

Investigating Sources of Superconducting Qubit Decoherence

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Abstract—Qubit decoherence is an obstacle that plague many superconducting quantum systems that are candidates for quantum computation. The mitigation of decoherence is necessary for quantum computers to operate reliably and not lose their information. However, our superconducting transmon qubit was not operating and an investigation was done. The findings of this investigation might be key to improving coherence time as well as preventing future qubit failure. Here, our superconducting qubit was inspected using various techniques such as using Laser Scanning Confocal Microscopy (LSCM), Energy Dispersive Spectroscopy (EDS), Electron Backscattered Diffraction (EBSD), and Atomic Force Microscopy (AFM). These analysis techniques were used to search for defects that might be caused by processing and foreign materials. So far, the LCM, EDS, and AFM techniques show a potential defect area. A potential cause of qubit failure might be the height variation in the niobium pad.

I. INTRODUCTION

A. Motivation

The advent of quantum computers will spark a revolution in computing technology due to its potential to be exponentially more powerful than the existing (classical) computers. Classical computers utilize transistors which can hold one bit of information which means that these devices can only hold one state at a time which is 1 or 0. The more transistors a microchip contains, the more powerful the microprocessor is. Current computing technology can hold billions of transistors on a single chip which is made possible by the shrinkage of transistors, however, transistor scaling is coming to an end as it is increasingly difficult to make transistors as they approach 10nm and beyond. At present, the most viable solution is quantum computing. Quantum computers are built using quantum bits (qubits) which utilize quantum phenomena such as superposition to operate. Similar two a transistor, a qubit can be in a state of either one or zero, but they can be in a superposition of both states meaning it can be in both states superimposed to each other. For this reason, quantum computing is exponentially more powerful than classical computing. To put things into perspective, classical computing power scales in proportion to $2n$ while quantum computing power scales proportionally to 2^n where n is the number of qubits/transistors [1]. In an ideal case, a thirty-one-qubit processor may be just as powerful as a two billion transistor microchip. Another thing to mention is that quantum computers can solve many problems either more

efficiently or completely intractable to classical computers. Applications include molecular modeling, artificial intelligence, and secure communication. For example, it can take ten years and one billion dollars to develop a new drug due to current computing technologies limitations in the molecular modeling necessary to simulate the molecules of the new drug. With a quantum computer, molecular modeling will be performed much faster and will consequently reduce the cost of making the new medicine. As a result, the wait time and the cost of the medicine will be reduced allowing it to be more readily available for people in need [3].

B. Qubit Operation Basics

Before this technology have any practical use, a fundamental component must be developed. A quantum bit or a qubit is the basic building block of a quantum computer. There are many types of qubits such as those that utilize optical photons, trapped ions, and electron spins. As mentioned before, qubits can be in either $|0\rangle$, $|1\rangle$ or superposition which expands the Hilbert space expressed as $|\psi\rangle = a|0\rangle + b|1\rangle$. The probability amplitudes a and b can be normalized $|a|^2 + |b|^2 = 1$. A great analogy is the Bloch sphere. Looking at figure 1., the Bloch sphere has a well defined $|0\rangle$ state and a well defined $|1\rangle$ state. If the red arrow is pointing straight up, it will be in the $|0\rangle$ state, if it is pointing straight down, it is in the $|1\rangle$ state. If the arrow is pointing in a direction that is not one or zero, then it is in a superposition[2].

