Analysis of Commercially Available Electrical Components for Amplification of Quantum Processor Read Out

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***Abstract--* Amplifiers for quantum processors are required to function at cryogenic temperatures near 850 millikelvin to enable the measurement of state changes in single electron transmitters (SET). However, minimal data has been collected on the functionalities of various electrical components below 4 K. In this work we measured a select number of commercially available capacitors, resistors, and transistors in an ICEOxford cryostat and report the change in component parameters as a function of temperature. Using these values, we simulated our cryogenic amplifier circuits to better understand circuit performance at low temperatures. We hope these results will enable the engineering of better amplifiers for the SETs.**

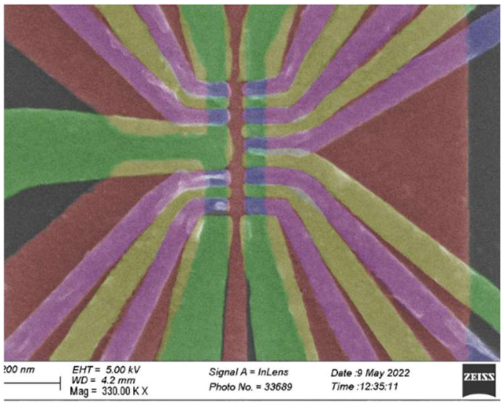

Figure 1: Framework of a 4-qubit quantum processor used in the lab

I. INTRODUCTION

Single electron transmitters (SETs) are effectively nanoscale transistors that are sensitive to the change in gate voltage by a single charge. These are used for device readout for silicon-based quantum processors [1, 2]. In silicon quantum dot devices, quantum readout occurs through spin-selective tunneling of electrons out of a processor like the device shown above in Figure 1 [3]. In this configuration, the readout signal consists of a single charge moving approximately 100nm in the device. To detect this movement, the charge is placed close to the gate of a SET charge sensor, which capacitively affects the current running through the sensor. Due to the very small differences in energy between the different spins of an electron, which are used to encode quantum information, the SET must operate at cryogenic temperatures. Otherwise, thermal noise [4] can lead to a scrambling of the quantum state known as relaxation. The resulting change in current through the sensor is less than 1nA in state-of-the-art devices and must be measured on timescales of order microseconds, meaning that an amplifier must be used to enable this bandwidth.

For the aforementioned reasons, the amplifier must be placed near the SET at cryogenic temperatures. If current is brought up to room temperature before amplified, the current will be affected by Johnson noise [5]. This would dilute the results and make the readings for the SET much less accurate. Additionally, because all wires have an innate capacitance to them, a longer wire would introduce parasitic capacitance and resistance in the current, which would limit the measurement bandwidth.

Electrical components based on semiconductors can experience an effect called carrier freeze-out at cryogenic temperatures, in which the electrons in the components do not have enough energy to jump between the conduction bands [6]. Due to this phenomenon, we can expect that below a certain threshold temperature at which carrier freeze-out occurs our transistors will cease to function. Effectively, the source and drain of the transistor will stop conducting, as if the transistor isn't even connected to the circuit, or in an intermediate regime there will be a large series resistance.

This investigation tested and documented the effects of cryogenic temperatures on the components needed for amplification of the SET devices. By understanding the effects of cryogenic temperatures on these components, it allows for us to create more robust accurate amplifiers for the SETs that can amplify the signal from the SETs without disrupting the current with thermal noise, excess capacitance, or other outside sources of interference.

II. BACKGROUND

A. *High-electron-mobility transistor (HEMT)*

Traditionally, transistors are a vital portion of amplifiers. Field-effect transistors (FET) consist of three terminals, where the outer two terminals are either positively or negatively doped. The middle terminal is always the inverse of the outer two terminals. These three terminals are called the emitter, base, and junction. If both the emitter and junction terminals are negative the transistor can be classified as an NPN transistor, while having the emitter and junction terminals being positive classifies it as a PNP transistor [7].

