Developing Readout System for Cryogenic Temperature sensors

Capstone Report

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Abstract:

This capstone project focused on the development of a readout system for cryogenic temperature sensors. This project required design of the printed circuit board, which using a microcontroller ESP8266 will manage 4 multiplexers. Wireless capabilities of ESP8266 help to multiplex between 8 channels remotely and choose appropriate samples for 4 wire measurement. Early prototypes required an iterative process, and faced manufacturing challenges due to limitations of milling machine capabilities. However, PCB fabrication from JLCPCB significantly enhanced the durability and efficiency of the board. Nevertheless, first designs faced difficulties with noise and dimensions, which was the reason to develop a new PCB. Final version of PCB successfully passed tests and achieved desired goals. Project also included installation of CryoBoss software into the new server and integration of it with LabVIEW, which provides efficient data acquisition and visualization of cryogenic sensors like Lakeshore372. Moreover, capstone included work with Microwave Kinetic Inductance Detectors (MKIDs) and critical temperature measurements. Superconducting samples were wire bonded and then installed into cryostat in order to monitor superconducting properties. Nonetheless, after addressing all issues, the results were positive depicting both critical temperature and resonance frequencies of MKIDs. Overall, results depicted temperature sensing capabilities and provided a detailed view into superconducting device bonding, measuring processes. This could be a foundation for future works in low-temperature applications within quantum computing and astrophysics.

Contents

Chapter 1

Introduction

1.1 Cryogenic Temperature Sensors

In recent decades, the development of reading systems for cryogenic temperature sensors has become very important where accurate measurements of low temperatures are needed. Cryogenic temperatures, usually defined as temperatures below 123 K ($-150\,^{\circ}$C), play an important role in the study of special physical phenomena and the development of technologies based on such principles. At such low temperatures, quantum effects begin to appear. Consequently, special properties such as superconductivity and superfluidity can be realized using materials that exhibit zero electrical resistance and frictionless fluid flow [1, 2, 3]. Precise measurement, minimisation of noise, and control of cryogenic temperatures become much more necessary in harnessing such phenomena toward applications that include quantum computing, astrophysics, and advanced sensor technologies [4, 5, 6, 7].

1.2 Cryogenic Readout Systems

Cryogenic readout systems for temperature sensors are crucial in the main quantum computing application. A qubit is a basic unit of quantum information that, due to quantum superposition, simultaneously can be both 0 and 1. This makes a quantum computer much faster than a regular one. While Cryogenic CMOS systems research low-power and scalable control electronics at 4K for the management of qubit operations efficiently [8], photonic quantum computing platforms focus on integration techniques that also include superconducting detectors for maintaining low loss on-signal with heat management at low temperatures [9]. Additionally, temperature sensors such as PT100 are also considered in design considerations on PCBs and offer effective heat transfer along with the accuracy of temperature measurements in cryogenic conditions [10]. There are also other cryogenic detector technologies, such as Microwave Kinetic Inductance Detectors—a technology that provides signals through kinetic inductance variations. These detectors have high sensitivity especially at extremely cold temperatures. It is also vital to handle large arrays of detectors efficiently in cryogenic readout systems. MKIDs employ more sophisticated techniques, such as Frequency Division Multiplexing, which simplify the readout of detector arrays on a large scale by reducing system complexity while maintaining the performance at high levels [11, 12].

1.3 Recent Advancements

Some papers introduce a new approach in temperature detection. For instance, the first one uses a composite TVO resistor-based temperature measuring system for temperature monitoring [13]. Another method consists of the metal-insulator-transition (MIT) effects utilized in titanium-oxide-based devices that could be fit for both critical and differential temperature sensing. This could offer a switch between modes selectively, thus enhancing precision and versatility in cryogenic temperature readout systems [14]. Applications are various and may give rise to readout systems problems related to low signal levels, noise, thermal management, and electromagnetic interference. Some of them need further calibration with a view to ensure reliable operation at extreme environmental conditions [15, 16]. Future cross-field collaboration, such as in materials science and nanotechnology, or thin-film photovoltaics can be crucial for the development of cryogenic sensor technology due to its improved sensitivity and efficiency in difficult conditions [17].

1.4 Design Considerations

Nowadays, research and development are still focusing on wireless and hardware technologies on cryogenic-related technologies. An excellent example lies in the development of a passive pressure-sensing method with respect to cryogenic temperatures ($-196\,^{\circ}\mathrm{C}$ or 77.15 K) by overcoming the limitation of current sensors with long wires and low temperature tolerance [18]. Other examples include the integration of ORSS system for economical multi-channel sensor networks. It effectively handles measurements in a compact, low-cost PCB design, using multiplexing techniques to switch between multiple sensors in sequence, minimizing the need for separate measurement hardware [19]. This is also supported by the low-cost microcontroller-controlled four-wire resistive temperature detector (RTD) circuit when it offers high-accuracy temperature measurement [20]. To ensure accurate monitoring and minimize thermal effects on-chip thermometry and localized heating management can be applied [21].

In order to start designing a readout system for a cryogenic temperature sensor, I started by designing a PCB with appropriate ICs like multiplexers. In my PCB design, the ESP8266 microcontroller could control the four multiplexers, enabling efficient switching and data collection from multiple sensors in cryogenic environments, thus combining robust temperature sensing with wireless control capabilities.

To begin designing a readout system for a cryogenic temperature sensor, I started by creating a PCB with the necessary components, such as multiplexers. In this design, the ESP8266 microcontroller manages the four multiplexers, allowing for efficient switching and data collection from multiple sensors in cryogenic conditions. Switching itself can be connected wirelessly due to the capabilities of the microcontroller.

1.5 Ethical and Professional Responsibilities

- **Ethical Responsibility:**

  In my project, where I will create a readout system for cryogenic temperature sensors, there are several areas in the field of ethics that I need to pay attention to. First of all, it is the integrity of the data I have collected in my research and experiments. In case of errors on my part when collecting data, it can harm not only a couple of researchers who will derive conclusions or references based on my article, but also the entire scientific world. This is because it can be regarded as both negligence to the experiment and falsification of data, which is not accepted in an intelligent and developed society. To avoid these errors, I will do all the research in good faith, rechecking the data in order to carry out not only validation but also confirm the accuracy of my research.

  Another area that I need to pay attention to in my project is the careful handling of equipment. Since I work in a laboratory with very precise and expensive equipment, I have to use it carefully. This will not only be fair to the owner of the property as a professor or university, but also to subsequent researchers who will use the equipment after the menu

  The last note in this section may be about data security, especially the microcontroller or computer that is used to process data from hardware. It is necessary not only to check portable devices like flash drives, but also to secure files inside the system so that an unauthorized user cannot get them.

- **Informed Judgments:**

  To ensure that the decisions made during the multiplexing project are justified, an approach that takes into account technical and social aspects is necessary. For reasonable technical experiments, first of all, careful work is carried out when choosing electric components. First of all, the capabilities and limitations of the ESP8266 microcontroller. Its characteristics in the datasheet should be checked for the presence of a Wi-Fi module at a certain frequency for uninterrupted wireless operation. Moreover, general purpose pins, in order to already make a plan for connecting the remaining electrical components and chips. Further, after the purchase, actions should be carried out to check for operability and, first of all, for signal integrity and bandwidth. The next step will be to check the integrity of the components that will be used. Corresponding changes such as resistance, capacitance and signal integrity checks should also be checked. From a societal perspective, it is important to understand the broader impact of the project. Interaction with the scientific community and potential end users, provides valuable information about the needs and expectations of society. Such interaction will show that the objectives of the project are consistent with the promotion of the improvement of measurement technologies in cryogenic fields. Ethical considerations also influence judgments, ensuring that decisions do not unintentionally harm individuals or communities.

- **Global Context:**

  The multiplexing project based on the ESP8266 microcontroller and cryogenic measurements is important in a global context, not only its technological contribution but also applicability in various regions. Compliance of the project methodologies with international standards contributes to cooperation with international research universities. This alignment increases the relevance of the project and facilitates cross-border knowledge sharing. Moreover, this study can serve as a tool for future researchers who have limited access to cryogenic temperatures. The elimination of these gaps may encourage the further development of scientific progress in this area. And for regions that have all the necessary conditions, they will provide a complete guide to conducting research where new innovations can be stimulated in the future. Besides, the economic role is also played by attention in a global context. It is considered that not all regions have good sponsorship or resources. The development of a system that is scalable and adaptable to various budget constraints increases its global applicability and promotes involvement in scientific research. Since the project must take into account the global context, it provides not only cultural but also regulatory features of each country. For example, data privacy and electronic waste disposal. These considerations show that the benefits of the project will be large-scale with minimal potential problems in various global settings.

- **Economic Impact:**

  The project involves designing a readout system for a cryogenic temperature sensor using the ESP8266 microcontroller, multiplexers and cryogenic plant has both short-term and long-term economic consequences, including benefits and challenges. Short-term effects include initial equipment costs (Keithley 2450, Lakeshore Model 372) and research and development, prototyping and testing costs. These initial costs can create a burden, but the project can improve research capabilities and reduce labor costs by automating measurements. The long-term effect is to save money and time for measurements. Researchers no longer need to manually switch between the resistors in the cryo-installation, risking damage to the wires and equipment. Moreover, due to the readout system, researchers can immediately obtain graphs of the dependence of temperature on resistance rather than using external programs and software to create them separately. Intellectual property (IP) considerations also play a role in the economic situation. Patents or licenses can provide competitive advantages and financial returns. However, this may lead to legal costs in the future, which can also take up a significant part of the time. Potential issues include maintenance costs and scalability. As the system expands, additional costs may be required to accommodate more resistors or integrate with other measuring devices.

- **Environmental Impact:**

  An environmental impact assessment of the project is necessary to ensure environmental sustainability. Power consumption is a key factor, as the ESP8266 microcontroller, multiplexers, Keithley 2450, Lakeshore Model 372 require power. Using energy-efficient components and optimizing the firmware to reduce energy consumption can minimize the energy costs of the project. In my project, microcontroller-controlled multiplexers automate measurements, reducing manual work, energy consumption, and material losses. This increases efficiency and minimizes errors (human factor). The human factor can lead to improper energy management and, in the worst cases, destroy the device with careless actions. And such measuring instruments can be very harmful to the environment because of the components they are assembled, namely metals or plastics. Automation reduces the chance of such cases and prolongs the service life of the system, which ultimately reduces the environmental impact and promotes the introduction of more environmentally friendly methods. It is also worth considering soldering, which may release toxic fumes. Lead oxide can be very harmful to humans and the environment. However, the room is equipped with a hood to ensure good ventilation. Within the framework of this project, ways to reduce the environmental impact have already been considered. Energy-efficient components were selected to reduce energy consumption, and recyclable materials were selected to minimize waste. In addition, I treat electronic waste responsibly, ensuring the proper disposal of old components. These efforts are aimed at reducing the environmental impact of the project and supporting sustainable development.

- **Societal Impact:**

  The project has significant potential that can benefit society in various direct and indirect ways. Advancement in scientific research is a major public good. By providing accurate and efficient measurements of resistors under cryogenic conditions, the project supports research in areas such as materials science, superconductivity and quantum computing. Studying this project, researchers and students can explore a wide variety of topics - from hardware and software development to materials science, cryogenics and even astronomy, gaining practical experience and deepening their understanding of different areas of scientific concepts. These achievements can lead to the development of new technologies and stimulate innovation that will benefit society as a whole. The project's innovations can also benefit healthcare. Precision measurement technologies are essential for the development of medical devices and diagnostic tools. And research in the field of cryogenics can help in the development of MRI technologies. The project indirectly benefits schools and research centers with limited resources, fostering equal opportunities for education and research. This enables a wider range of students and researchers to participate in cutting-edge studies. Students can gain knowledge in pcb design and microcontroller computing in the process. Which in the future can lead them not only to the scientific world but also to large companies where such specialists are needed. The social impact is not only to help them find a good job in the future, but also their life goal. Consequently, their development and discovery in these areas may also influence both science, society and the whole world.

