Manufacturing low dissipation superconducting quantum processors

Ani Nersisyan*, Stefano Poletto*, Nasser Alidoust*, Riccardo Manenti*, Russ Renzas, Cat-Vu Bui, Kim Vu, Tyler Whyland, Yuvraj Mohan, Eyob A. Sete, Sam Stanwyck, Andrew Bestwick, Matthew Reagor†
Rigetti Computing
Berkeley, CA, USA
†matt@rigetti.com

Abstract—Enabling applications for solid state quantum technology will require systematically reducing noise, particularly dissipation, in these systems. Yet, when multiple decay channels are present in a system with similar weight, resolution to distinguish relatively small changes is necessary to infer improvements to noise levels. For superconducting qubits, uncontrolled variation of nominal performance makes obtaining such resolution challenging. Here, we approach this problem by investigating specific combinations of previously reported fabrication techniques on the quality of 242 thin film superconducting resonators and qubits. Our results quantify the influence of elementary processes on dissipation at key interfaces. We report that an end-to-end optimization of the manufacturing process that integrates multiple small improvements together can produce an average $T_1 = 76 \pm 13 \mu s$ across 24 qubits with the best qubits having $T_1 \geq 110 \mu s$. Moreover, our analysis places bounds on energy decay rates for three fabrication-related loss channels present in state-of-the-art superconducting qubits. Understanding dissipation through such systematic analysis may pave the way for lower noise solid state quantum computers.

The total energy decay rate of a resonant mode such as a qubit can be understood as the sum of decay rates through all coupled loss channels. Equivalently, if the fraction of energy stored in each lossy element is known (the participation ratios $p_i$), then the qubit decay rate can be related to an intrinsic quality (or loss tangents $\tan \delta_i$) of these elements [1]–[4], as

$$\gamma = \sum_i \gamma_i + \Gamma = \omega \sum_i p_i \tan \delta_i + \Gamma,$$  

where $\omega/2\pi$ is the qubit mode frequency and $\Gamma$ accounts for other types of loss mechanisms, e.g., radiative decay. Each loss channel $\gamma_i$ bounds the relaxation times ($T_1 \leq 1/\gamma_i$). Improvements to $T_1$ may come from decreasing participation ratios or decreasing loss tangents, resulting in negative $\delta_{\gamma_i}$. The goal of an end-to-end fabrication process optimization is to introduce multiple compatible improvements to loss channels, $\Delta \gamma = \sum_i \delta \gamma_i$.

In this study, we quantify interface specific losses by comparing groups of qubits that were made with identical fabrication processes, except for the steps which define a specific interface (Fig. 1a-c). We first consider the influence of the metal-substrate (MS) interface (Fig. 1a). We compare the control substrate surface treatment, consisting of a standard clean [5] and subsequent immersion in buffered oxide etch (BOE), against two additional treatments: Ar$^+$ ion milling [6]–[9] and exposing to hexamethyldisilazane (HMDS) [10]. After substrate treatment, wafers are coated with Nb through physical vapor deposition (PVD), which completes the MS interface. Next, we focus on the metal-air (MA) and substrate-air (SA) interfaces defined in the subtractive patterning step (see Fig. 1b). Large device features ($\geq 10 \mu m$) are defined with optical lithography followed by reactive-ion etching (RIE) with SF$_6$ to remove the exposed metal and achieve over-etch into silicon. After stripping the resist, the wafers are exposed to oxygen plasma ashing and again immersed in BOE solution.

Finally, we investigate the metal-metal (MM) interface defined in connecting the Al Josephson junctions (JJs) to the rest of the Nb circuitry (Fig. 1c). The JJ definition process consists of patterning a bilayer resist with electron beam lithography, followed by double-angle evaporation of two Al layers with a controlled oxidation in between. We study two different methods of achieving good contact transparency between Al and Nb: designing large metal overlay [11], [12] or depositing an additional Al layer (the “bandage” layer) across the two metals [8]. A schematic of these layers is shown in Fig. 1d.