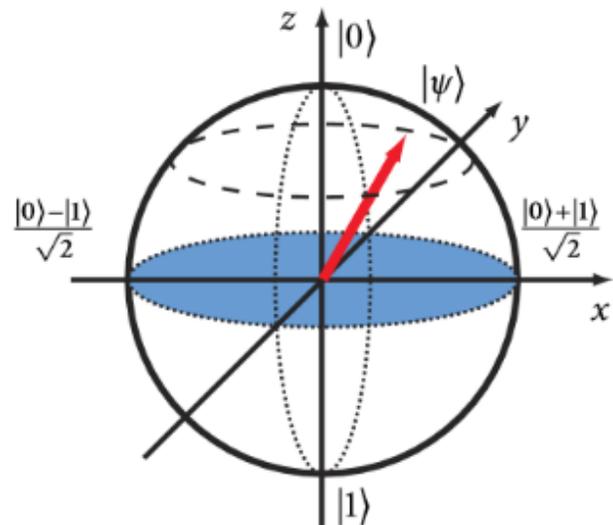


Fig. 1. Figure 1. Bloch Sphere [2]

*This work is supported by Fermi National Accelerator Laboratory

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C. Superconducting Qubit Under Consideration

The qubit that this paper focuses on are three-dimensional superconducting transmission line shunted plasma oscillation qubit (transmon qubit). A superconductor is a material that has theoretically no resistance. Referring to figure 2a, this qubit is made using a cooper pair box which is two superconductors A and B capacitively shunted forming a Josephson Junction (JJ) where C is the insulating material. The qubit is then connected to two superconducting niobium pads that function as antennae (figure 2b).

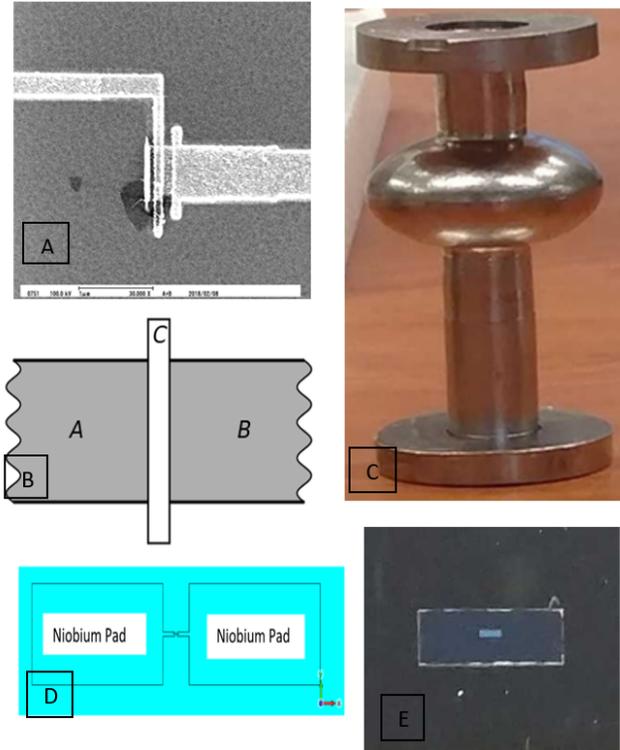


Fig. 2. Figure 2. a) (top left) JJ where A and B are the superconductors and C is the insulating material [4]. b) (top right) Niobium pad that connects the JJ to the microwave photon. c) (bottom left) Actual SEM image of JJ. d) (bottom middle) superconducting resonator. e) (bottom right) camera shot of the qubit.

The superconducting material is aluminum and the insulator that is used is aluminum oxide. This qubit is considered three dimensional since the resonator and the qubit combination is a three-dimensional device which allows the photon to oscillate in many directions. Therefore, the electric and magnetic fields of the photon will propagate in the x, y, and z axis. The qubit will be placed in the center of the resonator at its equator (figure 2d). The superconducting circuit behaves much like an atom. This qubit system acts as an artificial atom. When light strikes an atom, the electron will go from a ground state to an excited state (figure 5). Similarly, the superconducting circuit acts as an artificial atom however the impedance change when light enters it. The photon going through the resonator gets trapped and oscillate in the cavity while interacting with the qubit. If the qubit is in the ground state, the photon will excite it. In

the excited state the circuit impedance reduces, and voltage increases. When the light exits, the qubit will decay meaning that the impedance reduces. The photon will reflect from the cavity and excite the qubit again. To be sure that the qubit is working, there should be an interaction between the qubit and resonator evidenced by the dispersive shift. The dispersive shift is a shift in the resonator frequency (figure 6). In the case of this qubit, the dispersive shift was not found. Because of this, a failure analysis investigation was conducted to help determine the possible cause of the qubit failure.

