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Impact of non-idealities on the conductance characteristics of superconductor-insulator-normal metal-insulator-superconductor tunnel junctions

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Abstract. We have investigated the effect of asymmetry in tunnelling resistance of individual normal metal-insulator-superconductor (NIS) tunnel junctions that constitute a SINIS pair, both experimentally and theoretically. Our results clearly demonstrate that any finite asymmetry in the tunnelling resistance gives rise to an excess current, as compared to its symmetric counterpart, both below and around the gap edge. The signature of this excess current is visible almost up to the critical temperature. We find that this apparent broadening of the density of states is purely electrical in origin. Our calculations also show that any finite resistance that is in series with the tunnelling resistance, such as the resistance of normal metal island or the line resistance in case of two probe measurements, leads to a suppression of the conductance maxima at the gap edge. This is a manifestation of the finite voltage drop across the series resistor. Our experimental results validate our theoretical prediction.

1. Introduction

Voltage induced quasiparticle tunnelling in a superconductor-insulator-normal metal-insulator-superconductor (SINIS) tunnel junction is a novel concept with many potential technological applications such as solid state cooling and thermometry [1]. The principle of cooling in such devices is based on the existence of forbidden energy states within the gap (Δ) of the superconductor which allows only the high energy electrons in the Fermi tail of the metal to tunnel into the superconductor [2, 3, 4]. Moreover, the conductance characteristics of such SINIS junctions are extremely sensitive to the temperature of the normal metal which makes these junctions ideal for accurate thermometry at very low temperatures [5].

An ideal SINIS junction consists of two NIS junctions connected in series with the tunnelling resistances of the individual junctions assumed to be equal. Moreover, the resistance of the normal metal is assumed to be negligible as compared to the tunnelling resistances of the junction. Experimentally, however, these assumptions are not strictly true as inaccuracies in lithography and variation in local film thickness and morphology can give rise to a difference in the tunnelling resistance of the two junctions fabricated otherwise under similar conditions. In addition, what one experimentally measures is the sum of the individual junction resistances (if no extra contacts to the normal metal are made) and thus it is important to understand how the conductance characteristics differ if the individual resistances vary in such a way that their sum is constant. This is the main focus of the present work. An additional goal is to understand the

impact of the finite resistance of the normal metal and other series resistances that appear (for example line resistances in two probe measurements), in the limit where they are comparable to the tunnelling resistance.

In this paper, we present some of the experimental and the corresponding theoretical results of the impact of asymmetric tunnelling resistance and finite series resistances on the conductance characteristics of SINIS tunnel junction devices. A knowledge of these results is not only essential for a more accurate interpretation of the results of SINIS junction based cooling and thermometry experiments, but they can also be exploited to optimize the performance of such devices. Our experimental and theoretical findings support each other.

2. Method

2.1. Theoretical Model

Let us consider a SINIS junction whose tunnelling resistance is R_T . This value is actually the sum of the tunnelling resistance of the two individual NIS junctions that constitutes the SINIS junction. We denote the individual resistances by R_1 and R_2 such that $R_T=R_1+R_2$. The expressions for current flowing through the individual junctions are given by

$$I_1 = \frac{1}{eR_1} \int_{-\infty}^{\infty} D_S(\epsilon, T_S) D_N(\epsilon + V_1, T_N) (f_S(\epsilon, T_S) - f_N(\epsilon + V_{SIN}, T_N)) d\epsilon \quad (1)$$

$$I_2 = \frac{1}{eR_2} \int_{-\infty}^{\infty} D_N(\epsilon, T_N) D_S(\epsilon + V_2, T_S) (f_N(\epsilon, T_N) - f_S(\epsilon + V_{SIN}, T_S)) d\epsilon \quad (2)$$

