Fabrication of Manhattan-style Josephson Junctions

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Primary CNF Tools Used: Angstrom-Q, JEOL 6300 E-beam Lithography System, Zeiss Ultra SEM, GCA AS200 i-line Stepper, Heidelberg DWL2000, AJA Sputter 1

Abstract:

Qubits based on superconducting quantum circuits are one of the most promising platforms for quantum computing [1]. The critical component of these superconducting qubits is the Josephson Junction. We use a Josephson Junction which is a superconductor-insulator-superconductor interface that relies on the tunneling of Cooper pairs through the thin insulating barrier [1]. Once below the critical temperature of the superconducting material, the Josephson Junction can now conduct a current without any applied voltage, exhibiting the Josephson Effect. This nonlinear current creates the key anharmonicity needed to create a qubit [2]. In this research, we fabricate Manhattan-style Josephson Junctions in the Angstrom-Q and characterize the oxidation process.

Summary of Research:

The main two types of Josephson Junctions are Dolan and Manhattan-style. Dolan-style junctions rely on a shadow evaporation method where Electron-Beam lithography on the JEOL 6300 is performed onto a PMMA/MMA resist stack. During this lithography, a bridge is defined, and two evaporations are performed at different angles with an oxidation in between. This overlap between the two evaporation defines our junction area, a key factor in determining the properties of the Josephson Junction. The main downside to this style is that the bridge used is fragile and can frequently collapse, therefore halting the fabrication process. Additionally, the bridge can vary between lithography runs due to resist thickness. This inconsistency in the bridge leads to an inconsistency in junction area, which changes the parameters of the qubit. In an effort to increase reproducibility in our qubit fabrication, we began to fabricate Manhattan-style Josephson Junctions using the new Angstrom-Quantum evaporator, designed specifically for this purpose. Manhattan-style junctions (Figure 1) are a bridge-less technique that use a similar PMMA/MMA resist stack, but instead rely on an evaporation into two different trenches [3]. As opposed to Dolan-style junctions, in this case, the area of our junctions is only determined by the lithography. This, coupled with the fact that there is no bridge involved, increases our reproducibility between fabrication runs.

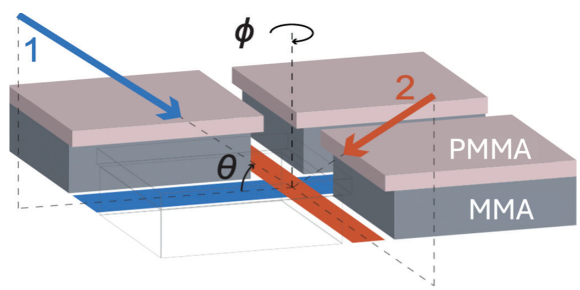

Figure 1:

The main reason we care about the area of our junction is that it affects critical current, I_c, the maximum current the junction can hold before returning to a non-zero resistance state. The critical current is given by the Ambegaokar–Baratoff relation (Figure 2a), in which the superconducting gap of Aluminum is known and the normal state resistance, R_n, can be obtained by a room temperature two-probe resistance measurement. From the critical current, we can then determine the Josephson Energy, E_J (Figure 2b). E_J is a key term in the Hamiltonian of our circuit and determines the circuit dynamics, primarily our qubit frequency, a critical

a)

$$I_c = \frac{\pi\Delta}{2eR_n}$$

Δ = Superconducting gap
R_n = Normal state resistance

b)

$$E_J = \frac{\Phi_0}{2\pi} I_c \propto I_c$$

Magnetic flux quantum: $\Phi_0 = \frac{h}{2e}$ =constant

Figure 2:

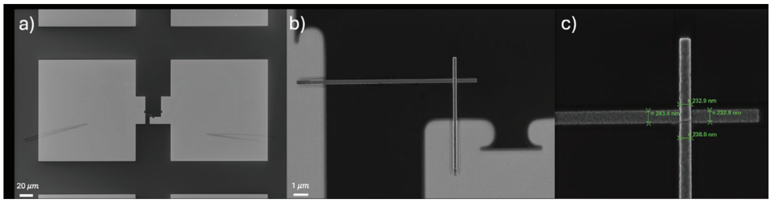

Figure 3:

