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# Temporal stability of Y-Ba-Cu-O nano Josephson junctions from ion irradiation

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**Abstract**— We investigate the temporal stability of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  Josephson junctions created by ion irradiation through a nano-scale implant mask fabricated using electron beam lithography and reactive ion etching. A comparison of current-voltage characteristics measured for junctions after fabrication and eight years of storage at room temperature show a slight decrease in critical current and increase in normal state resistance consistent with broadening of the weaklink from diffusion of defects. Shapiro step measurements performed 8 years after fabrication reveal that device uniformity is maintained and is strong evidence that these devices have excellent temporal stability for applications.

**Index Terms**—ion implantation, Josephson junctions, nanolithography, yttrium barium copper oxide.

## I. INTRODUCTION

JOSEPHSON JUNCTIONS are employed in many different disciplines of science and in numerous diverse applications such as sensitive magnetometry, ultra-fast rapid single flux quantum logic, quantum computation, voltage standards, telescopes, wide-bandwidth receivers and quantum limited amplifiers. The majority of these applications use low transition temperature ( $T_C$ ) superconductors and require cooling to around 4 K. This requirement complicates most applications because of the large weight and power consumption of the cooling system. The use of high- $T_C$  Josephson junctions operating around the boiling point of nitrogen may be a solution to dramatically reduce the size, weight and power requirements, which are respectively about 200, 75, and 150 times smaller for a 80 K system in comparison to one at 4 K [1].

Since the discovery of high- $T_C$  superconductivity in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO), researchers have tried in earnest to develop a reproducible and scalable Josephson junction technology like Nb- $\text{Al}_2\text{O}_x$ -Nb low- $T_C$  junctions. The difficulty in realization of an YBCO junction technology stems from its superconducting coherence length which is very short and

highly anisotropic, typically 2 nm in the  $a$ - $b$  plane and 0.2 nm along the  $c$ -axis direction [2]. As a result, the superconducting order parameter is susceptible to structural and chemical changes on atomic length scales. Thus, very small defects in the Josephson barrier or at the interface between the barrier and electrodes can drastically affect the critical current  $I_C$  since it depends exponentially on the length of the barrier. YBCO Josephson devices are further complicated by highly anisotropic electrical transport: conductivity along the  $c$ -axis is 2 orders of magnitude smaller than that in the  $a$ - $b$  plane [2]. Such anisotropy precludes the possibility of growing epitaxial multilayers to form sandwich type junctions because the highest quality thin films of YBCO have  $c$ -axes orientated normal to the substrate.

Despite these difficulties a promising technology has emerged that employs ion irradiation to reduce  $T_C$  and  $I_C$  in a narrow region of a superconducting bridge [3]. Above the narrow region  $T_C$  and below the undamaged electrode  $T_C$  the irradiated area behaves as a Josephson junction. Since these devices are planar, conduction remains in the  $a$ - $b$  plane and because there are no interfaces between different materials there are fewer defects near the barrier to disrupt superconductivity. Furthermore, they have the advantage that they can be arbitrarily positioned on the substrate, and can be very densely spaced ( $\sim 150$  nm) [4].

The first weaklinks using ion irradiation were demonstrated by White et al [3] in 1988 and many others followed with similar techniques for single junctions and SQUIDs [4]-[11]. A decade later, in 2004, tens of junctions in arrays were fabricated showing uniformity as good as ramp junctions [4], [10]. In 2007 hundreds of junctions [12] and 2008 tens of thousands [13] of junctions were demonstrated on large scale SQUID arrays.

The two common criticisms of this technology are low  $I_C R_N$  products, and skepticism about the stability of the barriers. The first issue we addressed in prior work by showing that higher  $I_C R_N$  can be achieved by using large arrays of junctions [4],[10],[12],[13]. Short term stability over a span of nine months was reported on by Katz et al [14], but there is a lack of data in the literature for longer time periods. In this work, we investigate the long term temporal stability of the junctions 8 years after they were fabricated.

## II. EXPERIMENT

The junctions used in this study were fabricated in February 2004 on two different samples from 200-nm thick

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YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7- $\delta$</sub>  films grown on LSAT and Al<sub>2</sub>O<sub>3</sub> substrates. Detailed reports of the fabrication process are reported in references [4], and [10]. In brief, electrodes and four-point bridges were patterned using photolithography and argon ion milling. Afterwards junctions were fabricated by 200 keV neon irradiation with a dose of  $1 \times 10^{13}$  ions/cm<sup>2</sup> through a narrow 50 nm trench created with nanolithography in an 800 nm thick layer of hard-baked photoresist.

After fabrication, samples were cooled in an evacuated dip-probe and the temperature dependence of the resistivity was measured along with current-voltage characteristics for various temperatures. After these initial measurements samples were stored in a desiccator for 8 years and were measured again for comparison with the prior results.