Chapter 2

Methodology and Discussion

2.1 Initial Project Sketch and Schematic

To commence the development of the readout system, I began by creating a conceptual sketch of the project. The sketch had interface with resistors, which, inside the cryogenic device, included four multiplexers for switching purposes and a microcontroller for managing communication and control. The main idea was to connect 32 inputs coming from the cryogenic device with four output pins in the screw connector, facilitating integration with a sensor capable of measuring both resistance and temperature. Translating the sketch into a digital schematicm which can be seen in **Figure 3**, I used EasyEDA for many reasons. EasyEDA has integration with the PCB manufacturer JLCPCB. Compared to Altium Designer, which requires a monthly subscription and is better suited for large-scale industrial designs, EasyEDA offers a user-friendly, intuitive interface and is perfect for budget projects, making it a cost-effective tool. While KiCad is a popular open-source alternative, it lacks an integrated component library like LCSC and a web-based platform.

2.2 PCB Design and Iterative Redesign Process

The PCB design phase was gradual and repetitive, involving multiple versions be fore achieving the desired outcome. Initially, I designed the board with Atmega8L and Atmega328U microcontrollers but soon replaced them with the ESP8266 for its built-in Wi-Fi capabilities, which simplified communication and reduced the need for additional external components like MAX3232 (UART converter). The ESP8266 also has a higher clock speed and memory capacity, and its main advantage is support for development environments like Arduino IDE or PlatformIO. I also selected the 74HC4051D 8-to-1 analog multiplexer for the switching mechanism, as it offered a way to handle the multiple input channels. The 74HC4051D's compact size, fast switching times, and wide operating analog voltage range made it an excellent choice for this project, ensuring transmission without significant distortion or delays. The final board design prioritized compactness, placing all four multiplexers beneath the microcontroller that would later be mounted to the board connector pins.

Early prototypes of the PCB were fabricated using Nazarbayev University's LPKF PCB milling machine. However, this approach faced significant issues. The first boards had leakage currents, with unintended electrical connections caused by narrow trace widths. Using a multimeter in continuity mode, I identified these faults and made adjustments, including increasing the trace width, distance between traces, and redesigning the board dimensions. Despite adding solder masks (thin polymer layers) for insulation, subsequent boards still faced connectivity issues due to imprecise milling and alignment. I concluded that the LPKF milling machine is limited in capabilities and has difficulty printing my board. LPKF PCB boards depicted in **Figure 10** and **Figure 11**.

To solve these problems, I decided to order from JLCPCB, which provides professional PCB manufacturing in China. This addressed recurring problems regarding the manufacture of the PCB, as JLCPCB is famous for its precise production and printing. The primary challenge I faced during that period was the delivery time, as JLCPCB's milling machines are located in Hong Kong. The whole process took one month, and at that point, I was uncertain whether the PCB I had designed would function as intended. Final PCB layer and Render, that was finished in the end of December 2024 shown in **Figure 4** and **Figure 5**.

2.3 ESP8266 Code for Multiplexing

While waiting for the PCB delivery, I focused on programming the microcontroller and configured the ESP8266 to control the multiplexers, enabling switching between the eight resistors' outputs. The decision to use the ESP8266 for this application was based on its functionality with Wi-Fi connectivity, reducing the need for external devices. This simplification allowed achieving a compact design with remote control. The code was written using the PlatformIO IDE and utilized libraries for Wi-Fi management. The code was designed to allow remote control of the multiplexers through a simple web interface hosted on the ESP8266's IP address.

The web server provides a form-based interface where users can select one of the eight resistors by number (from R0 to R7). When a resistor is selected, the control pins of the multiplexers—D5, D6, and D7—are set to represent the binary equivalent of the resistor number. Control pins were decided in the schematic design process and are controlled by a microcontroller. D5 corresponds to the least significant bit, D6 to the middle bit, and D7 for the most significant bit. The logic behind the code uses bitwise AND operations for specific values 0x01, 0x02, and 0x04, which are 001, 010, and 100 in binary form, respectively. Since the AND operation can be considered a multiplication, this allows checking the values incoming from the server for the chosen resistor.

The web interface was styled with embedded CSS (Cascading Style Sheets), making it user-friendly. Additional feedback messages were incorporated into the system, such as displaying the currently selected resistor and blinking an LED (connected to D4) based on the resistor number. The LED blinks a number of times equal to the selected resistor index to show selection in real time. The program operates in AP mode, allowing the ESP8266 to act as an access point. This removes the need for an external Wi-Fi network and enables direct communication with the device. Code for the ESP8266 can be seen in Appendix section: **Figure 1, Figure 2**.

2.4 Integrating LabVIEW with CryoBoss Software

A computer is a necessary component to run the software required for my project. The laboratory possesses the HPE ProLiant ML310e Gen8 Server, which was utilized as the central computing unit, running essential software to process and control the readout system.

The development of the readout system for cryogenic temperature sensors requires a data acquisition system and real-time visualization of sensor readings and performance. LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a suitable software for this task, as it uses graphical programming (drag-and drop blocks of functions) instead of lines of code. Furthermore, to take measurements from the HPD (High Precision Devices, Inc.) Cryostat equipment, I needed CryoBoss software that can not only parse the data from the sensors but also control and change conditions in the Cryostat's environment. Integration with a LabVIEW 2015 Runtime Environment is a crucial step for activating the CryoBoss software. This requirement was set by the manufacturer and does not allow initializing and opening the CryoBoss software using another version of the Runtime Environment.

After successfully initializing the CryoBoss software, I started configuring its hardware parameters and Lakeshore 372 AC Resistance Bridge and Temperature Controller settings according to the operation manual. This allowed me to get current values of the temperature and current inside the Cryostat. Next, the most important part was establishing communication with the NI Distributed System Manager. The System Manager connects with the CryoBoss network, giving access to use its shared variables in the LabVIEW environment for data acquisition. CryoBoss has different types of shared variables: Controls (Write Only) and Outputs (Read Only). Both of these are crucial for a readout system. At this moment, this allows me to generate an XY graph or a control system using PID in LabVIEW.

2.5 Finishing Cryoboss Setup

The Cryoboss system, that I installed last in Fall 2024 to work with the ADR cryostat from HPD Inc., turned out was not fully finalized. Although we were able to start the cryostat itself and get information from Lakeshore sensors from there, we had interference between data and problems with connected devices, especially with the compressor, which showed a lot of errors. In addition, the graphs themselves were not quite proportional to the periods, and in particular the excel spreadsheet that recorded measurement data showed unclear values. At the same time, everything also worked well on the old computer. After a while, having delved into the problem, I realized that it was about additional drivers for each device. Namely: Cryomech, Lakeshore, UPS, SRS_Calibration, USB-to-Serial Converter Drivers. This explained all the interference and inconsistencies. After successfully installing them and restarting the system, everything worked. Now we are running Cryoboss itself from a powerful new computer, and the entire environment has now become more convenient for taking measurements.

2.6 ADR Cryostat work principle

ADR is an adiabatic demagnetization refrigerator, or in other words cryostat, that has capability of achieving ultra-low temperatures that are approaching absolute zero ($-273.15°$C or 0 Kelvin), which can be considered as the coldest possible temperature in the universe. It utilizes its magnetic properties to reach temperatures in the millikelvin range. Currently, our Energetic Cosmos Laboratory has ADR cryostat from High Precision Devices Inc. .

In order to have an understanding of the working principle of ADR, I will briefly explain key physics principles that it uses [22]:

- **Adiabatic Process**
  Is a process when a system changes without heat flowing in or out. If you quickly squeeze the jar (without giving the time for heat to escape), the air inside gets warmer. If you reverse fly, the air gets cooler. No heat entered or left, however the temperature changed.
- **Paramagnetism**
  Some materials have tiny particles (electron spins) inside them that normally point in random directions. When these materials are put in a magnetic field, these tiny particles line up in one direction. This ordering releases heat. When the magnetic field is removed, tiny particles become random again, absorbing the heat in the process and making the material more cold.
- **Entropy**
  It's basically a measure of disorder or randomness. High entropy means things are random and disordered. Low entropy means things are neat and organized. Nature always tries to increase entropy over time.
- **Thermal Isolation**
  This means preventing heat from flowing in or out of the system (cryostat).

The work process of the ADR Cryostat:

1. **Initial Cooling:** The system starts with pre-cooling using liquid helium to reach about 4 Kelvin ($-269°$C).
2. **Magnetic Alignment:** Strong magnetic field is applied to a special material (paramagnetic refrigerant material).
3. **Thermal Isolation:** The paramagnetic refrigerant material is thermally isolated.
4. **Demagnetization:** The magnetic field is slowly reduced.

5. **Temperature Drop:** Demagnetization causes the temperature to drop dramatically.

6. **Maintaining Cold:** The system is kept isolated to maintain ultra-cold temperature.

7. **Experiment:** The measurements can be performed at extremely low temperatures.

8. **Recycling:** Due to the measurements or other factors, heat leaks into the system and warms it up. In order to remove heat again, the process of reapplying the magnetic field and then demagnetization should be done again.

2.7 MKID - Description

These are detectors made of superconducting materials. Their main ability is to sense the photon and measure its energy with high accuracy[23].

Key physical principles of MKIDs:

- **Superconductivity**
  Special state some materials enter when cooled to extremely cold temperatures. In this state, electrical resistance completely disappears, and electrons can flow without any energy loss. If we imagine the normal wire as a crowded hallway where people (electrons) bump into each other including the walls as they move, slowing down (resistance). A superconductor is like a hallway where people (electrons) can move through perfectly without bumping into anything (without resistance).
- **Cooper Pairs**
  In a superconductor, electrons don't move individually. Instead, they bound together in low temperatures forming "Cooper pairs". These pairs move through the material in perfect harmony, which is why there is no resistance. This phenomenon is related to quantum mechanics and has a more complex explanation, but my work is more focused with electronics.
- **Kinetic Inductance**
  Inductance normally comes from magnetic fields in coils of wire. However, in superconductors, there is kinetic inductance that comes from the inertia of the moving Cooper pairs. It takes effort to get a heavy object to move or stop, it takes energy to change the motion of Cooper pairs.
- **Microwave Resonator**
  It's a circuit designed to oscillate at specific microwave frequencies. A good analogy might be how a tuning fork that emits an A note vibrates if 440 Hertz is applied to it. The MKID circuit forms a resonator with very precise natural frequency.
- **Quasiparticles and Pair-Breaking**
  When a photon with enough energy hits the superconductor it can break apart Cooper pairs. The resulting unpaired electrons are called "quasiparticles". These quasiparticles disrupt the perfect flow of current.
- **Resonant Frequency Shift**
  Shift in the resonant frequency after the appearance of the quasiparticles in the superconducting material (in our case in MKID).

Working process of MKID

Initially, the MKID is placed in the ADR cryostat, at its lowest level. Next, after closing the installation, we start the cooling process. After the temperature reaches absolute zero, we start taking measurements. Measurements are made by sending a photon through an optical cable to the surface of the MKID.

