University of Michigan **Physics 441-442**
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Electronic Properties of Metals and Semiconductors

(Note: This experiment can be very time-consuming. Attaching the leads to some of the samples can be quite challenging. The connections are very fragile and great care must be taken to prevent the connections from breaking due to thermal shock or ice formation. Most of the measurements can be made between liquid nitrogen temperature and room temperature. You will need approval from the instructor before liquid helium can be ordered. Delivery time is about 1 week.)

A. Introduction

The purpose of this experiment is to investigate electrical conduction in various classes of solids. We will look at two basic types of materials: a simple crystalline metal (Cu) and a doped semiconductor (Si).

As we will see, one can learn a great deal about the basic mechanisms of electrical conduction in solids by making measurements as a function of temperature. This is because the ingredients of the conduction process (e.g., excitation and scattering of electrons) are often very temperature dependent. Therefore, in our studies of electrical conduction we will meet some of the techniques and instrumentation commonly used in low-temperature physics: cryostats, low temperature thermometers, and sensitive DVMs for electrical measurements.

Experimental set-up – The apparatus (Fig. 1) consists of a simple cryostat that will cool samples to temperatures between 300°K and 4.2°K, the boiling point of liquid helium (^{4}He). The cryostat is designed to be inserted into the neck of an LHe storage dewar. This allows cooling without having to transfer helium, as in a conventional cryostat. Variable temperature is achieved simply by lowering and raising the sample through the temperature gradient inside the storage dewar. Electrical connections to the sample and electronic thermometer (calibrated Si diode) are provided.

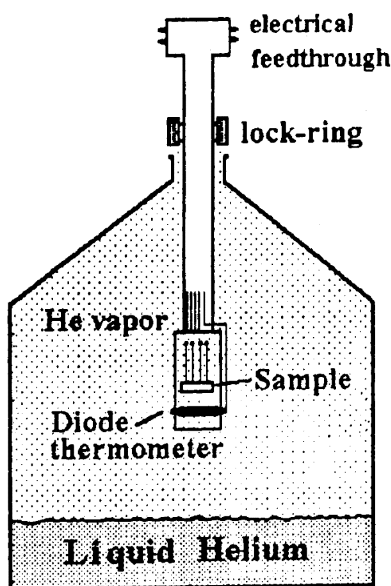


Fig. 1: Low-temperature cryostat for electrical conduction measurements.

Four-terminal measurement of electrical resistance

The standard technique for measuring the resistance of high conductivity metals, such as gold, is to attach *four probes* to the sample as shown:

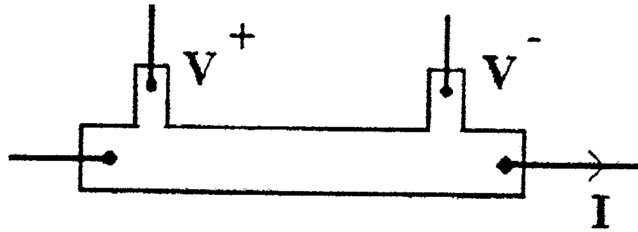


Fig. 2: Four-probe technique for electrical resistance measurements.

A fixed current, I, is supplied to the sample while the potential difference, $V=V^{+}-V^{0}$ between two points on the sample, is measured. The resistance, R, is defined as V/I. We will use SI units where I is in amps, V in volts, and R in Ohms. Traditionally, a constant current source is used to provide I, and V is usually measured using a sensitive digital voltmeter (DVM). We will use a four-terminal digital multimeter in which I is provided internally and the division V/I is performed internally to give a reading of R directly. Typical values of I range from 0.1 A to 1 A; this is kept small to prevent sample heating.

Often it is useful to define a 'normalized' resistance that takes into account the size and shape of the sample, so that the *resistivity* ρ is expressed as follows:

$$\rho = \frac{RA}{L} \quad \text{(ohm-m)}$$

where L is the distance between the potential contacts (see Fig. 2) and A is the cross-sectional area of the conducting channel. The advantages of the four-probe method are that it eliminates any contribution from the measuring leads and also avoids problems that may occur due to poor current contacts.

B. Experimental Procedure

The first sample, a metal. is a length of Cu wire. Cut a length of fine varnished Cu wire about 1 m long. Measure its length and diameter carefully, or use the wire gauge to determine its diameter. Solder the wire to the current and voltage terminals on the sample holder. The current and voltage connections can be joined together in the case of a metal. (Why is this?). Provide a current of approximately 1 amp for the metal sample. Operate the power supply in constant current mode. Use a DVM to measure the voltage across the sample. Why is this voltage different (smaller) than the voltage reading on the power supply? With the sample at room temperature, verify that the resistivity of the wire is what is expected for Cu. Measure the resistivity as a function of temperature.

If gold film samples are available, make measurements on these.

