Notes on Superconductivity: Tunneling

Pre-lab
1. Draw a cross section of the SIN junction.
2. Why is it necessary to use all four contact pads? Would it be satisfactory to use only two of them for both current and voltage leads?
3. You will use a function generator (a voltage source) and a variable resistor to measure the I-V characteristics of your junctions. However, what you measure directly will be a V-V characteristic (the voltage from the function generator) and the potential difference across your junction. How do you get to the I-V characteristics of your junctions?
4. How do you expect your I-V characteristic to change at 4 K compared to at 0 K?
5. How can you determine the superconducting gap and the superconducting transition temperature from the I-V characteristic at 4 K?
6. How does the quartz crystal thickness monitor work? Does the reading of the thickness monitor correspond to the actual thickness of the film?
7. Does it matter whether you apply a current to the sample and measure the voltage or apply a voltage and measure the current?
8. How do the two pressure gauges on the evaporator work?
9. For an SIN junction, is the current <u>exactly</u> zero for $|V| < \Delta/e$?
10. For a Josephson junction, is the voltage <u>exactly</u> zero for $I < I_C$?

<u>Concept</u>

When two metals are separated by very thin (approximately $1 - 5$ nm) insulating barrier and a voltage is applied across the insulator, it is possible for a current to flow due to quantum mechanical tunneling of carriers. The electrical properties of such a device depend strongly on whether either or both of the metals is superconducting. We will consider three types of junction: normal-insulator-normal (NIN), superconducting-insulator-normal (SIN) and superconducting-insulator-superconducting (SIS).

For both NIN and SIN junctions, the current **i** arises from the random tunneling of individual charge carriers. Because of the Pauli exclusion principle, tunneling can occur only if there are occupied (filled) electronic states in one metal with the same energy as unoccupied (empty) electronic states in the other metal. Roughly speaking, the current is proportional to the range of energies for which there are filled states on one side and empty states on the other:

$$i \propto \int n_1(E)[1 - n_2(E + eV)]dE,$$

where n(E) is the electron occupation function.

For a normal metal at low temperature,

$$n(E) \quad = \quad \begin{array}{ll} 1 & \text{for } E < E_F \\ 0 & \text{for } E > E_F \end{array}$$

where E_F is the Fermi energy. So for an NIN junction, we find $i \propto V$. That is, an NIN junction behaves like a simple resistor.
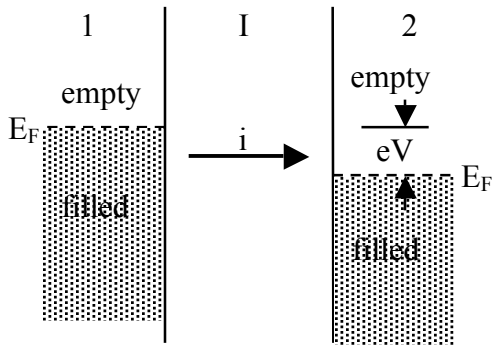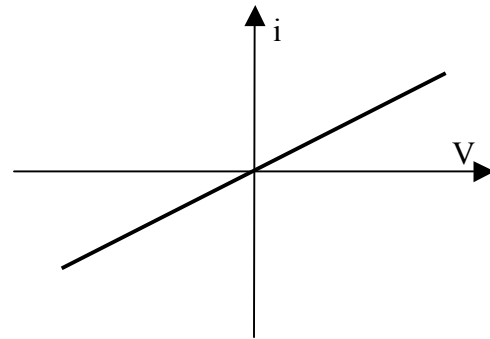
Fig. 1 (a): NIN Jct., density of states   (b): NIN Jct., i-V curve

