LAB 2:THIN FILM TUNNELING

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Contents

1 Abstract

The purpose of this lab was to observe the properties of tunneling in a metal in superconducting state. To do this, the voltage drop across a thin film between a normal metal and a superconducting metal at low temperatures was analyzed. Liquid helium was used to bring the temperature of the setup down to about 1.7K. The thin film tunneling was studied by creating a chip and measuring the voltage drop across across junctions using the 4 wire method. A function generator with a triangle wave was used as an input and the data was collected with a digital oscilloscope. The data of the voltage drop, along with a known resistance, was used to find the current and plot the I-V curves of the circuit. It was found that as the temperature decreases, the width of the band gap increases.

2 Introduction & Theory

Superconductivity is a phenomenon that was first observed by H. Kamerlingh Onnes 3 years after his discovery of liquid Helium. Liquid Helium has a boiling temperature of about 4K depending on the pressure. The discovery of it allowed physical systems to be cooled down temperatures which don't naturally occur on the Earth. What he observed when cooling metals was that the electrical resistance of the metals would disappear at a low temperature, which he called critical temperature T_c, and that this temperature was an intrinsic characteristic of the metal itself. The hallmarks of superconductivity are perfect conductivity and perfect diamagnetism. This means that the magnetic field is not just prevented from entering the superconductor but also that any original field is expelled from it. This second phenomenon is called the Meissner.

To explain the absence of thermoelectric effects, there has to exist an energy gap between the ground state and the excited states of the system. This gap has to be of the order of kT_c. A better understanding of this didn't come until 1957, where Bardeen, Cooper, and Schrieffer proposed the know accepted BCS theory of superconductivity. Weak attractive interactions between negatively charged particles cause instability of the ground state of the electron gas. The fermions have an energy lower than the Fermi energy, and have equal and opposite momentum and spin, so they are bound. This weak interaction between the electrons disrupts the metal's lattice, as ions get attracted to these electrons, increasing the positive charge density, which attracts electrons. There is a point where the attraction due to the disruption of the charge density overcomes the same-charge repulsion of the electrons and they become bound. Because the binding energy is less than the Fermi energy, the electrons pairs overlap.

The Hamiltonian of the system can be expressed by a sum of two components, one of a free quasiparticle fermion gas and one mean-field interaction. The second term has a negative binding energy to account for the energy due to the effective electron attraction. The binding energy is mathematically analogous to an energy gap, so it is called the superconducting energy gap. The semiconductor analogy predicts the temperature dependence as following:

$$\Delta(T) \approx 3.06 k_b T_c \sqrt{1 - \frac{T}{T_c}} \tag{1}$$

for high temperatures and

$$\frac{\Delta(T)}{\Delta(0)} = tanh(\frac{T_c}{T}\frac{\Delta(T)}{\Delta(0)}) \tag{2}$$

more generally, for all temperatures.

The technique we used to measure the energy gap in this experiment was developed by Giaever in 1960. A thin insulating oxide film will be deposited in between two thin metal films. From quantum mechanics, we know there is a nonzero probability of electrons crossing, or tunneling, from one of the metal plates to the other. When a voltage greater than the binding energy of a Cooper pair is applied to the junctions, an electric current should be able to flow. The pattern that this yields shows the current dropping to zero as the voltage approaches the binding energy at zero temperature. [1]

During this lab, we will be looking at $I - V$ curves, where I is the current and V the applied voltage. There are two equations that can describe these relationships:

$$I = A|T|^2 \rho_1(0)\rho_2(0)eV \tag{3}$$

for the metal in a non-superconducting state and

$$I = A|T|^2 \rho_2(0) \int_{-\infty}^{\infty} \rho_{1s}(E)[f(E) - f(E + eV)]dE \tag{4}$$

for the metal in superconducting state. In these equations, ρ_1 and ρ_2 are the energy-dependent densities of states of the two metals, T is the temperature, eV the applied voltage, $f(e)$ is the Fermi function, and A is a constant. The Fermi-Dirac distribution function can be seen in Figure 1. As we approach 0K, we expect the function to become a step function with a step when the energy equals the Fermi energy.