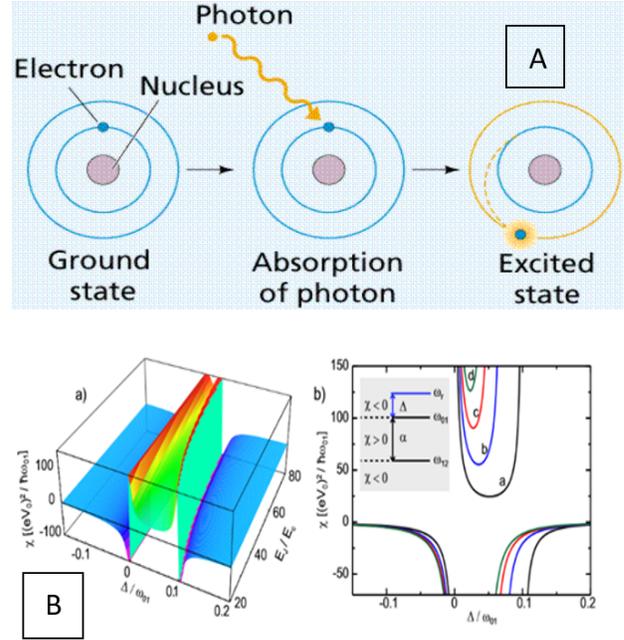


Figure 3. a) atomic excitation [5]. b) dispersive shift of the qubit [7]. [2]

II. METHOD

A. Tools and Techniques

The LSCM is a technique that uses a Laser Confocal Microscope for profilometry and surface roughness measurements. This technique uses a laser to determine height and depth of features on the specimen. A laser goes through an objective lens that hits the surface of the sample which then gives off photons. A photodetector converts the photons from the sample to electrical signals that contains information about the sample surface. From there an image is constructed pixel by pixel. This tool is beneficial to qubit failure analysis as it has the capability of showing surface defects on films.

Scanning Electron Microscopy is an excellent tool to obtain high resolution images of samples. This tool can also perform elemental analysis to help determine what chemicals are on the sample as well as elements that dont belong. This generates an electron beam that hits the sample. Two types of electrons are generated. The first type is secondary or surface electrons. This happens when the electron beam hits atoms of the specimen which absorbs the energy of the electron and gives off their own electron. The detector picks up the

secondary electron and use these electrons to form the image on the screen.

The other type of electrons are backscattered electrons. These electrons do not come from the atoms but reflect from the surface. The higher the acceleration voltage of the electron beam, the deeper the electrons penetrate. Sometimes backscattered electrons can be used to increase the yield of secondary voltage. X-rays are produced by electrons that go deep into the sample and get absorbed. The absorption of the electron produces characteristics x-rays which is used for EDS elemental analysis. EBSD is a technique used to study crystallographic structure of materials. The electrons travel along a crystalline plane and generate Kikuchi bands and the widths of these bands are detected by Bragg's law.

The final type of analysis that was conducted was the Atomic Force Microscopy. Atomic force microscopy is a high-resolution technique that is used to analyze surface topology. The main components of atomic force microscope are a cantilever, a laser, piezoelectric, and a photodiode. There are two modes that were used in this research which are contact mode and non-contact mode. In contact mode, a laser beam is focused on the cantilever and reflected from the cantilever's tip to the photodiode. As the cantilever's tip moves across the sample surface, it will move up or down depending on the topology of the sample. The piezoelectric is connected to the cantilever which converts the cantilever's motion into electric energy. Surface topology images are formed from the piezo-voltage and laser intensity difference. In non-contact mode, the tip of the cantilever does not touch the sample, however the photodiode detects the tip's resonant frequency and the image is indirectly formed using the cantilever's oscillations. Non-contact mode is not as accurate as contact mode but unlike contact mode, the sample would not be damaged.