As explained earlier, at absolute zero, our superconductor has Cooper pairs that can collapse at sufficient energy. After the photon hits the Cooper pair, it splits it into quasiparticles. The number of quasiparticles is proportional to the energy of the absorbed photon. The appearance of these quasiparticles changes the kinetic inductance of the superconductor. The more quasiparticles there are, the greater the kinetic inductance.

This kinetic inductance subsequently affects the shift of the resonant frequency and the phase response. Next, using a Vector Network Analyzer (**Figure 22**), we expose our MKID to a frequency range and monitor the amplitude and phase of the received signal. Our system then shows frequency shifts that indicate photon absorption. The size of the shift is proportional to the energy of the photon, allowing the MKID to see not only the presence of the photon, but also its energy (color).

Next, the quasiparticles begin the process of recombination into a Cooper pair back, which takes them from 1 microsecond to 1 millisecond.

2.8 Bonding - Description

Wire bonding refers to the process of joining two or more materials together to create a reliable connection between them using a wire. It looks similar to soldering, because it can be used to connect two terminals using aluminum wire. In case of wire bonding, this aluminum wire is 25 micrometers thick, which is thinner than an eyelash. It is very crucial in the context of MKIDs and Critical Temperature measurements.

For MKIDs it has minimal thermal impact. MKIDs operate at extremely low temperatures, and it is important to minimize thermal conduction paths that could introduce unwanted heat. It also has controlled loop height, which helps to minimize inductance that would degrade microwave signals.

For critical temperature measurement, wire bonding provides excellent electrical connections with minimal resistance, which is crucial for accurate four-point resistivity measurements. It also minimizes EMF voltages that could introduce measurement errors. Wires can often be removed without damaging the sample, allowing sample reuse in the future.

The main feature is that wire bonding does not need to heat the surface or use flux residues or solvents that could contaminate the superconducting surface.

2.8.1 Bonder Explanation

In our Energetic Cosmos Laboratory, we use the iBond5000 Dual Bonder that can operate in wedge and ball modes. For our research, wedge mode is enough. Although it has 12 parameters, I will describe the main ones I calibrate each time:

- **Search** – Controls the height of the bonding head at which it stops above the bond surface. Optimal height: 75–100 µm above sample.
- **Power** – Amount of ultrasonic energy applied to the bond.
- **Time** – Duration of ultrasonic energy and bonding force.
- **Force** – Downward force exerted by the bonding head.
- **Loop** – Height the bonding head rises after the first bond.
- **Tail** – Length of the wire protruding after the second bond.
- **Tear** – Length of the tear movement after the second bond.

Initially, the bond wire is fed through a tool called a bonding wedge. The wire is pressed against the bonding surface (MKID, critical sample, or pad) with a controlled force. Ultrasonic energy is then applied while maintaining this pressure. This creates a bond at the desired point. The needle moves to the second bonding location and repeats the process.

2.8.2 My Experience with a Bonder

I started working with the iBonder5000 when we used a new PCB for critical temperature measurement. My goal was to bond the pad from the PCB to the sample, and vice versa.

The first step is placing the sample in the holder (**Figure 21**). After fixing it with varnish, I position it on the bonder. Then I:

- Install the bonding wedge using hex keys.
- Feed the wire through two small holes — one visible, the other blind and angle.

Initially, inserting the wire took 1–2 hours. Over time, I adapted and now it takes 5–10 seconds. Perfect insertion of aluminum into the wedge can be seen in **Figure 18**. This image was done in the side angel, in reality it should be shifted by 90 degrees, so that wire was from the backside of the wedge. After insertion:

1. I calibrate the **Search** parameter.
2. Then adjust **Force** based on dent made on sample.
3. Gradually increase **Power** until bonding is successful.

This is done for the first bond (**Figure 14**), then repeated for the PCB pad. Even with optimal settings, deviations may occur due to imperfections on the sample surface.

2.8.3 Problems Occurring While Bonding

Despite learning how to use the bonder, I faced issues:

- **Clogged Wedge:** Broken threads stuck in the wedge's lower hole (**Figure 9**), this results in a situations where Wire could not be inserted through the tip of the wedge (**Figure 17**). I tried:
  - Rotating needle 180°
  - Using napkin fibers or eyelashes
  - Blowing with pressurized air
  - Using vibration mode of bonder
- **Wedge Breakage:** Sometimes it breaks from prolonged use.
- **Expired Aluminum Wire:** More prone to breaking and bonding failure.
- **Laser Misalignment:** Needs regular adjustment.
- **Needle Drop:** Accidental lever movement drops needle dangerously.

2.8.4 Sample Holder Installation

During bonding, I use two aluminum wires from the sample to the PCB terminal for reliability. After bonding:

- For temperature measurement: I apply silver paste (**Figure 19**) to the PCB back to improve thermal contact.
- I attach the PCB to the cryostat's lower level. (**Figure 16**)
- For MKID: I screw the device to the cryostat and connect optical cables for photon input. (**Figure 15**)

I need also to mention importance of checking the set-up before installation. First is the electronics of Cryostat. Using simple resistors ranging from 2 Ohm to 15 kOhm. I connect them into the cryostat and waiting the scan of the Cryoboss system. If electronics successful, I will notice the resistor value either in Lakeshore Equipment or on the graph in the Cryoboss software. Another important thing is to check the contacts of the PCB with multimiters continuity test. There could be problem where tail of one connection could touch another terminal or another aluminum wire, which in result could create a shore circuit. Continuity mode of the miltimeter also help to identify the short circuit which could be resulted due to excess of the silver paste on the sample holder. This checking techniques help to prevent mistakes from the beginning. Ignoring this mistake lead to the problems with a measurements and waste of time and materials to assemble and cooling down cryostat.

2.9 Testing Methodology

To commence the testing the PCB board will be checked for the current leakage trough the multimeter's continuity mode. The same process will be done after soldering integrated circuits as well as other components to check their proper installation. Next step is assembling of the system. Microcontroller will be checked to his Wi-Fi capabilities, as well as it's ability do define which channel of the multiplexers will be opened. It can be checked using select bits of multiplexers which are controlled by ESP8266. The next step is connection of the Voltage supply ot the board as well as sensor to test the value of the voltage on the resistors. The voltage will be supplied itself through the jumper wire imitating the voltage on the resistor. Then using phone or computer that connected to the ESP8266 through the Wi-Fi I turn on the channel to which voltage supply is connected. The result should be voltage reading no the multimeter, which should be equal to the input voltage.

Chapter 3

Results

3.1 Final PCB Design and Testing

The design that was done in Fall 2024 and printed by JLCPCB was perfect in terms of connection, with all 32 inputs and 4 output channels functioning as intended. This was verified using the continuity (sound check) mode of the multimeter. Multiplexer switching using the ESP8266 microcontroller was continuous, with no observed signal distortion or connection errors. However, my design did not consider the dimensions of the board in relation to its connection with external sources. Additional problems appeared due to the proximity of connectors and screw terminals in the layout.

The input and output terminals were positioned too close to the microcontroller, causing overlaps with the ESP8266 module. To address this issue, I had to partially disassemble the screw terminals, leaving only their leads exposed to make connections. Despite this, only 8 of the initially designed 32 inputs could be tested effectively because the ESP8266 covered several connectors. (**Figure 12**)

In order to test the PCB, I extended connections between the microcontroller and the connectors using male-to-female jumper wires. This allowed me to check the functionality of all input channels. Initial tests using a voltage source and a multimeter showed the PCB's ability to handle signals as expected. This test was done to check and confirm its reliability before integrating the PCB with sensors like the Lakeshore 372.

Understanding the limitations of the first designs I created new PCB (**Figure 13**), which again ordered from JLCPB. Now it was much more easier to do a connection between the source and the sensors. Moreover, I increased space between integrated circuits to potentially reduce the noise that resulted in previous testing.

3.2 Testing Web Interface and Channel Performance

The IDE codecontrolled by the ESP8266 demonstrated switching between the input channels. After connecting to the ESP's access point, I could control the selection of channels through the web page. This web interface is hosted on the default IP: 192.168.4.1. The selected channel was displayed on the serial monitor in PlatformIO and on the website, confirming switching functionality.

In the Fall 2024, testing each channel with a 3.3V input source demonstrated consistent results. Since it was only testing phase, i decided to use one voltage supply to simulate voltage on one resistor. Even though I had 8 slots for 4 wires, which is required for 8 resistors, I could check it with only one channel. Whenever Multiplexer opens the desired channel, output sensor should show input voltage on that resistance. For the test I take 4 wires, where 3 of them were connected to ground and 1 wire to the voltage supply. The input to the sensor (which in my case was multimeter) also had three wires connected to the ground probe and one to the voltage sensing probe. Then I just turned on the system and mircocontroller to change how circuit is behaving. By connecting to the ESP8266 through Wi-Fi I controlled and selected desired channels. The selected channel displayed the correct voltage of 3.2–3.3V, as expected. Non selected channels showed a slightly lower voltage of 2.1V, likely caused by noise in the circuit. Despite this minor discrepancy, the system reliably distinguished between active and inactive channels, validating its performance. However, the next day, problems arose in the system itself. The issue was that many contacts had open circuits. When analyzing each connection, it was revealed that the multiplexer was damaged, causing the experiment to be temporarily suspended and requiring a new batch of multiplexers to be ordered. Additionally, the design was improved and reordered with assembly from JLCPCB.

During the Spring 2025, more precisely on March I received my newly ordered PCB and proceed to test with the same method. Soldering process was much more easier as well as the construction of the setup. Previous version had problems which required to use additional 32 jumper wires, while new version needed only 8. Testing was done on the same conditions and it was considerably better than before. Not only it had smooth readings it had lower noise than before. The selected channel showed 3.26V while the input was 3.3V. Measuring of not used channels showed 0.1V and some times even smaller, which is approximately 3% error. It is also confirms that my theory about the distance between integrated circuits could result in the greater noise.

3.3 CryoBoss and LabVIEW environments

CryoBoss currently displays the temperature, voltage supply, and current. Using LabVIEW, I was able to monitor and access shared variables designed by HPD. These shared variables allowed the creation of XY data graphs, providing a visual demonstration of the readout system from the cryogenic temperature sensors. Additional work is ongoing to expand functionality. One challenge involves rewriting and editing log files generated by CryoBoss. This will enable the creation of graphs for data from other channels of the Lakeshore 372 in the future. The integration will improve monitoring and analysis in cryogenic applications. At the moment, I was able to enable the last Channel 4 for the measurements. However, there are still difficulties in making it visible and shared in LabVIEW. Despite challenges with connector placement and limited access to all inputs, the system successfully demonstrated accurate performance in controlling and monitoring cryogenic temperature sensors. Future improvements will focus on optimizing the PCB layout and expanding functionality to log and graph data from additional channels.

3.4 MKIDs and TC bonding results

In the beginning of January 2025, I started to do bonding samples. There were two types of MKIDs:

- National Institute of Standards and Technology from the United states.
- Nanofabrication Physics laboratory of Nazarbayev University

This **Figure 20** shows two different MKIDs in two different sample holders.

Overall, 4 MKID samples were bonded, where 3 of them from NU and 1 from NIST. Unfortunately, NU samples did not show any results, and firstly I thought that the problem could lie in my bonding, even though I did it as precise as possible. Moreover, I always showed resulted bonding to the professor Mehdi Shafiee before we are used them to the measurements, and with his confirmation only we proceeded to the next step. Then we decided to check the NIST sample as a reference in order to understand why samples form NU do not shows any result. Bonding of the NIST samples was the same as for the NU MKIDs, but it showed noticeable results.