By integrating equation (3), we should get a trend similar to the one on Figure 2. The

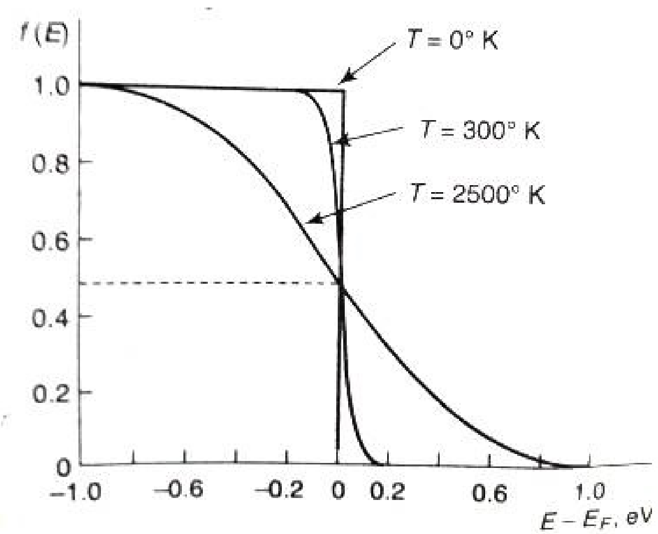


Figure 1: Fermi-Dirac distribution function (Source: https://www.elprocus.com/)

thin solid line is the observed trend of the current along a normal metal to normal metal junction. The thick solid line represents the trend that a junction between a normal metal and a superconductor would have. [2]

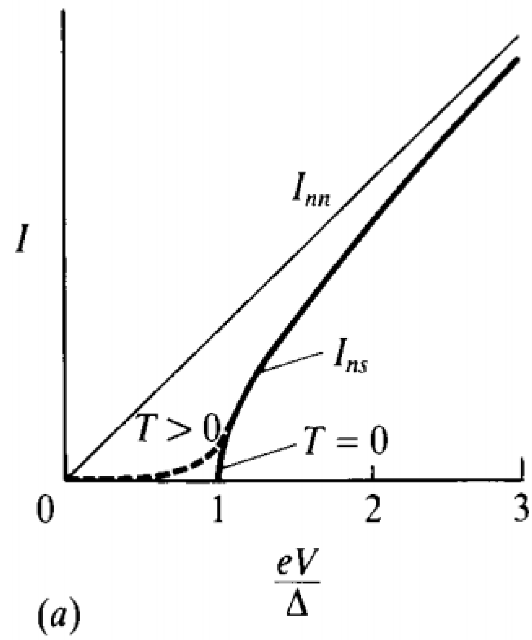


Figure 2: I-V curve for a superconducting metal (Source: Michael Tinkham, "Introduction to Superconductivity")

What we observed during the lab was the formation of the energy gap in order to have current flow when there is a junction between a normal metal and a superconductor. The energy gap Δ above and below the Fermi energy needs to be overcome by the applied voltage. By finding a point of discontinuity in the slope of the current vs voltage plot, we are able to directly measure the gap.

Based on the theoretical background, we expect to have no band gap at room temperature or at 77K when cooling the system with liquid nitrogen. As we decrease the temperature, we expect to see a band gap developing. In an I-V curve, this would be a shift from a straight line to something more similar to a cubic relationship. The band gap width should increase as the temperature decreases. We are expecting to see a relationship similar to the one on Figure 3, where we can see that the band gap width decrease as a function of time.

