Thin-Film Tunneling with Superconductors

Tianyi Zhou, Fan Zhang

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Abstract

In this experiment we studied the thin-film tunneling effect of SIN tunnel junction by measuring the I-V curve for several different temperatures. We made a sample slide with three In-AlOx-Al junctions by evaporation method, cooled down to achieve the critical temperature of In by employing LN_2 and LHe, and measured the voltage across the junction by 4-wire measurement. The room temperature resistance of three junctions are $1.744 \pm 0.020\Omega, 0.491 \pm 0.005\Omega, 7.210 \pm 0.081\Omega$. Our experiment showed the I-V characteristics of SIN junctions below critical temperature, qualitatively confirmed the temperature dependence of energy gap near critical temperature predicted by BCS theory. The energy gap measured is lower than theoretical value. We are not able to quantitatively confirm the temperature dependence of energy gap in this experiment. We attribute this failure to the measurement taken during unstable cooling process.

1 Introduction and Theory

1.1 Superconductivity and BCS theory

The electrical resistance of certain metals suddenly drops to exactly zero when cooled to sufficiently low temperature. This phenomenon, called superconductivity, was first observed in 1911 by Kamerlingh Onnes. Later in 1933, Meissner and Ochsenfeld discovered that these kind of materials expel all applied magnetic field. This effect now known as Meissner effect, was given a phenomenological explanation by the brothers Fritz and Heinz London in 1935. Materials with both properties of zero electrical resistance and perfect diamagnetism are defined as superconductors. Not until 1957 with the proposal of BCS(Bardeen, Cooper and Schrieffer) theory, the microscopic origin of superconductivity was completely understood. [1]

One basic idea of BCS theory is the formation of Cooper pairs. Cooper showed that at low temperature, an arbitrary weak attraction can bind pairs of electrons in metal into a bound state with lower energy $E_F - \Delta$ than the Fermi energy E_F. In conventional superconductors, this weak attraction is provided by interactions between electrons and phonons in the lattice structure. Small energy gap Δ suggested a phase transition in which there was a kind of condensation. In the BCS framework, superconductivity is actually a macroscopic effect which results from the condensation of Cooper pairs. [2]

BCS theory predicts the dependence of the value of the energy gap Δ at temperature T on the critical temperature T_c. For weak-coupling superconductors, $\Delta(T)/\Delta(0)$ is a universal function of T/T_c which decreases monotonically from 1 at $T = 0$ to 0 at T_c, as shown in Fig.????. One needs to solve the following equation self-consistently. [3]

$$\frac{\Delta(T)}{\Delta(0)} = tanh(\frac{\Delta(T)}{\Delta(0)}\frac{T_c}{T}) \tag{1}$$

At zero temperature, energy gap is given by

$$\Delta(T = 0) = 1.764 k_B T_c \tag{2}$$

Near critical temperature, energy gap asymptotes to

$$\Delta(T \to T_c) = 3.07 k_B T_c \sqrt{1 - \frac{T}{T_c}} \tag{3}$$

1.2 Tunneling Current

In 1960, Giaever discovered tunneling effect of single charge carriers experimentally, which made the field of superconductivity one step forward. He deposited two thin metal films on top of one another with only a very thin insulating oxide film separating them. Due to the quantum mechanical probability of electrons tunneling through the insulating layer, a current will flow through the junction under applied voltages greater than the energy required to break a Cooper pair($eV > \Delta$). This makes the current sharply drop to zero as $eV \to \Delta$ at zero temperature. Through observation of the behavior of the I-V curve of the junction, one can directly observe the energy gap. [4]

For a NIN(Normal metal-Insulator-Normal metal) junction, the tunneling current is given by

$$I_{NIN} = \frac{2\pi}{\hbar}|T_n|^2 D_l(E_F) D_r(E_F) eV \equiv G_{NIN} V \tag{4}$$

where $|T_n|^2$ is the tunneling probability, $D(E)$ is the density of states at energy E, subscript l and r denotes left or right electrode, G_{NIN} is the normal conductance of the NIN junction.

For a NIS(Normal metal-Insulator-Superconductor) junction, the density of states of quasiparticles in superconductor $D_s(E)$ is related to the one in the normal metal $D_n(0)$ near the Fermi energy by

$$\frac{D_s(E)}{D_n(0)} = \begin{cases} \frac{E}{(E^2 - \Delta^2)^{1/2}}, |E| \geq \Delta \\ 0, |E| < \Delta \end{cases} \tag{5}$$

where energy E is measured from the Fermi energy E_F. And tunneling current is given by

$$I^q_{NIS} = \frac{G_{NIN}}{e}\int_{-\infty}^{\infty} \frac{E}{(E^2 - \Delta^2)^{1/2}}(f(E) - f(E + eV))dE \tag{6}$$

If we define differential conductance as

$$G^d_{NIS} = \frac{dI_{NIS}}{dV} \tag{7}$$

and take the limit $T \to 0$, one can derive

$$G^d_{NIS} = G_{NIN} \frac{E}{(E^2 - \Delta^2)^{1/2}} = G_{NIN} D_S(E = eV) \tag{8}$$

This means that a measurement of dI_{NIS}/dV probes the superconducting quasiparticle density of states function directly. [5]

1.3 Cooling Process

In this experiment, we employ cryogenic liquids to achieve critical temperatures. The boiling point at atmospheric pressure of liquid nitrogen(LN_2) and liquid helium(LHe) is 77K and 4.2K respectively. In order to achieve the critical temperature of Indium(3.41K), we need to reduce the temperature of liquid helium through evaporative cooling techniques which exploit the relationship between temperature and vapor pressure.

