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Quantum Computing: Spring 2024

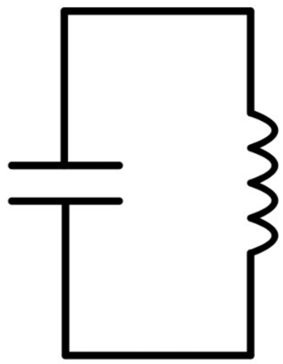
Quantum Final Paper

1 Introduction

Quantum computers offer a new paradigm in computing based on quantum mechanical principles such superposition as entanglement. Such a computer could be useful in simulating quantum physics and computing algorithms intractable on classical computers. The fundamental building block for a quantum computer is the "quantum bit"known as a qubit. Around the world, the development of a scalable, physical qubit is ongoing. Many hardware platforms exist that meet the DiVincenzo criteria [3], to construct a physical quantum computer, such as trapped ions, neutral atoms, or superconducting qubits. Superconducting qubits are an especially promising hardware platform for quantum computing owing to their fast gate speeds, efficient control and readout, and scalability [4]. This report will outline the development of the transmon, one of the most widely researched superconducting qubits in academia and industry. Realizing the potential of the transmon qubit depends on overcoming decoherence, the loss of quantum information by the qubit due to interactions with its surrounding environment. This report presents how materials-based advancements can be applied to the transmon towards achieving longer coherence times. This report is contextualized and based on interviews regarding the research of Matthew P. Bland, a PhD candidate in Quantum Engineering at Princeton University working to improve the coherence times of superconducting qubits through materials-based advancements and device architecture. [1]

2 Superconducting Circuits

Certain metals, such as aluminum (Al), niobium (Nb), or tantalum (Ta), superconduct when cooled below their respective critical temperatures. Superconductivity is a phenomenon that occurs when a pair of electrons form a Cooper pair, a charge carrier able to move through the metal without resistance. Superconducting circuits can be fabricated by patterning thin films of superconducting metals deposited on insulative substrates. Like normal circuits, superconducting circuits are comprised of various circuit elements, such as capacitors and inductors. The most basic circuit that can be constructed is a LC-oscillator, consisting of an inductor in parallel with a capacitor.



Figur 1: LC-oscillator circuit diagram

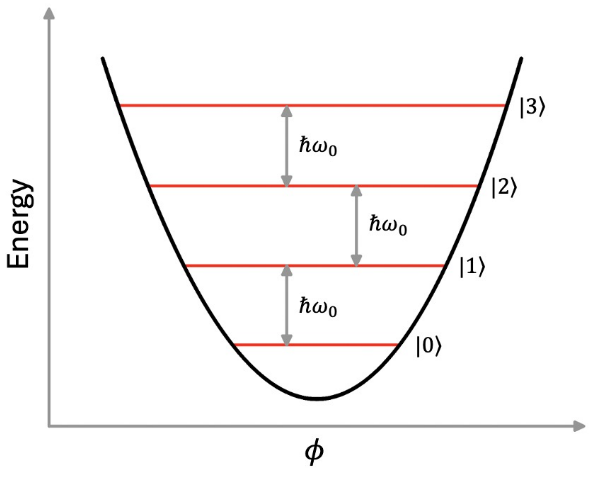
The LC-oscillator can be thought of as a system with potential and kinetic energy. Allocating the inductive energy as the potential energy and the capacitive energy as the kinetic energy for the system, the Hamiltonian for the system can be written as

$$\hat{H} = E_C \hat{n}^2 + E_L \hat{\phi}^2$$

Here, E_C is the charging energy, given as $\frac{e^2}{2C}$, and E_L is the inductive energy, given as $\frac{\phi_0^2}{2L}$. This Hamiltonian can also be expressed in terms of the ladder operators as

$$\hat{H} = \hbar\omega_r \left(\hat{a}^\dagger \hat{a} + \frac{1}{2} \right)$$

Here ω_r is the angular resonance frequency of the resonator. This equation shows that the LC-oscillator can be described as a simple harmonic oscillator, and the energy diagram for the harmonic oscillator is shown in Figure 2.

