Role of interface in quantum devices

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The quality factor of niobium thin film structures used in superconducting quantum circuits is constrained by a native surface oxide layer, resulting in two-level system loss. This leads to a higher loss in the microwave resonators as well as two-level losses (TLS) in the qubit. To address the impact of the surface oxide layer on the niobium thin film, several methods are proposed, including surface passivation through another metal capping layer[1], self-assembly of an organic monolayer[2], and surface treatment[3]. Various thin metal capping layers, such as Al, Ta, TiN, and others,[4,5] have been explored, demonstrating enhancements in the quality factor and qubit lifetime compared to uncapped niobium metal film. However, it's noted that these capping layers themselves tend to form a 3-5 nm thick oxide on the surface, introducing surface defects in oxidized metals. Nitrogen plasma treatment of niobium leads to nitrogen doping more than 5 nm into the surface, accompanied by a suppressed oxygen presence, resulting in a fourfold enhancement in performance compared to un-passivated samples. On the other hand, the self-assembly of an organic monolayer prevents oxidation on the surface; however, it may not be as suitable for prolonged exposure in ambient environments or subsequent qubit fabrication processes. In this context, ideal passivation methods or metals should possess the following characteristics: 1) Formation of Thin Self-Limited Oxide Layer: The passivating material should form a very thin <1 nm oxide layer with self-limited oxidation. This effectively shields the underlying superconductive layer from further oxidation. 2) Minimization of Oxide Compositions: The material should form a minimal number of oxide compositions to reduce the occurrence of surface defects associated with oxide vacancies. 3) Chemical Resistance: Capping layers should be chemically and environmentally resistive to ensure that multiple fabrication processes do not adversely affect the surface quality.
To enhance the performance and reliability of superconducting quantum circuits, it is important to find an appropriate passivation method or metal with specific characteristics such that both TLS as well as dielectric losses can be minimized. In this study, we have carefully selected a few hitherto unstudied metals as a capping layer which forms an oxide thickness of ~0.6 nm[6] without affecting the crystal structure and surface resistance of the superconducting niobium thin film. The X-ray diffraction analysis showed a shift in the [110] peaks, indicating uniform compression of the crystal lattice and a reduction in the crystallite size from 20 nm to 18 nm. The atomic force microscopic results showed that the ruthenium capping reduces the exposed grain boundary by approximately 20% and the RMS roughness value changes from 1.05 nm to 0.85 nm with the capping layer. We will present a detailed report on the effect of the capping layer on the superconductivity and the internal quality factor of the niobium resonator.

References

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