

Interfacial Symmetry Controls Transparency and Thermal Stability in Nb/ZrO₂/Nb Josephson Junctions

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Primary CNF Tools Used: AJA sputter deposition system; GCA 6300 DSW 5X g-line wafer stepper; PT770 etcher; Oxford 81 etcher; SC4500 even-hour evaporator; DISCO dicing saw

Abstract:

Niobium-based Josephson junctions are attractive for superconducting electronics because niobium has a large superconducting energy gap and high critical temperature relative to aluminum. Their performance, however, is highly sensitive to the chemistry and structure of the ultrathin tunnel barrier. We investigate how interface termination controls transport and thermal stability in niobium/zirconium oxide/niobium junctions. Symmetric junctions containing zirconium at both barrier interfaces are compared with asymmetric junctions containing zirconium at only one interface. Measurements across multiple junction diameters, chips, and fabrication batches showed that symmetric barriers have lower resistance-area product and higher transparency. Sequential annealing further shows that oxidation completeness is an important determinant of thermal stability.

Summary of Research:

Josephson-junction properties depend exponentially on the thickness, composition, and uniformity of the tunnel barrier. Conventional aluminum oxide barriers provide excellent performance but limit the use of higher-critical-temperature superconductors and can undergo oxygen redistribution during processing. Zirconium oxide provides an alternative crystalline barrier for refractory niobium junctions [1]. Our objective is to determine whether the interface materials of the tunnel barrier can be used to control transparency without changing the nominal zirconium oxide deposition.

Fabrication:

The Josephson junctions are fabricated from Nb|Zr|O₂|Nb multilayers deposited by sputtering. Symmetric junctions are produced by adding a 1 nm zirconium

layer at the upper zirconium oxide interface, forming an Nb|Zr|O₂|Zr|Nb structure, while the remaining deposition and fabrication steps are unchanged from Ref. [1]. For this analysis, the nominal zirconium layer that is oxidized to create a barrier thickness is 3 nanometers. Circular area junctions with diameters ranging from 2 to 9 micrometers were patterned using the GCA 6300 DSW 5X g-line wafer stepper. The junction mesas were defined by chlorine-based inductively coupled plasma etching in the PT770 etcher. After mesa formation, a silicon dioxide spacer layer was deposited using the SC4500 evaporator.

The upper wiring layer was subsequently deposited by AJA 1. The completed wafers were diced using the DISCO dicing saw and electrical measurements were performed using a four-probe probestation.

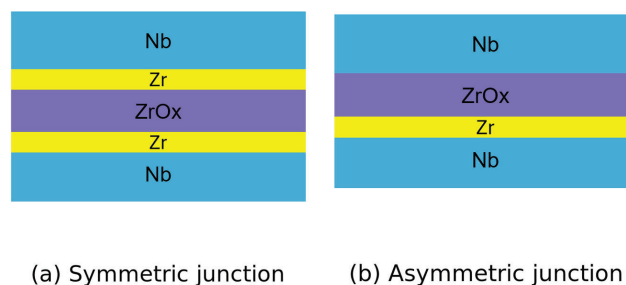


Figure 1: Symmetric and asymmetric niobium/zirconium oxide/nickel Josephson-junction architectures.

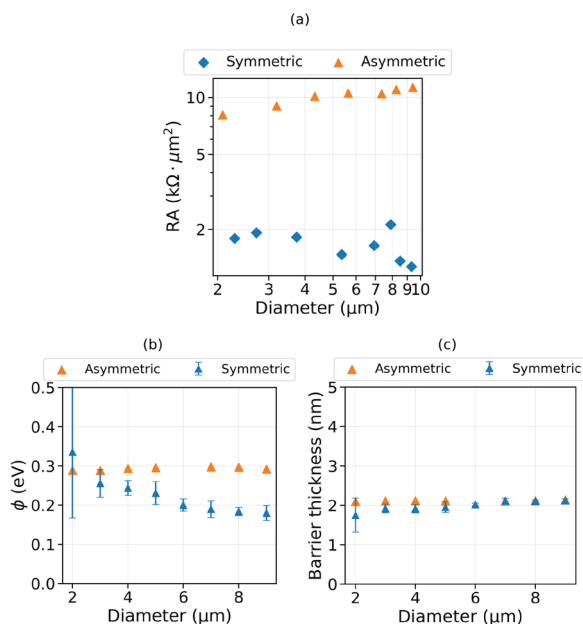


Figure 2: Comparison of room-temperature transport parameters for symmetric and asymmetric junctions: (a) resistance-area product, (b) effective barrier height, and (c) effective barrier thickness as functions of junction diameter.

Four-probe room-temperature measurements revealed a reproducible reduction in the resistance-area product of the symmetric junctions relative to the asymmetric junctions (Fig. 2a). Tunnelling parameters were extracted by fitting the low-bias current–voltage characteristics using the Simmons tunnelling model [2] and are shown in Figures 2b and 2c. The fitted effective barrier height was approximately 0.2 electronvolts for symmetric junctions and approximately 0.3 electronvolts for asymmetric junctions.

Low-temperature measurements below 20 mK confirmed that the room-temperature difference persists in the superconducting state. Symmetric junctions exhibit larger critical-current and lower normal-state resistance, together with stronger subgap conduction (Fig. 3). Reproducible subgap features in several symmetric devices are consistent with multiple Andreev reflection [3], although the limited number of resolved orders requires a conservative assignment.

Junction type	J_c (A/cm^2)	R_n (Ω)	$\Delta/\Delta_{\text{Nb}}$
Symmetric (3nm, 6 μm)	57.67	55	0.62
Symmetric (5nm, 6 μm)	35.4	72	0.67
Asymmetric (3nm, 6 μm)	1.45	862	0.96

Figure 3: Comparison of critical-current density (J_c), normal-state resistance (R_n), and normalized superconducting energy gap ($\Delta/\Delta_{\text{Nb}}$) for symmetric and asymmetric junction architectures.

Thermal stability is evaluated by comparing 3 nm symmetric and asymmetric junctions. The asymmetric architecture showed smaller changes in low-bias resistance and fitted barrier parameters over the measured range. These observations show that interface termination and oxidation completeness must be considered together when designing a transparent and thermally robust barrier.

Conclusions and Future Steps:

Symmetric zirconium termination provides a strong means of increasing transparency in Nb|Zr|O₂|Zr|Nb Josephson junctions. This behavior could result from a modified oxygen distribution across the barrier. Annealing measurements further show that junction stability depends on the amount of residual zirconium available for continued oxidation. Future work will quantify microwave loss and determine whether the improved direct-current transport can be translated into low-dissipation superconducting circuits.

References:

- [1] J. Choi et al., “Low barrier ZrOx-based Josephson junctions,” APL Materials 13, 111103 (2025).
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