From the graph on **Figure 25** can be seen frequency measurements on range 3.5-4.7 GHz. Each downward sharp drop represents individual resonator, which absorbed photon energy on its unique resonant frequency. This dip depth vary from 10 to 16dB below baseline. This indicate difference in coupling strength among resonators. The gradual increase from 18dB to 24dB shows that there is frequency dependent system attenuation. Obtained results confirms successful resonator operation.

These graphs (**Figure 23**, **Figure 24**) show critical temperature measurements for a Titanium Nitride (TiN) sample. Both graphs display the same phenomenon: the superconducting transition. Y-axis shows the electrical resistivity of the TiNm while X-axis shows temperature. The transition to normal resistance occurs as temperature increases. In other there is a transition from superconducting state to non-superconducting state. There is sharp transition around 1.5K and 3K. We can define the critical temperature as midpoint of this transition 2.25K.

Chapter 4

Conclusion

The development of the readout system for cryogenic temperature sensors required PCB design, an ESP8266 microcontroller for control and website hosting, and software such as LabVIEW and CryoBoss for data acquisition. The Fall 2024 design of the PCB, assembled by JLCPCB, solved earlier problems like current leakage and damaged connections, which appeared in the prototypes made by the LPKF machine. However, initial design problems such as the proximity of connectors and screw terminals to the ESP8266 microcontroller demonstrated a need for future dimensional redesign. When selected through a website, inputs demonstrated the correct voltage level, validating the accuracy of the system, despite huge noise that appeared at unselected channels of the multiplexer. From my point of view, this problem could be solved when all 32 inputs are connected. But at that moment I was wrong. Then, after testing redesigned new PCB, which had greater distance between integrated circuits, and greater dimensions itself so that it will not block connection of usb from the computer. Results from new board was successful. Not only it was easier in terms of connection, soldering and assembling the system, it also had much more lower noise, which could be neglected.

The configuration of LabVIEW and CryoBoss brought new capabilities to the system's monitoring. Shared variables from CryoBoss are crucial for the creation of XY graphs, providing a real-time visualization of temperature and other sensor data. However, challenges remain in enabling all channels of the Lakeshore 372 and editing CryoBoss log files for enhanced data logging and graphing capabilities.

This project highlighted problems such as multiplexer failure in the Fall 2024 during testing and the need for reliable components and further improvements to the PCB lay out. Despite these challenges, the system demonstrated moderate performance in controlling and monitoring cryogenic sensors. Nevertheless, focus that was set previous year was achieved by on optimizing the PCB layout to resolve spatial constraints and expanding system functionality.

This project also included the bonding of the MKIDs and TiN samples which were measured later. Measurements provide evidence of successful MKID device fabrication and characterization from NIST. It also helped to indicate and notice the problems for the Nanofabrication laboratory of Nazarbayev University, which will this helped them understand that there are a couple of omissions in their fabrication process that should be taken into account, which will help them revise their plan and the production algorithm of the MKID. This will not only help with their research, but it will also help them send their samples or make production of MKIDs, which they could sell as NIST does. The Titanium Nitride demonstrate a clear superconducting transition with critical temperature approximately ate 2.25K. The frequency sweep measurement reveals multiple resonators across 3.5-4.7 GHz band. These results could be used as a foundation for further optimization of resonator coupling, quality factor or enhance detector sensitivity in future.

This project not only develops the cryogenic readout system but also lays the foundation for further research in quantum computing, astrophysics, and other fields requiring precise low-temperature measurements.

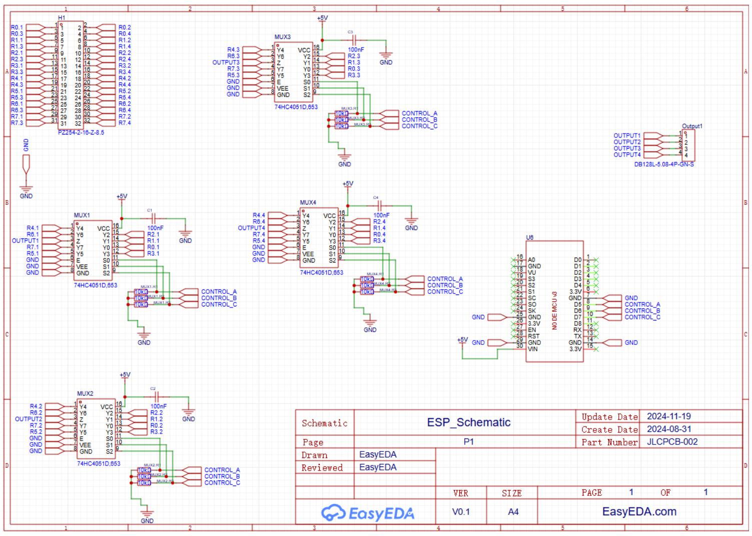
.1 Appendix: Supplementary Images

```
void setup() {
  Serial.begin(115200);
  delay(1000);
  Serial.println("Multiplexer Control Initialized");

  pinMode(controlPin0, OUTPUT);
  pinMode(controlPin1, OUTPUT);
  pinMode(controlPin2, OUTPUT);

  digitalWrite(controlPin0, LOW);
  digitalWrite(controlPin1, LOW);
  digitalWrite(controlPin2, LOW);

  // Connection with Wi-Fi network
  Serial.println();

  WiFi.mode(WIFI_AP);
  WiFi.softAP("ESP8266_Multiplexer", "12345678");

  Serial.println();
  Serial.println("Access Point Started.");
  Serial.print("IP address: ");
  Serial.println(WiFi.softAPIP());

  server.on("/", handleRoot);
  server.on("/select", handleSelect);
  server.begin();
  Serial.println("HTTP server started");
}

void loop() {
  server.handleClient();
}
```

Figure 1: Code for PCB - Setup 1

```
void handleSelect() {
  if (server.hasArg("resistor")) {
    int resistorNumber = server.arg("resistor").toInt();

    if (resistorNumber >= 0 && resistorNumber <= 7) {
      currentResistor = resistorNumber;

      digitalWrite(controlPin0, (resistorNumber & 0x01) ? HIGH : LOW);
      digitalWrite(controlPin1, (resistorNumber & 0x02) ? HIGH : LOW);
      digitalWrite(controlPin2, (resistorNumber & 0x04) ? HIGH : LOW);

      Serial.print("Resistor ");
      Serial.print(resistorNumber);
      Serial.println(" selected.");

      for (int i = 0; i <= resistorNumber; i++) {
        digitalWrite(ledPin, LOW);  // LED on
        delay(300);
        digitalWrite(ledPin, HIGH); // LED off
        delay(300);
      }
```

Figure 2: Code for PCB - Setup 2



Schematic	ESP_Schematic	Update Date	2024-11-19
		Create Date	2024-08-31
Page	P1	Part Number	JLCPCB-002
Drawn	EasyEDA		
Reviewed	EasyEDA		
VER	SIZE	PAGE 1 OF 1	
V0.1	A4	EasyEDA.com	

