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Superconducting Nano Wire Josephson Junction Fabricated using a Focused Helium Beam

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***Abstract*— Conventionally the etching process for superconducting circuits uses Ar$^+$ ion milling, which causes disorder and heat that degrades the material that limits the feature sizes to a few microns. We present a novel technology to fabricate superconducting circuits using a focused helium beam to locally disorder the material at the nanoscale. We apply the fact that disordered Y-Ba-Cu-O is insulating to define the circuit without physical sputtering. We demonstrate nanowire Josephson junctions with widths down to 50 nm without any degradation of properties.**

I. INTRODUCTION

TRADITIONALLY SUPERCONDUCTING circuits made from high transition temperature superconductors (HTS) are patterned using an argon ion mill. HTS materials are extremely sensitive to processing and degrade easily. Chemical etching can only be used on large features to tens of microns. Dry etching with isotropic Ar$^+$ milling is required for smaller feature sizes, however, overheating of the material by ion milling causes deoxygenation which in most cases transform the superconductor into an insulator. Therefore, the critical dimension for dry etching is limited to a few microns. Recently there are advancements in fabricating nano wires with an Ar$^+$ mill by using protective layers in the milling process [1,2].

In this work, the authors demonstrate a novel simple technique to pattern HTS by using direct-write ion lithography with a focused helium ion beam. We successfully demonstrate the ability to pattern nano wire Josephson junctions as small as 50 nm within $YBa_2Cu_3O_{7-\delta}$ (YBCO) films. The main ideas in this method are that HTS materials are extremely sensitive to disorder, the electrical transport properties undergo a superconducting insulator transition with increasing disorder [3]. The disorder in the materials is generated using high energy ion irradiation creating point defects in the material. Regions that are irradiated by the ion beam transition to an insulator. It is important to note that the high energy ions shoot through the superconducting films and implant deep in the substrate. Also since helium is an inert gas the process maintains the same chemical composition of the initial film. The dose needed for generating disorder in YBCO is far less than the dose necessary to see any noticeable milling which means short patterning time. Shorter processing time reduces damage caused by heat which preserves the material quality. Lastly, since the focused helium beam spot is less than 1 nm, nano wire junctions patterned using this method have much smoother edges than ion milling.

II. EXPERIMENT

For our experiment, large feature and electrodes on the test samples were prepared by patterning 4 μm wires with standard photolithography and broad beam Ag ion milling from 30-nm thick YBCO films grown on sapphire. Film thickness was chosen to be 30 nm because Monte Carlo simulations from the Stopping and Range of Ions in Matter software [4] show that 30 keV helium ions will completely penetrate the film and implant into the substrate with a well-defined disordered region. The disorder density is uniform throughout the depth of the superconducting film. Nano wires were made by irradiating insulating barriers to constrict the current path in the 4 μm wires as shown in Fig 1.

In order to precisely determine the nano wire width we added a Josephson junction into the nano wire [5]. Since the bridge and the nano wire superconduct below a critical temperature, the lead resistance goes to zero and the measurement is equivalent to a 4-point measurement on the junction. Measurement of the Josephson junction parameters, maximum super current (I_C) and voltage state resistance (R_N), provides an accurate way to determine the wire width restricted by ion beam patterning. To pattern the we used a lower dose of 6×10^{16} He$^+$/cm^2 to write a Josephson junction in the circuit, and a dose to 2×10^{17} He$^+$/cm^2 to define the insulating barriers that define the nano wire width. Four test samples were made with wire widths of 50 nm, 250 nm and 500 nm, and a 4 μm control sample without narrowing the wire.

