PHYS 403

Lab Report (100 pts) Grading Method

Names_____ Xinyu Wang, Eric Yu ______

CRITERIA	Eugene	Alexey
Science overview (20)	20	
Procedures (30)	30	
Results / Analysis (30)	29	
Technical quality of the report: graphs, figure captions, tables, references, check spelling etc. (20)	20	
Final Totals (100)	99	100

100

OTHER COMMENTS:

Nice report and good data analysis. Would be useful to show some raw data (dI/dV or d^2I/dV^2) obtained at close temperatures but from different junctions. Also would be great to compare 2Δ for bulk Sn

Great job!

Determining gap value of superconducting tin using first and second derivative measurements of tunneling current

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Abstract

Measurements of the gap value of a superconductor at different temperatures provide a test of BCS theory and may reveal non-BCS superconductors. We determine the gap value of superconducting tin between 1.4K and 3.4K using measurements of the first and second derivatives of tunneling current through three different samples or junctions. We find a relationship between the gap value and temperature across this large temperature range that roughly agrees with the BCS prediction for temperatures near T_c, with Δ_0 slightly above 50% of theoretical value while fitted value of n slightly less.

1 Introduction

Under a critical temperature T_c, certain solids become superconducting. When a solid is in a superconducting state, it exhibits zero electrical resistance and is highly diamagnetic. An important trait of superconductors is a temperature-dependent energy gap Δ in the distribution of energies available to an electron. In the Bardeen-Cooper-Schrieffer theory of superconductivity (BCS), the charge carriers in superconductors are paired up electrons called Cooper pairs, which are bosons that can all occupy the ground state and are responsible for the traits of a superconductor. When the Cooper pairs are broken, an energy of 2Δ is released [4]. One way of experimentally measuring the value of Δ is by measuring the tunneling current between a superconductor and a normal conductor separated by a thin insulating film.

To understand tunneling, first think about the classical scenario of a ball thrown at a wall. If you throw the ball and don't give it enough energy to go over the wall, then the ball will bounce back. In quantum mechanics, the same thing happens most of the time. If a free electron with energy E is traveling toward a potential barrier with some width L and a height U_0 such that $E < U_0$, there is still a chance that upon measurement, the electron can be found on the other side of the barrier (Fig. 1). The probability that the electron tunnels through the potential barrier is small compared to the probability that it is reflected, and depends on the energy of the incident electron, and the width and height of the potential barrier [1].

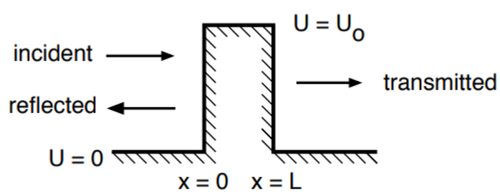

Figure 1: A free electron incident to a potential barrier can be reflected (with higher probability) or transmitted (with lower probability). When the electron is transmitted, we say it has tunneled through the potential barrier.

Because of this phenomenon, in the presence of a potential difference, a current will still flow through two conducting metals even if a thin insulating film separates them. This current of electrons jumping across the potential barrier the insulating film creates is called the tunneling current. If one of the conducting metals is replaced by a superconductor (creating a normal-metal/insulator/superconductor sandwich), then the superconducting energy gap Δ can be determined from the relationship between the tunneling current and the applied potential. Because of the presence of an energy gap in the superconductor, when a voltage $|V| < \Delta$ is applied, the tunneling current is significantly less than if there were no energy gap (normal conductor) since those energy levels are forbidden in the superconductor (Fig. 2) [5].

Starting from BCS, the energy density of superconducting electronic states $N_S(E)$

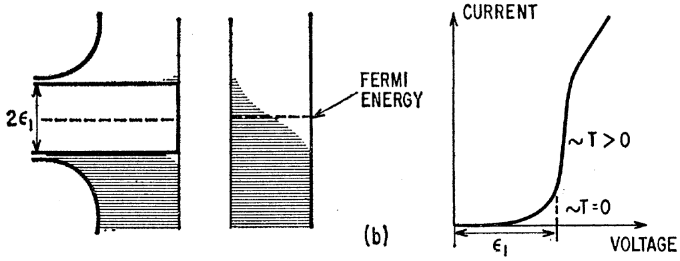

Figure 2: The relationship between applied voltage and measured tunneling current can be used to determine Δ (ϵ_1 here). On the left, the superconductor (with the gap $2\epsilon_1$) is separated from the normal conductor by an insulator. As shown, for energies near the Fermi energy, electrons (shaded in region) are unable to tunnel from the conductor to the superconductor because of the gap in allowed energies in the superconductor [5].