Figure 3: Full Schematic of PCB

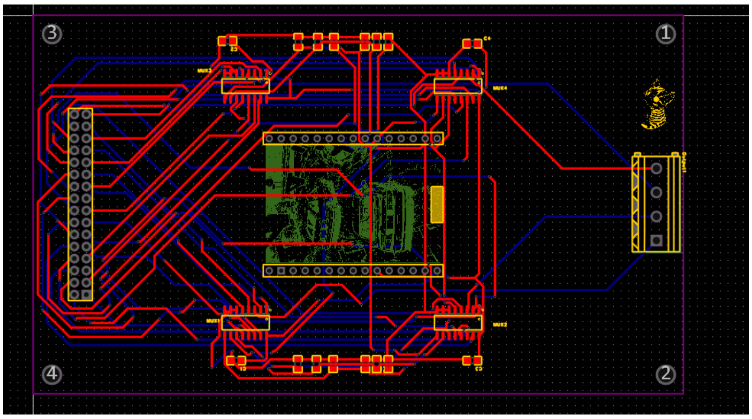


Figure 4: PCB Layer Design

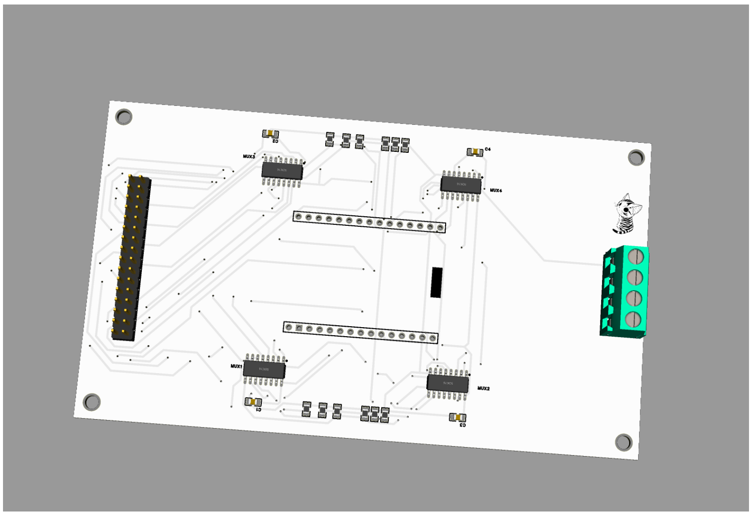


Figure 5: 3D Render of PCB Design

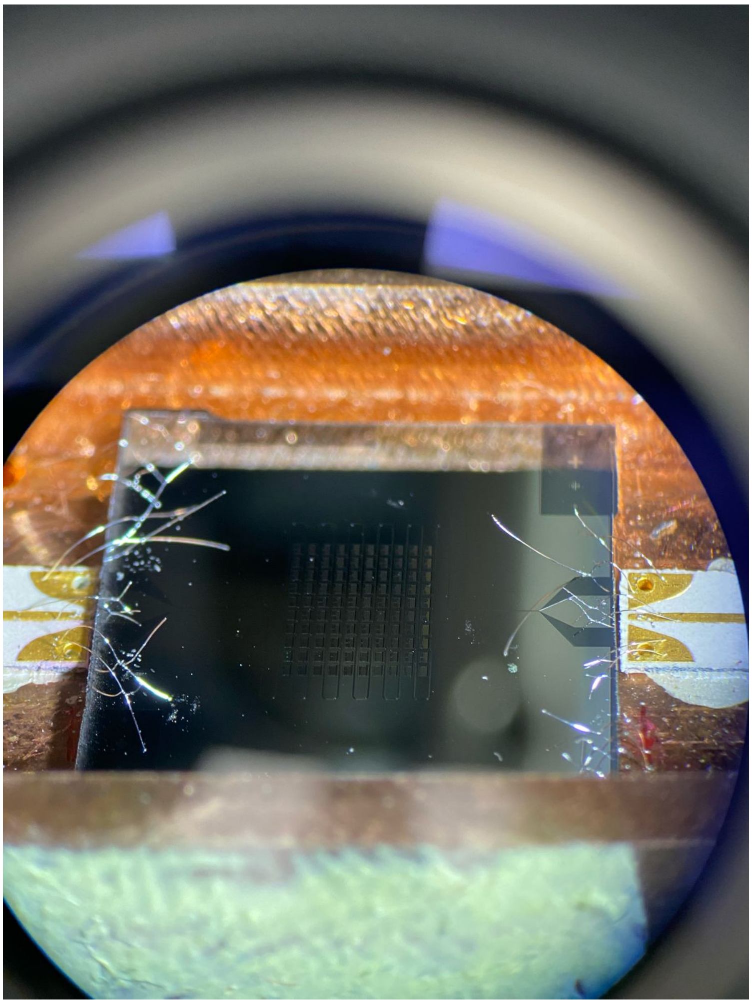


Figure 6: Bonded MKID

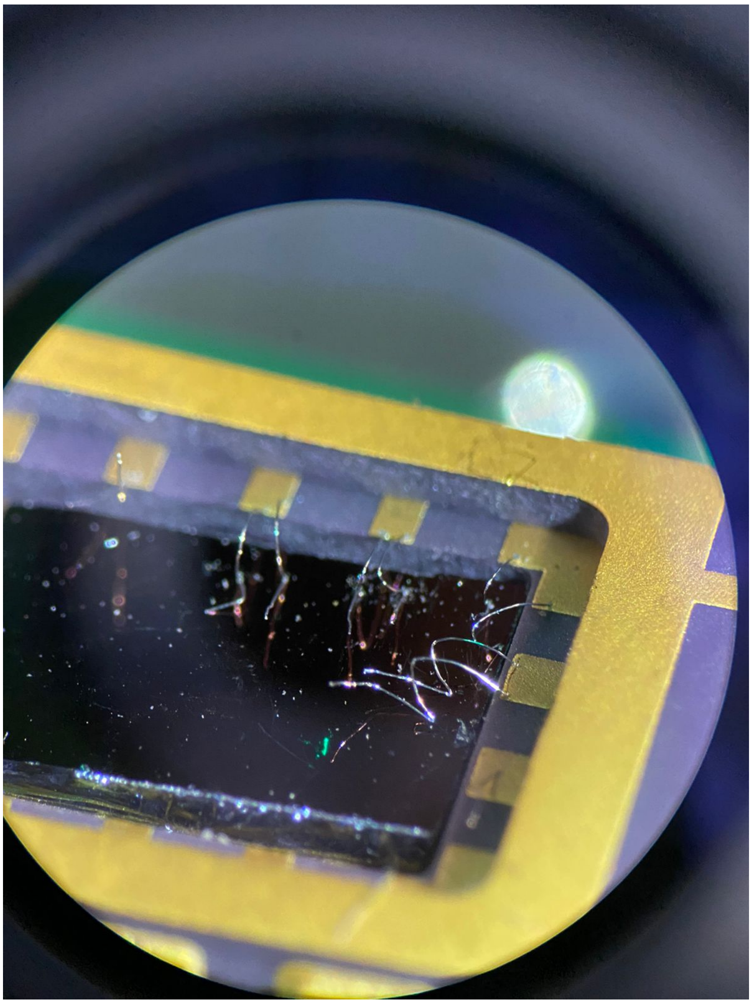


Figure 7: Bonded Sample Scars

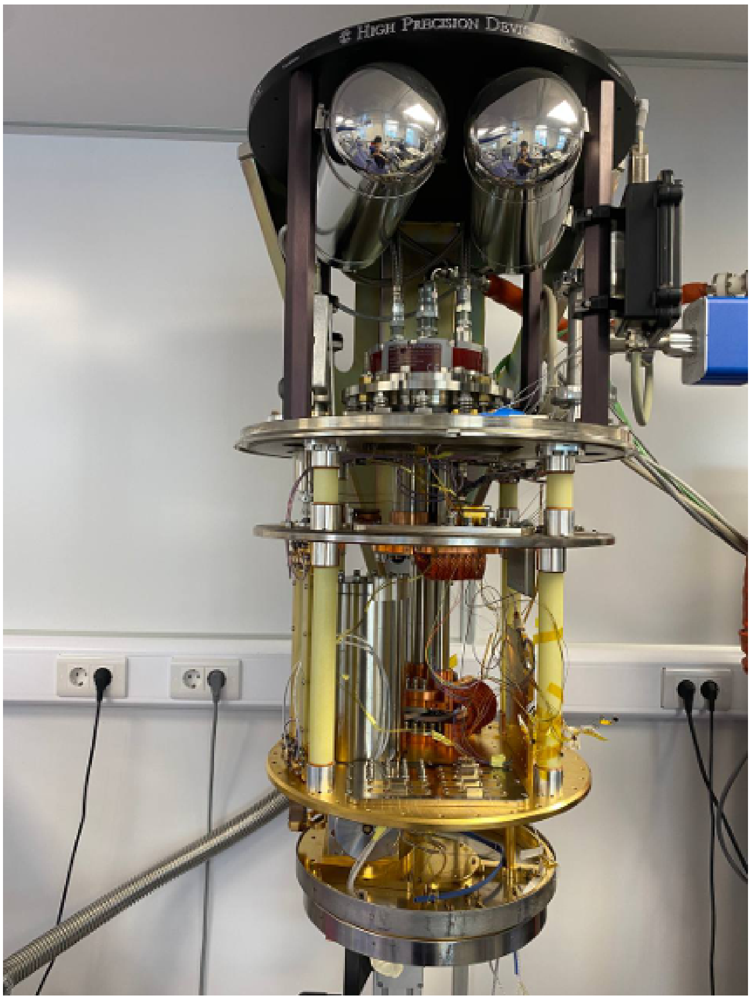


Figure 8: Cryostat Assembly

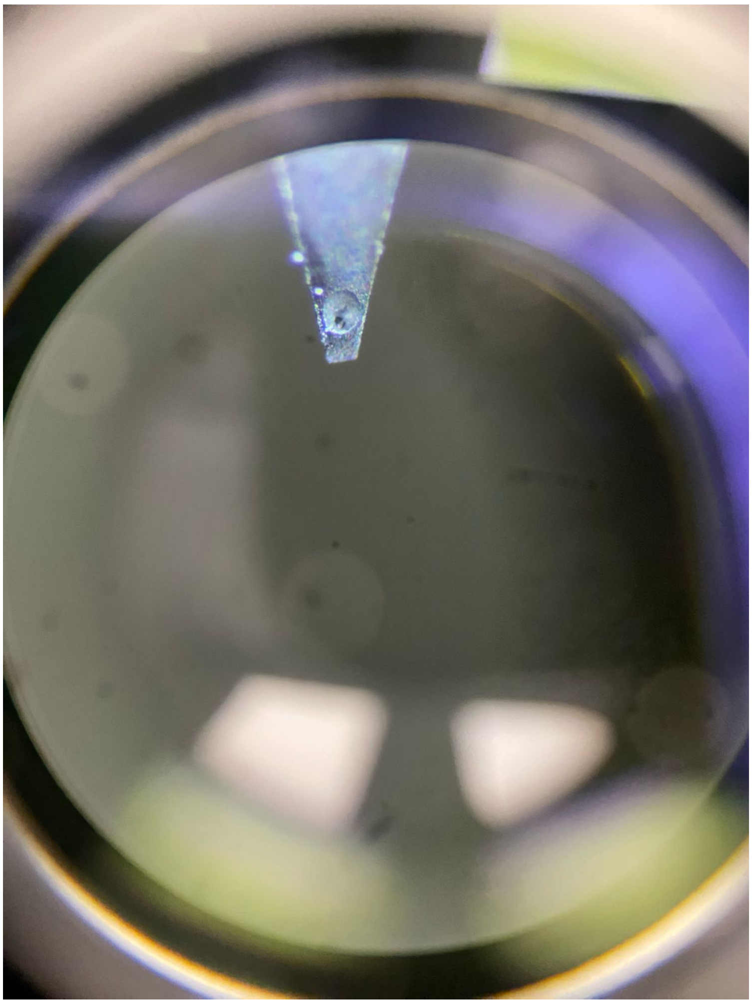


Figure 9: Contaminated Wedge

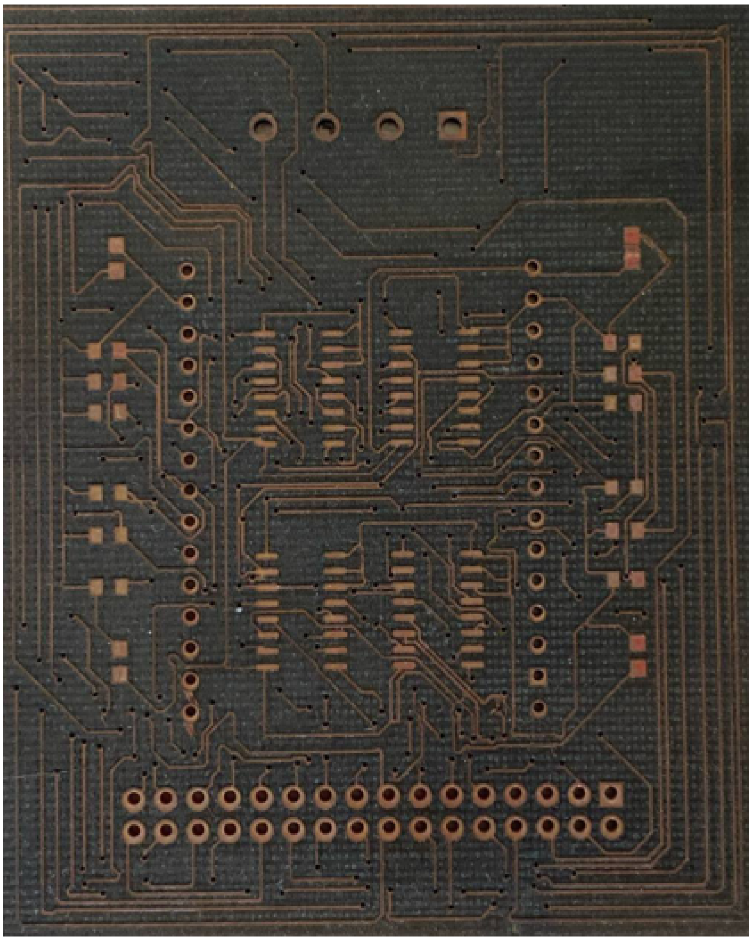


Figure 10: First PCB Design - NU