### III. RESULTS AND DISCUSSION

Fig. 1 shows the temperature dependence of the resistance for a 9 junction series array 3 months and 8 years after fabrication. There is no detectable change in  $T_C$  of the electrodes 87 K, however the superconducting transition of the weaklink shifts by approximately 1 K after 8 years. Furthermore there is a very slight increase in resistance.

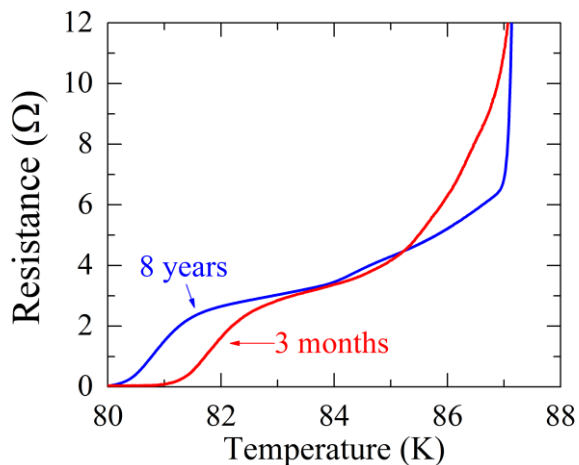


Fig. 1. Superconducting transitions for an array of 9 Josephson junctions in series, measured both 1 month and 8 years after fabrication.

Current-voltage ( $I$ - $V$ ) characteristics, depicted in Fig. 2, for a single Josephson junction measured on a different sample both 1 month and 8 years after fabrication exhibit the same trend. For this junction we show temperatures where both curves have critical currents of about 200  $\mu$ A and resistively shunted junction (RSJ) characteristics. For our analysis we chose to hold  $I_C$  constant opposed to temperature because the  $I$ - $V$  characteristics at low temperatures become flux-flow [10] and complicate direct comparison. To maintain the same critical current after aging the junction needs to be cooled 2.6 K more which we interpret as a decrease in the  $I_C$  of the weaklink. Furthermore, the normal state resistance  $R$  at 200  $\mu$ A increases 16% from 211 m $\Omega$  to 244 m $\Omega$ .

These two results are consistent with diffusion of defects.

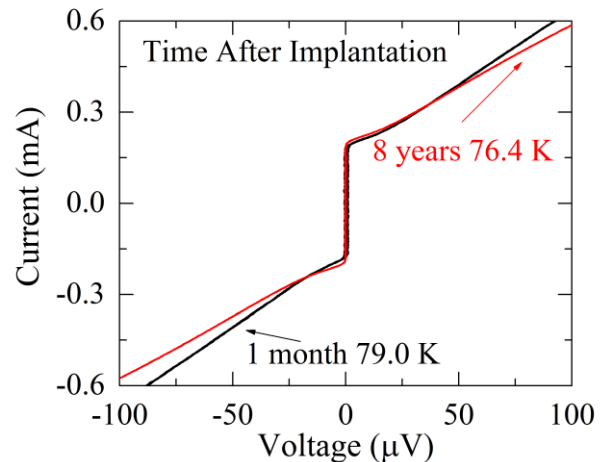


Fig. 2. Current voltage characteristics for the same Josephson junction measured both 1 month and 8 years after fabrication.

Over time the defects created by irradiation spread out and create a wider weaklink resulting in a lower  $I_C$  and higher resistance. This model is in excellent agreement with work done by Katz et al where he measured  $I_C$  and  $R$  for irradiated junctions with different barrier lengths [7]. To examine the quality of junctions we subjected a single junction to RF radiation to examine its Shapiro steps. Fig. 3 shows that after aging the Shapiro steps retain their sharpness and amplitude and no degradation of the steps was observed.

We also studied the 9 junction series array under RF radiation at 79 K and show the results in Fig. 4. Fig. 4(a) shows the array 1 month after fabrication with very sharp giant Shapiro steps at 9 times  $h/2ef$ , where  $f$  is the frequency of the RF radiation. In contrast, the giant Shapiro step for the array after aging becomes less uniform and more rounded Fig. 4(b).

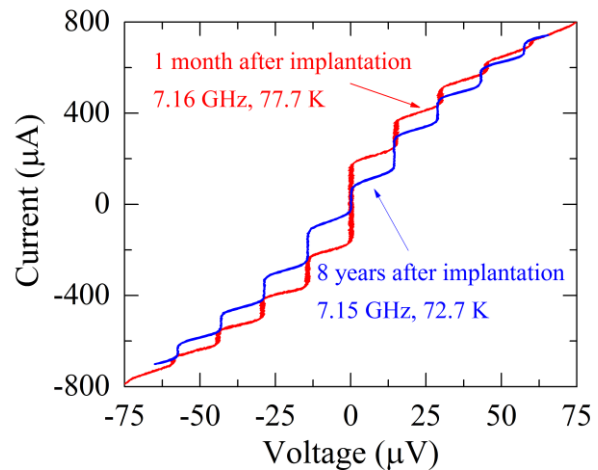


Fig. 3. Shapiro steps in the current-voltage characteristics of a single Josephson junction under RF radiation, measured 1 months and 8 years after fabrication.