in an ideal superconductor is

$$N_S(E) \propto \frac{|E|}{\sqrt{E^2 - \Delta^2}}. \tag{1}$$

For the normal-metal/insulator/superconductor sandwich, the tunneling conductance dI/dV is proportional to $N_S(E)$, which gives the relationship between conductance and potential difference

show the equation for tunneling current first

$$\frac{dI}{dV} \propto \frac{|eV|}{\sqrt{(eV)^2 - \Delta^2}} \quad [1]. \tag{2}$$

The above equation can then be fitted to determine a value for Δ. Another way to determine the gap value 2Δ is by looking at the distance between the positive and negative peaks (Fig. 3) [2].

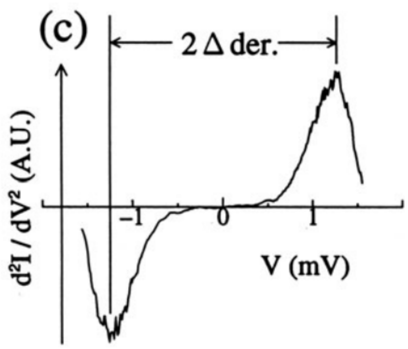

Figure 3: The gap value 2Δ can be determined by calculating the distance between the negative and positive peaks when the second derivative d^2I/dV^2 is graphed against the applied voltage V [2].

According to BCS, the temperature dependence of the energy gap near T_c is given by

$$\Delta(T) = 3.2 k_B T_c \sqrt{1 - (T/T_c)} \quad [3]. \tag{3}$$

In practice, this relationship will be fitted to a power law dependence

$$\Delta(T) = \Delta_0 \left(1 - \frac{T}{T_c}\right)^n . \tag{4}$$

The value of n will be compared to the theoretical value of 1/2 and the value of Δ_0 will be compared $3.2k_BT_c$. The gap value 2Δ is fundamental to superconductors, and measuring its temperature dependence for different materials serves as a test for the breadth of BCS. Accurate measurements of 2Δ are also crucial for probing new types of superconductors that may fall outside of BCS [2].

2 Procedure

2.1 Sample Preparation

In this experiment, we use electron tunneling to measure the gap value in the BCS superconductor tin ($T_c \approx 3.722$) using an aluminum/aluminum-oxide/tin sandwich; here aluminum ($T_c \approx 1.20$) is the normal conductor and aluminum oxide acts as the thin insulating layer that electrons tunnel through. To create this sample, we vacuum deposition. First, a single long aluminum strip with a thickness ∼1500Åis deposited onto a glass substrate. Then the sample is left in atmosphere to oxidize, creating a layer of aluminum oxide with a thickness ∼30Å. Finally, four (for redundancy) shorter strips of tin are deposited with a thickness ∼3000Å, creating a sample like the one in Fig. 4. The four 'squares' where the tin and aluminum intersect are the previously described sandwiches where electron tunneling will take place.

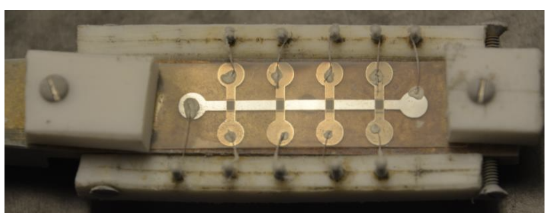

Figure 4: Sample with a horizontal strip of aluminum (which has a thin layer of aluminum oxide on it) and four vertical strips of tin. The sample is attached to the dipstick that will suspend the sample in liquid helium. The four intersections between the horizontal and vertical strips are where the tunneling current will occur. A wire is connected to the circular pad at the end of each strip.

2.2 Cryogenic Setups

The sample is then mounted on a dipstick and copper wires are attached to each of the ten pads with silver paint (see Fig. 4). An external measurement can then be connected to the dipstick that can apply a potential across a junction and measure the conductance (dI/dV). The dipstick is placed in the cryostat (the blue cylinder in Fig. 5), where it is cooled down to ~77K using liquid nitrogen, and then to ~4K using liquid helium. Once the sample is submerged in liquid helium, the mechanical pump depicted in Fig. 5 is used to further decrease the temperature (by decreasing the pressure in the cryostat) up to ~4K.