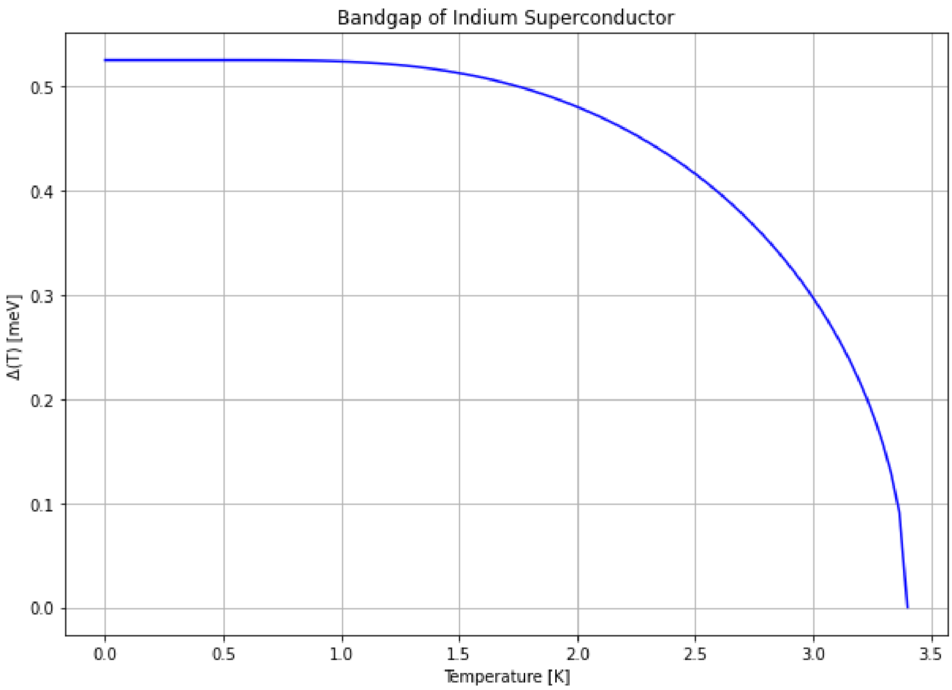


Figure 3: Theoretical relationship between band gap width and temperature for indium.

3 Experiment

The first part of the experiment consisted in making a slide that would work as a chip in our electric circuit in order to measure the resistance drop along a superconductor to normal metal junction. The slide was made by using a glass slide that we put in the evaporator. The first metal we used was Chromium, to make the contacts strong. Eight dots of chromium were placed in the following arrangement:

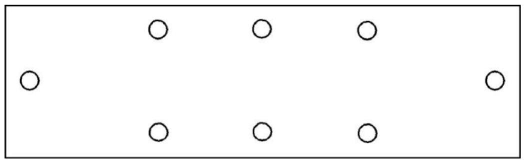


Figure 4: Position of the chromium

The next metal we evaporated was aluminium. Aluminium is a metal that will not go into a superconducting state even at liquid helium temperatures. The aluminium was deposited on a long-thin line along the middle of the slide, connecting the two farthest chromium dots.

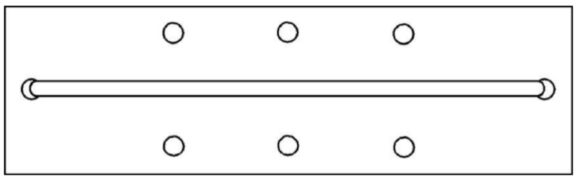


Figure 5: Position of the aluminium

After the aluminium was deposited, we brought the system back to atmospheric pressure in order to let it oxidize. The oxide layer that is formed over the aluminium is the layer that the electrons will have to tunnel through when a current is applied.

The third and last metal we deposited was Indium. The indium was deposited in thin filaments perpendicular to the aluminium connecting the other 6 dots by pairs. Indium is a metal that will go into a superconductive state at liquid helium temperatures. The junctions between the aluminium in non-superconductive state and the indium in a superconductive state is what we are interested in observing.

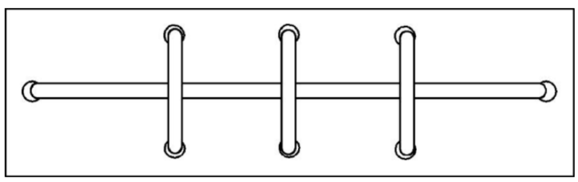


Figure 6: Position of the indium

After the slide was finished, we worked on making a circuit that we could use to measure the voltage drop and current along the different aluminium-indium junctions.

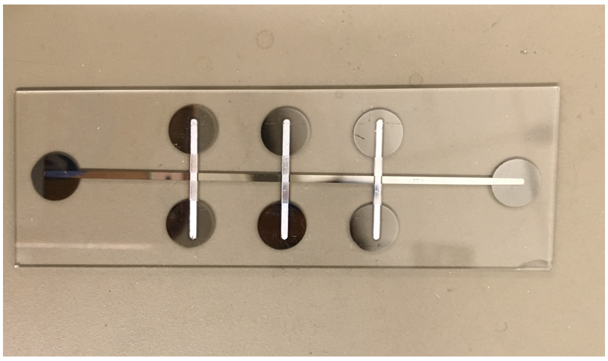


Figure 7: Picture of the finished slide.

The method that we used to measure the voltage drop is called the 4-wire measurement. The method consists on having 4 wires. Along one side of the circuit we would have a differential amplifier. The differential amplifier has a very high resistance so there is virtually no current flow along that part of the circuit. Hence, the measured voltage drop is the voltage drop along the junction. A schematic of the circuit (and a picture of the actual circuit) is found on Figure 8.