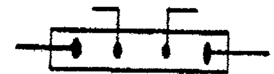
We will use a piece of doped Si for the semiconductor sample. This will allow us to measure the temperature dependence of the resistivity from ambient to liquid helium temperatures. We will see different regimes of temperature dependence: Below room temperature we expect to observe "ex-

trinsic" behavior dominated by the dopant charge carriers, and at the higher temperature we should see "intrinsic" behavior governed by carriers arising from the excitation of electrons from the valence band into the conduction band. In Si, the intrinsic regime does not kick in until a bit above room temperature, but you can see its onset even at T=300°K. At the lowest temperatures (below about 20°K) there will not be enough thermal energy to excite even the relatively shallow dopant states and the sample will become insulating.

A dopant level of ~10^{17} cm^{-3}, corresponding to a resistivity of ~10 ohm-cm, is about ideal for this measurement. Either n-type or p=-type silicon can be used. Instead of the DC power supply that we used for the Cu wire sample, it is necessary to use the much more sensitive AC impedance meter for the silicon sample. This is because the resistivity of Si is so much higher than a metal and therefore the current in the sample is much smaller than the 0.1 – 1 amp we used for the Cu sample. This meter automatically gives the resistance of the sample, and is provided with 4 inputs: I+ I-, V+ and V-, making 4-terminal measurements very convenient.

Dice a piece of size ~2 cm × 2 cm from the wafer provided. The process of dicing the wafer involves scribing (scratching) lines across the surface of the wafer and breaking it along the line. Then, using indium metal, solder four small contacts on the piece as shown in Fig. 3. The distance between the dots should be about 2 mm. Put the sample on a hot plate for about 20 minutes to anneal the contacts. This helps the indium to diffuse into the silicon and improves the contact. After you have made the contacts, measure the resistance between them using an ohmmeter. Is the contact ohmic? How would you check using the ohmmeter? [Hint: if the contact is not ohmic it will exhibit rectification. Try reversing the ohmmeter leads.] Estimate the expected resistance for a resistivity of 10 ohm-cm to see if you are in the right ball park.

Fig. 3: Arrangement of electrical contacts for Si sample.



Electrical Measurements

Make a series of resistance measurements on each sample at various temperatures between ambient and 4.2°K by slowly lowering the sample holder down into the He vapor of the storage dewar. You will need to use the screw-clamp to prevent the tube falling too quickly into the dewar. **Be careful not to touch any cold surfaces during this procedure – beware of frostbite!**

For the metal samples, measurements at ~20°K intervals should suffice; however, for the semiconductor sample, you will find that its resistance will vary rapidly with temperature and more frequent measurements may be necessary. Make a quick run first to get a feel for how the resistance varies and plan your measurement procedure accordingly. The region below T=30°K, where the resistance starts to climb very rapidly is particularly important. Try to get as many measurements as you can in this region.

Theoretical Background

Metals – The essential feature of a *metal* is that the conduction band states are partly filled even at absolute zero temperature. This is the result of either an odd number of valence electrons per atom, as in Cu, Ag, Au etc., or the occurrence of a band overlap (as in Be, Mg, Ca, and other divalent metals). For a perfect sample of metal with no defects and no thermal vibrations (at T=0LK_, the resis-

tance would be zero (i.e., infinitely conducting). The resistivity of real metals arises from non-conservative scattering which transfers energy to the lattice (observed as "I^2R" Joule heating). Scattering can arise from random defects and impurities or from thermal vibrations of the lattice (phonons). At the lowest temperatures only the scattering from the (static) defects and impurities will be important. Therefore by cooling the metal to very low temperatures one can separate out the contributions from phonons and static defects.

It is usual to discuss resistivity, $\rho(T)$, or its inverse, conductivity $\sigma(T)$, in terms of a mean scattering time, τ, which is the average interval between collisions of the conduction electrons, e.g. with a phonon or an impurity. We write the conductivity as

$$\sigma = \rho^{-1} = \frac{ne^2\tau}{m} \tag{1.1}$$

where n is the density of conduction electrons, m is the effective mass of the conduction electron, and e is the electronic charge.

For the region $T \gg \theta_D$ (the "Debye Temperature", characteristic of the phonon energies), phonons are the major source of scattering. In this classical regime all of the phonon modes are equally populated and the scattering time is just inversely proportional to the density of phonons. This density is determined by the Bose-Einstein distribution

$$\langle N \rangle = \left[\exp\left(\hbar\omega / kT\right) - 1\right]^{-1}$$

where $\langle N \rangle$ is the average occupancy of a phonon mode with frequency ω. $\langle N \rangle$ can be expanded: $\left(1 + \hbar\omega / kT + O\left(1/T^2\right) + \ldots - 1\right)^{-1}$ so that when $kT \gg \hbar\omega$, $\langle N \rangle$ is proportional to T.

$$i.e. \quad \tau \sim 1/T$$

from Eqn. 1 we get $\sigma \sim \tau \sim 1/T$

Therefore the resistivity $\rho \sim T \quad \text{for} \quad T \gg \theta_D$

At very low temperature $T \ll \theta_D$, as already indicated, ρ is independent of T and only depends on the defect or impurity scattering. In this case the scattering time τ is related to the density of defects which can be characterized by a *mean free path* $\ell = v_F\tau$, where v_F is the conduction electron mean speed ("Fermi velocity").