In a superconductor, there is a gap at the Fermi level, in which there are no electronic states. The width of this gap corresponds to the energy required to break a Cooper pair. The density of states is as shown in Fig. 2(a). In this case, no current can flow until the voltage exceeds Δ/e, and the i-V curve is as shown in Fig. 2(b).
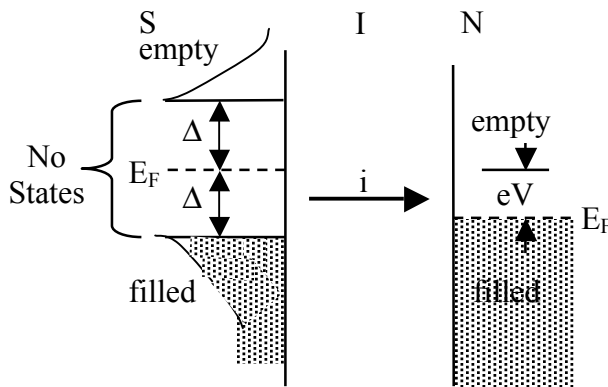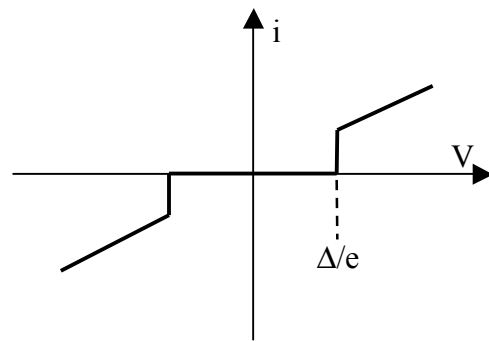

Fig. 2 (a): SIN Jct., density of states   (b): SIN Jct., i-V curve

If both of the metals are superconducting, and the barrier is sufficiently thin, a second type of tunneling can occur. Josephson tunneling involves the correlated tunneling of pairs of electrons, and the kind of qualitative argument used above cannot be used. In this case, it turns out that it is possible for a non-zero current to flow with no voltage across the junction. The i-V curve is as shown in Fig. 3. Josephson junctions form the basis of precision measurements of h/e, are used in SQUID magnetometers and are utilized in the fastest electronic instruments. Josephson junctions may also become useful in Quantum Computing.
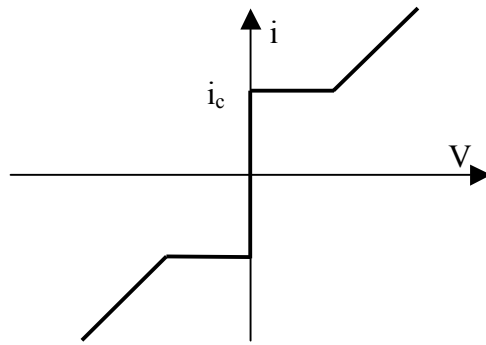
Fig. 3. Josephson Jct. i-V curve

Experiment

You will first fabricate SIN tunnel junctions and measure their i-V characteristics. Later on you will fabricate SIS Joesephson junctions.

SIN tunnel junctions

The basic method of making the SIN junctions is illustrated in Fig. 4. You will first (a) deposit a 150 – 200 nm thick layer of Al ("N") on the Si substrate in the form of a narrow strip. Next (b) you will deposit a ~ 100-nm thick layer of Pb(Bi) over the contact pads of the Al. Then you will expose the Al to O_2 gas in order to form the Al_2O_3 ("I") insulator on the surface of the Al. The integrity of the insulator will determine the I-V characteristics of your SIN junction. You should vary the oxidation time and the dosage of O_2:Ar gas to improve the performance of the insulator layer. Start with ~ 150mbar of O_2:Ar (20%:80%) and ~ 15 minute exposure time. Note that the Pb(Bi) layer on top of the Al contact pads keeps the oxide from forming there, allowing you to have good electrical contact to the Al underneath. Next, (c) you will deposit a ~150-nm thick Pb(Bi) film as your S layer. Finally, (d) put a **very-thin** layer of conducting Ag paint over each of the four contact pads. Electrical connections to the outside are made via spring-loaded pins that press down on each pad. Because the Pb(Bi) films are so soft, they need to be "hardened" by this overlayer of Ag paint before the pins press down on them.

(a) (b) (c)

Al layer   Pb(Bi) layer,   Final Pb(Bi) layer
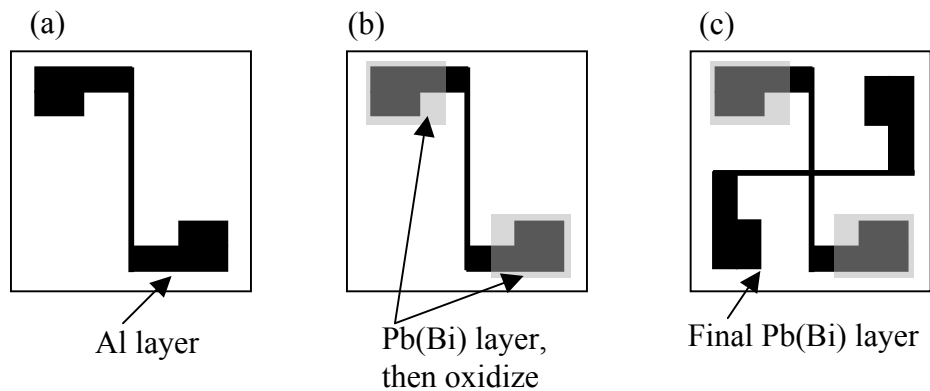   then oxidize