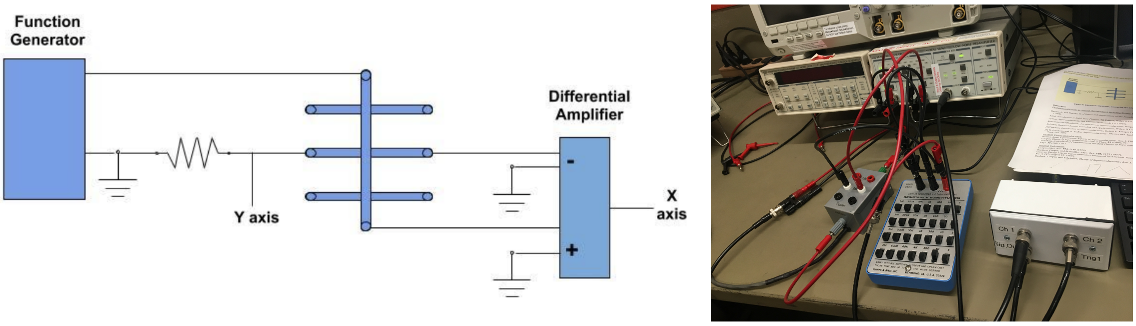


Figure 8: **Left:** Schematics of the circuit used for the measurements of the lab. **Right:** Picture of the actual circuit.

We used the computer Digilent Waveform system as a function generator and as a oscilloscope. This allowed us to sync the data collection with the wave we were producing and easily collect the data directly on the computer. After this, we took measurements at room temperature and made sure that the circuit worked. Once the room temperature measurements were done, we did measurements when the system was at liquid hydrogen temperatures. Since both of this seemed to be working, we proceeded to do the liquid helium cooling process.

In order to cool down the system to liquid helium temperature, we used a cryogenic Dewar system. This is a system of nested Dewar where the outermost one is filled with liquid nitrogen and the innermost one with liquid helium. There are valves to control the pressure of the innermost Dewar . The pressure of the innermost Dewar is known, which allows us to calculate the temperature of the slide. Using this systems allows us to have a more efficient use of the liquid helium. The first step is to cool down the whole system by consistently adding liquid nitrogen to the outermost Dewar. This gets the system to a temperature of around 77K. After approximately two hours of cooling it, we added the liquid helium to bring the temperature down to about 4K. We used the vacuum pump to lower the pressure on the inner Dewar until we reached about 10 mm Hg, at which the inner temperature is about 1.7 K. A schematic of the system can be seen

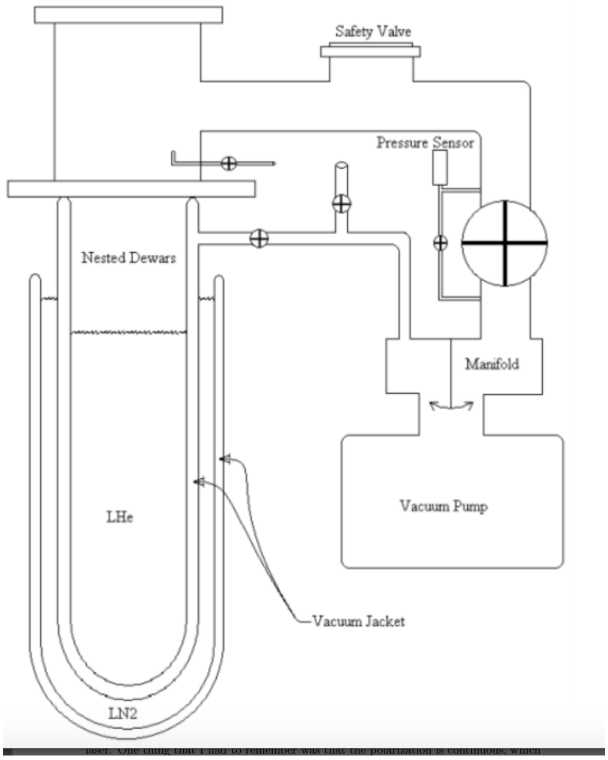


Figure 9: Schematic of the double Dewar system used to get the system down to superconducting state.

After the measurements were take, we made sure the pressure of the system was released and there was a way for the helium and nitrogen gas to escape. This is to prevent an explosion from pressure buildup to occur in the lab.