For the amplifiers in the lab, a special transistor called a high-electron-mobility transistor (HEMT) [3, 8] is used instead of FET transistors. While there are different types of HEMT transistors, they typically have the same main components. Instead of an emitter, base, and collector terminals, HEMT transistors consist of a source, gate, and a drain. Additionally, instead of being directly connected, the source, gate, and drain are separated. The three terminals are placed on top of a layer known as a barrier, which is used to determine the resistance of the transistor. Underneath the barrier is a layer called the substrate. Between the barrier and the substrate is a layer in which the electrons can freely flow. This layer is called the two-dimensional electron gas (2DEG). Instead of directly allowing the electrons to flow between the terminals like in a classical transistor, the HEMT connects the source and drain through the 2DEG.

In this lab, the resulting current from the SETs go through a two-stage amplification process, with the first stage occurring at 1 Kelvin and the second stage occurring at 4 Kelvin. In the first stage of previous designs, a single HEMT transistor is used as an amplifier, while three HEMT transistors are used to further amplify the current in the second stage of amplification. In addition to HEMT transistors, the two stages of amplification also use capacitors and resistors to help eliminate noise from the read out. Images of these two stages as well as the simulated circuits shown previously.

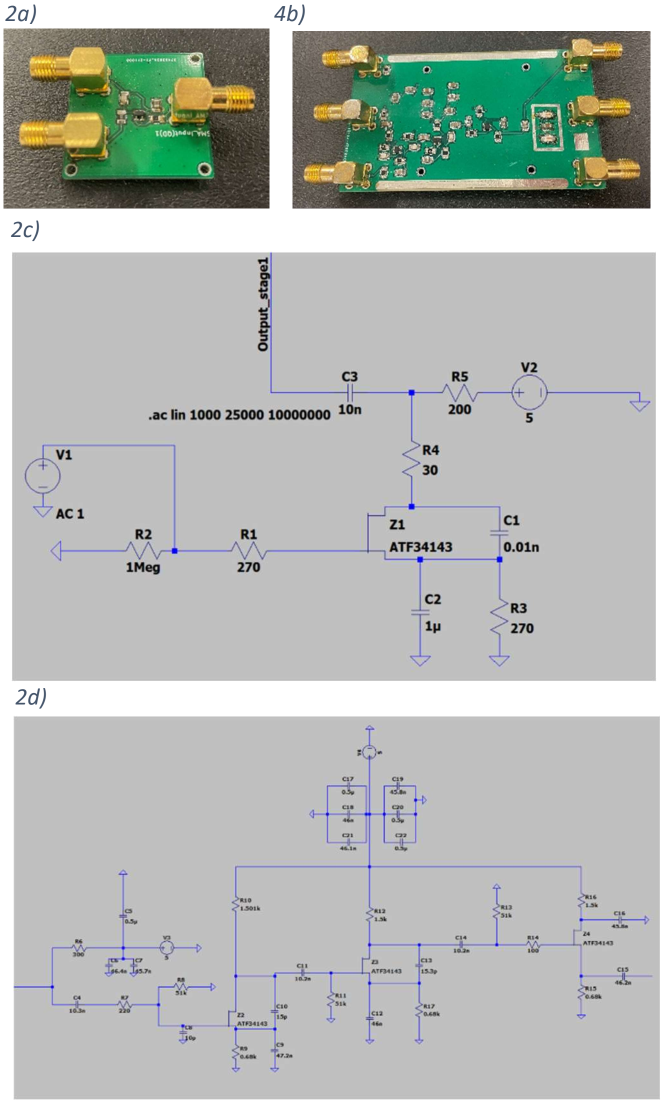

Figure 2: a) Image of first stage amplifier. | b) Image of second stage amplifier. | c) Simulated circuit of first stage amplifier. | d) Simulated circuit of second stage amplifier.