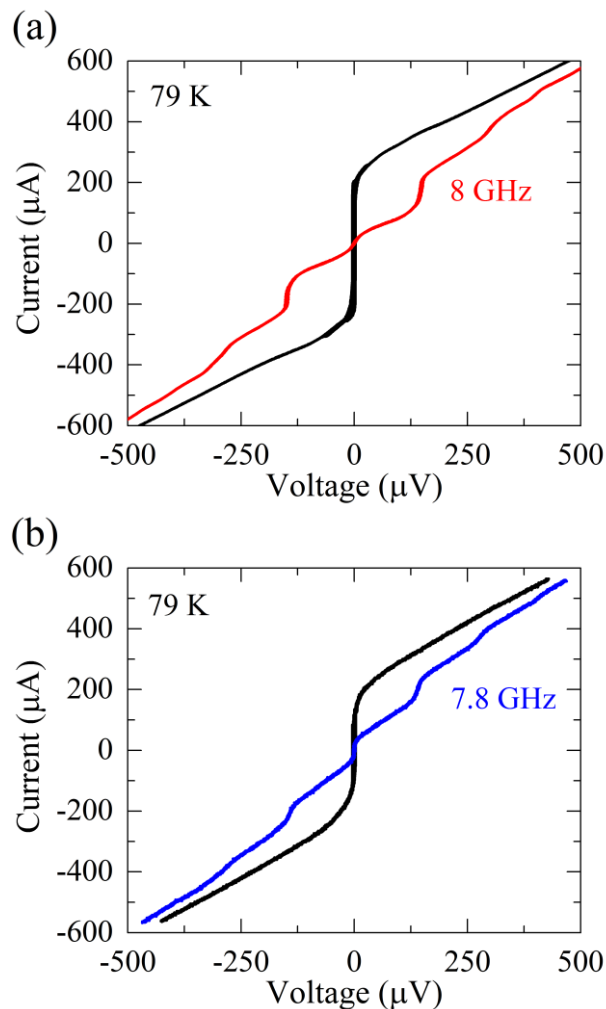


Fig. 4. Giant Shapiro steps in current-voltage characteristics for a 9 Josephson junction series array with and without RF radiation 1 month (a) and 8 years (b) after fabrication.

To test whether this is related to a decrease in uniformity from diffusion or simply the effect of operating temperature we cooled the device further to 77 K and repeated the measurement (Fig. 5). At lower temperatures the step becomes more uniform and is nearly vertical in the center with less rounding. This indicates that at this lower temperature the individual junction resistances become more uniform because the positions of the Shapiro steps are determined by the bias current and individual junction resistances.

#### IV. CONCLUSION

In conclusion we have performed a study on the temporal stabilities of Josephson junctions fabricated with ion irradiation and nanolithography. Our data strongly suggest diffusion of defects broadens the barrier, but these changes are subtle and only slightly reduce operating temperature. Furthermore, the increase of resistance is a beneficial effect and could yield a mechanism for increasing the  $I_c R$  product of these junctions for improved devices. In addition, we conclusively show that these junctions are very stable over a time period of eight years and have retained excellent resistively shunted junction  $I$ - $V$  characteristics.

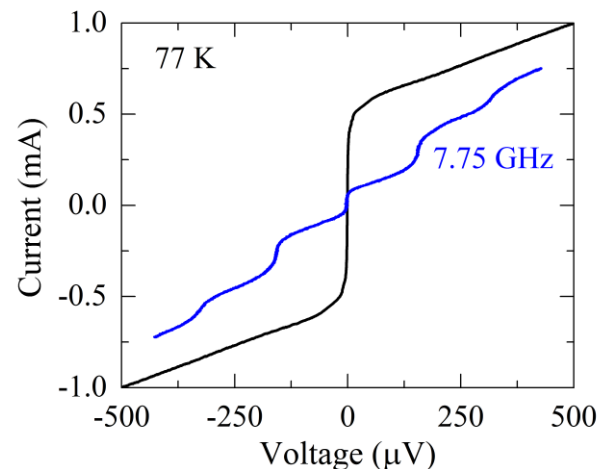


Fig. 5. Current-voltage characteristics for a 9 Josephson junction series array with and without RF radiation 8 years after fabrication.

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