and the current and three voltage signals were recorded by a four channel oscilloscope. Since there was only a small current passing through the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ island (for the preamplifiers less than 1 nA), the characteristics of the junctions appeared not to be affected by the sampling current.

The Josephson supercurrent at a working temperature, lower than the critical temperature of the damaged region, is established in the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film beneath the narrow mask slits where the Cooper-pair wave functions from either side overlap with each other.¹² The junctions' areas are indicated by dashed line rectangles in Fig. 1(b). Other parts of the damaged $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film (shaded regions) stay in the normal state, acting as additional resistive shunts to the junctions. A finite element analysis shows the total R_n is decreased approximately 20% by the shunts. The additional resistive shunts can reduce the spread in R_n and thus improve the phase-locking of the junctions in an array.¹³ Figure 1(a) shows that the mask bridge edges are much smoother than the patterned $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ bridge edges. Translated from the sharp edge of the mask, the undamaged $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film should have a straight boundary line to the damaged film. Under our experimental conditions, the edge of the bridge made by photolithography typically has a ripple as large as $0.2 \mu\text{m}$; the edge of the mask made by e-beam lithography has a ripple of less than 20 nm. Therefore, the junctions on the same bridge made by e-beam lithography have an average length variation less than 1% compared with those made by photolithography which have about 5% variation.

Figure 2 shows the results of I - V measurements carried on a Josephson junction pair at 63 K. The center-to-center distance between the two junctions (h in Fig. 1) in this pair was 800 nm. The widths of the mask slits (d in Fig. 1) were 70 nm and ion fluence was $2 \times 10^{13}/\text{cm}^2$. Curves A, B, and C are the I - V curves of junction A, B, and the junction pair. They are shifted horizontally for clarity. There was no applied microwaves in (a), while 12 GHz microwave radiation

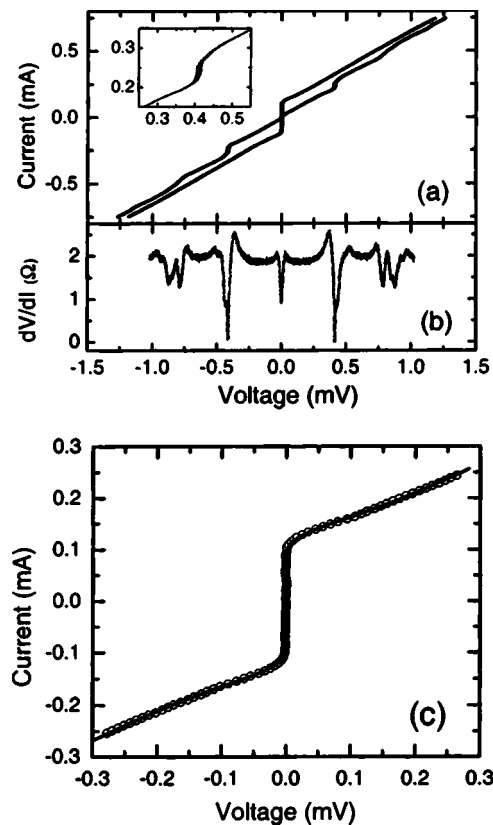


FIG. 3. (a) The current-voltage characteristics of a ten-junction array with and without 20 GHz microwave radiation at 78 K. The first-order giant Shapiro step in detail is shown in the inset. (b) The dynamic resistance vs voltage curve of this junction under the same radiation. (c) The single junction RSJ model (solid line) fits the ten-junction array I - V characteristic (open circles).

was applied to the junction in (b). Curve A can be shifted to overlap curve B quite accurately in both cases, which shows that the two junctions have nearly identical I - V properties. In fact, within the precision of our measurement system, we could find no difference in I_c or R_n of these two junctions. All the curves can be fit well by the RSJ model. In (b), on curve C Shapiro steps occur at $V = N \times nhf/2e$, where $N=2$ is the number of junctions, f is the microwave frequency, order number $n=0, \pm 1, \pm 2$ and ± 3 . All the steps are flat and have the same widths with the corresponding steps on single junction I - V curves. We did not see any apparent mutual phase-locking between the two junctions of any junction pairs we have made. One of the possible reasons can be the coherence length of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ is much shorter than those of conventional superconductors (e.g., Sn). To let order parameters of two junctions affect each other, we may have to put junctions even closer than 150 nm. At this distance, current through the middle electrode will have impact on the two junctions either by induced magnetic field or current injection.¹⁴ This introduces a difficulty of characterizing one junction while current biasing the other junction independently as in conventional superconducting Josephson junction pairs.¹⁵

Figure 3 shows I - V and dV/dI - V curves of a ten-junction array with and without microwave radiation at 78 K. Flat giant Shapiro steps occurred at ten times the single Shapiro step voltage $V_{\pm 1} = \pm 0.414 \text{ mV}$ indicating that all ten junctions are phase-locked to the microwave radiation. The flatness of the first steps is confirmed by the dy-

dynamic resistances at $V_{\pm 1}$ reaching zero. However, on the $dV/dI-V$ curve two peaks appeared around where the second steps should be. Neither of them reached zero. From this, we conclude that the junction parameters of the array were not absolutely identical.