Previously, research has shown the effects of cryogenic temperatures on some of our electrical components down to 4 Kelvin [2]. Their work on resistors has shown that metal film resistors have a high tolerance to temperature, having only a slight increase of resistance near 0 Kelvin. This can be seen in [2, Fig. 2.3a]. Due to this research, we can reasonably simulate the amplifier at cryogenic temperatures by gathering data on the capacitor and transistors alone. Nevertheless, it is prudent to test resistors at low temperature, as some metals such as aluminum or tantalum superconduct at 1K. The majority of thin film resistors are based on NiCr, however, which remains resistive at helium temperatures.

III. METHODS

A. *Equipment*

For the experiment, various commercially available capacitors and HEMT transistors were selected to be tested at various temperatures. The measurement of the electrical components occurred in an ICEOxford cryostat, which uses Helium-2 to supercool the cryostat to temperatures around 1.4 Kelvin. To measure the temperature of the cryostat, a calibrated cryogenic temperature sensor from Lake Shore Cryotronics, model CX-1030-SD-HT-1.4L was attached to the sample plate of the probe and connected to a multimeter on the outside of the cryostat.

A SPICE program was used to simulate the amplifier based on the cryogenic data from the various electrical components. Below is the original simulation of the two-stage amplification, with original values for each component. The first and second stage of amplification are connected through Output-stage1 as shown in Figure 2 c above.

B. *Capacitor Measurement*

For the measurement of capacitors, the components were attached to the sample plate of the probe. The two components were connected to an additional two multimeters on the outside of the probe. As the cryostat cooled down, a computer program pulled the capacitance values from the multimeters connected to the components, as well as the resistance value from the multimeter connected to the temperature sensor. After the cryostat reached its base temperature, the program ended its data collection loop and stores the data for the experiment.

C. *Transistor Measurement*

For the measurement of HEMT transistors, three transistors were tested at temperatures of 77 K. To do this, the stage 1 amplifier shown in Fig. 2a on the previous page was modified to hold each HEMT device. This modification consisted of changing the 30-ohm resistor to a 230-ohm resistor to account for the 200-ohm resistor that usually sits at stage two. Additionally, another 100-ohm resistor was added off board to the resistor port of the amplifier. A total of 30dB of attenuation was added to the amplifier to reduce the voltage going into the amplifier. Finally, a DC block was connected to the output of the amplifier to apply a bias as well as connect the amplifier to a Field Fox spectrum analyzer to output the data.

IV. RESULTS AND SIMULATION

A. *Capacitor Data and Simulation*

For the six capacitors, capacitance data was collected down to temperatures of roughly 1.5 Kelvin. The values of each capacitor at temperatures of 77 K(liquide nitrogen), 4K (liquid helium), and 1.5K(pumped, liquid helium) can be found in Table 1 below.

Table 1: Table of capacitance values for tested capacitors

Capacitor	77 K	4 K	1.5 K
15µF 25 V JB 0805	3.03µF	0.52µF	0.50µF
47µF 10V JB 0805	6.16µF	1.14µF	1.09µF
1µF 20V TANT 1206	0.91µF	0.86µF	0.71µF
10µF 16V TANT 1411	8.95µF	8.61µF	7.01µF
22µF 10V X7R 0805	4.58µF	0.90µF	0.83µF
10µF 10V X7R 0805	1.71µF	0.33µF	0.31µF

The raw data for each capacitor has been graphed and plotted in **Error! Reference source not found.** on the following page. As seen from the graphs, the JB 0805 and X7R 0805 capacitors both lose more than 90% of the innate capacitance at 4 Kelvin. From the graphs, both JB and X7R capacitors show a relatively linear decay of capacitance below temperatures of 100K. However, the tantalum (TANT) capacitors show much more resilience, losing only 14% capacitance at 4 Kelvin and only 29% capacitance at 1.5 Kelvin. Furthermore, the capacitance decay of the TANT capacitors shows a very minor decay above temperatures of 4 Kelvin. However, below this temperature, the capacitance of the TANT capacitors drops much faster.

