Application of Focused Helium Ion Beams for Direct-write Lithography of Josephson Junctions in $YBa_2Cu_3O_7$

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July 18, 2015 (STH33, HP98). 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. Advances in gas field focused helium ion beams [1] provide a new promising approach to predictable and scalable high-T_c superconducting electronics technology by direct-write lithography of Josephson junction barriers.

Recently we have demonstrated *a-b* plane superconducting Josephson tunnel junctions in $YBa_2Cu_3O_{7-\delta}$ (YBCO) by utilizing a 500-pm diameter focused helium ion beam to demonstrate a very narrow (~nm) tunnel barrier between two superconducting electrodes [2]. The key to this method is that YBCO is very sensitive to point defects in the crystal lattice caused by ion irradiation. Increasing irradiation levels has the effects of increasing resistivity and reducing the superconducting transition temperature. At very high irradiation levels YBCO becomes insulating.

Circuit features for electrical contacts, and 4-µm wide strips of YBCO were patterned with conventional photolithography into a YBCO thin film etched down in the barrier area from 150 nm to only 30 nm thickness. 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 fluences ranging between 10^{14} and 10^{18} He^+/cm^2. 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.

The current-voltage characteristics (*I-V)* are shown in Figure 1(a) for a typical SNS Josephson junction written with a dose of 2×10^{16} He^+/cm^2 and measured at several temperatures. The resistance is ~1 Ω, roughly 10 times larger than that of typical ion irradiated weak links reported in the literature. Inset 1(b) in Figure 1 shows the temperature dependence of resistance (R_n) and critical current (I_c). The resistance decreasing with temperature indicates the barrier is a conductor. I_c substantially increases with decreasing temperature which is typical for SNS junctions, because the barrier is becoming a stronger superconductor at lower temperature. The diffraction pattern of the supercurrent in applied magnetic field shown in inset 1(c) clearly demonstrates the dc Josephson effect.

In stark contrast to the SNS junction, Figure 1(d) shows *I-V* for several temperatures of a SIS junction fabricated by irradiation with a higher dose of 6×10^{16} He^+/cm^2. Unlike the $R(T)$ shown in Figure 1(a), the resistance of this junction, shown in inset 1(e), increases as temperature is decreased indicating that the barrier is an insulator or semiconductor. Furthermore, unlike in the SNS junction, the critical current only weakly depends on temperature as expected for a strong insulating barrier. It slightly increases as the thermal noise is reduced and fluctuations are suppressed. The diffraction pattern for this junction is shown in inset 1(f).

At higher current bias, inset 1(g), the SIS nature of *I-V* is more apparent and conductance peaks are visible at $V = \pm 32$ mV reflecting superconducting energy gap behavior.

We measure the differential resistance using a lock-in amplifier and $\mathrm{d}I/\mathrm{d}V$ is plotted in Figure 2(h). We assume the conductance peaks represent a superconducting energy gap, 2Δ, and plot it as a function of temperature as shown in inset 2(i). This data fits surprisingly well to the BCS gap temperature dependence with only the two parameters $2\Delta = 33$ mV and $T_c = 77.8$ K.

In another recent paper, we compared DC washer SQUIDs with SIS and SNS junctions fabricated using this method [3]. Both the SIS and SNS junction devices exhibited a well-behaved voltage modulation of approximately 3/4 and 1/2 I_0R, respectively. Measurements were taken for a large magnetic field (B) range to observe SQUID's $V(B)$. Figure 2(a) shows the data for the SNS SQUID at 50 K. To characterize the noise, we connected the SNS SQUID to a flux-locked loop and measured the output on a signal analyzer. The results are shown in Figure 2(b) with and without bias reversal reducing the critical current noise. The $1/f$ knee occurs around 1 kHz and the white noise level is about $2\mu\ \Phi_0\mathrm{Hz}^{-1/2}$. This may be improved with better magnetic shielding and design optimization such as slots in the electrodes to prevent flux trapping and smaller metallic contacts to limit Nyquist noise.