If we assume the volume of atoms in liquid state is negligible compared to gaseous state, by Combining Clausius-Clapeyron relation and ideal gas law, one can derive the vapor pressure during phase transition between liquid and gaseous helium is given by

$$P = A \cdot exp(\frac{-L}{nk_B T}) \tag{9}$$

where A is some constant decided by initial value, L is the latent heat of the transition. (more detailed derivation in lab manual [4]) From this we can see that by reducing the vapor pressure of the gas above the liquid helium, one can induce a reduction in the temperature of the liquid. And we expect the temperature to hit some kind of asymptotic power limit(about 1.5K).

Normal liquid helium(above λ point 2.2K) is not a sufficiently good thermal conductor to establish equilibrium on the time scale of minutes. As the vapor pressure is decreased, the helium near the top of the fluid will cool as explained above, whereas the temperature of the helium on the bottom will lag. Since the density of liquid helium increases with decreasing temperature, as the pressure is changed a density gradient is formed in the liquid as well. Thus stratification develops between the cold, dense layer of helium above and hot, less dense helium below. By undergoing convection, the liquid helium will achieve equilibrium.

Below 2.2K, liquid helium transited to superfluid phase, where the thermal conductivity of helium increases drastically and fluid can be assumed to be isothermal at all times.

2 Setup and Procedures

2.1 Junction Preparation

We made our SIN junction by depositing Chromium, Aluminum and Indium on ordinary glass microscope slides with evaporator. As shown in Figure 1, eight dots of Chromium was deposited first and was to be used as connecting electrodes. After Aluminum strip was deposited and the slide was cooled for 4 minutes, we vented the evaporator back to atmospheric pressure for 18 minutes and created the oxide layer on top of Al. Three strips of

Indium was deposited right after the evaporator chamber pumped back down. See the lab manual [4] and Dean's list [6] for detailed procedure of thin-film fabrication. Deposition rate and thickness of our metal films are listed in Table 1.

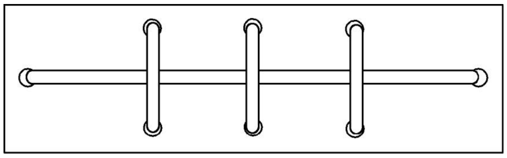


Figure 1: Arrangement of metal films

Metal	Deposition rate (Å/s)	Thickness (kÅ)
Cr	3.5∼7.9	1.014
Al	5∼18.6	0.864
In	∼25.8	2.554

Table 1: Deposition rate and thickness of metal films.

2.2 Measurement and Data Taking

2.2.1 Electronic apparatus

In order to investigate the I-V curve, we employ an adjustable voltage source to bias the junction. Since the voltage needed is quite small (in mV order), a differential amplifier is used to measure the junction voltage. A constant resistor is in series with the junction so that by measuring the voltage across this resistor we can get the current in the circuit. As shown in Figure 4, we use the 14-bit A-D converter with a computer as the function generator and oscilloscope. Through the WaveForms2015 software, we can control the voltage source, scope display and save data in a faster and more convenient way.

2.2.2 4-wire Measurement

As shown in Figure 3, 4-wire measurement is used in this experiment to make more accurate measurement of junction voltages. R_1, R_2, R_3, R_4 denotes the resistance of the top, ML, MR, Bottom arm respectively(If we are measuring the middle junction for instance). R_0 is the resistor in series with the junction. Since the input of the AD converter has the impedance of 1MΩ, which is extremely high compared to the junction resistance, the current runs through R_3 and R_4 is negligible and hence the voltage drop across them is negligible. In this case, what we measure in CH2 is almost exactly the voltage across the junction.

2.2.3 Data taking

Channel 1 and channel 2 of the AD converter scope monitors the voltage across R_0 (V_1) and voltage across the junction(V_2), respectively.In this case, current is $I = \frac{V_1}{R_0}$, and voltage is $V = \frac{V_2}{G}$, where G is the gain factor of the pre-amplifier. In order to optimize the signal through pre-amplifier, we need to set a higher gain. And the energy gap of Indium $\Delta_{In} = 10.5 \times 10^{-4} eV$ at 0K, which implies the turning voltage is $\sim 1mV$. In order to achieve this voltage across the junction, we do not want the resistor in series too big. Balancing this two aspects, we choose $R_0 = 51 \pm 2\Omega$ resistor and multimeter measures the value to be $51.68 \pm 0.01\Omega$.