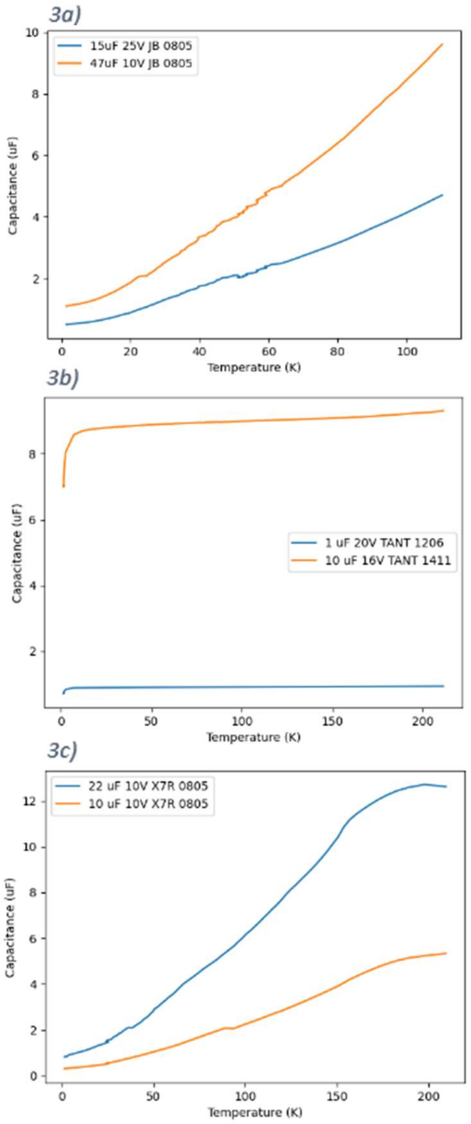

Figure 3: a) Graph of data for 15 and 47µF JB 0805 capacitors. | b) Graph of data for 1 and 10µF TANT capacitors. | c) Graph of data for 22 and 10µF X7R 0805 capacitors

To simulate the effects of cryogenic temperatures on the amplifier assuming no change in transistors, the data for the capacitors were plugged into the Spice simulation as seen in Fig. 2a and Fig. 2b.

The original circuit, whose gain graph is shown in Fig. 4a on the following page, has a peak of 82.61dB at 774KHz. This corresponds to 1.82e+8 total power gain. The bandwidth of the original circuit is at 79.6dB, which occurs at a frequency of 3.74MHz. For the modified circuit, in which the gain graph is shown in Fig. 4b, the peak of the graph also occurs at 82.61dB. However, the peak of the graph occurs at a slightly lower frequency of 773 KHz. The bandwidth of the modified circuit, which is also at 79.6dB, occurs at 3.73MHz.

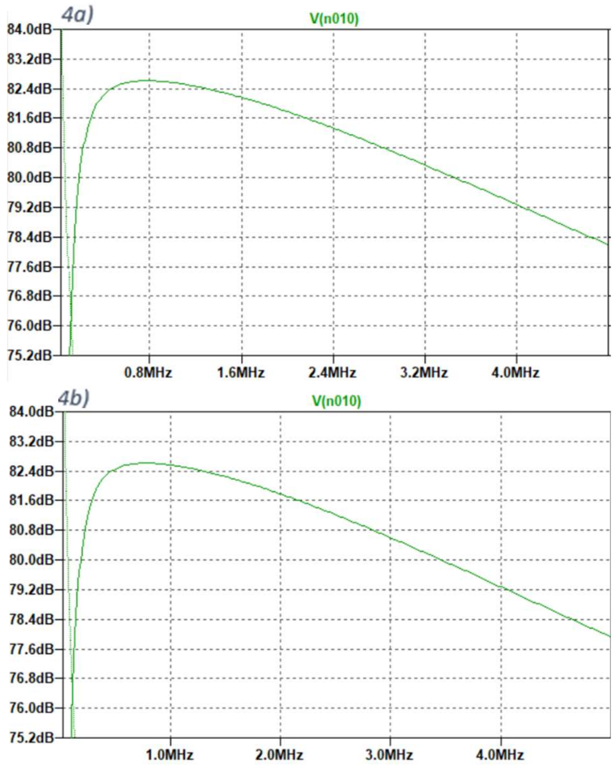

Figure 4: a) Simulated graph of original amplification | b) Simulated graph of modified amplification

The differences between the original and modified circuits are very small and inconsequential. Although there is a change, the change is not significant enough to warrant a redesign of the circuit. However, the modified simulation does not account for any change in the transistor at cryogenic temperatures.