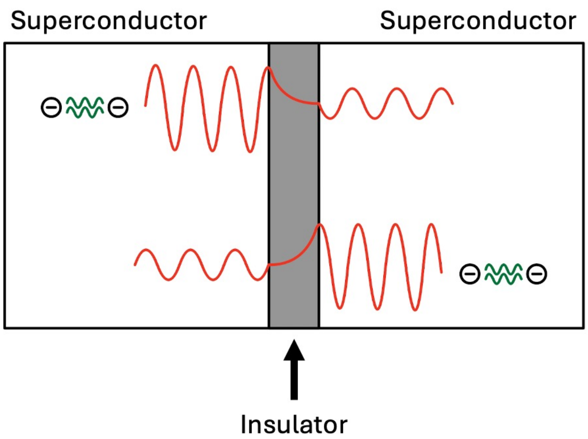


Figur 2: Energy diagram for the LC-Oscillator

Here, the quadratic potential of the LC oscillator induces equally spaced energy levels by $E = \hbar\omega_r$. Because of the energy levels being linearly spaced, the circuit cannot be used as a qubit. This is because a pulse that brings the system from the $|0\rangle$ to $|1\rangle$ state would also drive the system from the $|1\rangle$ to $|2\rangle$ state and further. The circuit must be altered such that the energy levels can be individually addressed.

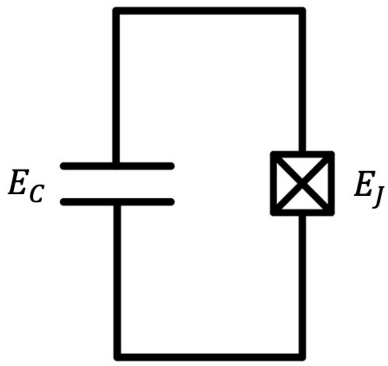
3 The Transmon Qubit

To introduce nonlinearity into a superconducting circuit, a new circuit element must be introduced, called the Josephson Junction.



Figur 3: Josephson junction

As shown in Figure 3, the Josephson Junction consists of an insulating barrier sandwiched between two superconducting layers. The insulating layer is thin enough such that the Cooper pairs in the superconducting layers are able to tunnel from one layer to the other. Because of the tunneling effect enabled by the insulating layer, the Josephson junction possesses a nonlinear inductance. By replacing the linear inductor in the LC oscillator with the Josephson junction, which acts as a nonlinear inductor, the transmon qubit can be realized as shown in Figure 4.

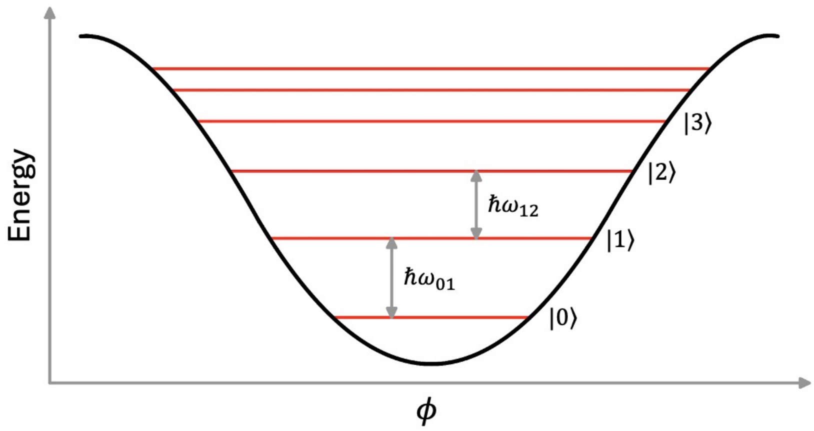


Figur 4: Transmon circuit diagram

The Hamiltonian for this circuit can be written in terms of the charge ($\hat{n}$) and flux ($\hat{\phi}$) operators as follows.

$$\hat{H} = 4E_C\hat{n} - E_J\cos(\hat{\phi})$$

Here, E_J is the Josephson energy, and the system is in the limit where $\frac{E_J}{E_C} > 50$. The energy diagram for this circuit is shown in figure 5.