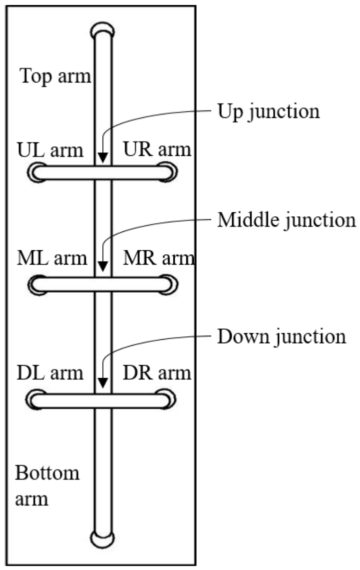


Figure 2: Electronic apparatus

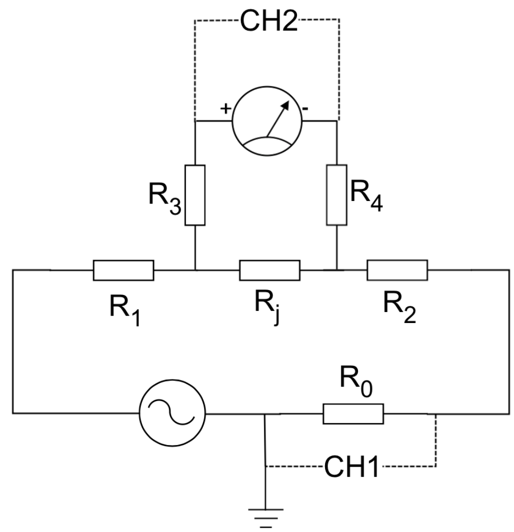


Figure 3: 4-wire measurement circuit

2.3 Cooling Down

At the beginning of the cooling process, we evacuated the jacket of the LHe(inner) dewar (see Figure 5) and then let a small amount of air admitted to the jacket to increase thermal conduction during the precool phase. Then LN_2 was put into the outer dewar and it took about 2 hours to cool the system down to a stable 77K environment. Next LHe was added into the inner dewar and lower temperatures were achieved by the pressure decreasing process described in Section 1.3. Data of three junctions was taken by the method described in Section 2.2 at LN_2 temperature(77K) and at 12 different temperatures from 4.22K to 1.56K during the cooling process.

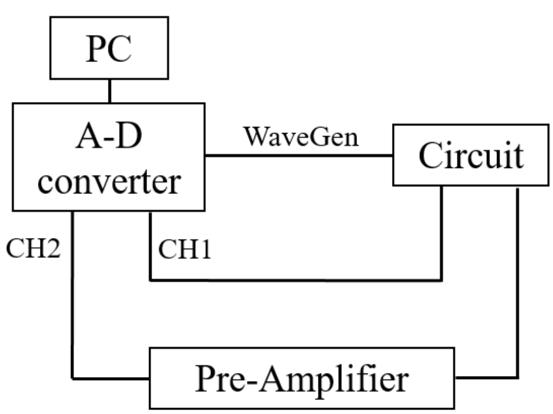


Figure 4: Electronic apparatus

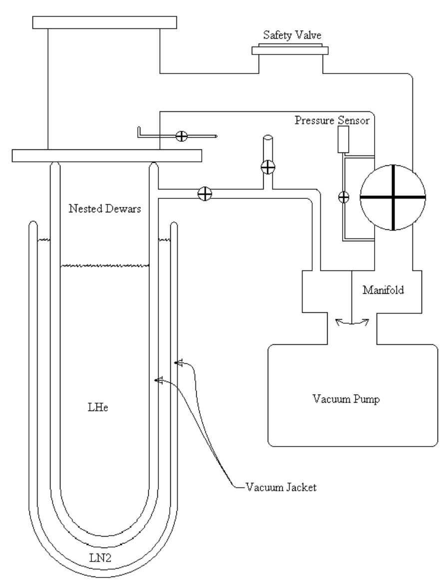


Figure 5: Cryogenic dewar system, adapted from the lab manual [4]

3 Data Analysis

After the electronic apparatus is set up, we feed a 10Hz triangle wave through wave generator, then make a 200ms single run of the oscilloscope and take data of 8000 points in two channels. So every time we make a measurement, we get four sweeps of the IV characteristics, as shown in Figure 6.

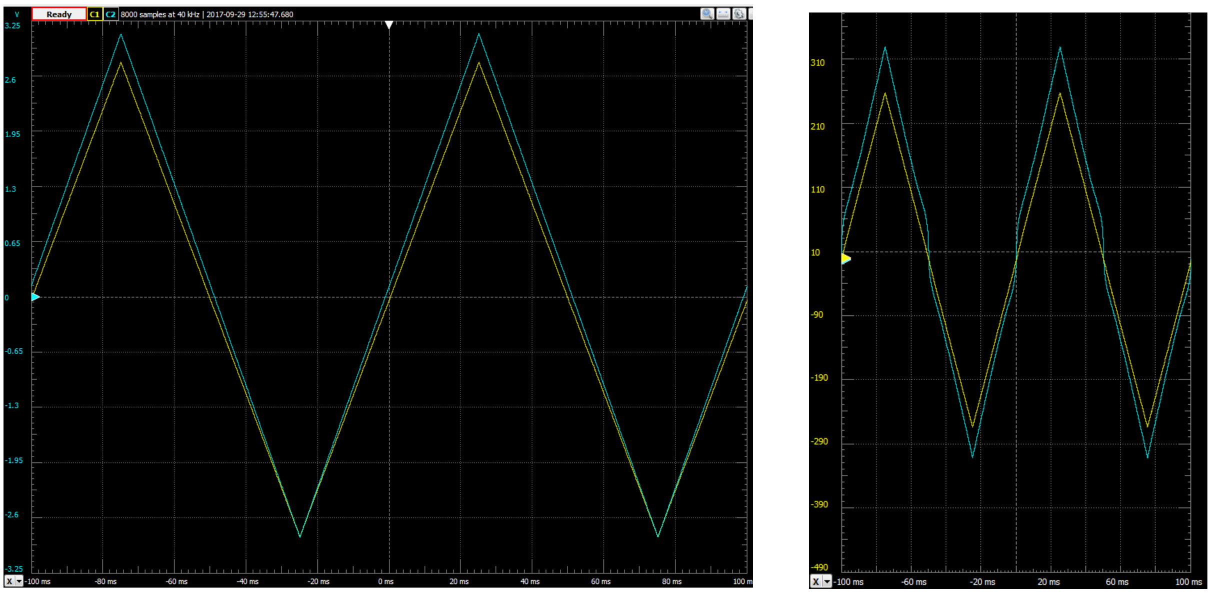


Figure 6: Scope display of two channels, measuring middle junction at 77K(left) and 1.56K(right)

From figure 6, we can see that when channel 1 hits zero, channel 2 is a non-zero value, which means we always have an offset in channel 2. To compensate for this, we deal with the offset before plotting IV curve. Offset is just simply sum of the maximum and minimum value divided by 2. Every data point gets a new value of original value minus the offset.