Once the setup was working, we used the function generator to create a triangle wave with an amplitude of 2 volts peak to peak. Using a triangle wave allowed us to sample different voltages and see the relationship of the current as a function of voltage. The voltage drop was measure along the three junctions, up, middle and down. In order to know the temperature of the innermost Dewar, we used the pressure measurement and converted it using a conversion table. At higher pressures, the temperature of the liquid Helium was greater. So as we were decreasing the pressure, we were decreasing the temperature as well.

4 Data Analysis

The data was collected with Digilent WaveForms Oscilloscope Acquisition software. The data processing and analysis was done with Google Colab. The notebooks can be found on the shared Google Drive.

The first plots developed were I-V curves. These were calculated using the formula:

$$V = IR$$

We knew the resistance of the differential amplifier had a gain of 100 and the external resistor used was 40 Ωs. This allowed us to calculate the current based on the voltage drop that the oscilloscope measured. When plotting the I-V Curve at room temperature, we obtained the following plot:

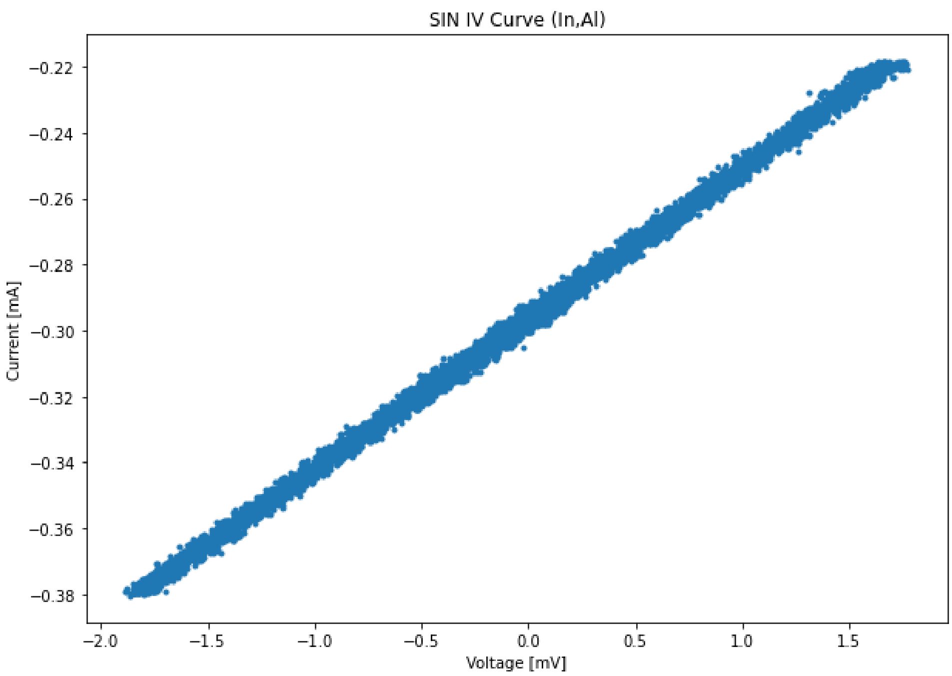


Figure 10: I-V curve at room temperature

This plot matches our hypothesis. It is a straight line, which means there is no gap and the indium is not in a superconducting state. The triangle wave want from -2 volts to 2 volts, so these are the endpoints of our line.

In order to get a quantitative idea of what the data looks looked like, the next plot was a comparison between I-V curves at different temperatures. In Figure 11 we can see the I-V curves of our system at 273 K, 4.0 K and 1.75 K. We can clearly see how the shape changes from a line to a curve that looks like a cubic or tangent function.