Fig. 4. Procedure for fabricating SIN tunnel junctions

The thickness monitor that you will use is a different distance from the evaporation boats than the substrate. First use geometry to correct the thickness monitor reading in order to estimate the thickness of the film at the substrate. You should measure the in-plane dimensions of the Pb(Bi) film and the two-terminal resistance of this film just above and below its superconducting temperature. You can then use the known resistivity of the Pb(29% Bi by weight) alloy to estimate the thickness of the film and compare your result with that from geometry.

Things to do: Establish relationship between resistance at 4.2 K of the tunnel junction and the product (time×pressure) of O_2 exposure. Make a plot of i vs. V and compare it with theory for T = 4.2 K. If you have time, you can place your sample in another cryostat and cool it down ~ 1.5 K where the i vs. V plot will look different and can also be compared with theory.

SIS Josephson tunnel junction

We are still trying to produce reliable SIS junctions. Here is a tentative procedure to follow. It is important to have the first S layer [Pb(Bi)] as smooth as possible. Pb(Bi) does not go down smoothly on Si, but it should go down smoothly on Al, since Al makes a smooth film on Si. See Fig. 5. The first step (a) is to deposit ~ 3nm of Al on the Si in the form of a dot. Step (b) is to deposit a ~ 100nm thick Pb(Bi) strip over the dot. In step (c) you deposit a ~5-nm thick layer of Al as a dot over the Pb(Bi) strip and then oxidize the Al surface. Try to improve the quality of the insulating layer by using different O_2:Ar pressure and exposure time. Start with ~ 150 mbar O_2:Ar (20%:80%) for ~15 minutes. Next, (c) you deposit a ~ 100 nm thick layer of Pb(Bi) to complete the junction. In order to avoid 'shadow effect' in the deposition of the second strip, your Pb(Bi) target should be oriented such that the vapor falls equally on both sides of the first strip. Finally, (d) put a **very-thin** layer of conducting Ag paint over each of the four contact pads, as you did for the SIN junction. Measure the i vs. V properties.
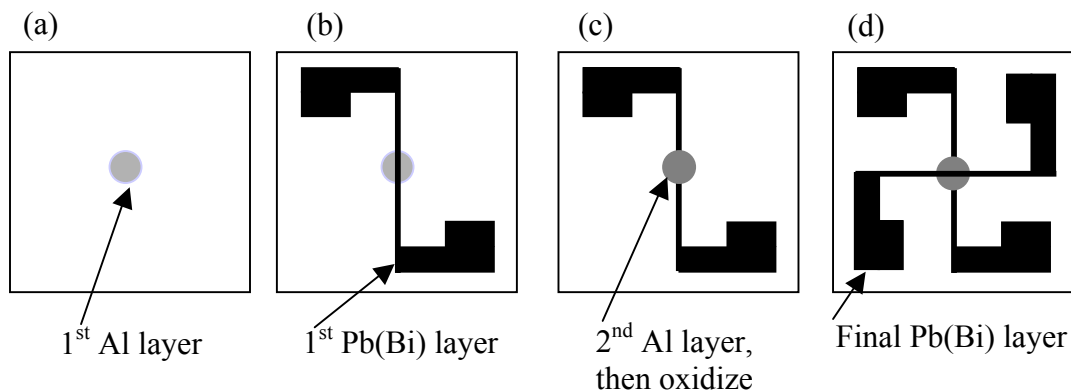

Fig. 5. Procedure for fabricating Josephson tunnel junctions

Readings:

Kittel, Intro. to Solid State Phys., Ch. 12, esp. sections on Tunneling.
Tinkham, Intro. to Superconductivity, Ch. 6.
R.P. Feynman, R.B. Leighton and M. Sands, The Feynman Lectures on Physics, Ch. 21.