3.1 300K and 77K Resistance

At room temperature 300K and LN_2 temperature 77K, In and Al are just normal metal. Following Ohm's law, the I-V characteristics should be a straight line(as shown in figure 6 (left)) and the slope of the line is conductance of the junction. By simple linear regression(code attached in Appendix A.1), we get the resistance of three junctions at two temperatures listed below.

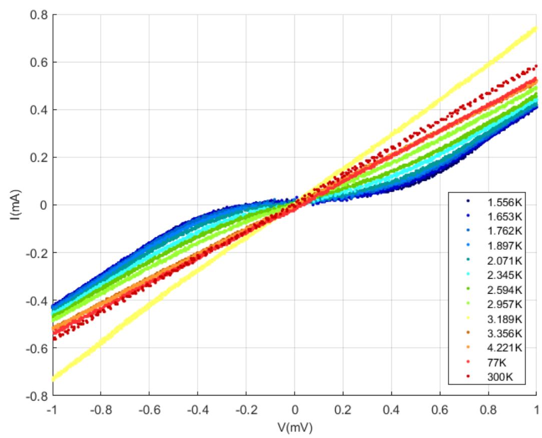
Junction	$R(\Omega)$ at 300K	$R(\Omega)$ at 77K
Up	1.744±0.020	1.873±0.021
Middle	0.491±0.005	0.598±0.007
Down	7.210±0.081	6.299±0.070

Table 2: Resistance of three NIN junctions at 300K and 77K

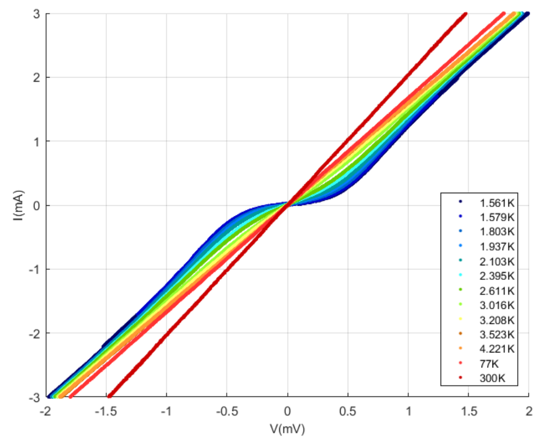
We can see that after LN_2 is added, the resistance of the up and middle junction slightly rises. But the down junction resistance has a 12% drop. We will investigate this in detail by plotting I-V curve.

3.2 I-V Curve Plotting

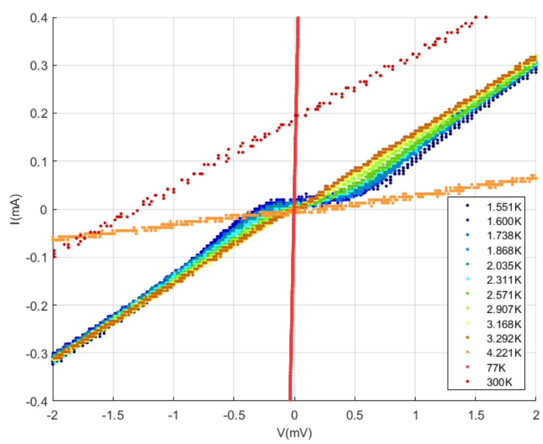
We first take an overall look at I-V data of three junctions we get at all 13 temperatures ranging from 300K to 1.5K, and plot the three I-V curve in figure 7.



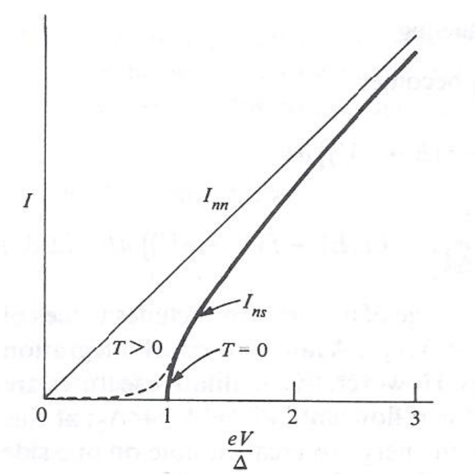
(a)



(b)



(c)



(d)

Figure 7: I-V curve of (a)up, (b)middle, (c)down junction at 13 different temperatures. (d) I-V curve in theory, adapted from the lab manual [4]

We can see that the behavior of resistance of down junction is not consistent at first three high temperatures(330K, 77K, 4.221K). We attribute this inconsistency to the poor connection of this junction and the electrode. Also notice that in section 3.1 we calculated the room temperature resistance and relatively small resistance of middle junction makes the range of measured current bigger, compared to the up junction. Therefore, in the following data analysis section, we choose the middle one as the interested junction. Then let's have a look at the IV curve of middle junction in detail. As shown in figure 8, at high temperature IV curve is a straight line with slope which is conductance according to Ohm's law. At temperature lower than critical temperature $T_c = 3.41$K, it is no longer straight and as the bias voltage increases, the slope increases to some certain value and then asymptotic to straight line. This behavior is consistent with the theory.