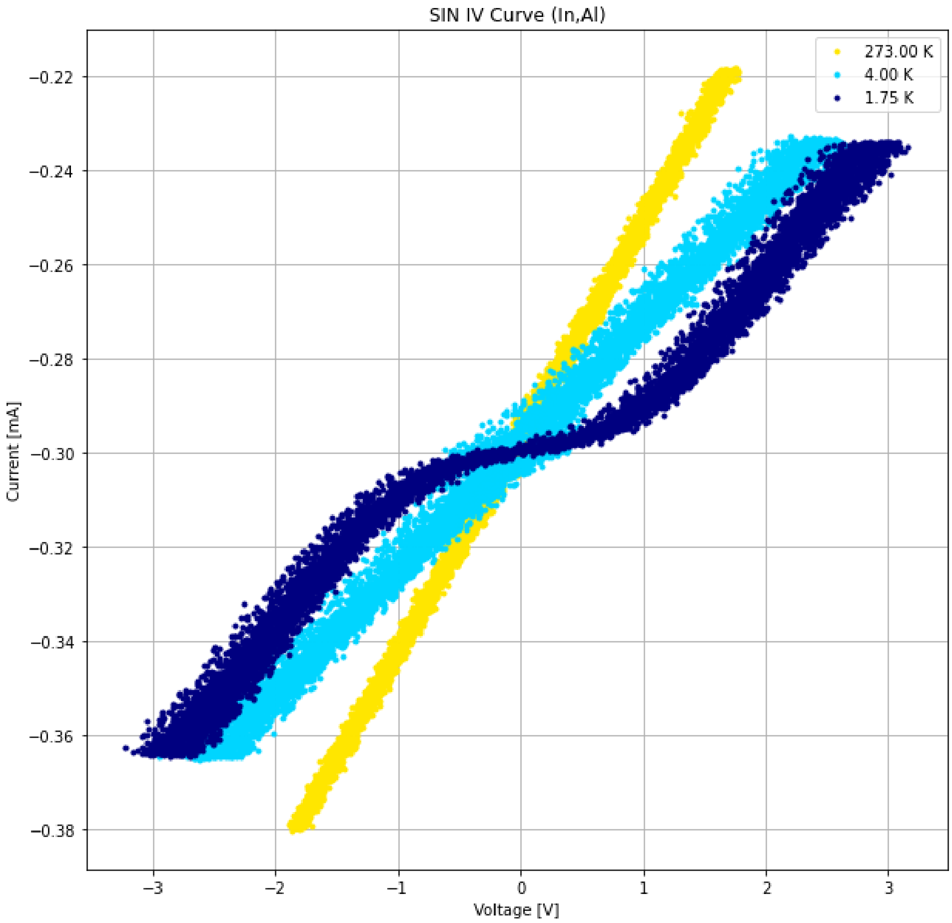
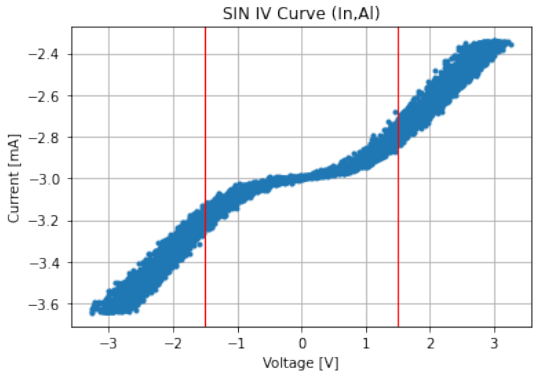


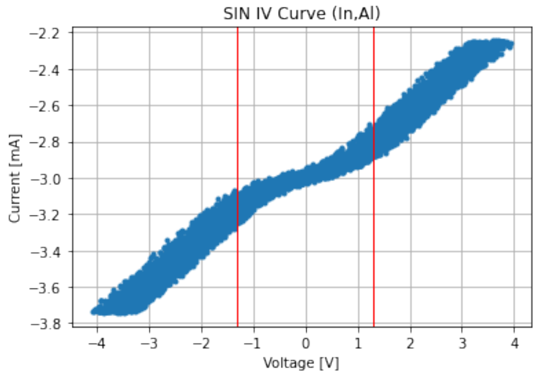
Figure 11: I-V curves at room temperature, 4K and 1.75

In order estimate the width of the band gap, I manually found the points where the sloped changes (decreased) on each one of the measurements. I was originally going to do a curve fit and find the derivative of the fit but I encountered problems with this system. I will discuss the problems later on the report.

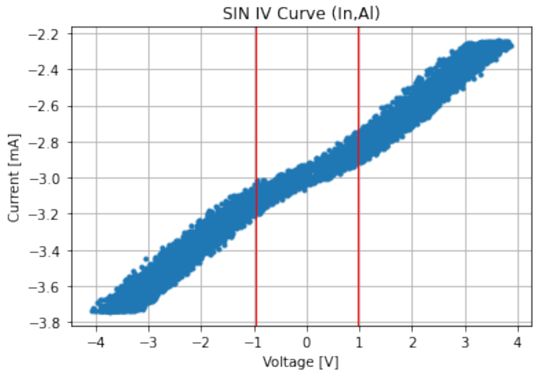
In Figure 12 we can see the pattern of the I-V curves and the band gap widths that I calculated. The pattern in the data is clear. As the temperature increases, the data resembles a line more and that width of the gap decreases. It was very hard for me to see the gap after 3.2K so that was the last measurement I took before calling the data linear and saying that the indium was no longer in superconducting state.