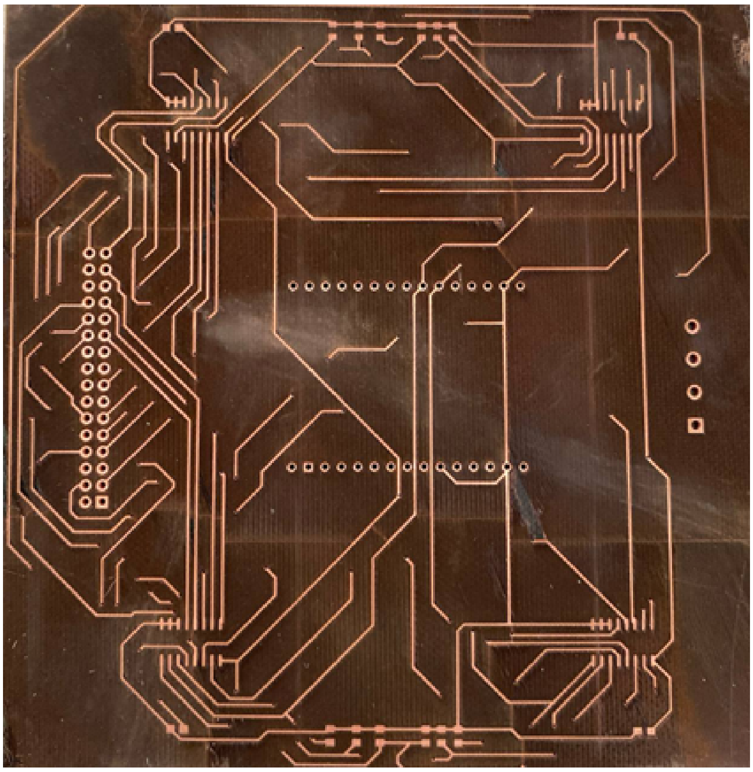


Figure 11: Second Version of PCB at NU

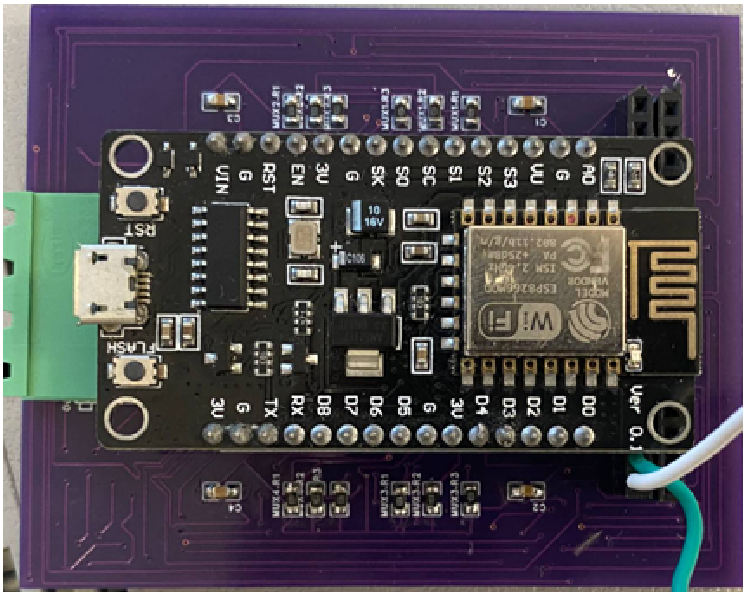


Figure 12: First Version Ordered from JLCPCB

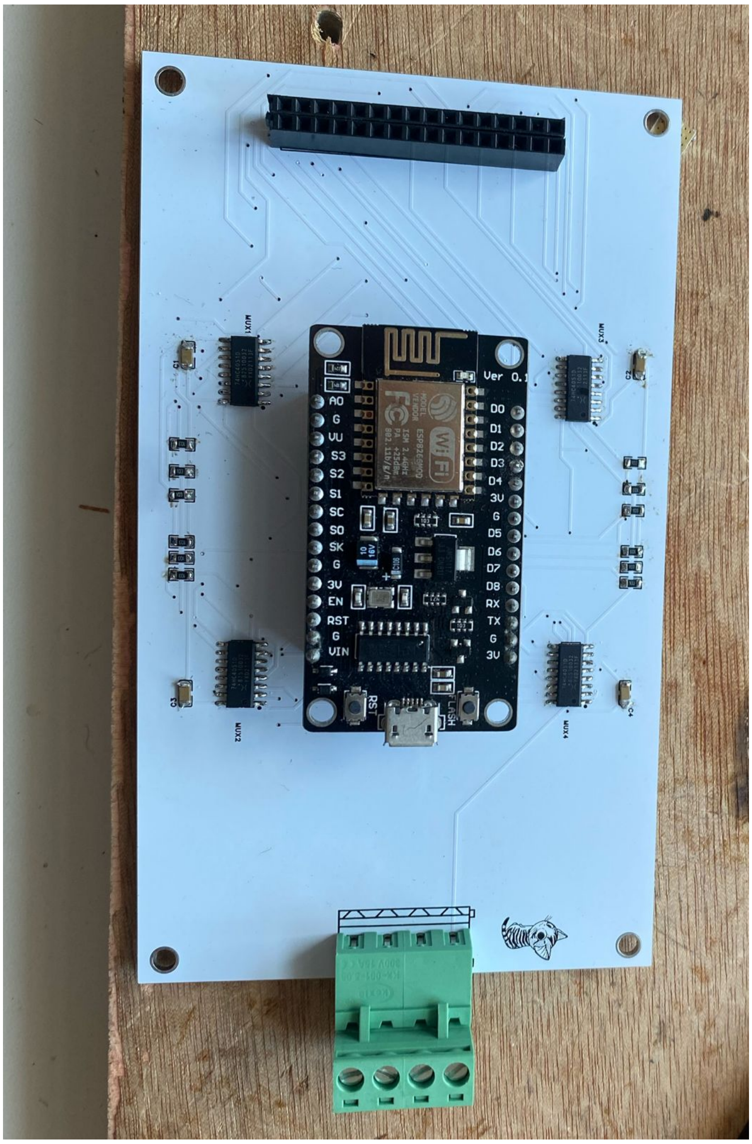


Figure 13: First Version Ordered from JLCPCB

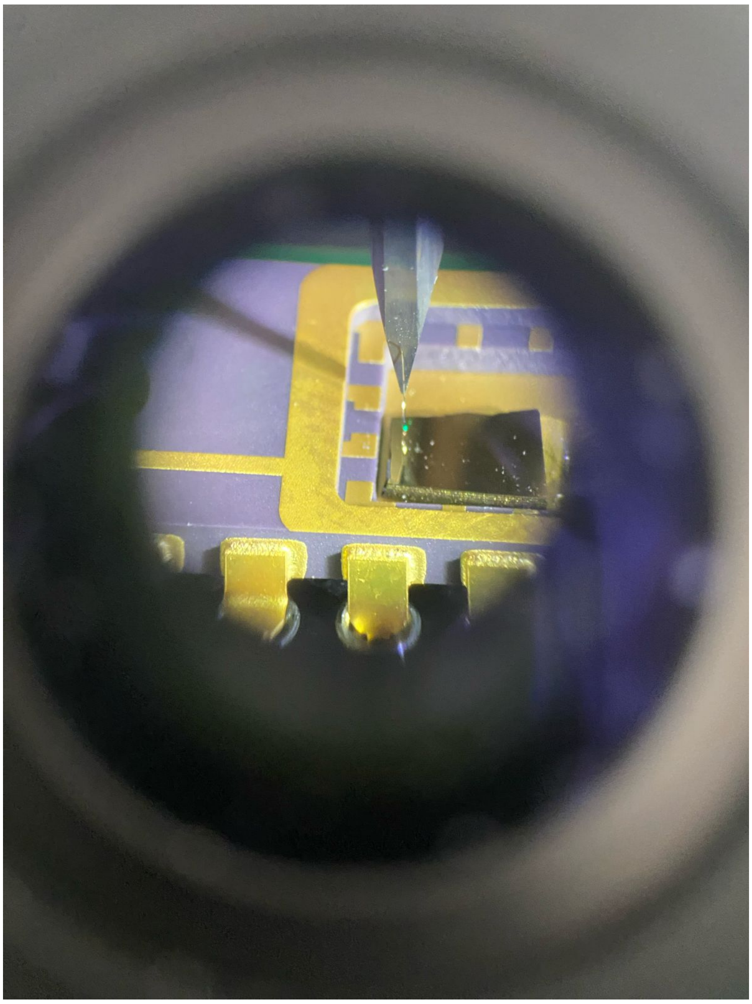


Figure 14: First Stitch Bonding in Process

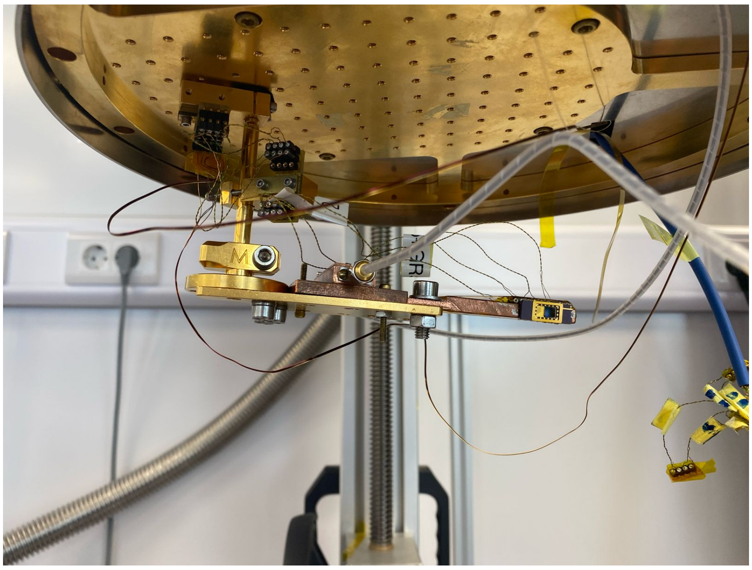


Figure 15: Installed MKID for Temperature Measurement

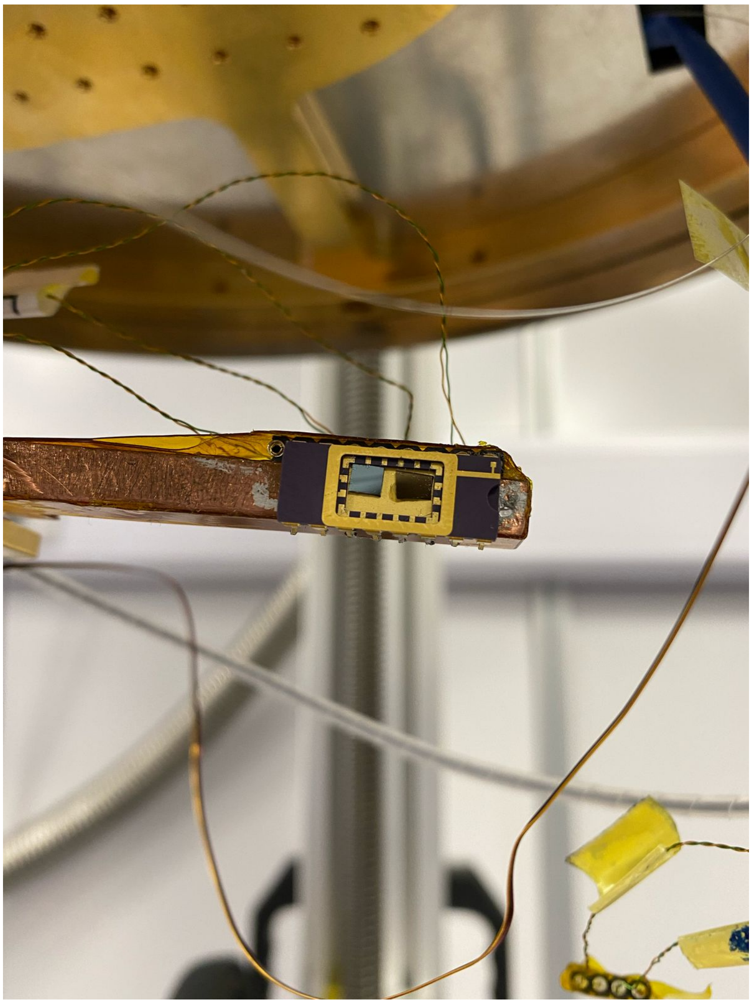


Figure 16: Installed TC Sample