I. RESULTS

Preparation of the silicon surface is conducted using one of three methods: no further treatment (control), ion milling, or HMDS passivation. These treatments determine the interface below the Nb device structures, such as the CPWR and qubit capacitors. Measurements of single photon internal quality factors for resonators fabricated with each of these three methods are shown in Fig. 2a. We find that HMDS passivation increases the internal quality factor of Nb resonators to $\overline{Q}_i = (1.06 \pm 0.25) \times 10^6$ (devices Rd6-Rd8), consistent with observations from NbTiN on silicon resonators [10]. These high quality factors are attributed to the hydrosilylation reaction that inhibits the formation of a native silicon-oxide layer at what becomes the MS interface [10], [13], reducing the dielectric loss at this interface. To illustrate the effect on qubits, we compare the relaxation times of a representative subset of qubits made with the control process versus HMDS passivation (Fig. 2b). We find $T_1^C = 40 \pm 9 \mu s$ for eight qubits from the control group (Qd1) and $T_1^H = 70 \pm 22 \mu s$ for twenty four qubits from the HMDS group (Qd2-Qd4), where $T_1$ is the arithmetic mean of the individual qubit $T_1$ with the standard deviation over qubits. Therefore, similar to the effect...
on resonator quality factors, HMDS passivation improves the relaxation times of qubits.

We compare the relaxation times of qubits with tapered and anisotropic etch profiles (Qd2-Qd4 and Qd5-Qd7, respectively) which are otherwise identically fabricated. As shown in Fig. 3b, the qubits with tapered profile outperform those with anisotropic profile having $\bar{T}_1 = 70 \pm 22 \mu$s as indicated by the horizontal lines. Following the analysis in the previous section, we estimate a reduction of $\delta\tau_{\text{MS}} = -(19 \pm 13)$ kHz, where XA indicates combined MA and SA. Note that while the standard error in this estimate is large, we also find that 92% of the qubits with the tapered profile have $T_1$ greater than or equal to that of the best qubits from the anisotropic group. We attribute this difference to the roughened Nb edges produced by the more aggressive RIE for the anisotropic etch, which are more likely to host two-level system (TLS) defects [14]. Furthermore, we observe a weaker internal quality factor power dependence for trenched than for tapered resonators, suggesting a different leading-order loss mechanism for the two.

The average relaxation times for devices fabricated with the overlay technique and with the bandage layer are presented in Fig. 4c-d, respectively. The samples with the overlay are divided into three categories based on the size of the Al/Nb overlay: small $(5500 \mu$m$^2$), medium $(8000 \mu$m$^2$), and large $(11000 \mu$m$^2$) (geometries shown in Fig. 4a). We find that the relaxation times of devices are affected by the size of the overlay. Devices with small overlay underperform the other two geometries showing $\bar{T}_1 = 45 \pm 13 \mu$s, while qubits with medium and large overlays have average $\bar{T}_1 = 70 \pm 22 \mu$s and $\bar{T} = 65 \pm 20 \mu$s, respectively. We note that one of the eight qubit devices with medium overlay remarkably shows an average of $\bar{T}_1 = 86 \pm 33 \mu$s, and two of the qubits on this device each have $T_1 = 114 \pm 19 \mu$s. The samples with the bandage layer are grouped according to the ion milling voltage (200 V or 400 V). For these devices, the data indicates that ion milling Nb can negatively affect qubit relaxation times (Fig. 4d), similar to results obtained for resonator devices. Devices ion milled at 200 V have $T_1 = 76 \pm 13 \mu$s, while those ion milled at 400 V have $T_1 = 50 \pm 15 \mu$s. We have obtained similar results for qubits that were not treated with HMDS (see Table I). These observations suggest that minimizing ion milling on metal can be advantageous for achieving longer qubit relaxation times.