III. RESULTS

A. Laser Scanning Confocal Microscopy

The first method that was done was LSCM. The LSCM is best suited for taking images of bulk samples, and features that exceed 10 microns. Comparing figure 5a to figure 5b, the highest magnification that the LSCM have is 150x, but it still can't resolve the JJ region since it is approximately three microns. A potential defect was detected on one of the pads of aluminum shown in figure 5a but unlike the SEM, the material that would make up the possible defect can't be verified. After taking measurements using 50x and 150x resolution, values ranging from 90nm-230nm were detected.

B. Scanning Electron Microscopy and Electron Diffraction Spectroscopy

The SEM was used to determine if there are any foreign materials on the sample or to see if the materials that do belong appear in areas that may cause the device to not operate properly. The SEM was used after the LSCM to investigate the potential defect that showed up on the niobium pad. Looking at figure 6 b and c, the SEM revealed a

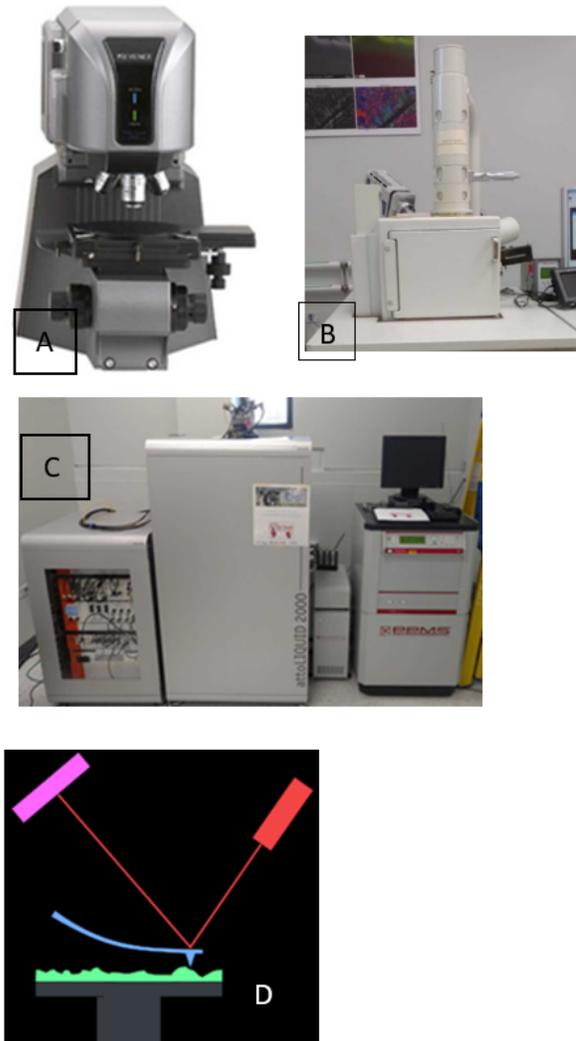
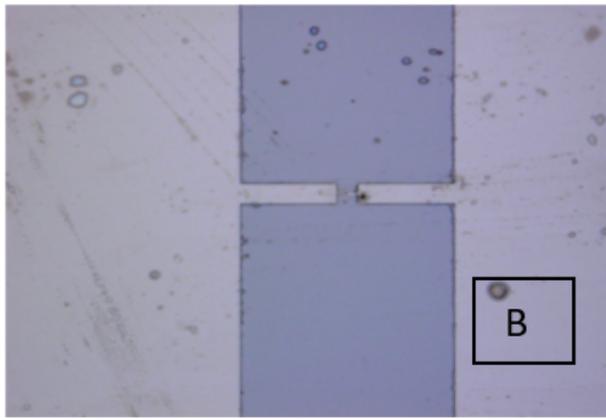
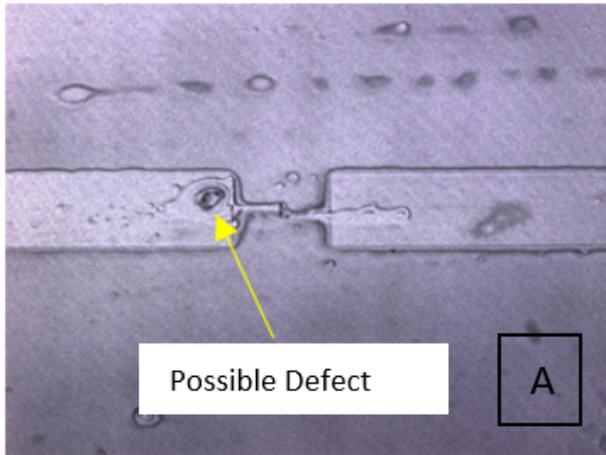


