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Application of Focused Helium Ion Beams for Direct-write Lithography of Superconducting Electronics.

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The 1986 discovery of high transition temperature (high-T_C) superconductivity in copper-oxide materials set in motion an intense research effort to develop superconducting electronics operating at and above liquid nitrogen temperatures (77 K). Scientists and engineers worked with fervor to develop these new exciting materials but soon discovered that they were much more complicated than imagined. Anisotropic electrical properties and a very short superconducting coherence length eliminated the possibility of using classical superconducting electronic structures. These new materials demanded novel device architectures that proved very difficult to realize. Nearly three decades have passed and progress in high-T_C superconducting devices has been very slow because process control at the sub ten nanometer scale is required to make high quality Josephson junctions: the basic building block of superconducting electronics. Recent advances in gas field focused helium ion beams [1] provide a new promising approach for direct-write lithography of high-T_C superconducting materials [2] for the realization of a predictable and scalable high-T_C superconducting electronics technology.

In this work, we demonstrate *a-b* plane superconducting Josephson tunnel junctions for $YBa_2Cu_3O_{7-\delta}$ (YBCO) by utilizing a 500-pm diameter focused helium ion beam to create a very narrow (~nm) tunnel barrier between two superconducting electrodes. The key to this method is that YBCO is very sensitive to point defects in the crystal lattice caused by ion irradiation [3]. Increasing irradiation levels has the effects of increasing resistivity and reducing the superconducting transition temperature. At very high irradiation levels YBCO becomes insulating and no longer conducts or superconducts [3].

To obtain smaller feature sizes required for high quality Josephson junctions we have employed a focused helium ion beam to directly disorder a thin 25 nm thick YBCO film. Initially large circuit features for electrical contacts, and 4-μm wide strips of YBCO were patterned with conventional photolithography in a YBCO thin film that had an *in situ* deposited Au contact layer on top [2]. The starting YBCO film thickness was 150 nm, but the Au was removed and the YBCO was etched to a thickness of ~30 nm in the area intended for junctions. This thinning was to ensure that the helium ions fully penetrated the YBCO with very little lateral straggle. Samples were then loaded into a Zeiss Orion helium ion microscope and the 30 kV helium beam was scanned in a line across the 4-μm wide superconducting bridges. Numerous test samples were written with ion fluence ranging between 10^{14} and 10^{18} He^+/cm^2. At the lower values very little reduced T_C and Josephson current was observed. In contrast, at the higher doses the devices exhibited insulating behavior. In between these two extremes we were able to determine doses that could create very high-quality Josephson junctions with both metallic and insulating barriers. Figure 1 shows the ion damage profile for an ion implantation simulation for a dose of $6x10^{16}$ $ions/cm^2$ into a 30 nm thick YBCO film. The Josephson barrier appears to be very uniform throughout the depth of the film and only 2 nm wide.

After irradiations, test samples were characterized electrically by measuring the current-voltage *(I-V)* characteristics (Figure 2A). At low voltages the samples showed nearly ideal Josephson junction behavior with a zero voltage supercurrent that oscillated in magnetic field. At much higher voltages *(I-V)* exhibited insulator behavior (Fig. 2B). Using ac techniques we measured the differential conductance (*dI/dV*) which revealed the YBCO superconducting energy gap near 33 mV. This feature is a result of quasi particle tunneling which provides strong evidence that we have created an insulating barrier less than 2nm wide.

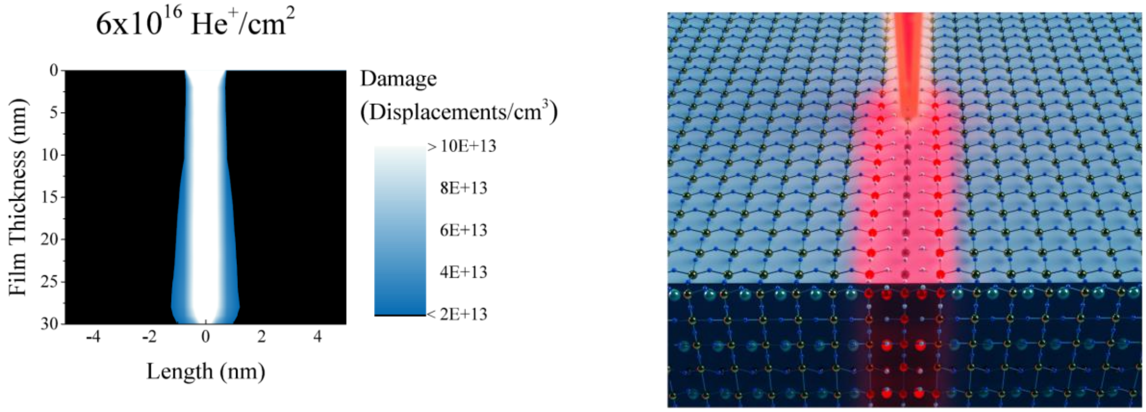

Figure 1. (left) Simulated 30 keV He ion irradiation of a YBCO film using Silvaco Athena. **(right)** A scale model of the focused helium ion beam creating a Josephson junction in a YBCO film.

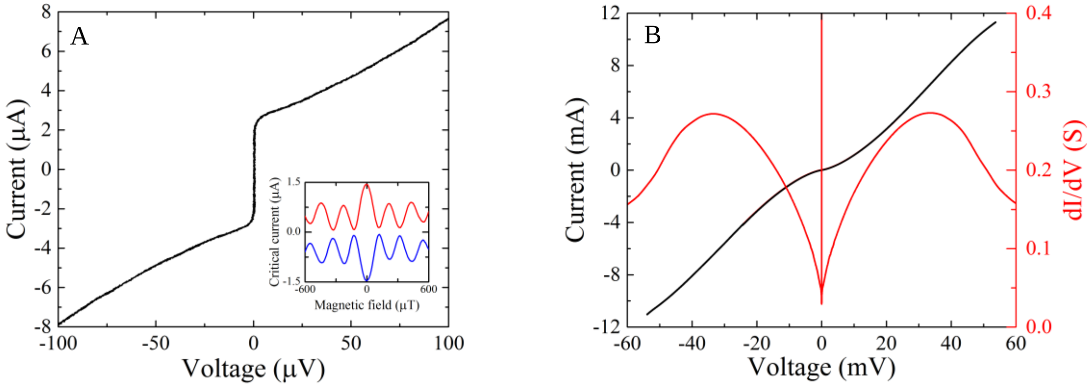

Figure 2. (A) Current voltage characteristics *(I-V)* for a YBCO Josephson junction written using a dose of $6x10^{16}$ ions/cm^2. The inset shows the quantum diffraction of the critical current in magnetic field. **(B)** Current voltage characteristics *(I-V)* for the same junction at higher voltage bias. Here the non-linearity reveals that the barrier has insulating properties. Measurement of *dI/dV* reveals the YBCO superconducting energy gap.

These results demonstrate the unique ability of focused helium ion beams for maskless direct write lithography of oxide tunnel barriers for electronic devices. This technique is not limited to superconductors and will work on any material that is sensitive to disorder.

References:

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