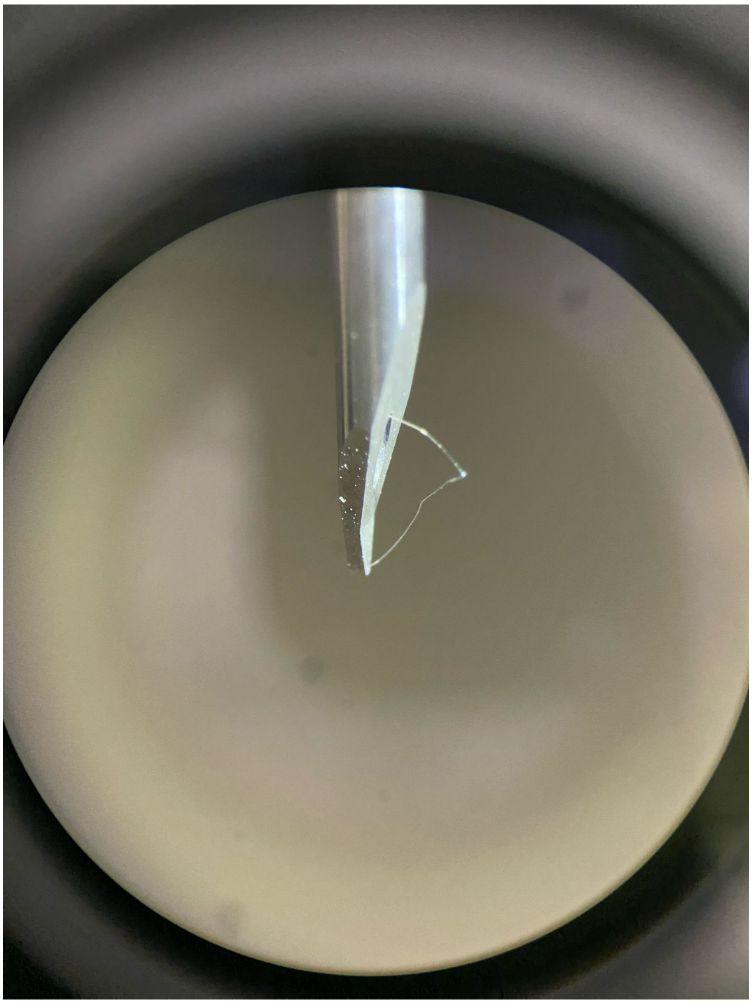


Figure 17: Needle Stuck in Bonding Tool

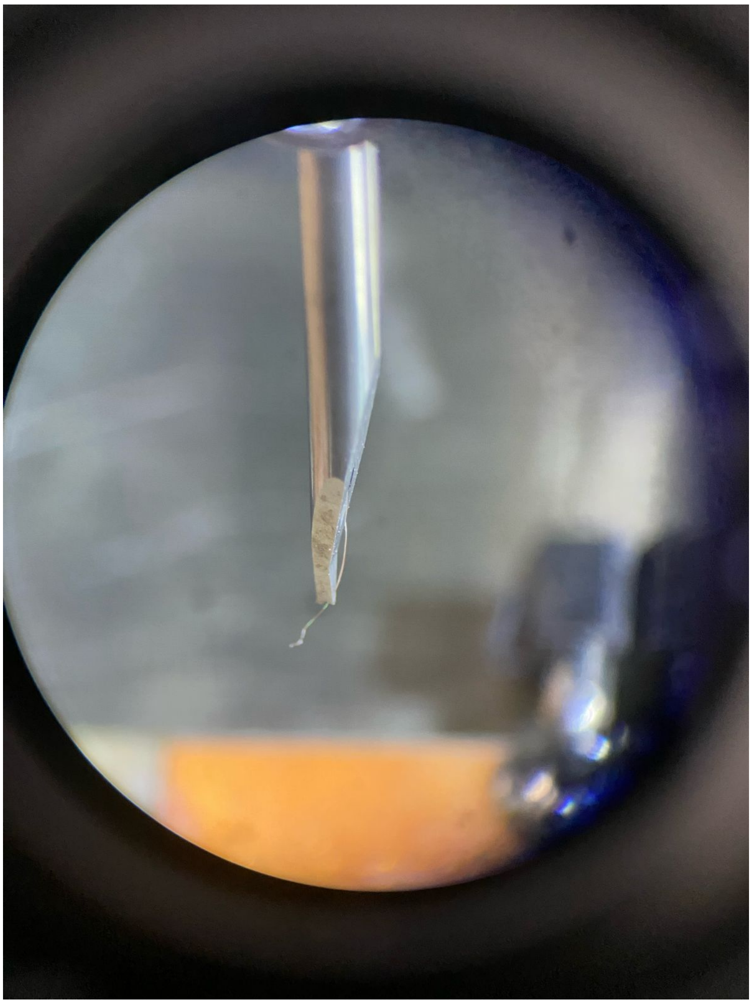


Figure 18: Microscopic View of Perfect Wedge Side

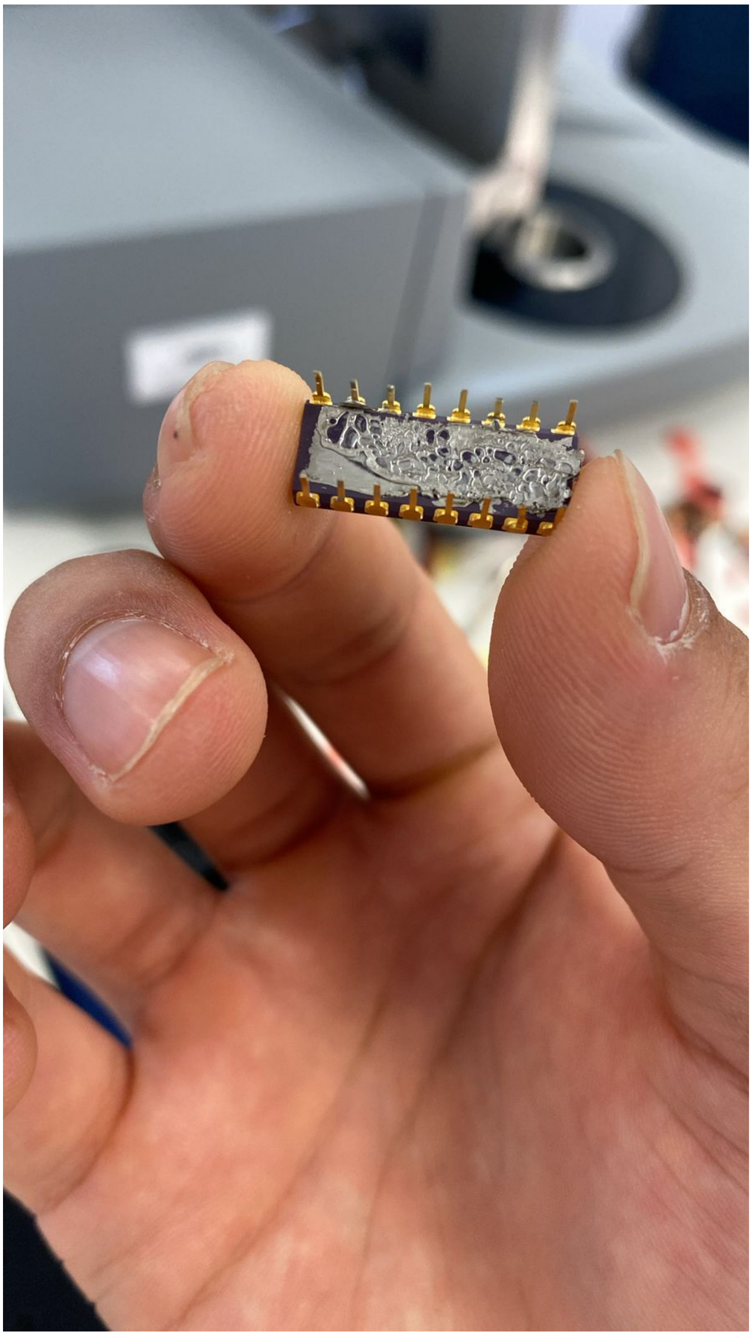


Figure 19: Silverpaste Preparation for Thermal Contact

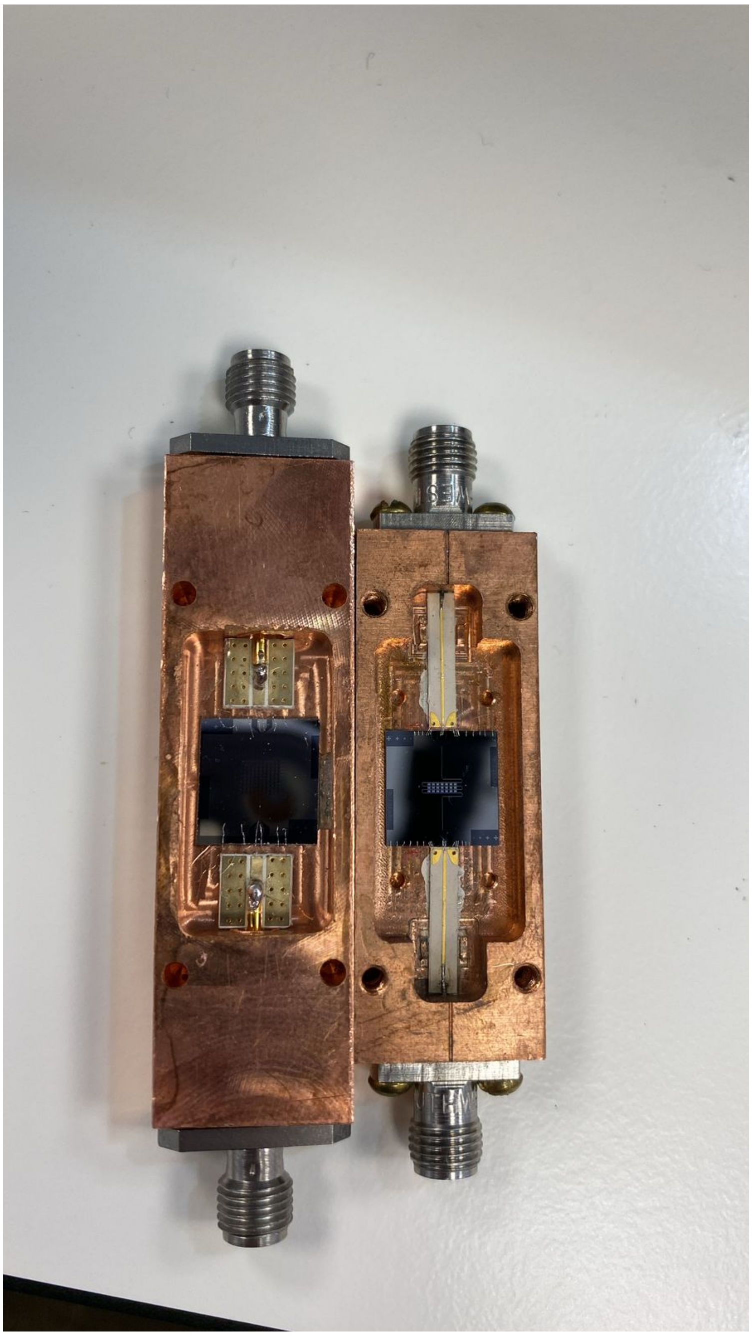


Figure 20: Two Bonded MKIDs

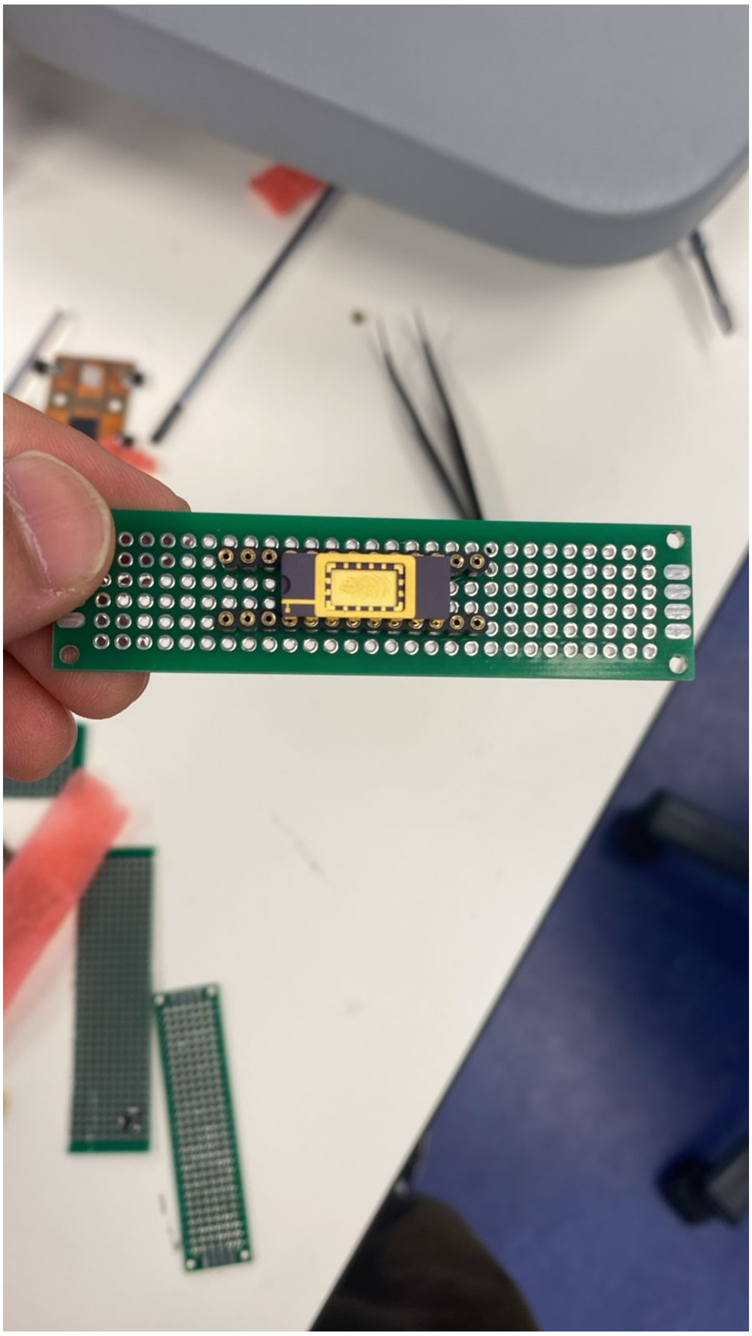
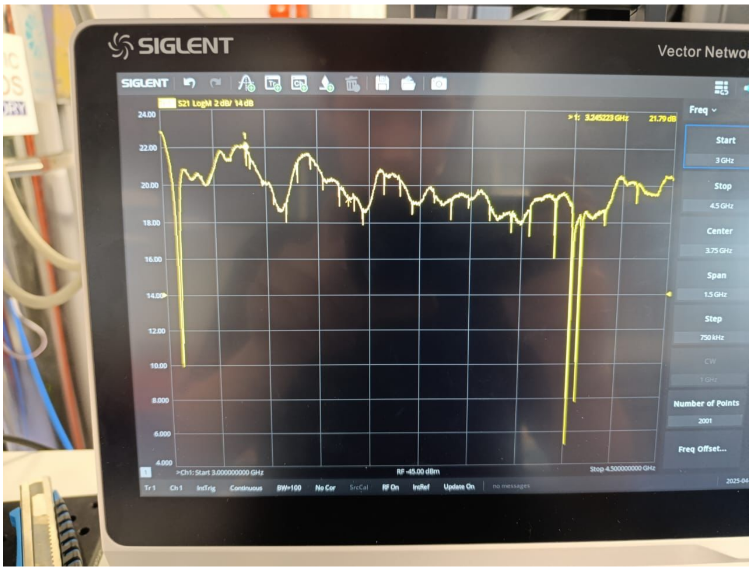


Figure 21: Custom Holder for TC Sample



Start 3 GHz
Stop 4.5 GHz
Center 3.75 GHz
Span 1.5 GHz