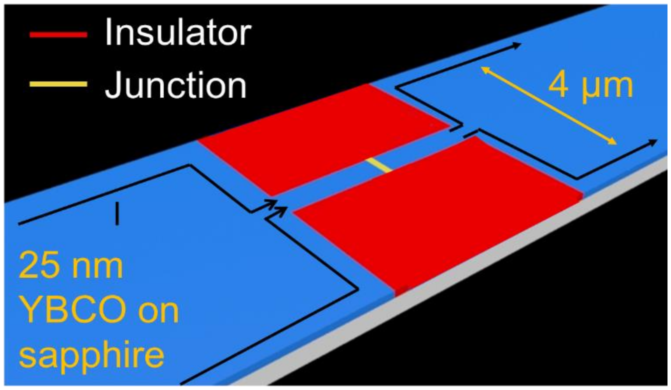

Fig. 1 A schematic of nano wire circuit design (not to scale). The current flow through the constriction in the wire between the two insolating region (red) irradiated by focused helium ion beam. Josephson junction (yellow) was inserted to probe the wire width and material quality after irradiation.

III. RESULTS

Current-voltage characteristics (*I-V*) of the samples were measured inside a vacuum cryostat cooled to 4.2 K in a liquid helium dewar. Fig. 2 shows the *I-V* for 50 nm, 250 nm, 500 nm and 4 µm wide wires. All of the junctions have an $I_C R_N$ product approximately equal to 400 µV as expected because the $I_C R_N$ product should reflect the material properties regardless of the scale. This implies that material quality in the wire remained the same and that there was no thermal damage from the focused helium ion beam process. Furthermore, R_N of wire width 50 nm, 250 nm, 500 nm and 4 µm are 210, 70, 38 and 5.6 Ω, respectively. These resistance values scale inversely proportional with the wire width $\left(\frac{1}{R_N} \propto w\right)$. Similarly I_C for the junctions are 2, 5.6, 10.3 and 70 µA, respectively, also scale proportionally with the width ($I_C \propto w$) as it should. These results strongly indicate that the current only flows through the restricted channel by the insulator as designed.

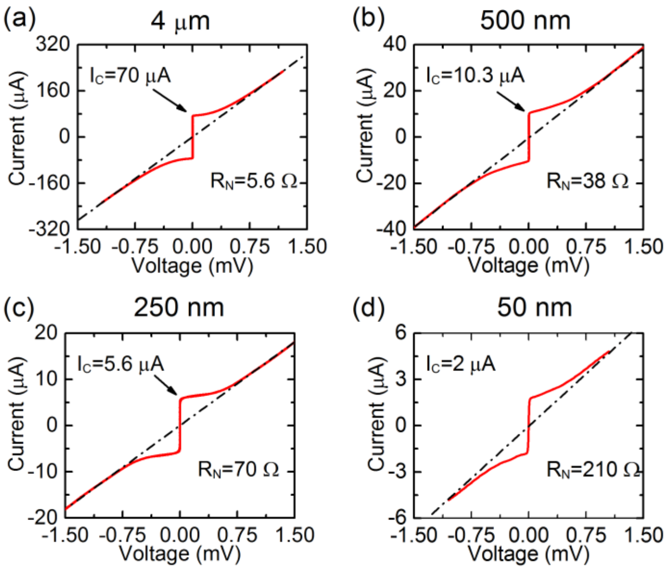

Fig. 2. Current-voltage characteristics of YBCO Josephson junctions with (a) 4 µm, (b) 500 nm, (c) 250 nm and (d) 50 nm. The red lines are measured data and R_N was extracted following the black dashed line passing through the origin. I_C of these samples are very well defined and extracted at a small threshold voltage.

IV. CONCLUSION

This new technology provides an improvement in patterning HTS. It is relatively easy and scalable to a wafer level process. Large scale Josephson junction arrays [6-9] and digital circuits [10-12] for communication [13-15] can greatly benefit from this technology due to the reliability and uniformity of the junction parameters. The reduction of lateral straggle of ion damage in this technique will allow for much closer inter-junction spacing for high density arrays [16]. Using nano wires can potentially further reduce noise on single quantum interference devices for medical use [17]. Taking advantage of modifying material properties through disorder, this technology can be applied to all materials that are disorder sensitive such as MgB_2 [18].

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