We believe this advance will have a significant impact for applications of superconducting electronics covering a wide spectrum, ranging from highly sensitive magnetometers for biomagnetic measurements of the human body, to large scale arrays for wideband satellite communications. For basic science, planar tunneling will become a powerful tool for studying electrical transport in superconductors and other materials.

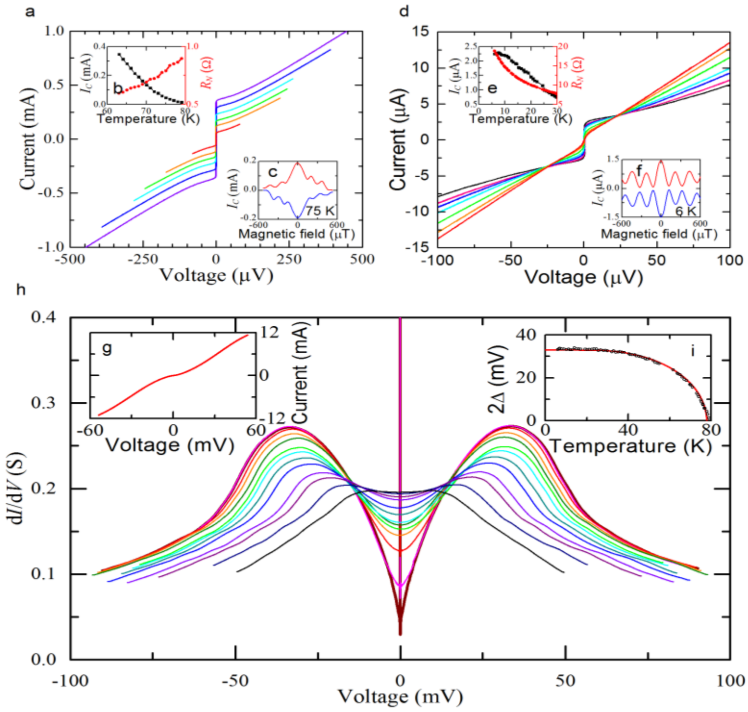

Fig. 1. Comparison of transport measurements for SNS and SIS Josephson junctions adapted from [2]: (a) SNS current-voltage characteristics measured for temperatures 63, 65, 67, 69, 71, and 75 K; (b) The temperature dependence of the I_c, R_n; (c) The diffraction pattern for the critical current in magnetic field applied perpendicular to the film; (d) SIS current-voltage characteristics measured at 5, 10, 12, 14, 16, 18, and 22 K; (e) The temperature dependence of I_c and R_n; **(**f) The diffraction pattern for the critical current in magnetic field applied perpendicular to the film at 6 K**;** (g) SIS current-voltage characteristics for a high voltage range; (h) $\mathrm{d}I/\mathrm{d}V$ for the temperatures ranging from 70 to 5 K in 5 K increments;. (i) Experimental temperature dependence of 2Δ and the BCS fit. © NPG 2015

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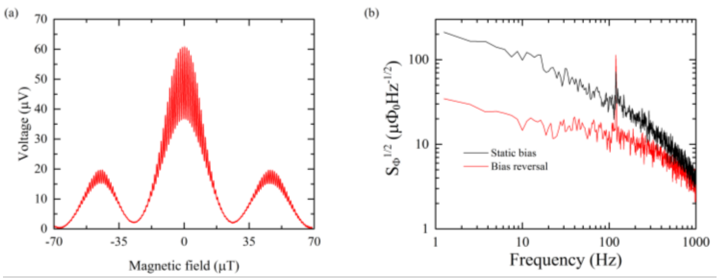

Fig. 2. Data for a SNS DC washer SQUID measured at 50 K adapted from [3] (a) Voltage as a function of magnetic field for static bias. Both the interference and diffraction pattern are visible; (b) Noise spectrum measured in a flux locked loop using both static and ac bias. © AIP 2015

References

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