Figur 5: Transmon energy structure

Because of the nonlinearity from the Josephson junction, the energy levels of the Transmon qubit are not evenly spaced. The energy states can be individually addressed; therefore, the $|0\rangle$ and $|1\rangle$ states can be used as a qubit.

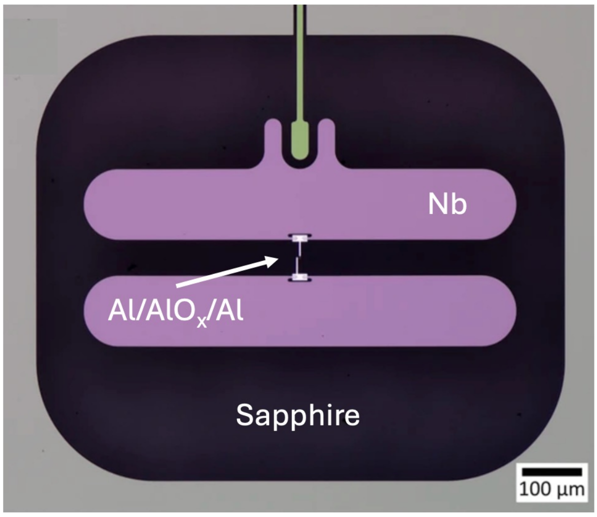
4 Materials-based Improvements to the Transmon Qubit

Physical quantum systems must be effectively isolated from its surroundings while also being measurable. Because of this, a nonzero coupling between a qubit, such as the transmon, and its environment is unavoidable. The loss of quantum information by the qubit to the environment through decoherence is a heavily studied area of research, as longer coherence times would enable higher gate fidelities, with long enough coherence times enabling scalable physical quantum computing.

Coherence time (T_2) is a combination of the energy-relaxation time (T_1) and the dephasing time (T_ϕ). The relationship between these properties is shown in the following equation.

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

In 2012, the coherence times of the transmon plateaued, not reliably improving beyond 100 μs. Although the superconducting metal used in the transmon is lossless below its critical temperature, loss can occur in the amorphous, insulative regions of the device, such as the oxides of the superconducting metal or the substrate. These can be visualized in Figure 6.



Figur 6: Nb-based Transmon [5]

To increase the coherence times of the transmon, the most dominant source of loss must be determined and mitigated.

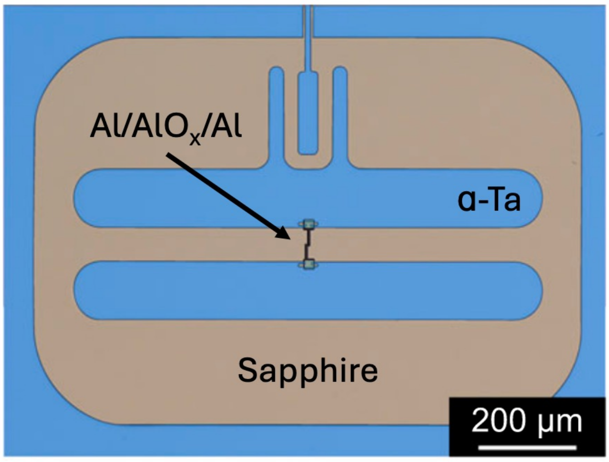
Loss can be quantified as the inverse of a quality factor (Q), which can be computed from the angular resonance frequency of the qubit (ω_q) and the relaxation time of the qubit (T_1) as shown below

$$Q = \omega_q \cdot T_1$$

It is predicted that the sapphire substrate should have a Q up to 100 million, indicating minimal loss; however, this would enable a T1 greater than 30 ms for a transmon at a standard resonance frequency. Because of this, it is likely that surface losses from the oxides dominate the total losses in the transmon.

