Fabrication of Nanoscale Josephson Junctions for Quantum Coherent Superconducting Circuits

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Primary CNF Tools Used: ASML stepper, JEOL 9500, Plasma-Therm 770

Abstract:

We fabricate nanoscale superconductor tunnel junctions and other structures for experiments involving quantum coherent circuits. Such circuits have shown great promise in recent years for explorations of quantum mechanics at the scale of circuits on a chip and for forming qubits, the foundational elements of a quantum computer. The quantum state of these superconducting qubits can be manipulated with microwave radiation at low temperatures. In addition, we are developing alternative techniques for probing the state of these qubits and controlling their quantum state using superconducting digital circuitry, as well as superconducting metamaterial structures with novel microwave mode spectra for coupling to superconducting qubits.

Summary of Research:

The unique properties of nanoscale Josephson junctions enable a wide range of novel superconducting circuits for investigations in many diverse areas. In recent years, circuits composed of such junctions have emerged as promising candidates for the element of a quantum computer, due to the low intrinsic dissipation from the superconducting electrodes and the possibility of scaling to many such qubits on a chip [1]. The quantum coherent properties of the circuits are measured at temperatures below 50 mK with manipulation of the qubit state through microwave excitation.

We are currently working on a variety of experiments involving these nanoscale Josephson junctions and other superconducting structures that allow us to probe novel quantum effects in our microwave circuits. We are fabricating superconducting circuits for forming low-temperature detectors of single microwave photons and for implementing a new scheme for the efficient readout of the quantum state of superconducting qubits [2,3]. We are also working with collaborators at the University of Wisconsin, Madison to develop hybrid quantum/classical superconducting chips that allow us to perform coherent quantum control of a superconducting qubit based on digital pulses from a Single Flux Quantum (SFQ) circuit [4,5].

In another effort, we are using particular combinations of superconducting lumped-circuit elements to engineer metamaterial transmission lines that exhibit novel mode structures characteristic of left-handed materials. We are fabricating such metamaterial transmission lines from Al and Nb films on Si and characterizing these at low temperatures [6]. We are working on experiments to couple these left-handed lines to superconducting qubits for experiments involving the exchange of microwave photons [7].

We pattern these circuits at the CNF with nanoscale structures defined with electron-beam lithography on the JEOL 9500 integrated with photolithographically defined large-scale features. The junctions are fabricated using the standard double-angle shadow evaporation technique, in which a resist bilayer of copolymer and PMMA is used to produce a narrow PMMA airbridge suspended above the substrate. Evaporation of aluminum (Al) from two different angles with an oxidation step in between forms a small Al-AlO_x-Al tunnel junction from the deposition shadow of the airbridge. We have developed a process for defining these junctions with electron-beam lithography and we perform the aluminum evaporations in a dedicated chamber at Syracuse.

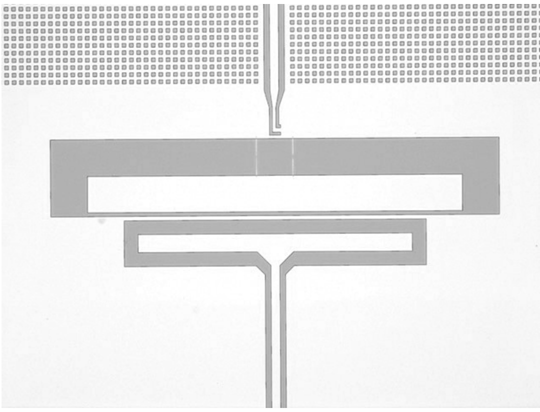

Figure 1: Optical micrograph of superconducting qubit for digital control experiments.

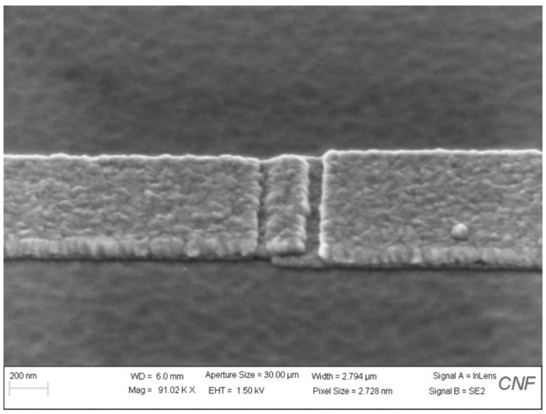

Figure 2: Scanning electron micrograph of Al-AlO_x-Al Josephson junction for superconducting qubit.