Fig. 4. Figure 4. (starting from the left) a) Scanning Laser Confocal Microscope, b) Scanning Electron Microscope, c) Atomic Force Microscope, d) AFM component-cantilever, laser, and photodiode

concentration of silicon and oxygen under the aluminum pad which may have caused that feature to appear but whether that feature will affect the operation of the qubit is still unknown. However, this measurement was done at 15 kV and the problem with doing an EDS analysis at that energy level is that some elements would not be detected since they require higher energy levels to excite the electrons that give off their characteristic x-ray. After scanning the sample from 17-25 kV, the EDS software was able to detect something that could not be found at a lower energy level. Looking at figure 7, the software detected tin, however, it is still difficult to verify that it is true since the theoretical spectrum of that element poorly fits the measured spectrum. EBSD analysis was attempted for the qubit, but it did not work. In principle, it should have worked revealing a pattern like figure 8 due to a 50nm information depth. A possible reason why this did not work was due to the 70nm electron beam size. Typically, the beam size should be small, and the current should be large



Niobium Step Height (nm)	
50x	150x
96	181
110	171
182	139
228	172

Fig. 5. Figure 5. a) (left) 150x magnification, b) (middle) 50x magnification, c) (right) measurement comparison between 50x and 150x.

relative to the type of sample under consideration. Figure 9 shows the image that was generated from EBSD analysis. The image is noisy since under 15 kV the penetration depth exceeds the Nb film thickness as shown in the Monte Carlo Simulation (figure 10) and as a result, the Kikuchi patterns of the Nb and Si films will be shown as an image superimposed on each other. Furthermore, under a standard set-up, an energy level of 20 kV is ideal.