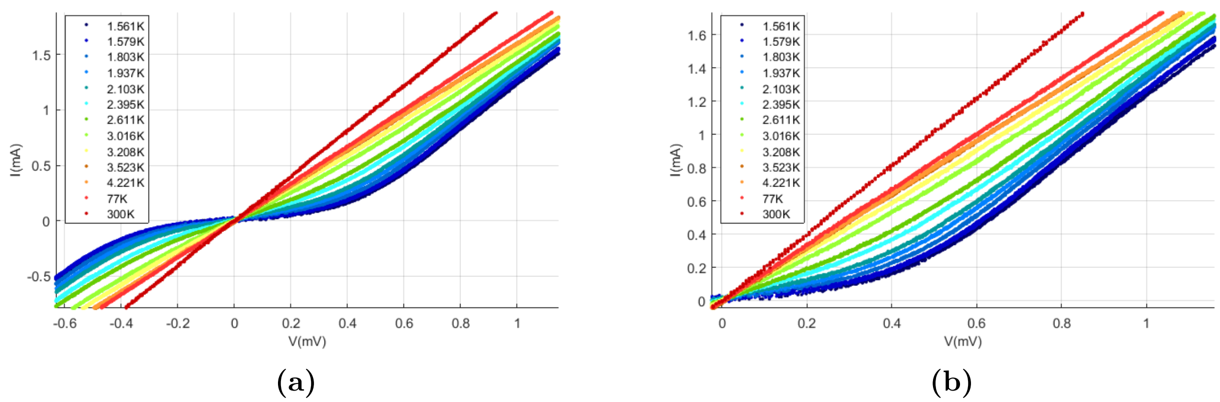


Figure 8: Zoom-in plot of IV curve of the middle junction at 13 different temperatures

3.3 Energy Gap Estimate

Next we would like to investigate and measure the energy gap from IV data plotted above. According to our theory, the density of state is related to the energy gap by Eq. 5. And the tunneling current is the integral of the product of density of state and the Fermi function as shown in Eq. 6. Therefore, we can plot the dI/dV curve to measure the energy gap.

3.3.1 Attempt of Energy Gap Calculation

All data are plotted as discrete points in figure 7b. To plot dI/dV vs V as a continuous curve, we have to first get a continuous function $I(V)$. In this experiment, we use a smoothing spline to obtain a curve fitting to the data points. The smoothing spline s is constructed for specified smoothing parameter p and it minimizes

$$p\sum_i (y_i - s(x_i))^2 + (1-p)\int (\frac{d^2 s}{dx^2})^2 dx \tag{10}$$

The smoothing parameter p is defined between 0 and 1. $p = 0$ produces a least-squares straight-line fit and $p = 1$ produces a cubic spline interpolant curve going through all the data points. The curve fitting toolbox in MATLAB allows us to do the fitting with input of all data points and specified fitting parameter p. We first set $p = 0.90$ and plot the all temperature dI/dV curve in figure 9.

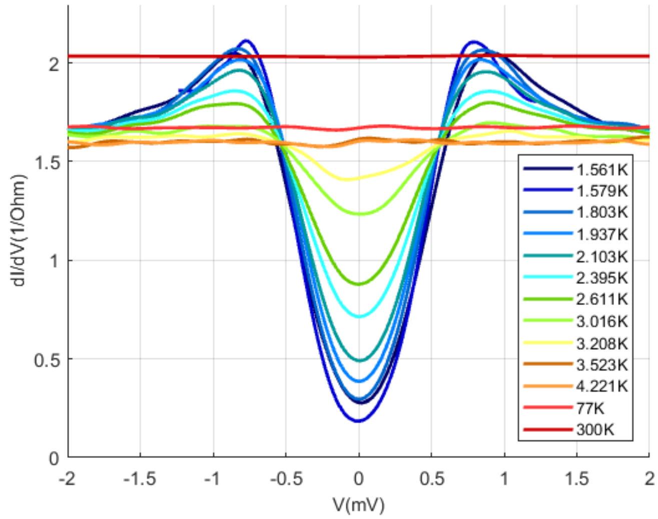


Figure 9: dI/dV curve for middle junction

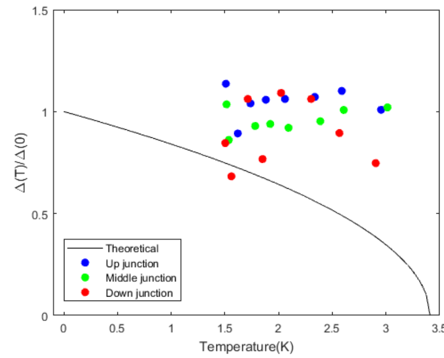
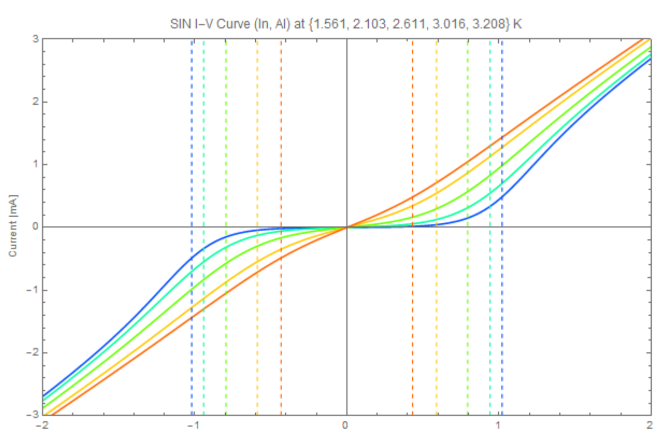


Figure 10: Temperature dependence of energy gap. Black line is the theoretical prediction by BCS theory in Eq. 3. Blue, green, red dots are calculated values from our experiment.