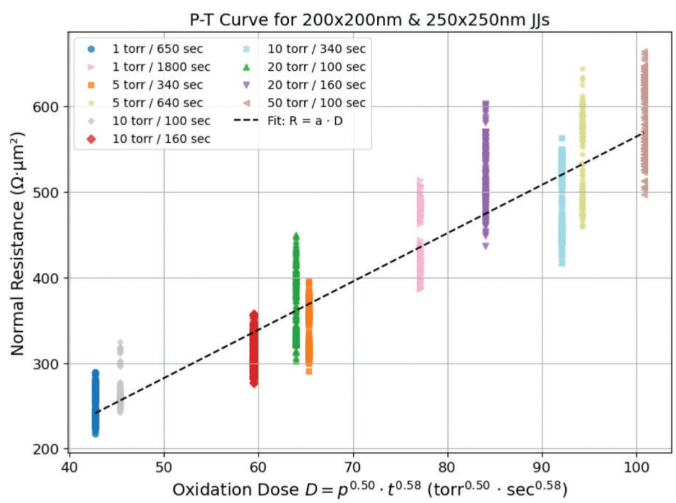

Figure 4:

number in benchmarking qubit performance [1].

Our fabrication process began by doing a standard HF clean of our 100mm Si wafer in order to remove the native oxide layer. Then we spun on a LOR 3A and S1813 photoresist stack before patterning bonds pads using the i-line stepper on a mask written in the Heidelberg DWL2000. After developing on a Hamatech automatic developer, we deposited Ti-seeded Pt using the AJA 1 Sputter tool. The 5nm of Ti acts as an adhesion layer for the 80nm of Pt which does not naturally oxidize, making it compatible with our probe station. After doing lift-off in Remover PG overnight, we spun on a PMMA/MMA e-beam resist stack. This allowed us to pattern our Josephson Junctions in the JEOL 6300 Electron-Beam Lithography system. Onto our wafer, we patterned 100 200x200nm and 100 250x250nm junctions. Before depositing, we cleaved our wafer into chips and developed them in IPA:DI (3:1) for 2 minutes. Once loaded into the Angstrom-Q, we do an in-situ argon milling to remove any unwanted oxide that could prevent poor contact. We then deposit 20nm of Al for our bottom electrode at a rate of 2 A/s and a chamber pressure <5e-8. Our oxidation step varies with pressures from 1 to 50 torr and 1 to 30 minutes. Our top electrode is 70nm of Al and is deposited at a similar chamber pressure as the bottom electrode. Before taking our sample out, we do a post-oxidation step instead of letting the sample oxidize arbitrarily in atmosphere. Then we do lift-off in heated DMSO at 80-90 C overnight. Finally, we measure room temperature resistance using a Keithley SourceMeter and a probe station with Tungsten tips. After probing resistance, SEM images were taken on the Zeiss Ultra SEM in order to calculate the area of our junctions and evaluate the success of lift-off (Figure 3).

We iterated on our fabrication many times in order to produce 20 data points across JJs with a 20nm bottom electrode. With this data, we plotted the normal resistance, resistance of our junctions times the area, versus the oxidation dose, a combination of the pressure and time of the oxidation. The value of the exponents assigned to pressure and time and the linear fit to our data was optimized (Figure 4). We observe our data aligns with our linear fit and with previous work [4]. We also compute the variability of junction resistance across a die and observe a variance <5%, which is acceptable for qubit devices.

Conclusions and Future Steps:

We successfully demonstrated the fabrication of Manhattan-style Josephson Junctions in the Angstrom-Q. We also characterized and optimized the fabrication process by constructing a pressure-time curve. This curve will allow us to determine the oxidation dose necessary to obtain a junction of a desired resistance with minimal trial and error.

The next step will be move away from Dolan-style junctions and incorporate Manhattan-style Josephson Junctions into our qubit fabrication process. As we do multiple fabrication runs, we will see whether the junction properties are reproducible and whether Manhattan junctions have any advantage over Dolan junctions. Another possibility will be to do an aging study of Josephson Junctions. This would involve measuring the resistance of junctions over at least a month and observing how the resistance changes over time.

References:

[1] Rasmussen et al., "Superconducting Circuit Companion---an Introduction with Worked Examples."

[2] Krantz et al., "A Quantum Engineer's Guide to Superconducting Qubits."

[3] Kreikebaum et al., "Improving Wafer-Scale Josephson Junction Resistance Variation in Superconducting Quantum Coherent Circuits."

[4] Zeng et al., "Direct Observation of the Thickness Distribution of Ultra Thin AlOx Barriers in Al/AlOx/Al Josephson Junctions."