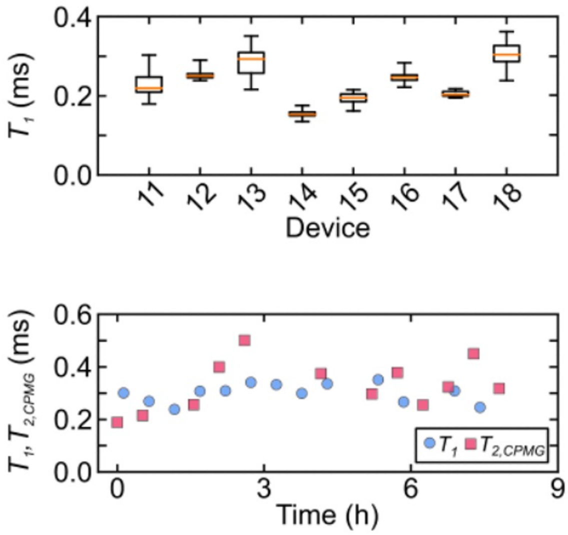
Niobium (Nb) is a commonly used material in the ground plane and the electrodes of a transmon; however, it possesses lossy oxides that cannot be subjected to aggressive cleaning methods. Tantalum (Ta) is a refractory metal that can survive aggressive acid cleans and possesses kinetically-limited oxides.[2] There are fewer suboxide species in Ta, and the oxide in Ta is also thinner than in Nb.[2] Additionally, Ta can be readily sputtered in two different phases, the tetragonal (beta) phase and BCC (alpha) phase. beta-Ta has a Tc around 0.5 K, while a-Ta has a Tc of 4.2 K. With higher Tc being more desirable, a-Ta is the most promising phase of Ta.

With many materials-based benefits of Ta compared to Nb, the ground plane and electrode material of the transmon was replaced with Ta in Place et al, as shown in figure.



Figur 7: Ta-based transmon [4]

Many Ta-based transmons were fabricated in this work, and the measured coherence times are shown in figure .



Figur 8: Coherence times of Ta-based transmons [4]

Here, a threefold increase in coherence times is demonstrated for Ta-based transmons compared to Nb-based transmons. This underscores the importance of materials-based improvements towards achieving higher coherence devices.

5 Conclusion

The adoption of Ta as the superconducting material in transmon qubits has led to substantial improvements in coherence times. By correlating materials properties with device performance, researchers can guide the development of novel materials and processing methods that push the boundaries of coherence times even further. Despite the promising results obtained with Ta-based transmons, further research is necessary to fully understand and mitigate the remaining loss mechanisms. Further work, such as in Crowley et al., the study of losses in Ta-based superconducting circuits continues.

Referenser

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[2] Kevin D. Crowley, Russell A. McLellan, Aveek Dutta, Nana Shumiya, Alexander P. M. Place, Xuan Hoang Le, Youqi Gang, Trisha Madhavan, Matthew P. Bland, Ray Chang, et al. Disentangling losses in tantalum superconducting circuits. *Physical Review X*, 13:041005, 2023.

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[4] Alexander P. M. Place, Lila V. H. Rodgers, Pranav Mundada, Basil M. Smitham, Mattias Fitzpatrick, Zhaoqi Leng, Anjali Premkumar, Jacob Bryon, Andrei Vrajitoarea, Sara Sussman, Guangming Cheng, Trisha Madhavan, Harshvardhan K. Babla, Xuan Hoang Le, Youqi Gang, Berthold Jäck, András Gyenis, Nan Yao, Robert J. Cava, Nathalie P. de Leon, and Andrew A. Houck. New material platform for superconducting transmon qubits with coherence times exceeding 0.3 milliseconds. *Nature Communications*, 12(1779), 2021.

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