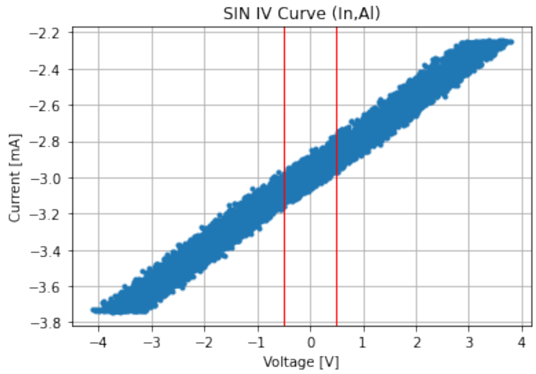
(a) 1.68K



(b) 2.2K



(c) 2.54K



(d) 3.2K

Figure 12: I-V curves and band gap width for temperatures

After finding the values of the gap with for the three junction at several temperatures, I made a plot of the relative gap width as a function of the temperature. I found the mean value between the measurements of the three junctions, and the standard deviation to plot the error bars. I tried to be as unbiased as possible in this estimated of the gap width, but it might be hard to be exact since changing the measurements slightly. Since the relative value was measured in comparison with the lowest temperature measurement, the error from this error propagated throughout the whole plot. This plot can be seen in Figure 13. Since we could not get to zero temperature, the lowest value which we used to normalize the data is a bit lower than it should. This drives the data points a little up. The general trend of the data matches the theory and our hypothesis.

Using this plot, I estimated the critical temperature T_c to be a little over 3.2K, maybe around 3.3K. This value is not too far off the theoretical value of 3.4K. The lowest

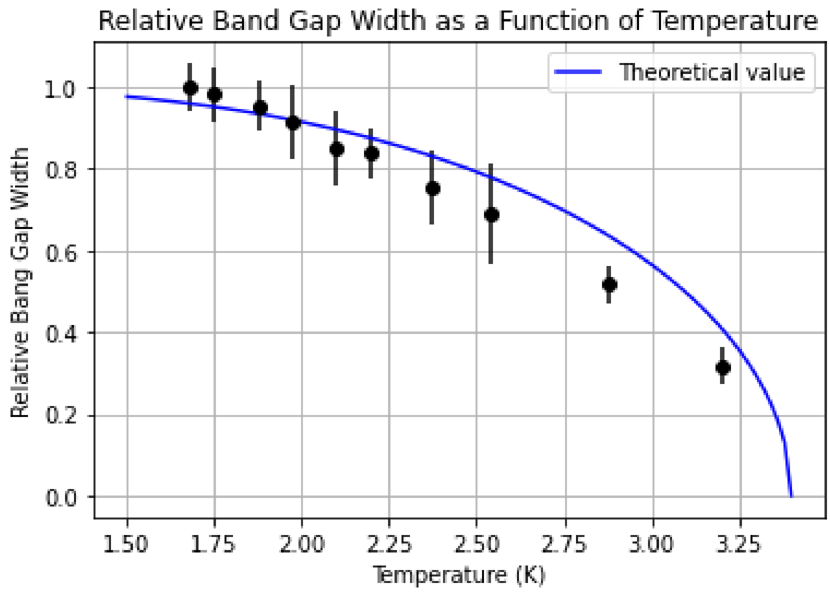


Figure 13: Mean values of the gap width as function of temperature compared to the theoretical values.

temperature yielded a gap size of approximately 1.5 volts, with a standard deviation of 0.0408.

One big part of the errors that came from this lab were due to an abnormal patter in one of our measurements. When the indium was cooled down to superconducting state, the data looked like two different curves. Figure 14 shows this pattern. It was hard to identify the width of the band gap. At the beginning, I tried to do data processing on this curve through binning and averaging. This ended up being a bad idea, as it flattened the pattern and most of the time I ended up having a straight line, which defeated the purpose. I am not sure what caused this problem, and it was not noticeable at room temperature or liquid nitrogen temperature because it was just a straight line. When collecting the data we did notice, but I thought that data processing would be enough to clean it. Since this wasn't very useful, I just estimated the gap width by eye, trying to keep it consistent from one temperature to the next. This was not ideal but since we didn't have another working slide, we had to settle for this messy data set.