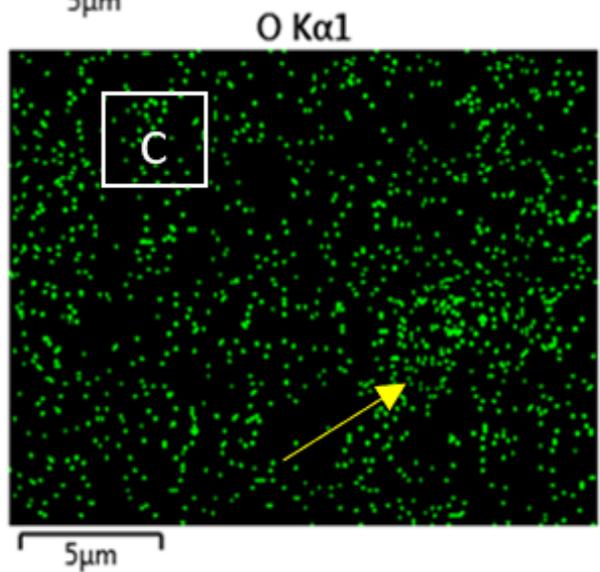
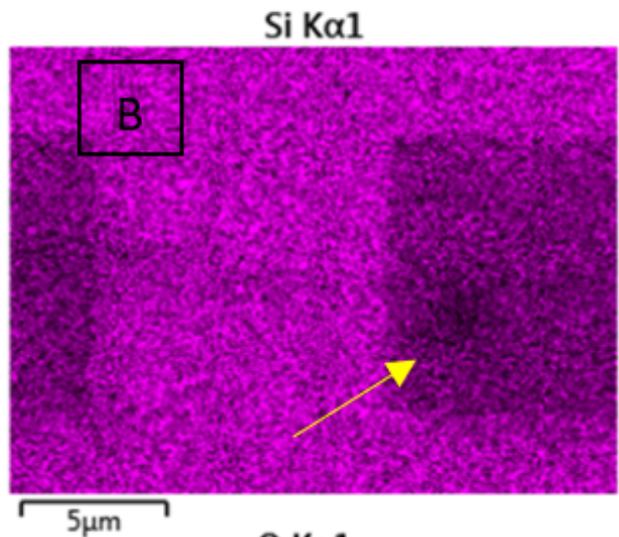
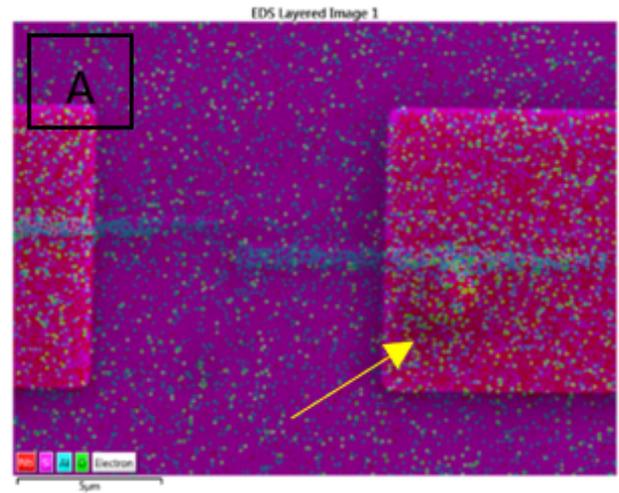


Figure 6. Figure 6. a) (left) Layered image, b) (middle) silicon, c) (right) oxygen.

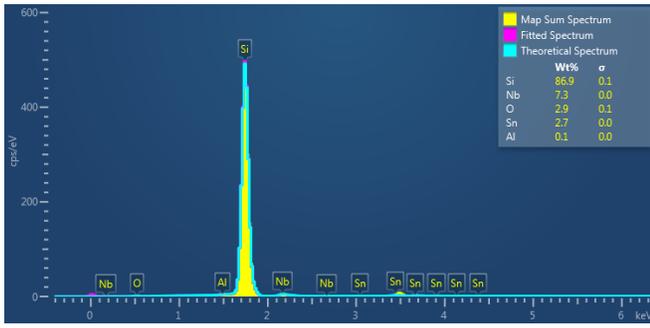


Fig. 7. Figure 7. EDS spectrum at 27 kV

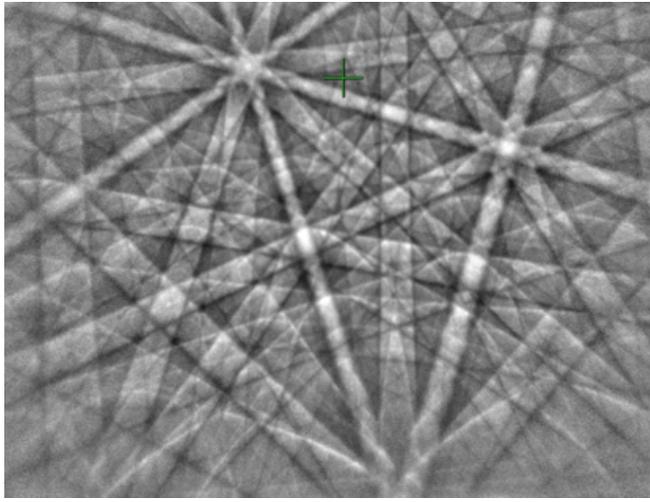


Fig. 8. Figure 8. Ideal Kikuchi pattern.