It is not practical to characterize individual junctions by probing every center electrode between adjacent junctions for a large- N array. To evaluate the junction parameters uniformity in the ten-junction array, we fit its current-voltage characteristic by the single junction RSJ model. We also take the thermal noise contribution into consideration.¹⁶ By fitting the single junction $I-V$ curve A in Fig. 2(a), we obtain noise temperature $T_N=72$ K, which is only a little larger than the measurement temperature 63 K. We attribute the extra noise to our measurement system, which appears not to be significant. Very good fitting results of the ten-junction array is illustrated in Fig. 3(c). We believe that the junction parameters spread in the array is sufficiently small, otherwise the fit would fail.

In summary, it is demonstrated that using nanolithography and ion damage process combined with photolithography, very similar high- T_c superconducting (HTS) Josephson junction pairs and close-parameter junctions in ten-junction arrays have been fabricated. They were phase-locked to applied microwave radiation. Flat giant Shapiro steps were observed and confirmed by the differential resistance measurement. We believe that the ion-damaged HTS Josephson junction is a good candidate to form large junction arrays

that can function at temperatures above 77 K for quantum voltage standards and other applications.

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- ¹S. P. Benz and C. A. Hamilton, *Appl. Phys. Lett.* **68**, 3171 (1996).
- ²S. P. Benz, C. A. Hamilton, T. E. Harvey, L. A. Christian, and J. X. Przybysz, *IEEE Trans. Appl. Supercond.* **8**, 42 (1998).
- ³J. Lukens, *Superconducting Devices*, edited by S. T. Ruggiero and D. A. Rudman (Academic, San Diego, 1990), Chap. 4, p. 135.
- ⁴S. P. Benz, P. D. Dresselhaus, and C. J. Burroughs, Jr., *IEEE Trans. Instrum. Meas.* **50**, 1513 (2001).
- ⁵J. M. Valles, Jr., A. E. White, K. T. Short, R. C. Dynes, J. P. Garno, A. F. J. Levi, M. Anzlowar, and K. Baldwin, *Phys. Rev. B* **39**, 11599 (1989).
- ⁶J. Hollkott, S. Hu, C. Becker, J. Auge, B. Spangenberg, and H. Kurz, *J. Vac. Sci. Technol. B* **14**, 4100 (1996).
- ⁷W. E. Booij, C. A. Elwell, E. J. Tarte, P. F. McBrien F. Kahlmann, D. F. Moore, and M. G. Blamire, *IEEE Trans. Appl. Supercond.* **9**, 2886 (1999).
- ⁸A. S. Katz, A. G. Sun, S. I. Woods, and R. C. Dynes, *Appl. Phys. Lett.* **72**, 2032 (1998).
- ⁹A. S. Katz, S. I. Woods, and R. C. Dynes, *J. Appl. Phys.* **87**, 2978 (2000).
- ¹⁰A. S. Katz, S. I. Woods, R. C. Dynes, and A. G. Sun, *IEEE Trans. Appl. Supercond.* **9**, 3005 (1999).
- ¹¹From Theva Dünnschichttechnik GmbH, Rote-Kreuz-Str. 8, D-85737 Ismaning, Germany.
- ¹²P. G. deGennes, *Rev. Mod. Phys.* **36**, 225 (1964).
- ¹³A. M. Klushin, W. Prusseit, E. Sodtke, S. I. Borovitskii, and L. E. Amantuni, *Appl. Phys. Lett.* **69**, 1634 (1996).
- ¹⁴W. E. Booij, A. J. Pauza, D. F. Moore, E. J. Tarte, and M. G. Blamire, *IEEE Trans. Appl. Supercond.* **7**, 3025 (1997).
- ¹⁵J. B. Hansen and P. E. Lindelof, *Rev. Mod. Phys.* **56**, 431 (1984).
- ¹⁶V. Ambegaokar and B. I. Halperin, *Phys. Rev. Lett.* **22**, 1364 (1969).