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Superconducting Nano Wire Circuits Fabricated using a Focused Helium Beam

E. Y. Cho[1], Meng K. Ma[1], Chuong Huynh[2], R. C. Dynes[1] and Shane A. Cybart[1]

[1.] Oxide Nano Electronics Laboratory, Department of Physics, University of California, San Diego, La Jolla, California USA.
[2.] Carl Zeiss Microscopy, LLC., Peabody, Massachusetts USA

Electrical circuits fabricated from high-transition temperature superconductors (HTS) are very difficult to pattern due to the lack of a reliable etching process. Chemical etching can be used for large features, but undercutting limits the feature size to tens of microns. Dry etching is required for smaller features, but there is no anisotropic reactive ion etch for these materials. Therefore dry etching must be done with isotropic argon ion milling. The ion milling process generates excess heat and unfortunately oxide superconductors are sensitive to high temperature. Overheating the material by ion milling causes it to deoxygenate which turns the superconductor into an insulator. Therefore to prevent overheating the critical dimension for argon ion milling is typically limited to a few microns.

In this work, we demonstrate an alternative method to pattern HTS by direct write ion lithography using a focused helium ion beam. In this method we demonstrate the ability to pattern nano wires as small as 250 nm within the plane of an HTS film. The key to this approach is that HTS materials are very sensitive to disorder, the electrical transport properties transition from superconductor to insulator with increasing disorder [1]. Irradiation of the superconductor material generates point defects creating a highly insulating region where the beam is scanned. The high energy ions shoot through the thin film and are implanted into the substrate without removing any material, this process is much faster than etching for dense oxides. Furthermore, because helium is inert it does not react chemically with the YBCO like gallium ions in conventional focused ion beams. In addition, the insulating barrier has a much smoother edge than a wire edge patterned by ion milling.

For our experiment, test samples were prepared by patterning 4 μm wires with standard photolithography and broad beam ion etching from 30-nm thick YBCO films grown on sapphire. We chose this thickness because Monte Carlo simulations using the Stopping and Range of Ions in Matter (SRIM) software show that 30 keV helium ions will completely penetrate the film and implant into the substrate [2]. This ensures a uniform disordered region throughout the superconducting film thickness. Nano wires were made by irradiating insulating barriers to narrow down the 4 μm wires as shown in figure 1. In order to precisely determine the wire width we added a Josephson junction into the center of the nano wire [3]. Measurement of the Josephson junction parameters, maximum super current (I_C) and voltage state resistance (R_N), allow us to accurately determine the wire width. To pattern the sample we first used a dose of 6×10^{16} He^+/cm^2 to write a Josephson junction in the circuit, and then the dose was increased to 2×10^{17} He^+/cm^2 to write the insulating barriers that define the nano wire. Two test samples were made with wire widths of 250 nm and 500 nm, and a third control sample without narrowing the wire.

Current-voltage characteristics of the samples were measured in a vacuum cryostat inside of a liquid helium dewar at 4.6 K. Figure 2 shows the results for 250 nm, 500 nm and 4 μm wide wires. All of the junctions have an I_CR_N product of about 400 μV as expected because the I_CR_N product should be a constant of the material. This implies that material properties in the wire remained the same and that there was no thermal damage. Furthermore, R_N are 70, 38 and 5.6 Ω, which scale inversely proportionally with the width $\left(\frac{1}{R_N} \propto w\right)$. I_C for the junctions are 5.6, 10.3 and 70 μA, which scale proportionally with the width ($I_C \propto w$) as it should. These results provide strong evidence that the current only flows through the nano filament as intended, and that we were successful in direct writing of nano wires.

This new technology provides an improvement in patterning HTS and enables fabrication of high density nano scale superconducting circuits and interconnects.

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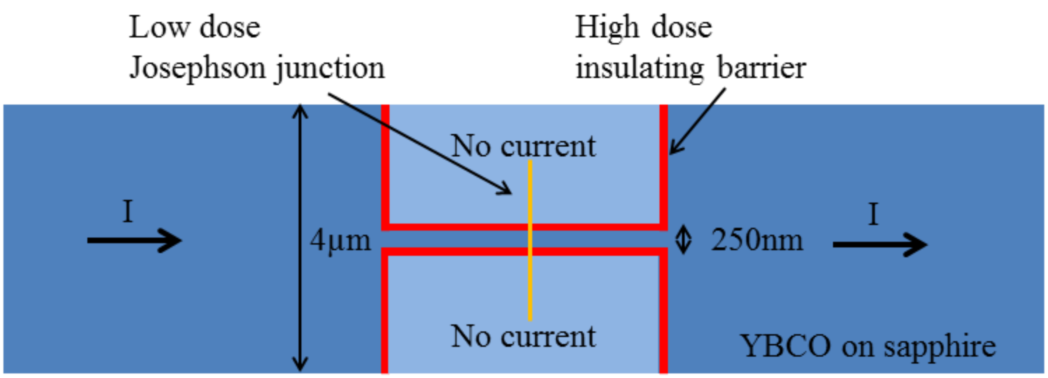

Figure 1. Schematic representation of a direct write nano wire. A 4 µm YBCO wire was narrowed down to 250 nm with insulating barriers (red lines). A Josephson junction was inserted in the middle of the wire with a lower dose (orange line).

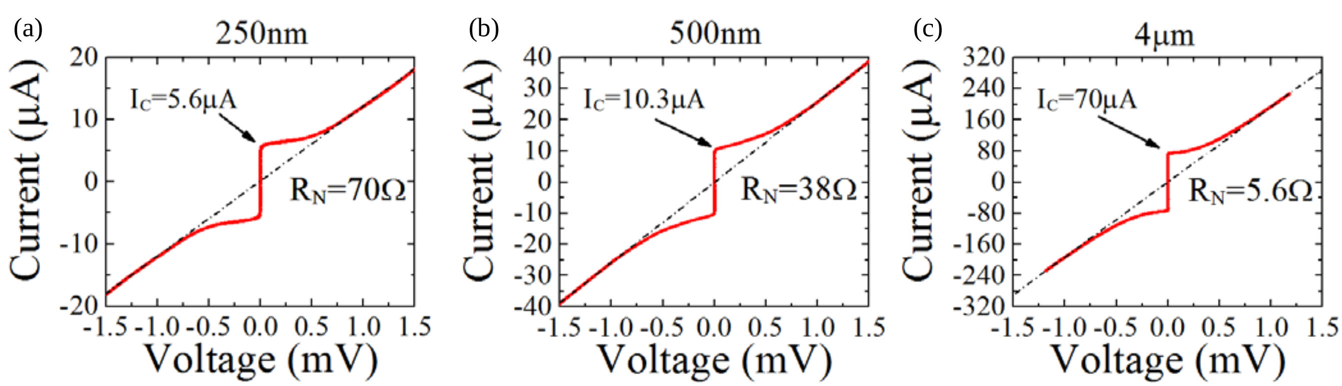

Figure 2. Current-voltage characteristics of YBCO Josephson junctions with wire widths of **(a)** 250 nm, **(b)** 500 nm and **(c)** 4 µm. The red lines are the measured data and the black dashed lines indicate extracted R_N.

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