Step 750 kHz
Number of Points 2001
>Ch1: Start 3.000000000 GHz
RF -45.00 dBm
Stop 4.500000000 GHz
Tr 1 Ch 1 IntTrig Continuous BW=100 No Cor SrcCal RF On IntRef Update On no messages

Figure 22: Vector Network Analyzer Output

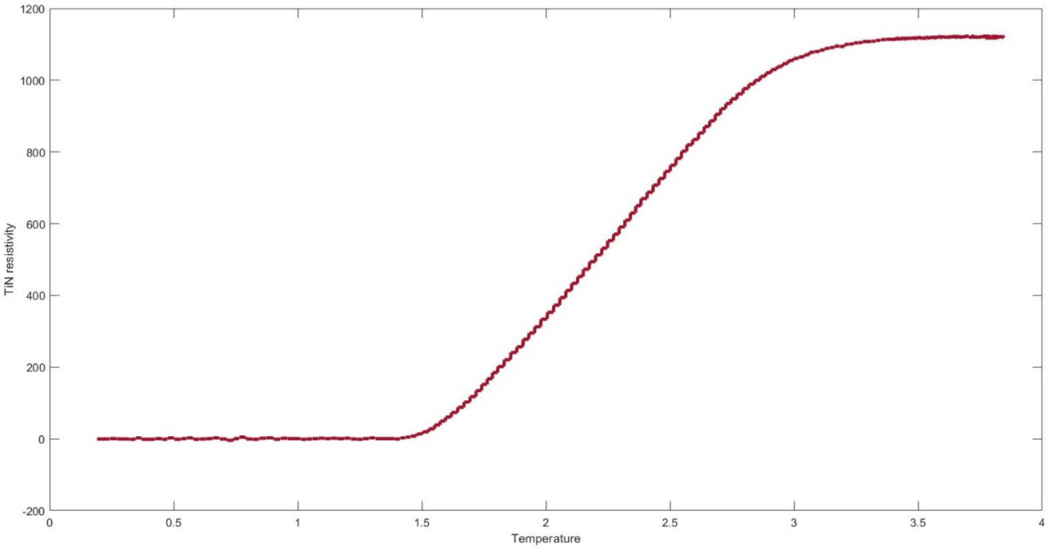


Figure 23: Temperature Coefficient Measurement Setup

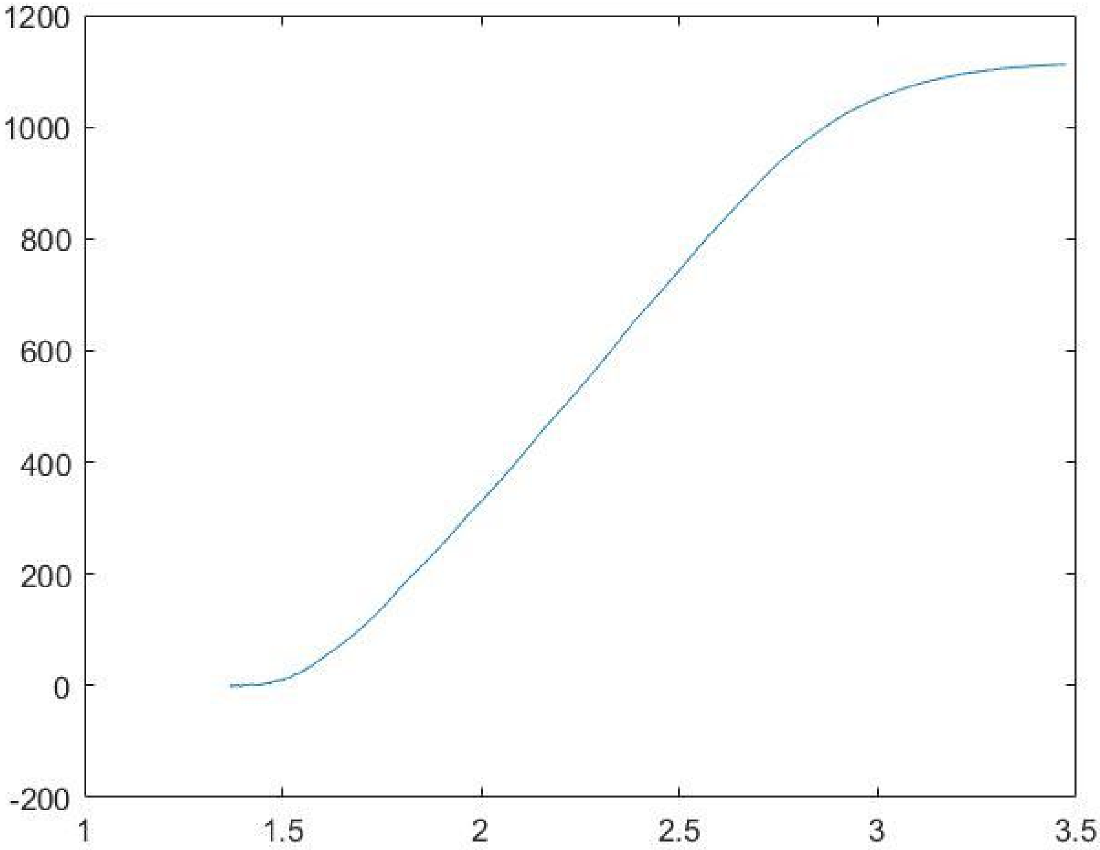


Figure 24: Measurement Graph - TC

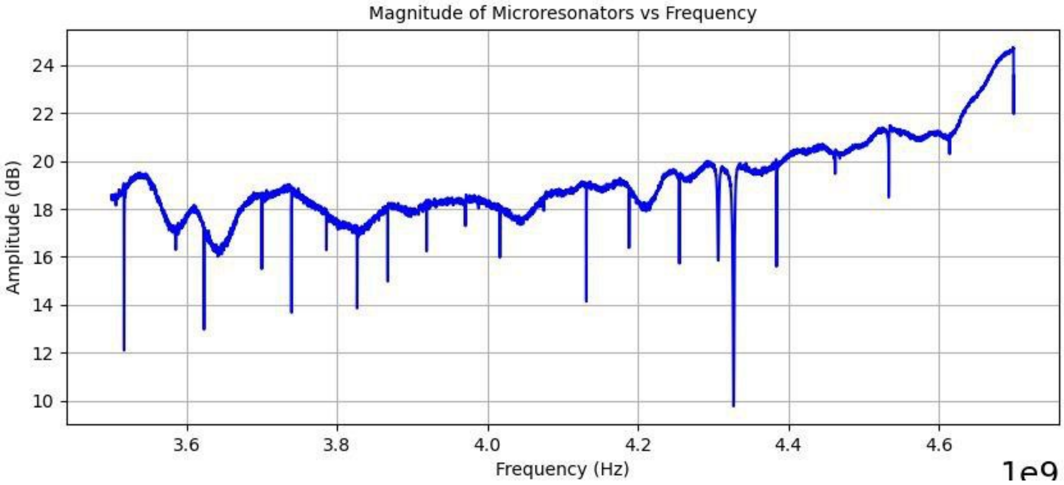


Figure 25: MKID Measurement Setup

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