B. *Transistor Data*

The three transistors that were tested were the ATF 34134, the ATF 33143, and the ATF 38243. The data for these three transistors can be found in the table below.

Table 2: Table of transistor data values

Transistor	293 K	77 K
ATF 34143	9.2dB	6.1dB
ATF 33143	12.2dB	13.5dB
ATF 38243	9.8dB	5.2dB

As seen in Table 2 above, both the ATF 34143 and ATF 38243 have very similar gain values. Both transistors have around 9dB of gain at room temperature and around 6dB of gain at 77K. However, the ATF 33143 shows significantly more gain, with 12.2dB of gain at room temperature and 13.5dB of gain at 77K.

V. DISCUSSION

During the experiment, we discovered that although the capacitance values of the capacitors change in cryogenic temperatures, the effect of the change has very little effect on the amplifier's circuit. However, the gain from the transistors were also changed at low temperatures. This means that the cause of the current malfunction in the amplifiers is likely due to unexpected changes in gain from the amplifiers, which would in turn affect the entire circuit.

In the future, we will fully characterize the cryogenic performance of the various HEMT transistors at temperatures closer to 850mK. This includes resistors as well. Although we assumed that the resistors would not change in cryogenic temperatures, we will still do tests to be much more precise. Additionally, we will test more capacitors and transistors that are used in the circuit to simulate the effects of cryogenic temperatures more accurately on the amplifier circuit. Finally, once all the components are characterized, we will redesign the amplification circuits with the cryogenic values of capacitance and gain in mind.

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REFERENCES

[1] M. H. Devoret. R. J. Schoelkopf. (2000, August) "Amplifying quantum signals with the single-electron transistor," in Nature vol. 406, pp. 1039–1046, doi: 10.1038/35023253

[2] H. Homulle "Cryogenic electronics for the read-out of quantum processors," Doctoral thesis, Delft Univ., Delft Netherlands, 2019, doi: 10.4233/uuid:e833f394-c8b1-46e2-86b8-da0c71559538

[3] J. Elzerman, R. Hanson, L. Willems van Beveren, *et al.* (2004, July) "Single-shot read-out of an individual electron spin in a quantum dot, " in Nature vol. 430, pp. 431–435, doi: 10.1038/nature02693

[4] F. Guagliardo, "Cryogenic electronic circuits operating at 1 Kelvin for characterization of quantum devices," PhD. thesis, Dept. Elect. Info., Poly. Univ. of Milan, Milan, Italy, 2011.

[5] J. R. Pierce, "Physical Sources of Noise," in *Proceedings of the IRE*, vol. 44, no. 5, pp. 601-608, May 1956, doi: 10.1109/JRPROC.1956.275123. [Accessed 6/20/2023]

[6] N. Ahmad, "Carrier freeze-out effects in semiconductor devices," in *Journal of Applied Physics*, vol. 61, pp. 1905-1909, March 01 1987, doi: 10.1063/1.338037. [Accessed 7/10/2023]

[7]S. Amos, M. James, *Principles of Transistor Circuits*, 9th ed. Woburn, MA: Newnes, 2000, pp. 22-25.

[8] M. N. A. Aadit, S. G. Kirtania, F. Afrin, Md. K. Alam, and Q. D. M. Khosru, "High Electron Mobility Transistors: Performance Analysis, Research Trend and Applications", in *Different Types of Field-Effect Transistors - Theory and Applications*. InTech, Jun. 07, 2017. doi: 10.5772/67796.