The intermediate regime $T \sim \theta_D$ is more complicated and the scattering in this case is a mixture of the above extremes. Moreover, the scattering from phonons is not linear in T in this regime because the short wavelength (higher energy) phonons which are effective in scattering electrons become less numerous at low temperatures and hence the phonon scattering cross section becomes strongly temperature dependent is this regime. In practice the resistance is found to vary approximately as T^5 in this intermediate temperature regime. You should be able to see this rapidly changing behavior in your data.

Semiconductors

The key feature of a semiconductor is the existence of an *energy gap* in the electronic band structure (see Fig. 4). Whereas simple metals typically have an odd number of valence electrons, leaving the

conduction band half empty, all materials classified as semiconductors have an *even number* of valence electrons and a band gap. With all of the electron states filled in the valence bands below the gap, there is no way for the electrons to pick up kinetic energy when subjected to an applied potential. Therefore, at low temperatures, such a material is an *insulator*.

It can become slightly conducting ("semiconducting") at higher temperatures when there is enough thermal energy to excite electrons across the gap into the upper electronic band ("conduction band"). This conductivity due to electrons crossing the band gap is usually not sufficient to make an electronic device such as a transistor, so additional charge carriers are introduced by adding an impurity to the semiconductor. This process, known as "doping", controls the conductivity of the material at room temperature.

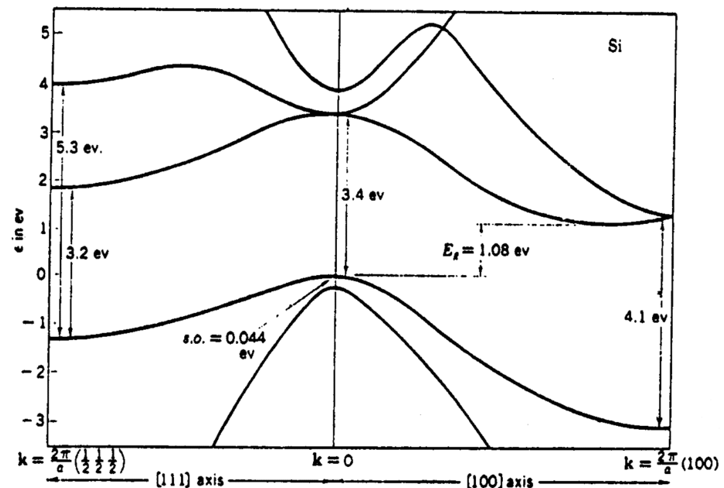


Fig. 4: Electronic band structure of silicon.

At higher temperatures $(T \gg \theta_D)$ the conductivity is determined mainly by electrons thermally excited across the gap. The behavior of the semiconductor is this regime is then said to be *intrinsic*. The probability of an electron making this jump is given by the Boltzmann distribution and the conductivity therefore follows an exponential temperature dependence:

$$\sigma = \sigma_0 \exp - \left(E_g / 2k_B T \right) \tag{1.2}$$

where E_g is the size of the energy gap, k_B is the Boltzmann's constant and σ_0 is a maximum conductivity determined by the scattering of electrons by phonons at high temperature.

Here it is assumed that the electron mobility, μ, (where $\sigma = \text{ne}\mu$) is only weakly temperature dependent compared to the exponential Boltzmann factor. In the temperature regime where dopant conduction is important, room temperature down to about 50°K, the mobility is the controlling factor in the charge conduction. We will take a closer look at these issues in the experiment on the Hall Effect. Note the appearance of the factor of ½ E_f in Eqn. 1.2. The ½ comes from the fact that the Fermi level is in the middle of the gap and both electrons and holes contribute to the conduction process. Note also the fact that the maximum of the valence band is not at the same wave vector as the minimum of the conduction band in Fig. 4. This is called the indirect gap, typical of Si and Ge; it means that momentum-conserving transitions of electrons across the gap are forbidden. In order

to conserve momentum some additional momentum $(\hbar k)$ must be provided to the electron. Collisions with high-energy phonons will make such indirect transitions possible. However, interaction with light (photons) will not provide the required momentum (why?); that is the reason Si and Ge are typically not used for optical devices such as LEDs and laser diodes.

Data Analysis

Plot appropriate graphs and analyze your results to answer the following questions:

1. Determine the scattering times, τ, and electron mean free paths, ℓ, in the copper wire at low and high temperatures.
2. Determine the scattering times, τ, and electron mean free paths, ℓ, in the two gold films at low temperature. Why are they different? Why is the resistivity of the very thin gold film less temperature dependent than for the thick film?
3. Explain the temperature dependence of the conductivity of the semiconductor sample. Determine E_g and the impurity conduction activation energy.
4. Determine the mean free path for the metglass sample. Try to explain the behavior you observe.