where V_1 and V_2 are the voltage across the individual junctions, subscripts S and N denote the superconductor and normal metal respectively, ϵ , e denotes the energy and the electronic charge, D_i, f_i and T_i respectively denotes the density of states, Fermi distribution and electron temperature of the i th electrode. Since the individual junctions are in series the current flowing through them, denoted by I , must be the same. Thus any asymmetry in the value of the individual tunnelling resistance gives rise to different voltage drop across the individual junctions. The line resistances and the normal metal resistance are equivalent to a resistance in series with the tunnelling resistances. We denote this series resistance by R_L . In experiments what one measures as the voltage drop across the junctions (denoted by V_T) is thus the sum of the actual junction voltages (denoted by V_J) and the voltage drop across R_L . Thus,

$$V_T = V_J + IR_L \quad (3)$$

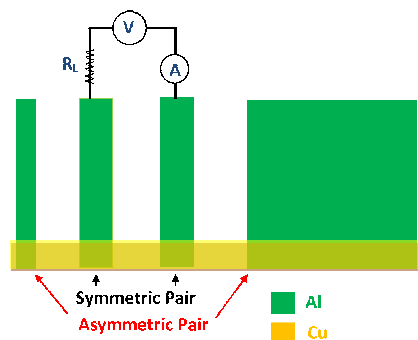


Figure 1. Schematic representation of the sample geometry. The two junctions with identical geometry (junction area: $200 \times 200 \text{ nm}^2$) forms the symmetric junction while the pair of junctions located the end forms the asymmetric junction with individual junction dimensions of 1000×200 and $110 \times 200 \text{ nm}^2$. The biasing scheme for measurement of conductance of the symmetric junction as a function of applied voltage for various values of series resistor is also shown.

2.2. Experimental

NIS junctions with aluminium, aluminium oxide and copper as the superconductor, insulator and the normal metal, respectively, were fabricated on oxidized silicon substrate using standard electron beam lithography and shadow evaporation techniques. The thickness of the copper and aluminium were ~ 30 and 20 nm, respectively. The insulator was formed by the in-situ room temperature thermal oxidation of the aluminium surface. In order to study the effect of asymmetry of the tunnelling resistances, we fabricated SINIS junctions having the geometry depicted in Figure 1. The asymmetric SINIS device consists of two junctions with areas 1000×200 nm² and 110×200 nm², while the corresponding symmetric junction had a dimension of 200×200 nm². The asymmetric junction had a total tunnelling resistance of 42.4 k Ω close to the value for the corresponding symmetric one ~ 44.4 k Ω . The measurements were carried out using a He³-He⁴ dilution refrigerator with a base temperature of ~ 50 mK. Each measurement line had two RC filters, one at 4 K and the other on the sample stage contributing to a total resistance of 2 k Ω per line. Additional high-frequency filtering was achieved by thermocoax cables connecting the 4 K stage and 50 mK stage. The temperature stability of all the measurements were kept below 10 mK using feedback control. For the measurement of the impact of finite resistances on the conductance characteristics we added external resistors in series with the symmetric junction circuit, as shown in Figure 1.

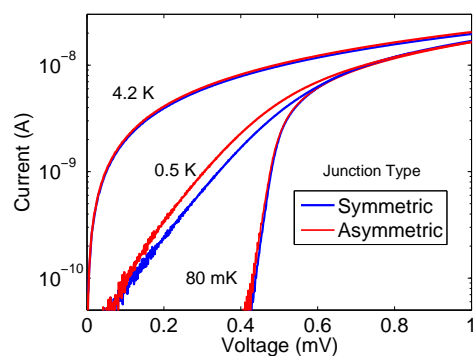


Figure 2. Current-voltage characteristics of asymmetric and symmetric junctions at base temperatures 0.08 , 0.5 and 4.2 K. An excess current below the gap voltage is clearly visible for the asymmetric junction.

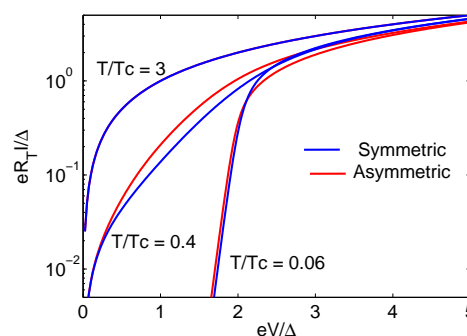


Figure 3. Numerical simulation of current-voltage characteristics of asymmetric and symmetric junctions computed for parameters corresponding to actual experiments carried out in Fig.2 .