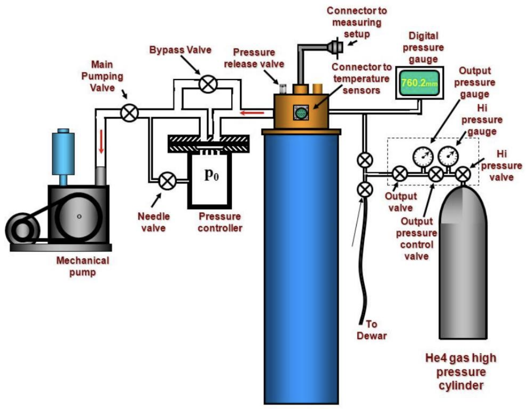

Figure 5: The cryogenic setup used. The blue cylinder is the cryostat in which the sample is submerged in liquid helium. The assortment of pumps and valves allow for fine control over the pressure in the cryostat, which in turn gives fine control over the temperature.

Data is collected by changing the applied DC voltage across a junction and measuring the conductance dI/dV (the LHS in (2)) and the second derivative d^2I/dV^2 (see Fig. 3) at certain temperatures.

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2.3 Data Collection and Analysis Procedure

We did our data collection at about 1.4 to 3.4 K temperature, with roughly a 0.4 K temperature step. We collected data by letting the DC voltage from -10 mV to 10 mV, with a 50m eV step to make it precise. We used our first sample (labeled as Sample 1) using junction 2 for the first two days with only making U_{dc} vs. first derivative plots. After junction 2 broke, we changed to junction 3 for the same sample and turned on the second lock-in amplifier to add second derivative measurements. We also prepared a new sample in the final two days and measured it with junction 2 again with the same temperature steps and plot data for both derivatives.

Since we got the proportionality of our 1st derivative dI/dV to the superconducting density by equation (2), we could make a fit

this is the same as equation (2)

$$\frac{dI}{dV} = A\frac{|eV|}{\sqrt{(eV)^2 - \Delta^2}} \tag{5}$$

for the U_{dc} vs. dI/dV plot collected by measurements at certain temperature above while A is some proportionality factor. We use Origin to define a tunneling function as (5) and fit for both positive U_{dc} and negative ones to get the Δ at each side, calculate the value of 2Δ (Δ at left plus Δ at right) and label them different temperatures (temperature are averaged at all data points since they are varying), materials, and a number of measurements (Figure 6a). For d^2I/dV^2, we could get the energy gap by directly measuring the distance between two peaks. (Fig. 3) We measured the peak voltage at right and minus the peak voltage at left to get 2Δ. Figure 6b is an example of our plot for DC voltage vs. d^2I/dV^2 plot for the first sample with junction 3 at temperature 1.55 ± 0.0006 K, with 2Δ calculated as 1.968 mV. Lastly, for each sample, junction, and the method we use (1st or 2nd derivative), we make a scatter plot for our measured energy gap with a certain temperature and fit in Origin with equation (4) to get the value for Δ_0 and n. The theoretical value for Δ_0 of Tin should be $3.2k_B \cdot 3.722$ K ≈ 0.001026 eV and $n = 1/2$.