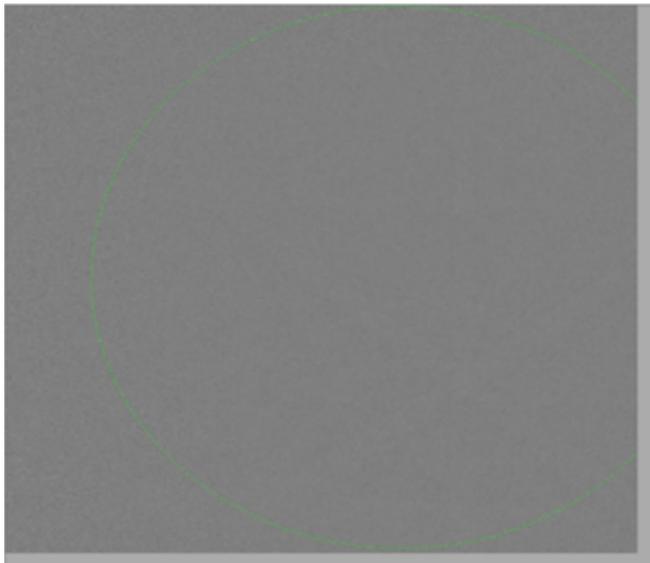


Fig. 9. Figure 9. Detected Kikuchi pattern.

C. Atomic Force Microscopy

The final analysis that was done was Atomic Force Microscopy. This tool can detect niobium hydrides on the sample. Film thickness values ranging from approximately

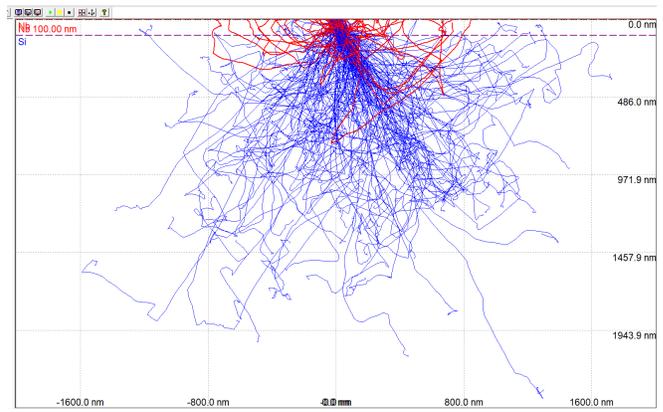


Fig. 10. Figure 10. Monte Carlo Simulation of electron penetration depth at 15 kV

90nm-200nm were recorded. Concerning hydrides, hydride detection is key since hydrides will bring the niobium from superconducting to normal conducting at cryogenic temperatures[7]. Once the device is normal conducting, it will no longer operate as a qubit. The chamber containing the sample was cooled down to 10 Kelvin. This must be done to detect the evidence of the hydride precipitates. However, the sample contained a lot of debris on it and after taking measurements at this temperature level, it will be hard to know that the hillocks that appear are hydrides (figure 12).

Measurement	Niobium Step Height (nm)		
	Area 1	Area 2	Area 3
1	100	100	130
2	110	110	150
3	110	120	160
4	110	110	150

Fig. 11. Figure 11. Niobium step height measurements.

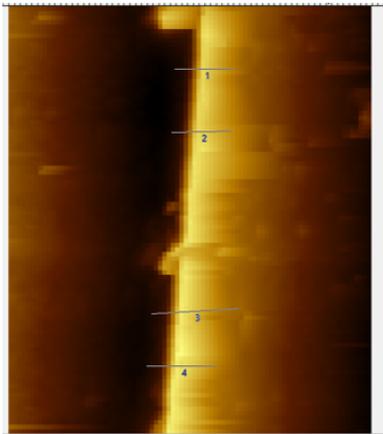
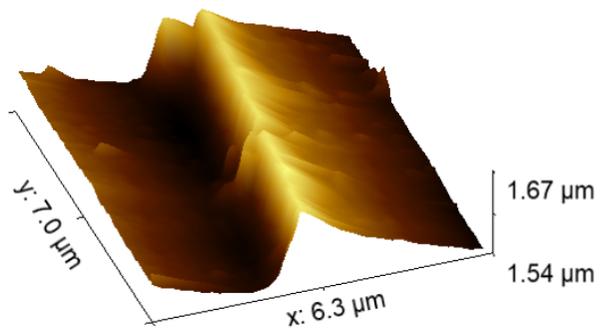


