Niobium Step Josephson Junctions

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The characteristics of superconducting Josephson junctions are strongly dependent on geometric factors. Novel junctions were fabricated using Nb thin film microbridges (thickness d = 25–200 nm) onto substrate steps of height h = 25–200 nm. We report current-voltage (*I-V*) and Josephson critical current I_c measurements over a temperature range T = 1.5–K. By varying the ratio d/h it was possible to alter the junctions from non-hysteretic to ones with strong hysteretic *I-V* behaviour. A step-like structure in the temperature dependence of I_c indicates complex vortex dynamics.

1. Introduction

The current-voltage (*I-V*) characteristics of a Josephson junction are characterized by a Josephson current for $V = 0$, a current plateau at the Josephson critical current I_c where the voltage suddenly increases to the gap voltage, and a linear region where the material is in a normal state [1]. At I_c thermally activated Josephson vortices enter the junction from both ends and flow to the centre at a fixed velocity thus giving rise to the observed rise in voltage.

The characteristics of Josephson junctions and their use in various devices are strongly affected by geometric factors. The Josephson penetration length, λ_J, gives a measure of the distance in which d.c. Josephson currents are confined to the edges of the junction, and can be used to classify junctions into "small" ($L < \lambda_J$) and "large" ($L > \lambda_J$) where L is the length of the junction [2]. Here, we report the characteristics of Nb thin-film junctions where the superconducting weak link is caused by a step milled onto the substrate.

2. Specimens and measurements

The thin film junctions consisted of niobium microbridges (width W = 1.5–20 μm, length L = 600 μm, thickness d = 25–200 μm) deposited by magnetron sputtering over a vertical step of height h = 25–250 nm which was previously ion-beam milled in the SiO_2 layer (1–2 μm) of thermally oxidized silicon wafers. Figure 1 shows two of the possible junctions geometries, and Fig. 2 shows the corresponding SEM images of the fabricated devices. It is important to note that magnetron sputtering does not produce conformal coverage on the step and hence $W \leq 0.1d$; also, $L >> W$, and thus all junctions belong to the "large" junction configuration [2]. For junctions with $d/h \leq 1$ the very thin film on the step forms a transverse "overlap" weak-link junction. As d/h becomes greater than unity the overlap becomes *in-line*; here, the junction barrier is due to a very thin defect layer which originates from the step. This in-line defect layer results in increased junction capacitance and is expected to lead to significant hysteretic behavior in the *I-V* which can be tuned by means of the ratio d/h.

The transport measurements were performed in a double-dewar glass helium system which was magnetically screened by two concentric μ-metal shields to allow zero-field cooling. The specimens were immersed in liquid helium and temperatures to 1.5 K were achieved by pumping on the liquid. Measurements above 4.2 K were done in cold helium gas. The temperature was monitored using a calibrated carbon-glass resistance thermometer (Lakeshore CGR-1-500-1.4L), and during measurements it was held fixed to ± 0.01 K.

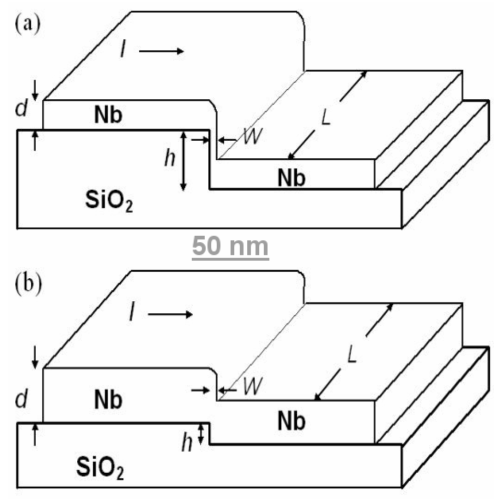

Fig. 1. Schematic of Nb junction formed over a step milled on the substrate: (a) $d/h < 1$ and (b) $d/h > 1$.

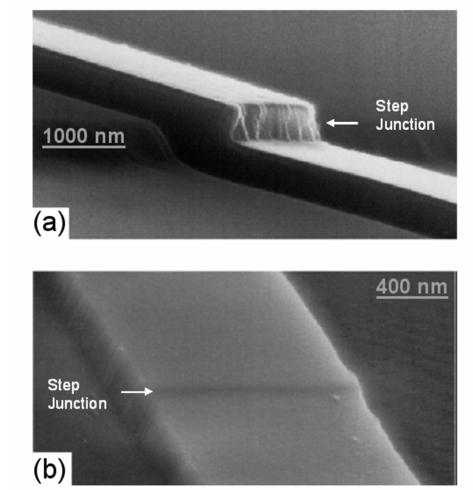

Fig. 2. SEM images of niobium step junctions corresponding to the schematic layout of Fig. 1.

3. Results

Typical *I-V* characteristics representing four different types of step junctions are shown in Fig. 3. All the measured junctions showed symmetric *I-V* curves with the normal resistance extrapolating to the origin. The film thickness to step-height ratio, *d/h*, varied from 0.24 to 5.3 for junctions A to D. For *d/h* less than or near unity the junctions showed standard *I-V* characteristics with a small degree of hysteresis (A, C).

For $d/h >> 1$ the in-line overlap forming the junction leads to significant hysteresis (e.g., junction D). Figure 4 shows results for a group of junctions on the same chip (d = 125 nm, h = 25 nm, L= 20–1.5 µm). These junctions have reproducible hysteretic behaviour, similar to that of planar or layered superconductor-insulator-superconductor (SIS) junctions.