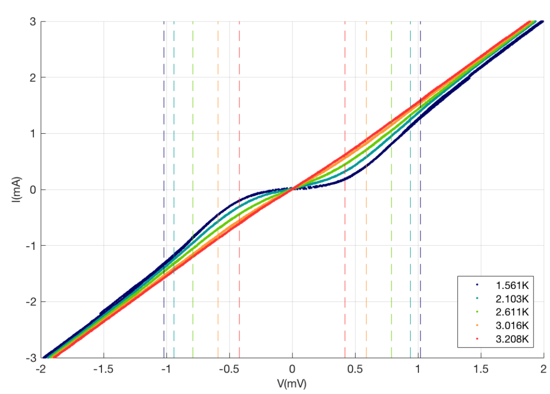
We calculate the energy gap by searching for the two voltage values where dI/dV hits maximum and taking the average of these two voltages(absolute value). The result of three junctions is shown in figure 10. We can clearly see that from our experiment it is hard to tell there exists a temperature dependence of the energy gap of SIN junctions.

3.3.2 Comparison of Experiment and Simulation Result

The failure of our first attempt of energy gap calculation is mainly due to the simplicity of our determination on leakage voltage. Besides, the theoretical curve plotted in figure 10 is only valid for $T \to T_c$. In this section, we conduct a simulation and calculate the energy gap by solving the Eq. 1 self-consistently, then plot the IV curve and dI/dV curve with calculated energy gap value marked on.

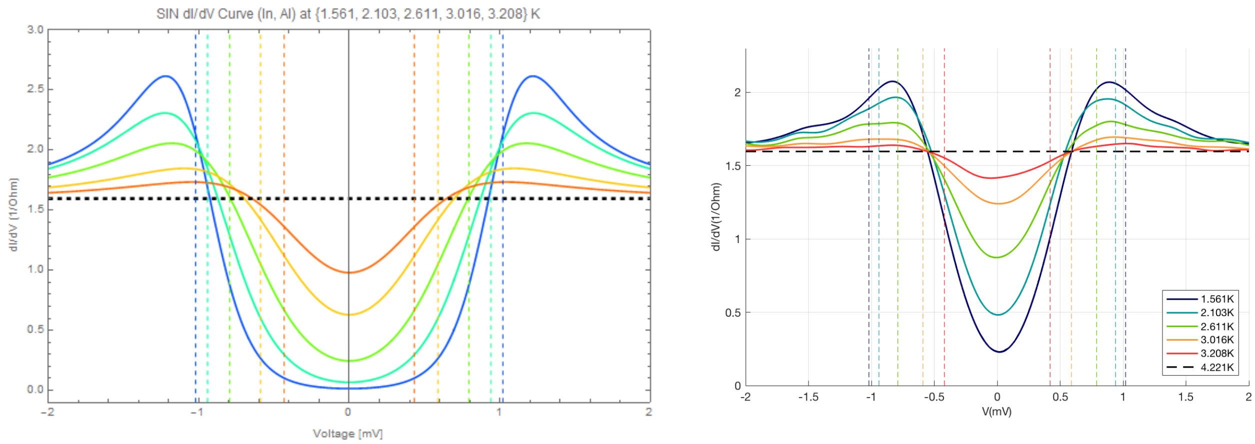


(a)



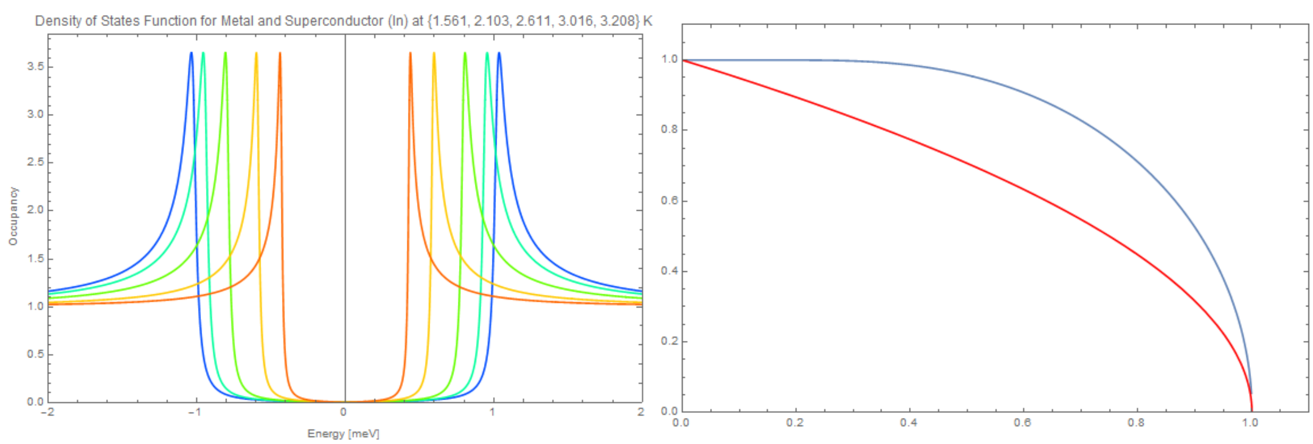
(b)

Figure 11: Simulated(a) and experiment(b) IV curve of middle junction at 5 different temperatures. Dashed lines in both figures are simulation leakage voltage.



