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Identifying Possible Two-Level-System Sources in Superconducting Qubit with Advanced Electron Microscopy

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Superconducting materials are promising candidates for solid-state quantum computers. The fabrication of superconducting qubits takes advantage of well-developed semiconductor fabrication technology, such as thin film deposition and lithography. However, the complex processing steps introduce defects at the interfaces and surfaces of the qubits that may be a source of two-level system (TLS) detrimental to the device's coherence time [1]. Thus, identifying and understanding structural features down to the atomic scale that act as possible TLS in both the Josephson junction (JJ) and resonators is key to superconducting qubit performance improvement. This talk will present our recent studies on the microstructure in 2D-transmon and 3D-Nb cavities. A combination of advanced microscopy techniques, including in-situ heating, high resolution (S)TEM imaging, and spectroscopy (EDS and EELS), is used to identify possible TLS sources.

Detailed atomic structure characterization of the $Al/Al_2O_3/Al$ interface in a superconducting circuit test device fabricated by Rigetti Computing is shown in Figure 1. The low magnification bright-field cross-section TEM image of the JJ shows a well-defined trapezoid shape (Fig. 1a). The evaporated Al layer has a polycrystalline structure, sometimes with {111} stacking faults inside. The $Al/Al_2O_3/Al$ interface is wavy and the Al_2O_3 layer between the Al metal is amorphous (Fig. 1c). A ~4nm amorphous layer was observed between the lower-Al/Si interface (Fig. 1d). EDS elemental mapping confirms that the amorphous layer is mainly aluminum oxide (Fig. 1b). The observed nonuniformity in the Al_2O_3 between the Al metal and the oxide layer between the lower-Al and Si substrate are both device's coherence limiting sources.

Niobium is another metal commonly used for superconducting quantum systems such as RF cavity, readout resonators, and interconnects. Microwave dissipation at the Nb/air interfaces is a major coherence limiting factor [2]. Research on structure and thermal stabilities of Nb-O's on Nb surface will also be discussed to guide future device design and optimization [3].

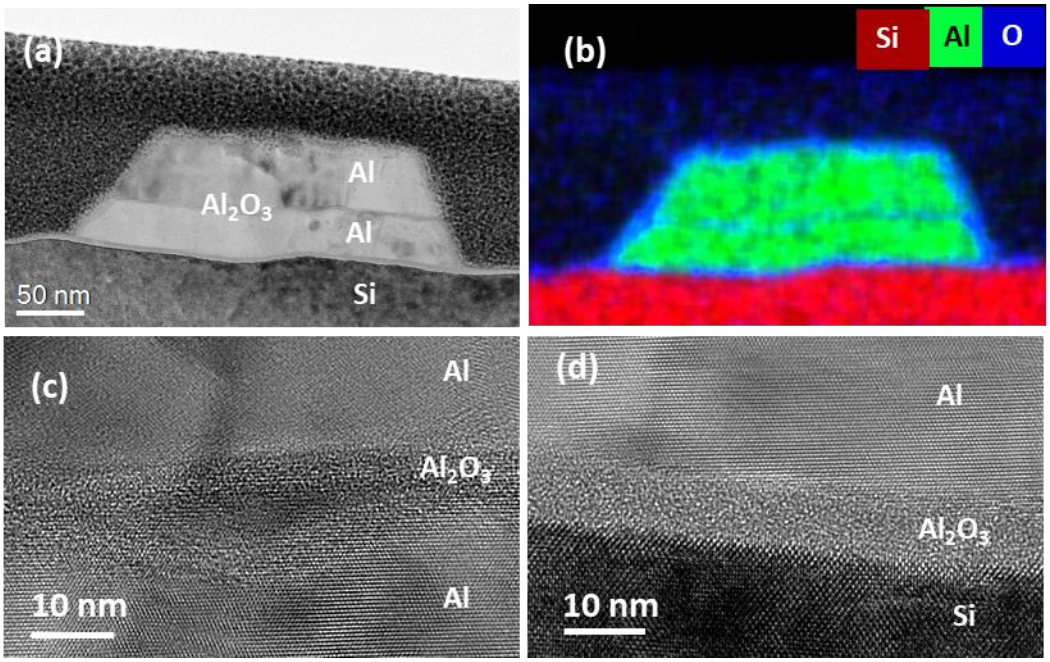

Figure 1. (a) Bright -field TEM image and (b) corresponding Energy Dispersive X-ray Spectroscopy (EDS) elemental mapping of a JJ. (c) High-resolution TEM image showing wavy amorphous Al_2O_3 layer (~2-3nm) inside the JJ. (d) High-resolution TEM image showing a ~4nm amorphous Al_2O_3 layer between the JJ and Si substrate.

References:

[1] WD Oliver and PB Welander, MRS Bull. **38**(10) (2013), p. 816. doi: 10.1557/mrs.2013.229
[2] A Romanenko and D Schuster, Phys. Rev. Lett. **119**(26), (2017), p. 1. doi:10.1103/PhysRevLett.119.264801
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