Nanofabrication of High-Transition-Temperature Superconductive Electronics with Focused Helium Ion Irradiation

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In Feynman's infamous 1959 lecture entitled, "*There's Plenty of Room at the Bottom* " he inspired and foreshadowed the emergence of nanoengineering. He suggested that finely focused electron and ion beams would aid our eyes and hands to precisely engineer structures at the atomic level. Currently, electron beam lithography systems and gallium-focused ion beams are ubiquitous in nanotechnology and can routinely be used to create structures of the order of tens of nanometers. However, the ability to scale to the sub-10 nm has been a technological challenge until the development of gas field ion sources (GFIS) over the past decade. The GFIS source utilizes a single crystal tungsten wire sharpened to just 3 atoms. Helium gas is field ionized by one of these atoms, creating a helium ion beam with a diameter of only 0.25nm! This instrument is emerging as an important tool for the sub-10 nm structuring of materials. Helium ion beams have significant advantages. Helium is small and chemically inert which allows it to be used for direct modification of materials properties without etching away material or employing resists.

My research group has been utilizing GFIS for direct patterning of ceramic high-temperature superconducting materials for quantum electronics. The helium ion beam induces nanoscale disorder from irradiation into the crystalline structure which converts the electrical properties of the material from superconductor to insulator. Insulating feature sizes of less than 2nm have been successfully demonstrated and many unique novel devices have been realized. Much of this success is due to the irradiation sensitivity of electrical transport in high-temperature superconductors. This sensitivity results from loosely bound oxygen atoms (~1-8ev) in the crystal lattice that are easily displaced into interstitial or anti-site defects.

Many novel applications in superconducting electronics are enabled by this technology. Our group has constructed quantum magnetic field sensors such as the nano superconducting quantum interference device array shown in Figure 1 for magnetic field sensing. Using HIM fabrication we also demonstrate ultra-low power quantum flux parametron digital logic devices (Figure 2). These circuits can perform digital operations with energy consumption five orders of magnitude lower than CMOS.

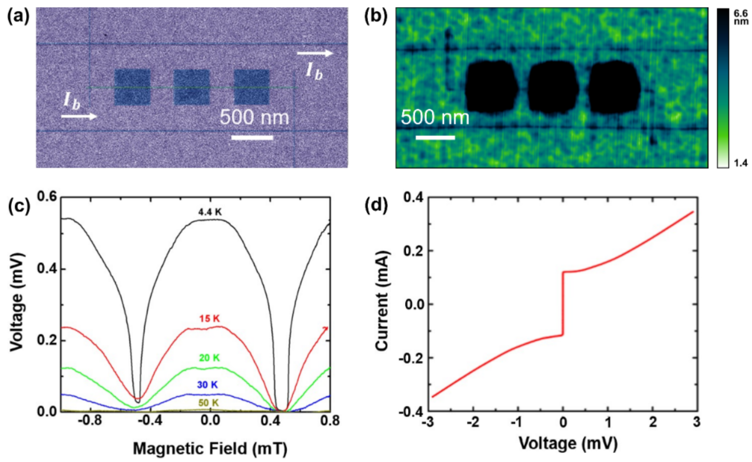

Figure 1: HIM image of three Nano-SQUIDs in parallel. Four 300 x2 nm Josephson junctions are created on both sides of the square squid loops. Vertical lines at the ends of the segment are used to isolate the top on the left and the bottom on the right so that the bias current, Ib traverses the junctions in parallel. (b) AFM image of an array showing the topography (c) The voltage-magnetic field modulation of the DC-biased array is shown for temperatures 4.2, 15, 20, 30, and 50 K. (d) The current-voltage characteristic for the array.

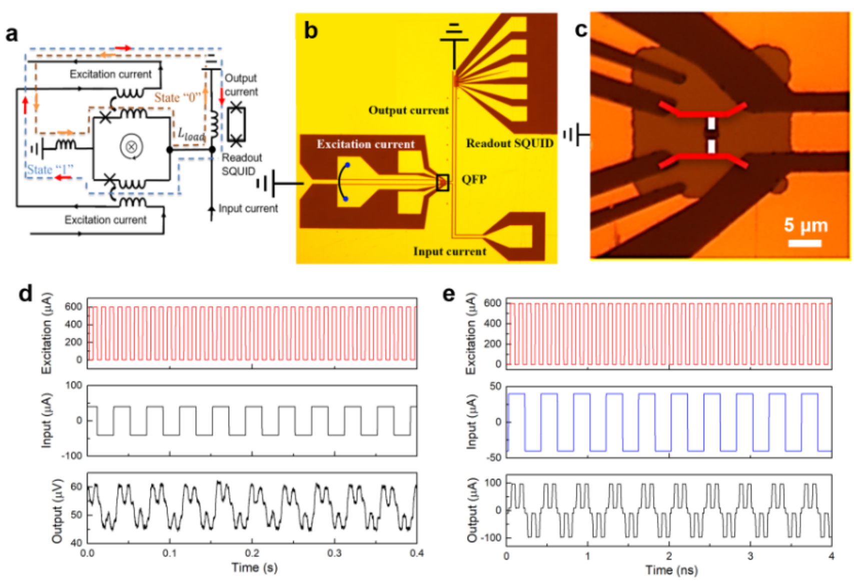

Figure 2: YBCO Quantum Flux Parametron (a) Circuit schematic for the YBCO QFP, highlighting the "0" and "1" logic states. (b) Optical photograph of the QFP input transmission line and readout SQUID. (c) The optical photograph of the exposed YBCO pattern on an expanded scale. The solid white lines represent the Josephson junctions directly written into the YBCO layer by the HIM. The red lines are insulating lines written to isolate the QFP from the excitation current. (d) The operation of the QFP switching gate was measured at 25 K. A steady output voltage was observed with 600 µA excitation current and ±40 µA input current at clock 100 Hz. (e) Simulation of the QFP operating at 10 GHz using the experimental circuit parameters.