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From Weak Links to Quantum Coherence: A Focused Ion Beam Perspective on Superconducting Tunneling Phenomena

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***Abstract*—Advancements in computing for large data sets and AI are increasing demands on processing power in Post-Moore's Law era. While AI computational processing demands are exponentially increasing, improvements in conventional semiconductors are slowing. There is an imperative need to move to novel computing architectures that are more efficient. Superconducting architectures offer faster, more efficient computing in both digital and analog (quantum, neuromorphic) regimes. Practical implementation of superconducting electronics remains an elusive scientific hurdle. Inspired by the improved 3D integration of finFETs in semiconducting technology, superconductive electronics may be improved through focused ion beam lithography of Josephson junctions. This technique has been demonstrated in both low critical temperature and high critical temperature superconductor Materials [1],[2]. This technique promises advances for superconductive electronics through the reduction of the dimensions of critical components, simultaneously improving scalability while reducing errors from trapped flux. Additionally, this approach provides a simplified fabrication process that reduces noisy interfaces.**

Several processes have been utilized to create superconducting junctions with focused ion beam techniques, enabling practical junction barrier design. Weak links have been demonstrated by milling superconducting electrodes into nanowire constrictions. Quantum coherent devices have been demonstrated in Josephson junctions fabricated with sufficiently concentrated ion irradiation that is of the scale of the superconducting coherence length. In cuprate materials, ion irradiation smoothly transitions the material from a normal metal to insulating material behavior dependent on the ion fluence. Gas field ion beam sources focus the ion beam below the superconducting coherence length resulting in tunable Josephson barriers. This technique gives unprecedented tunability of Josephson junctions, allowing studies that span the weak link junctions to overdamped Josephson junctions. Figure 1 shows resistivity vs. temperature data, where increasing ion fluence drives the $YBa_2Cu_3O_{7-\delta}$ (YBCO) through a metal-to-insulator transition. Additionally, the Stopping Range in Matter (SRIM) simulation plots resulting damage from a focused helium ion beam (FHIB) into YBCO, and shows the concentration of the ion damage is below the superconducting length scale in films up to 50

nm thick [3].This technique can be utilized to characterize in-plane carrier tunneling mechanisms in thin films utilizing planar Josephson junctions. YBCO is a highly anisotropic material featuring enhanced critical current densities in the *ab*-plane. Ion irradiated planar Josephson junctions offer a novel perspective into these materials that are promising for their ability to superconduct above liquid nitrogen temperatures. Figure 2 demonstrates utilizing FHIB lithography for fabrication of a superconducting quantum interference device in YBCO. Differential conductance measurements taken across these junctions characterize the density of states and barrier quality of this technique. A practical order parameter of cuprate superconductivity is defined and used to characterize material performance. Measurements of the order parameter are taken at variable angles to help determine the practical pairing symmetry. Measurements reveal a strong s-wave component with ≤30% d-wave contribution [4]. FHIB lithography offers precise, mask-free fabrication of nanoscale superconducting circuits, enabling direct writing of electrodes and Josephson junctions with tunable material properties. Its high resolution and flexibility support both rapid prototyping and scalable manufacturing, making it a powerful tool for advancing very large-scale integrated superconducting electronics, quantum computing, and next-generation superconducting technologies.

Keywords (Index Terms)—Focused Ion Beam, Carrier Tunneling, Josephson Junction

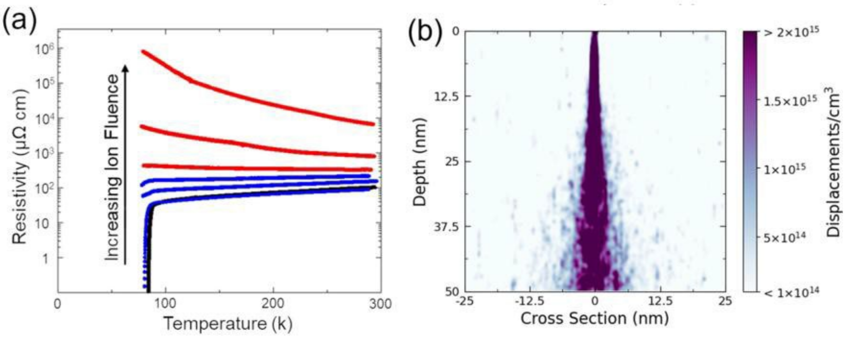

Figure 1 a) Resistivity vs. temperature of YBCO irradiation with helium ions, demonstrating a metal-to-insulator transition. b) Simulation of displacements in YBCO caused by focused helium ion irradiation, demonstrating concentrated to the coherence length up to 50 nm.

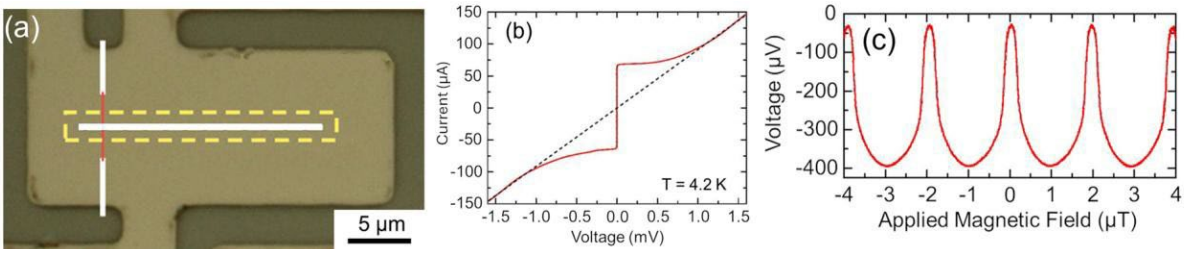

Figure 2) a) Maskless FHIB geometry of a SQUID, where white and red lines indicate insulating and Josephson barriers, respectively. b) Current-voltage characteristics of the FHIB SQUID showing RSJ behavior at 4.2 K. c) Corresponding magnetic field voltage response of the current-biased SQUID.

References

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