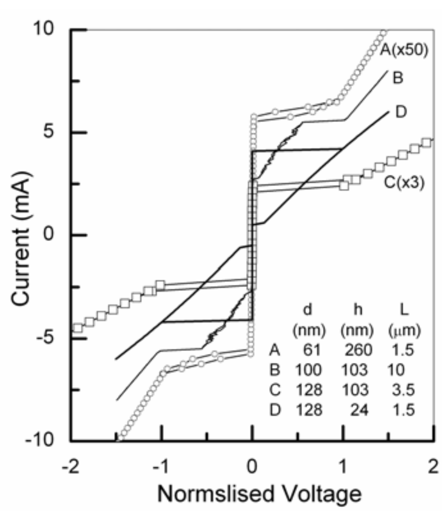

Fig. 3. *I-V* characteristics at 4.2 K of junctions with different ratio of film thickness to step height, *d/h*.

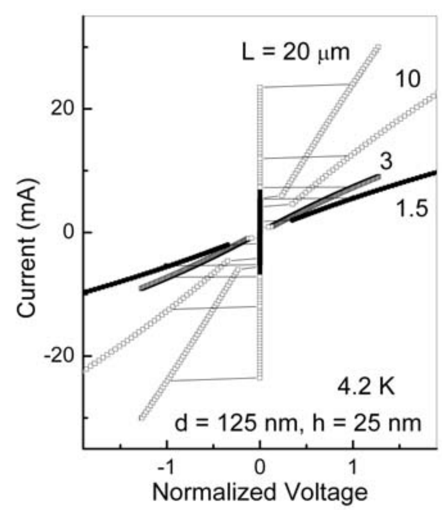

Fig. 4. Junctions with d/h = 5 showing highly hysteretic *I-V* characteristics.

To establish the temperature dependence of the Josephson critical current, $I_c(T)$, selected specimens were zero-field cooled to 1.5 K, then the *I-V* characteristics were recorded as a function of increasing temperature (1 K per hour). Figure 5 shows typical results for a junction with *d/h* < 1 and L = 1.5 μm. It is seen that I_c decreases in a series of irregular steps whereas one would expect a smooth decrease in accordance with the Ambegaoker and Baratoff model [3]. This behavior suggests that Josephson vortices are pinned at the edges of the junction and significant thermal activation is required to cause them to flow to the centre of the junction where they annihilate, thus producing an observable voltage. A similar behavior was observed in $YBa_2Cu_3O_7$ bi-crystal grain-boundary junctions [4] where individual Josephson vortices were activated by injecting low-power microwave signals (4.4 and 8.7 GHz) into the junction. (Note that this behavior of Josephson vortices is quite different to the avalanche-type or collective flow of Abrikosov vortices observed in Nb films [5].) Some junctions, formed on high substrate steps (*d/h* < 0.5), showed anomalous *I-V* behaviour such as two or more voltage steps in the *I-V* characteristics (Fig. 6). This behaviour is indicative of multiple weak link acting in parallel but with a common resistive shunt.

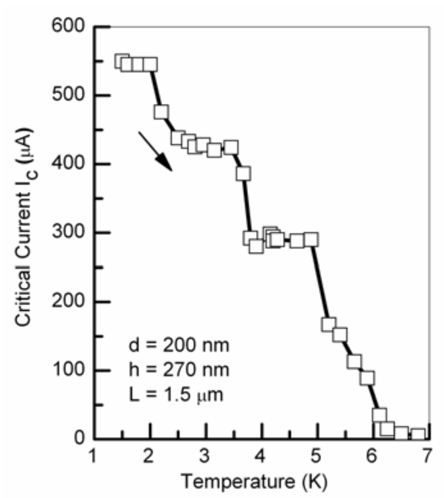

Fig. 5. Temperature dependence of the Josephson I_c..

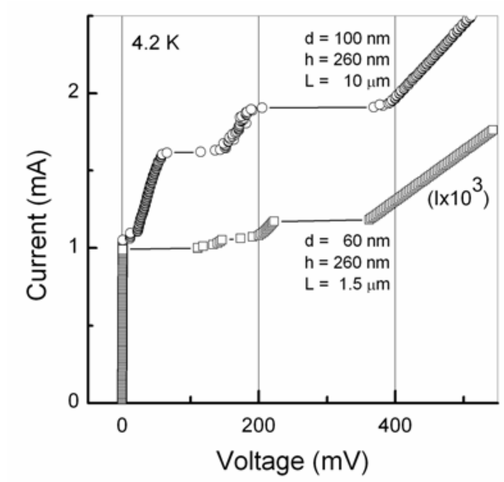

Fig. 6. Voltage steps in *I–V* of a junctions with *d/h* < 1

4. Conclusion

Josephson junctions, belonging to the "large" junction classification, were fabricated by patterning Nb films that were deposited over a step on SiO_2/Si substrates. By controlling the ratio of film thickness to step height, *d/h*, from about 0.25 to 5.3 it was demonstrated that the *I-V* characteristics could be varied from non-hysteretic to highly hysteretic. Other interesting observations include strong pinning of Josephson vortices at the edges of the junction, and voltage steps in the *I-V* characteristics due to multiple weak links acting in parallel.

References

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