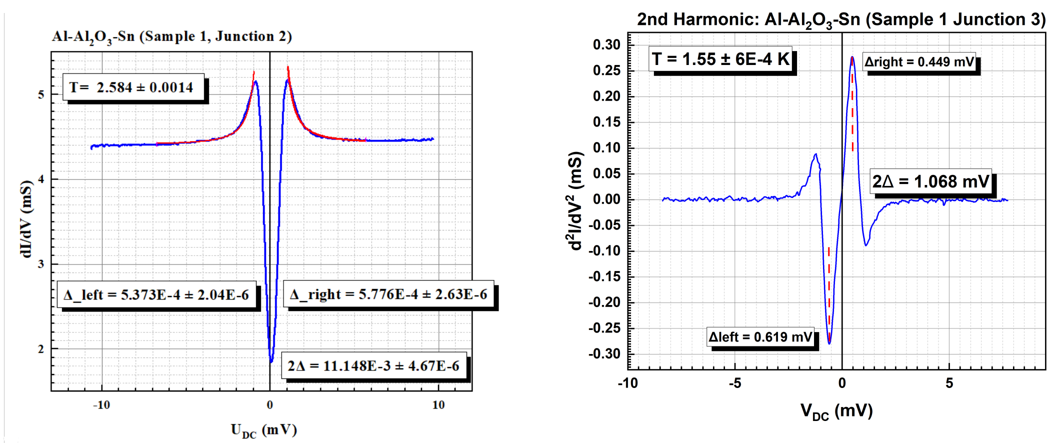

Figure 6: a) LHS is the sample driving DC Volatge (mV) vs. dI/dV (mS) plot of material Al-Al_2O_3-Sn in measurement "Sample 1 Junction 2" at temperature $T = 2.584 \pm 0.0014$ K with fitting lines and two Δ presented. The total energy gap 2Δ are calculated by the addition of two values. b) RHS is the sample driving DC Volatge (mV) vs. d^2I/dV^2 (mS) plot of the same sample (Sample 1) we made through junction 3 at temperature $T = 1.55 \pm 0.0006$ K with two peaks marked by red dotted lines. The energy gap is the distance between two peaks, which is labeled $2\Delta = 1.068$ mV.

3 Results and Analysis

2Δ vs temperature

Figure 7 is the temperature vs. 2Δ plot we got by fitting and extracting the value of Δ on both positive and negative V_{dc} through 1st derivative dI/dV plots. The scatter plot indicates the different samples and junctions we plot with. The black square dots represent the 2Δ fitting results we got from the second junction of our first sample, the red dot represents the results from the fitting of sample 1 junction 3, and the blue triangle represents the temperature vs. 2Δ plot for our measurement of sample 2. There are also fitting lines differentiated by corresponding colors that represent our result for fitting the plots with equation (4) and fixing $T_c = 3.722$ K. We did the same for 2Δ value we got from our d^2I/dV^2 second derivative plots, with black square now represent the results by sample 1 junction 3 and red circle now represents the result of sample 2 (Figure 8). We also made a fit for temperature vs. 2Δ for the results we got through two separate data sets while fitting lines are differentiated by corresponding colors of the scatter points. We see both the 1st and 2nd derivative shows a general trend of exponential decay, which generally coincides with the theory.

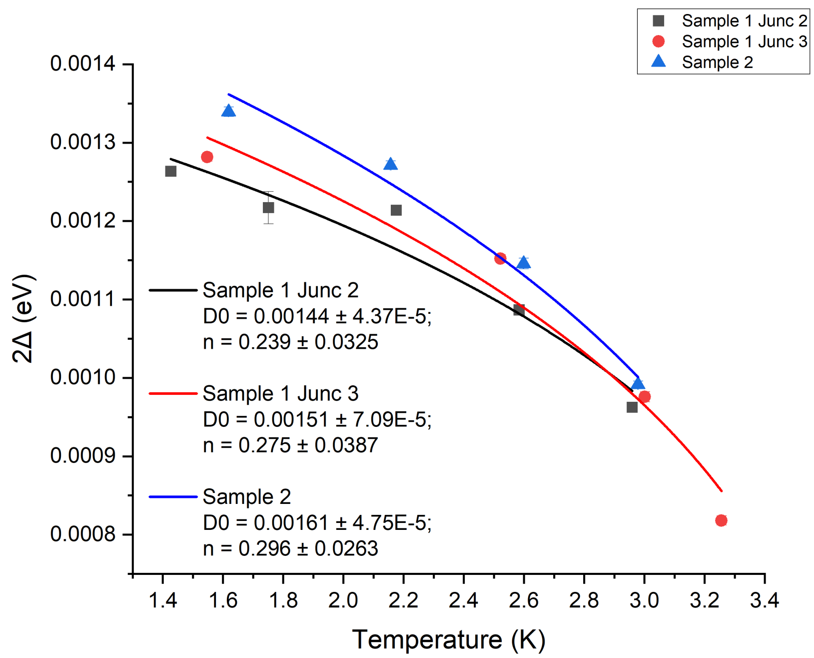

Figure 7: The scatter plot and fiting line with (4) made by Sample 1 Junction 2, Sample 1 Junction 3 and Sample 2 through the plot DC Voltage vs. dI/dV. Black squares and black fitting lines are responsible for the data taken by Sample 1 Junction 2; Red circles and red lines are for data collection of Sample 1 Junction 3;Blue triangles and blue lines are for data of Sample 2.