II. CONCLUSION

We have shown that carefully integrating multiple improvements together represents a promising path forward for quantum devices. Our work considered the quality of over 200 individual CPWRs and qubits. These circuits were made with 14 unique combinations of fabrication techniques. By finding the manufacturing parameters that minimize loss at key interfaces, we estimate an improvement to average qubit decay rate $\Delta \tau = (\delta\tau_{\text{MS}} + \delta\tau_{\text{XA}} + \delta\tau_{\text{MM}})$, assuming the dissipation channel eliminated within each module is unique. For the devices in this study, our analysis finds $\Delta \tau = -(30 \pm 16)$ kHz. We infer from this value that similar superconducting qubits fabricated with the steps shown in Fig. 1 can be brought from average relaxation times of $\bar{T}_1 \leq 1/\Delta \tau \sim 30 \mu$s to achieve reproducible relaxation times of $\bar{T}_1 > 70 \mu$s by addressing losses at interfaces. Applying this framework to modules beyond this study could result in lower noise solid state quantum computers in the future. We thank the Rigetti Fab-1 team, as well as the members of the Rigetti Software, Hardware, Quantum, and Technical Operations teams who enabled this work. Work at the Molecular Foundry was supported by the Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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The fabrication of superconducting qubits presented here consists of: 

- **a**, surface treatment of the Si substrate wafer and physical vapor deposition (PVD) of the Nb film that affect the quality of the metal-substrate interface; 
- **b**, subtractive patterning, consisting of optical lithography using positive resist (teal) and metal reactive-ion etching (RIE), followed by a cleaning step, that affect the quality of the device-air interfaces; 
- **c**, electron beam lithography of the Josephson junctions (JJs) using MMA and PMMA resists (purple) followed by double-angle evaporation of Al (blue) and liftoff that impact the metal-metal interface. Additional e-beam lithography, Al evaporation and liftoff steps are needed for bandage qubits. 
- **d**, Schematics of the device cross-section showing the interfaces that affect the performance of a superconducting device: metal-substrate (MS), substrate-air (SA), metal-air (MA), and metal-metal (MM).

**Fig. 1. Fabrication flow for superconducting quantum devices.**

**Fig. 2.** *Performance enhancement from metal-substrate interface treatment.* **a**, Internal quality factors ($Q_i$) at single photon powers of resonator devices prepared using three different surface preparation methods of the silicon substrate: ion milling (orange dots), control (teal triangles), and passivation with hexamethyldisilazane (grey squares). Crosses correspond to the measured $Q_i$, whereas the error bars indicate standard deviations for each device. **b**, Relaxation times ($T_1$) of qubit devices prepared using similar surface treatments: control (teal triangles) and HMDS passivation (grey squares). Crosses indicate the average of $T_1$ data collected for each qubit on a device, whereas the error bars indicate the standard deviations for each device.

**Fig. 3.** *Performance effects from subtractive patterning etch microstructure.* **a**, Quality factor measurements of CPWR devices with the anisotropic (d) profile. Results related to the tapered profile are represented by the mean of RD6, RD7 and RD8 (see Fig. 2a) and the standard deviation of these measurements (solid and dashed lines, respectively). The anisotropic profile underperforms this mean. **b**, Results for $T_1$ of the corresponding qubit devices are consistent with the CPWR results. The tapered profile is represented by the mean of Qd2, Qd3, and Qd4 (see Fig. 2b) and outperforms the anisotropic profile by a similar factor. **c-e**, Scanning electron microscope images of the cross section of the three patterning etch profiles used for this study. The dark regions at the bottom correspond to the silicon substrate, whereas the brighter regions on top show the Nb metal. The tapered profile (e) is our baseline profile, generated by a stop-on-silicon (timed) SF$_6$ etch process. The other two profiles are generated by an anisotropic (d) and isotropic (e) over-etch into silicon.
TABLE I
DEVICE FABRICATION PARAMETERS GROUPED BY INTERFACE TYPE. AS EXPLAINED IN THE MAIN TEXT, \(T_1\) (\(Q_i\)) IS THE MEAN VALUE OF THE RELAXATION TIME (INTERNAL QUALITY FACTOR) AVERAGED ACROSS A DEVICE WITH EIGHT QUBITS (RESONATORS). QUBIT (RESONATOR) FREQUENCY IS IN THE RANGE 3.8 - 4.2 GHZ (5.2 - 5.6 GHZ). LEGEND: M (METAL), S (SUBSTRATE), X (EITHER M OR S), A (AIR), I (ION MILL), C (CONTROL), H (HMDS), TA (TAPERED), IS (ISOTROPIC), AN (ANISOTROPIC), SO, MO, LO (SMALL, MEDIUM, LARGE OVERLAY).