(a) **(b)**

Figure 12: Simulated(a) and experiment(b) dI/dV curve of middle junction at 5 different temperatures. Vertical dashed lines in both figures are simulation leakage voltage. Horizontal dashed lines are the experiment measured value of conductance $G = 1.5963\Omega^{-1}$ at 4.221K.



(a) **(b)**

Figure 13: (a) Simulated density of state of middle junction at 5 different temperatures. (b) Temperature dependence of energy gap. Red line is high temperature approximation near T_c, equation shown in Eq. 3. Blue line is valid universally, equation shown in Eq. 1.

The simulation result shown in figure 11, 12, 13 tell us that, leakage voltage does not appear at maximum value of dI/dV. The dI/dV curve is a affected by both density of state function and Fermi distribution according to theory. Fermi distribution can be approximated to step function in low temperature regime($T \to 0$), but when it comes to high temperature the approximation is no longer valid. Thus it is quite hard to extract only information of density of state (and then energy gap) from the dI/dV curve.

Now for simplicity we only select 5 different temperatures below 3.41K and plot the curve for comparison. We find that with different choice of fitting parameter, the dI/dV curve will have huge difference. So it is quite important to choose a reasonable fitting parameter p in order to get a more accurate fitting. By investigating the fitting curve and data points, we decide that for different data set we choose different fitting parameter. We finally decide $p = 0.95$ for 1.561K, 2.103K and 2.611K, $p = 0.85$ for 3.016K and 3.208K. By comparison with simulation curve in figure 12, we can see that experiment curve appears to move closer to the axis in a way that it seems to be squeezed into center. Same thing can be observed in figure 11, where the nonlinear region is smaller than simulated one. This can be explained by our unstable cooling process. Our cooling process is quite fast so that there is little time for LHe to undergo convection, which means our temperature might not be the exact temperature in that moment.

4 Conclusions

In this experiment we fabricate the junction by depositing metal with evaporator, take the measurement of current and voltage across the junction by 4-wire measurement method, employ cryogenic liquids to cool down the junction, and investigate the temperature dependence of superconducting energy gap. From the IV curve and dI/dV curve plotted with experiment data points, we can see a temperature dependence of energy gap that the energy gap decreases monotonically with increasing temperature. And the squeezed curve gives us a lower energy gap compared to theoretical one.

This is a relatively complicated experiment because every step from sample fabrication to measurement in low temperature is quite complex and bulks of experiment techniques are included. Plus we are the first group doing this experiment in 2017fall, we ran into a lot of problems including short of LHe and poor function of equipment. These unexpected situations made us behind schedule.

Acknowledgement

We appreciate the great help of Prof. Rick Gaitskell for providing us Mathematica codes for simulation. Data in the LHe cooling process is taken by Fan Zhang.

References

[1] *History of superconductivity*, available at
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[3] *SIN Junction(Superconductor)*, available at
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[4] *Thin-Film Tunneling with Superconductors*, available at
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[5] K. Fossheim and A.Sudbo, *Superconductivity: Physics and Applications*, (John Wiley & Sons, Ltd. 2004).

[6] *Thin-Film Fabrication Tips*, available at
https://wiki.brown.edu/confluence/pages/viewpage.action?pageId=1164172.

Appendix

A.1 MATLAB codes of data extraction and offset reduction

```
%IV data extraction
%V = V2/Gain*1000 [mV]
%I = V1/R0*1000 [mA]

files = dir('*.csv');
Nfile = length(files);
R0 = 52.019;
G = xlsread('GreenParameter.xlsx','E2:E16');
for i = 1:Nfile
    filename = files(i).name;
    data = csvread(filename,6,1,[6,1,8005,2]);
    I = data(:,1)/R0*1000;
    V = data(:,2)/G(i,:)*1000;
    Ioffset = (max(I)+min(I))/2;
    Voffset = (max(V)+min(V))/2;
    I = I-Ioffset;
    V = V-Voffset;
    VI = [V I];
    dlmwrite(filename,VI,'precision','%.6f')
end
```

A.2 MATLAB codes of energy gap calculation

```
%Calculate energy gap at all temp
%Find the two maximum dI/dV value and average
%   the voltage value

files = dir('*.csv');
Nfile = length(files);
DeltaT = ones(Nfile,1);

for i = 1:Nfile
    %Import data
    filename = files(i).name;
    VI = csvread(filename);
    V = VI(:,1).';
    I = VI(:,2).';
    %Plot IV curve
    [IVcurve,~] = createFitB(V,I);
    %Caculate dI/dV
    dIdV = differentiate(IVcurve,V);
    %Find max dI/dV
    [maxslope,maxindex] = max(dIdV);
    Vmaxslope = V(maxindex);
    dIdV(maxindex) = 0;
    [max2slope,max2index] = max(dIdV);
    Vmax2slope = V(max2index);
    DeltaT(i,1) = (abs(Vmaxslope)+abs(Vmax2slope))/2;
end
```