There should no difference until Tc is the same in different pieces of the film.

3.1 1st Derivative Measurements

For Figure 7, we could clearly observe that all three samples do not differ by much. Sample 2 shows a higher gap relative to the other two, and Sample 1 Junction 2 measures a relatively low gap among all three. But after about temperature 3.0 K, all three fitting lines nearly converge to one single line, indicating that an exponential dropping fit is reasonable. The second data collection (around 1.7 K) for Sample 1 Junction 2 has a relatively high y-error, which can be observed through the plot by a long bar line. This coincides with the general trend that this point shows an abnormal drop compared to other black squares. Since this value is at the starting point of the decay, a smooth exponential dropping would have this value not be too low, or the following values should drop much faster to make the whole trend exponential, which would be too quick in this case. Also, the data point shows a "bounce back" after this data point, which means we may not take this data very well, partially causing the black fitting line predicts a lower 2Δ value. The blue fitting line robustly covers the blue triangles, as well as two of four red dots (the rightmost red points are also covered by the general behavior that the blue fitting line shows, as we can predict). So we may able to derive the fact that our very first data collection by the red dot (the one at the lowest temperature) may not be very good and the 2Δ may need to be higher. Thus we regard the blue fitting line as our best fit for the tunneling effect we measure. This corresponds to the fact that n theoretically should be equal to 0.5, and the blue fitting line is the one that best approaches this among all three fittings. It still has a relatively large 0.2-difference to the theoretical value for this parameter, but that may be a result of this experiment being done on a thin film, and that the fitting equation from BCS (eq. 4) is for temperature near the critical temperature. Also, our fitting for Δ_0 has generally a large difference to theoretical value $\Delta_0 = 0.001026$, which our 1st derivative plots shows at least 0.00144 (Sample 1 Junction 2). The exact error for the Δ_0 value for 1st derivative fits are $40.35\% \pm 4.26\%$ for Sample 1 Junction 2, $47.17\% \pm 6.91\%$ for Sample 1 Junction 3, and $56.92\% \pm 4.63\%$ for Sample 2. It could be due to the fact the sample quality was not good, since our first sample produced by the same procedure has a history that the junction broke up and we cannot do any measurements. It could also be the reason that we are using thin films. Since producing thin films may cause different crystal structures or orientations different than bulk material, we may have different electronic properties and measure different energy gaps.

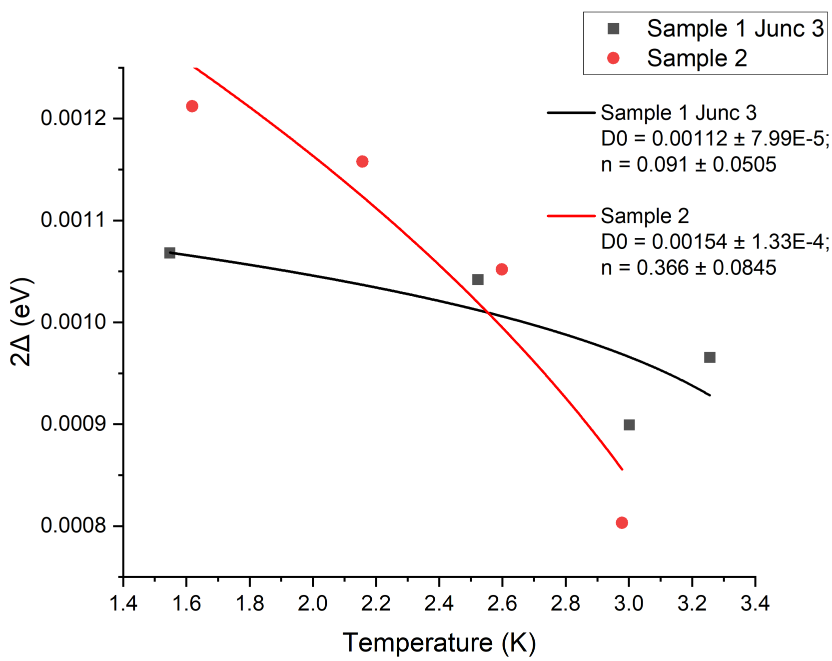

Figure 8: The scatter plot and fit with (4) made by Sample 1 Junction 3 and Sample 2 through the plot DC Voltage vs. d^2I/dV^2.