| Device | M-S | X-A | M-M | \(T_1\) \([\times 10^6]\) | \(T_1\) \[\mu s\] |
|--------|-----|-----|-----|-----------------|-----------|
| Rd1\(^i\) | I | Ta | - | 0.15 ± 0.03 | - |
| Rd2 | I | Ta | - | 0.24 ± 0.05 | - |
| Rd9 | C | Is | - | 0.66 ± 0.15 | - |
| Rd10 | C | Is | - | 0.81 ± 0.21 | - |
| Rd3 | C | Ta | - | 0.44 ± 0.23 | - |
| Rd4 | C | Ta | - | 0.86 ± 0.25 | - |
| Rd5 | C | Ta | - | 0.77 ± 0.31 | - |
| Qd1 | C | Ta | MO | 40 ± 10 | - |
| Qd16 | C | Ta | 400 V | - | 33 ± 10 |
| Qd17 | C | Ta | 400 V | - | 37 ± 13 |
| Qd18\(^i\) | C | Ta | 400 V | - | 39 ± 4 |
| Qd19 | C | Ta | 200 V | - | 45 ± 15 |
| Qd20 | C | Ta | 200 V | - | 52 ± 10 |
| Rd6 | H | Ta | - | 0.84 ± 0.18 | - |
| Rd7 | H | Ta | - | 1.18 ± 0.26 | - |
| Rd8 | H | Ta | - | 1.17 ± 0.18 | - |
| Qd2 | H | Ta | MO | 86 ± 30 | - |
| Qd3 | H | Ta | MO | 58 ± 10 | - |
| Qd4 | H | Ta | MO | 68 ± 14 | - |
| Qd8 | H | Ta | SO | 39 ± 9 | - |
| Qd9 | H | Ta | SO | 48 ± 14 | - |
| Qd10 | H | Ta | LO | 64 ± 23 | - |
| Qd11 | H | Ta | 400 V | - | 52 ± 16 |
| Qd12 | H | Ta | 200 V | - | 75 ± 16 |
| Qd13 | H | Ta | 200 V | - | 71 ± 9 |
| Qd14 | H | Ta | 200 V | - | 76 ± 17 |
| Qd15 | H | Ta | 200 V | - | 80 ± 14 |
| Rd11\(^i\) | H | An | - | 0.56 ± 0.14 | - |
| Rd12 | H | An | - | 0.29 ± 0.07 | - |
| Rd13 | H | An | - | 0.37 ± 0.08 | - |
| Qd5\(^2\) | H | An | MO | 38 ± 5 | - |
| Qd6 | H | An | MO | 36 ± 9 | - |
| Qd7 | H | An | MO | 19 ± 7 | - |

Fig. 4. Relaxation time enhancement from optimized Josephson junction contacts. a, Schematics of the qubit and the three different Al overlay configurations: small (orange), medium (teal), and large (dark grey). b, Scanning electron microscope image of a device fabricated with the additional Al bandage layer, as highlighted in the inset. Bandage layers are applied at the locations indicated by the orange boxes. c, Relaxation times of qubit devices prepared without any bandage layer between the Nb device and the Al JJ leads. d, Relaxation times of qubit devices prepared with an additional bandage layer. Two distinct voltages are used to ion mill the metal oxide prior to the deposition of the bandage layer: 200 V and 400 V.