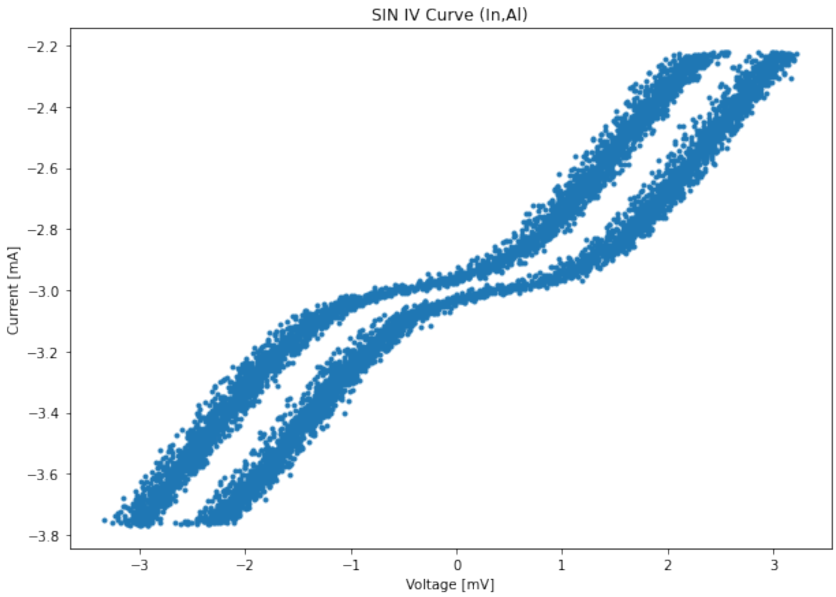


Figure 14: Middle measurement showing the split in the curve when in superconducting state.

5 Conclusion

The results of this experiment confirmed our hypothesis. The I-V curves that we plotted based on the data collected for the range of temperatures. I saw how the relationship between the current and the voltage drop changes as the temperature goes below the critical temperature. The pattern of formation and size of the gap width match the initial theoretical predictions. I was able to calculate a band width and see the pattern of decrease of the normalized band width as a function of temperature. It also allowed me to practice my data analysis and data cleaning skills to attempt to get smoother fits for the the curves. This was also a good reminder of circuits, and learning how to use a digital oscilloscope and function generator. It allowed me to learn how to use the evaporator and how to make the necessary slides. Another lab skill that I earned in this lab was learning about cryogenics, and cryogenic safety. I learned how to transfer liquid helium and liquid nitrogen in safe ways. To actually understand the theory behind the experiment, I had to read and learn more about the history of superconductivity and how the BCS theory was developed.

One of the major sources of error was already mentioned in the Data Analysis section, which was the presence of a split curve. Apart from that, we were not able to successfully produce our own slide. We worked on the slide under the supervision of the TAs, because we had a limited amount of time for this lab and wanted to get it correctly the first time. Even though we worked very carefully, the curves were out of phase, which was probably because some sort of short on the circuit. I think that exchanging the slides to test if our worked might have damaged the original one which lead to the separation of the curves when in a superconducting state. I think it was really helpful to have a working slide, because that allowed us to complete the experiment on time. If I had to redo the experiment, I would have liked to get my own slide to work. I would also like to investigate further about data fitting and data processing to make the process more automated. It almost became a brute force estimate of the width of the band gap for the three junctions at each temperature. The lab manual just says one can see the band gap on the I-V curves but having a better description of how they are seen or measure might have helped with the overall data analysis.

One thing that could be improved is the supplemental code. The code given on pdf form is for Mathematica. The Colab Notebook is outdated and it doesn't run. This makes it kinda complicated to follow. This is something that I think should be kept up to date so that students have an easier time importing the data and plotting it. I think supplying the chart to collect the data (which is over the setup in the lab) to students along with the lab manual. This would give a better idea of the information to record and the amount of measurements that should be recorded.

I also found annoying having to manually clean my data sets by deleting the first 17 rows (which had information about the digital oscilloscope) in each one of the different trials. I don't think there is much one can do about this but it was a very time consuming process that seemed pretty useless.

Bibliography

[1] Michael Tinkham. *Introduction to Superconductivity.* 2 edition, 1996.

[2] J. R. Scheiffer J. Bardeen, L. N. Cooper. Theory of superconductivity. *Physical Review*, 108(5), 1957.