3.2 2nd Derivative Measurements

For the 2nd derivative plots (Figure 8), Sample 1 Junction 3 and Sample 2 show a clear offset. Sample 1 Junction 3 has a 2nd derivative plot that shows the energy gap was initially relatively small at lower temperatures, with not much drop after going near a critical temperature, showing an inconspicuous decay. In this case, $n = 0.091 \pm 0.0505$, which is comparably low to the previous three samples we analyzed. This also is quite lower than our theoretical n value of 0.5, which means this data are not robust to make a reasonable decay plot. Also, the measurement of the energy gap at Junction 3 at a temperature of around 3.0 K is extremely low, even much lower than the one we measured at about 3.3 K, which is very abnormal. Generally, we can conclude that the 2nd derivative plot derived by our measurement of Sample 1 Junction 3 is not quite meaningful, which means our measurement and result has some problem and does not conform to normal rules and behavior predicted by theory. However, the 2nd derivative plot of Sample 2 is much better than Sample 1. We got $n = 0.366 \pm 0.0845$, which bets approaches the theoretical value among all our fits. In this case, $\Delta_0 = 0.00154 \pm 1.33 \times 10^{-4}$, which does not deviate much from our measurement and fit for 1st derivative. Though the n still does not get near 1/2 and Δ_0 still has 50.10% $\pm$ 7.79% departure from the theoretical value, it shows a good exponentially decay behavior, a greatest coherence of n value, and a reasonable Δ_0 for energy gap at zero temperature. The reason for this problem or error could be the same as we analyzed for the 1st derivative plot, to which the thin-film structure of the material or the fragile nature contributes. Sample 2 still shows a relatively better approximation and fitting behavior, which accords to our sample preparation procedure that we were the most skilled when preparing Sample 2 (prepared at last), using it only once, and using it a short time after it was made and do calibrations without any sign of breakage.

3.3 Future Experiments

For future experiments, we could minimize errors in the following aspects. First, we could skillfully prepare the sample and use them directly after we calibrate instead of waiting for a week and doing measurements. The "fresh" sample would definitely be more accurate and get more ideal results than the sample that has been made for a while. Also, we could reproduce the result by the same sample and junction, instead of using a different one every time. By reproducing on the same sample and junction, we could focus on and extract other factors that may cause the deviation from the theoretical value and predictions. Moreover, we could control the fabrication process and sample preparation of the thin film to make fewer errors. We could do some measurements at different thicknesses of materials and under different conditions to see if the results would be varied by the factor of thickness and explore more thickness-dependent effects. Another point is that we could measure one sample, or junction, with a shorter temperature step. This time we did it at about 0.4 K temperature gap, and our scatter plot seems "scattered" and sparse. If we can measure more energy gap values throughout the time with the same material, we may get a better fit and see if our sample is good. Lastly, since BCS theory makes some assumptions about electrons and protons, we can introduce other theories about coupling and interactions to get better estimations and predict our result in a more comprehensive way.

4 Conclusions

We did both our samples through 1.4 K to 3.4 K with even temperature steps and got 4-5 points for fitting for each sample and junction we measure. For T vs. 2Δ plot we got from DC Voltage vs. dI/dV plots through 3 measurements, all data shows an about-50% larger value for Δ_0 value respect to the theoretical one, and all value of n we got from measurement was below 0.3, which is obviously much lower than the theoretical $n = 1/2$. For the T vs. 2Δ fit we got from d^2I/dV^2 we got very bad fit through Sample 1 Junc 3 which shows a abnormal drop at about 3.0 K and the general fitting the worst. But the fitting for second derivative of Sample 2 got the best approximation for n above 0.35, while the Δ_0 still shows a deviation around 50%. Generally, Sample 2 perform a better result than both junctions of Sample 1, as we expected, by giving a better fit and more reasonable values. Larger Δ_0 and lower n are still observed even with better sample, which could be due to the thin film we used. We could try to fix error and improve our experiment in the future by making repeated measurement using one sample, make closer and denser temperature steps between lowest temperature and critical temperature to make better fits, trying to evaluate would the thin film structure alter the crystallic and electronic structure of the superconductor we made, and considering more comprehensive theory that would be responsible for the phenomenon we observe.

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