Fig. 12. Figure 12. Niobium step height

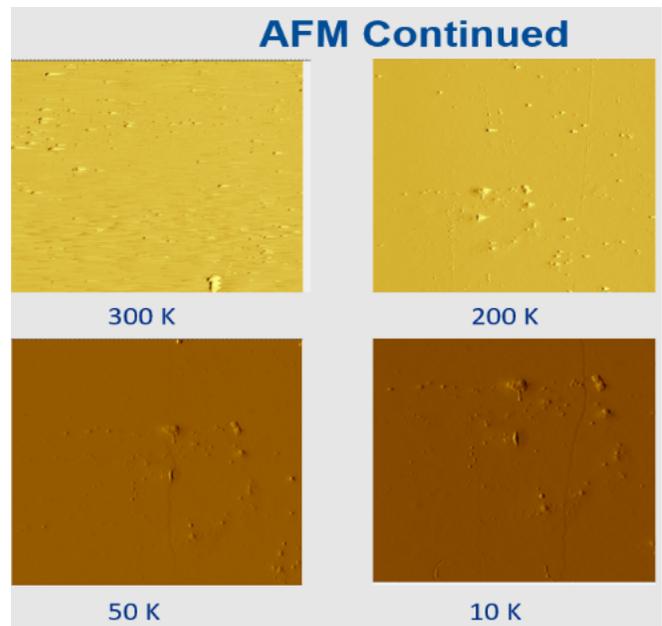


Fig. 14. Figure 14. Images taken at 300 K, 200 K, 50 K, and 10 K. Hydrides could not be verified due to existing debris on the sample.

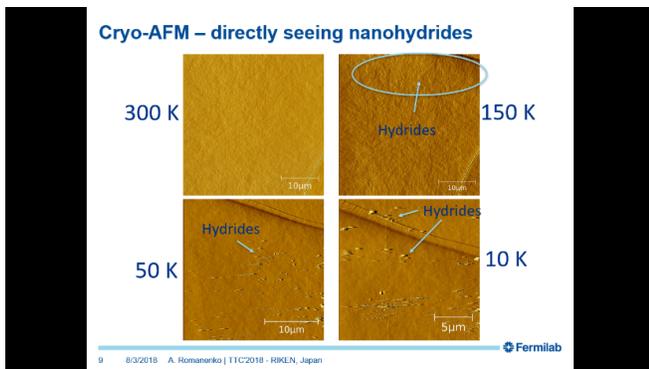


Fig. 13. Figure 13. Image of hydrides appearing at 150 K, 50 K, and 10 K.[7]

IV. CONCLUSION

The data taken from the AFM and the LSCM gave similar results about film thickness. Ideally, the niobium pad is supposed to be roughly 100nm, but the values range beyond 200nm which might impact device operation. The SEM have shown additional material that is believed to be tin, but the theoretical spectrum does not fit the measured spectrum. If extra time was allotted to this project, utilizing a focused ion beam instrument would be ideal as it allows for material cross section analysis. This way a defect in the device can be readily detected. Revisiting the EBSD analysis and adjusting certain parameters such as beam size and energy level would help better analyze crystallography. Better sample prep will be done to help distinguish real defects from debris. Qubit device modeling will be explored to determine if film thickness of the Nb will affect qubit operation. Finally, analysis and comparison of both working and non-working qubits will be done to see what features these devices have in common that affects device operation.

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