A.3 MATLAB codes of energy gap calculation

```
%Plot IV & dIdV curve at 5 temp in one plot
%Green (Middle junction) data

%Import data

files = dir('*.csv');
Nfile = length(files);
load ColorList
cellTemp = {'1.561K','2.103K','2.611K','3.016K','3.208K','4.221K'};
TempList = string(cellTemp);


%Plot IV curve
figure

for i = 1:Nfile
    hold on
    filename = files(i).name;
    VI = csvread(filename);
    V = VI(:,1);
    I = VI(:,2);

    plot(V,I,'.','MarkerSize',4,'Color',ColorList(i,:))

end

grid on
%axis([-1 1 -1.5 1.5]);
axis([-2 2 -3 3]);
ax1 = gca;
ax1.FontSize = 11;
xlabel('V(mV)','FontSize',11)
ylabel('I(mA)','FontSize',11)
legend(TempList,'Location','southeast')

%Simulation outcome
Delta = [1.02, 0.94, 0.79, 0.59, 0.42];
for j=1:5
    hold on
    plot([Delta(j),Delta(j)],[-3,3],'--','LineWidth',0.5,'Color',ColorList(j,:))
    plot([-Delta(j),-Delta(j)],[-3,3],'--','LineWidth',0.5,'Color',ColorList(j,:))
end

%Plot dIdV curve first 3 temp
figure

for i = 1:3
    hold on
    filename = files(i).name;
    VI = csvread(filename);
    V = VI(:,1);
    I = VI(:,2);

    [IVcurve,gof] = createFitA(V,I);
    dIdV = differentiate(IVcurve,V);

    plot(V,dIdV,'-','LineWidth',1.5,'Color',ColorList(i,:));
```

```
end

%Plot dIdV curve last 2 temp
for i = 4:Nfile
    hold on
    filename = files(i).name;
    VI = csvread(filename);
    V = VI(:,1);
    I = VI(:,2);

    [IVcurve,gof] = createFitB(V,I);
    dIdV = differentiate(IVcurve,V);

    plot(V,dIdV,'-','LineWidth',1.5,'Color',ColorList(i,:));
end

grid on
axis([-2 2 0 2.3]);
ax2 = gca;
ax2.FontSize = 11;
plot([-2,2],[1.5963,1.5963],'k--','LineWidth',1.5)

xlabel('V(mV)','FontSize',11)
ylabel('dI/dV(1/Ohm)','FontSize',11)
legend(TempList,'Location','southeast')


%Simulation outcome
Delta = [1.02, 0.94, 0.79, 0.59, 0.42];
for j=1:5
    hold on
    plot([Delta(j),Delta(j)],[0,2.3],'--','LineWidth',0.6,'Color',ColorList(j,:))
    plot([-Delta(j),-Delta(j)],[0,2.3],'--','LineWidth',0.6,'Color',ColorList(j,:))
end

function [fitresult, gofA] = createFitA(V, I)
% Fit: 'IV curve'.
[xData, yData] = prepareCurveData( V, I );

% Set up fittype and options.
ft = fittype( 'smoothingspline' );
opts = fitoptions( 'Method', 'SmoothingSpline' );
opts.Normalize = 'on';
opts.SmoothingParam = 0.95;
% Fit model to data.
[fitresult, gofA] = fit( xData, yData, ft, opts );
end

function [fitresult, gofB] = createFitB(V, I)
% Fit: 'IV curve'.
[xData, yData] = prepareCurveData( V, I );

% Set up fittype and options.
ft = fittype( 'smoothingspline' );
opts = fitoptions( 'Method', 'SmoothingSpline' );
opts.Normalize = 'on';
opts.SmoothingParam = 0.85;
```

```
% Fit model to data.
[fitresult, gofB] = fit( xData, yData, ft, opts );
end
```

A.4 Inventory Sheet

Thin Film Tunneling, B&H room 203
Inventory Sheet
08/08/17 AK

Start Up	#	Inventory	Close Out
X	1	Dewar Set-up	✓
X	1	Sample Probe	✓
X	1	LHe Vacuum System	✓
X	1	Jacket Vacuum Pump	✓
	1	Coating System with accessories	
X	1	Function Generator w/ Manual	✓
X	1	Low-noise Pre-amp w/ Manual	✓
X	1	Digital Oscilloscope w/ Manual	✓
X	1	14 bit Computerscope w/ Manual	✓
X	1	Digital Multimeter	✓
X	1	LN2 Funnel	✓
X	1	Liquid He Transfer Tube	✓
X	3	Pair Cryogenic gloves	✓
X	1	Boxes of Nitrile Gloves	✓
X	3	Pair Safety Glasses	✓
X	1	**Safety Manual in Room 203**	✓

Comments: ______________________________

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At start up this area was neat and orderly and the following items were discussed:
X Lab Door, X No Food or Drink in Lab, ✓ Detailed Evaporator Instructions,
X Cables & Connectors, ✓ Proper Handling of LN2 and LHe (Transfer Tube),
X Proper Handling of Sample Probe & X Lab Safety.

Tianyi Zhou (Student signature) 09/12/2017 (Date) [illegible] (Student signature) 09/12/2017 (Date) [illegible] (TA/Staff signature) 9/12/17. (Date)

At time of close out, this area was neat & orderly & all inventory items were present.

[illegible] (TA/Staff signature) 10/03/17 (Date)