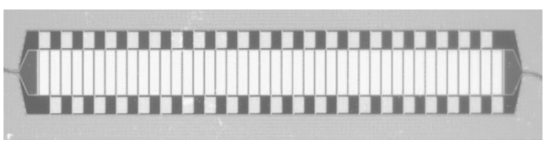

Figure 3: Optical micrograph of superconducting metamaterial transmission line resonator fabricated from Nb thin film on Si.

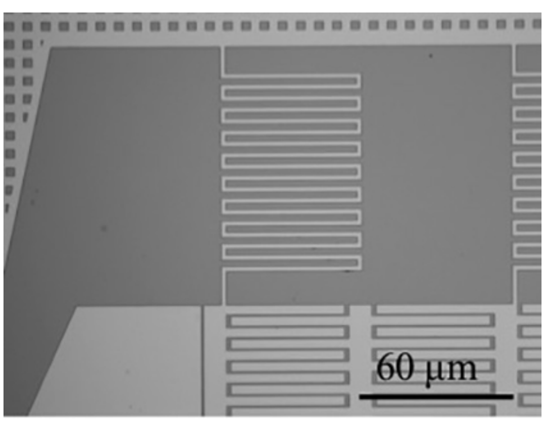

Figure 4: Optical micrograph of meander-line inductor and portion of interdigitated capacitor on metamaterial transmission line resonator fabricated from Nb thin film on Si.

We pattern large-scale features using the ASML stepper, with electron-beam evaporation of Al, sputter-deposition of Nb, and PECVD deposition of SiO_2.

Measurements of these circuits are performed in cryogenic systems at Syracuse University, including dilution refrigerators for achieving temperatures below 30 mK.

References:

[1] Clarke, J. and Wilhelm, F.K.; "Superconducting quantum bits"; Nature, 453, 1031 (2008).

[2] Govia, L.C.G., Pritchett, Emily J., Xu, Canran, Plourde, B. L. T., Vavilov, Maxim G., Wilhelm, Frank K., McDermott, R.; "High-fidelity qubit measurement with a microwave-photon counter"; Physical Review A 90, 062307 (2014).

[3] Opremcak, A, Pechenezhskiy, I., Howington, C., Christensen, B.G., Beck, M.A., Leonard Jr, E., Suttle, J., Wilen, C., Nesterov, K.N., Ribeill, G.J., Thorbeck, T., Schlenker, F., Vavilov, M.G., Plourde, B.L.T., McDermott, R.; "Measurement of a Superconducting Qubit with a Microwave Photon Counter"; Science 361, 1239 (2018).

[4] McDermott, R., Vavilov, M.; "Accurate Qubit Control with Single Flux Quantum Pulses"; Physical Review Applied 2, 014007 (2014).

[5] Leonard, E., Beck, M., Nelson, JJ, Christensen, B., Thorbeck, T., Howington, C., Opremcak, A.,Pechenezhskiy, I., Dodge, K., Dupuis, N., Ku, J., Schlenker, F., Suttle, J. Wilen, C., Zhu, S., Vavilov, M., Plourde, B, McDermott, R.. "Digital coherent control of a superconducting qubit"; Physical Review Applied 11, 014009 (2019).

[6] Wang, H., Zhuravel, A., Indrajeet, S., Taketani, B., Hutchings, M., Hao, Y., Rouxinol, F., Wilhelm, F., LaHaye, M.D., Ustinov, A., Plourde, B.; "Mode Structure in Superconducting Metamaterial Transmission Line Resonators"; Physical Review Applied 11, 054062 (2019).

[7] Indrajeet, S., Wang, H., Hutchings, M., LaHaye, M., Taketani, Bruno, Wilhelm, F., Plourde, B.; "Qubit Dynamics in a Multi-mode Environment with a Superconducting Metamaterial Resonator"; Bull. Am. Phys. Soc. 2019, http://meetings.aps.org/Meeting/MAR19/Session/P26.4.