3. Results and discussions

In Figure 2 we show the current-voltage characteristics of the symmetric as well as the corresponding asymmetric junctions at different bath temperatures. As seen clearly from the figure, below and around the gap voltage (2Δ) the current flowing through the asymmetric junction is more than the corresponding symmetric one. The magnitude of this excess current increases with increasing temperature. It should be pointed out here that although the tunnelling resistance of the asymmetric junction is about 4% smaller than the symmetric one, the current flowing through the asymmetric junction is about 25 and 50% higher than the corresponding symmetric one at temperatures 80 and 500 mK respectively. However at 4.2 K, which is above the superconducting transition temperature of Al, the current through the asymmetric junction is about 4% higher than its symmetric counterpart, as one would expect because of its 4% lower resistance. In order to verify our experiments we have carried out numerical simulation

corresponding to the experimental parameters and the results are shown in Figure 3. For these calculations we have assumed that the total tunnelling resistance of the symmetric and the asymmetric junctions are equal.

The impact of finite series resistance on conductance characteristics is shown in Figure 4. As seen clearly from the figure, an increase in series resistance gives rise to a decrease in the conductance maxima near the gap edge ($V \sim 2\Delta$). The peaks in the conductance arise due to the non-ohmic behaviour of the tunnel junction characteristics which, near the gap edge, allows a large change in current for a small change in voltage. However, when an ohmic series resistance is present in the circuit, the large change in current gives rise to a commensurate change in the voltage across the ohmic series resistor, thereby reducing the conductance maxima of the circuit comprising of the tunnel junction plus the resistor. Figure 5 shows the results of numerical simulations corresponding to the experimental parameters of Figure 4.

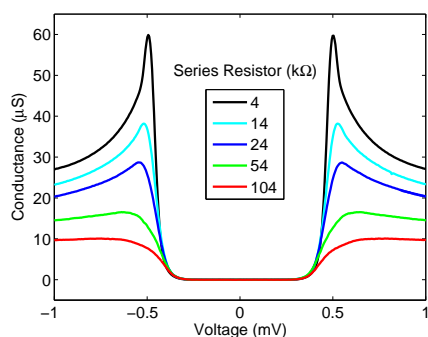


Figure 4. Measured conductance vs. voltage characteristics of the symmetric junction for various values of the series resistor. The bath temperature was maintained at 150 mK.

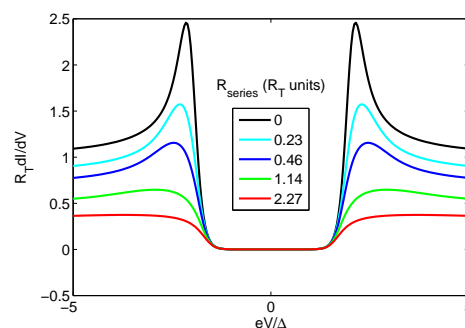


Figure 5. Numerical simulation of the conductance vs. voltage characteristics of the symmetric junction computed for parameters corresponding to actual experiments in Fig. 4.

4. Conclusion

In conclusion, we have observed both theoretically and experimentally that an asymmetry in the values of the tunnelling resistances of the individual NIS junctions that form a SINIS device can give rise to an excess current below the gap voltage as compared its symmetric counterpart. The origin of this excess current at a particular voltage is due to the different voltage drops across the asymmetric individual tunnel junctions when the same current flows through both of them. Furthermore, we have also observed that any finite resistance that is in series with the tunnelling resistance can give rise to a drastic reduction in the conductance maxima at the gap edge. The origin of this decrease is associated with the finite voltage drop across these series resistors and was verified by numerical simulations.

Acknowledgements

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