1.0 Learning Objectives

After successfully completing this laboratory assignment, including the assigned reading, the lab questions, and any required reports, the students will be able to:

1. Determine the bandgap energy for a semiconductor from a linear regression of measured data in the intrinsic region.
2. Explain why semiconductor conductivity changes with temperature.
3. Distinguish between intrinsic and extrinsic regimes and identify the applicable temperature range from an examination of measured data.
4. Express the mathematical relationships between carrier concentration and temperature in the intrinsic, extrinsic and ionization regimes.
5. Express the functional relationship between mobility and temperature in the intrinsic, extrinsic and ionization regimes.

2.0 Reference:

3.0 Theory

3.1 Conductivity of a Semiconductor

The conductivity of a semiconductor is given by:

$$\sigma = q (\mu_n n + \mu_p p)$$ (1)

where $\mu_n$ and $\mu_p$ refer to the mobilities of the electrons and holes, and $n$ and $p$ refer to the density of electrons and holes, respectively. Recall that in a doped semiconductor, majority carriers greatly outnumber minority carriers, so the Equation 1 can be reduced to a single term involving the majority carrier.

3.2 Effects of Temperature and Doping on Mobility of a Semiconductor

Conductivity of a material is determined by two factors: the concentration of free carriers available to conduct current and their mobility (or freedom to move). In a semiconductor, both mobility and carrier concentration are temperature dependent. Thus it is important to view the conductivity as a function of temperature which is expressed by:

$$\sigma = q [\mu_n(T) n(T) + \mu_p(T) p(T)]$$ (2)

There are two basic types of scattering mechanisms that influence the mobility of electrons and holes: lattice scattering and impurity scattering. We have already discussed lattice scattering in the context of metals; we know that lattice vibrations cause the mobility to decrease with increasing temperature.

However, the mobility of the carriers in a semiconductor is also influenced by the presence of charged impurities. Impurity scattering is caused by crystal defects such as ionized impurities. At lower temperatures, carriers move more slowly, so there is more time for them to interact with charged impurities. As a result, as the temperature decreases, impurity scattering increases, and the mobility decreases. This is just the opposite of the effect of lattice scattering.

The total mobility then is the sum of the lattice-scattering mobility and the impurity-scattering mobility. Figure 1 shows how the total mobility has a temperature at which it is a maximum. The approximate temperature dependence of mobility due to lattice scattering is $T^{-3/2}$, while the temperature dependence of mobility due to impurity scattering is $T^{+3/2}$ (see Figure 1). In practice
impurity scattering is typically only seen at very low temperatures. In the temperature range we will measure, only the influence of lattice scattering will be expected.

![Figure 1](image)

**Figure 1.** Approximate temperature dependence of mobility with both lattice and impurity scattering.

### 3.3 Temperature Dependence of Carrier Concentration

The carrier concentration in a semiconductor is also affected by temperature. The intrinsic carrier concentration is governed by:

\[
n_i = 2 \frac{2\pi kT}{h^2} \left[ \left( m_u m_p \right)^{3/4} \exp \left( -\frac{E_g}{2kT} \right) \right]^{3/2}
\]

where the exponential temperature dependence dominates \( n_i(T) \). To determine the total carrier concentration, we must also consider space-charge neutrality:

\[
n(T) = N^+(T) - N^- + \frac{n_i^2(T)}{n(T)}
\]

and

\[
p(T) = N^+_A(T) - N^- - \frac{n_i^2(T)}{p(T)}
\]

For a doped semiconductor, the temperature dependence of electron concentration can be seen in Figure 2. At very low temperature (large 1/T), negligible intrinsic electron-hole-pairs (EHPs) exist (\( n_i \) is very small), and the donor electrons are bound to the donor atoms. This is known as the ionization (or freeze-out) region. As the temperature is raised, increased ionization occurs and at
about 100K all of the donor atoms are ionized, at which point the carrier concentration is
determined by doping. The region where every available dopant has been ionized is called the
extrinsic (or saturation) region. In this region, an increase in temperature produces no increase in
carrier concentration. Referring to Equation 4, this is the region where \( N_D'(T) = N_D, N_A'(T) = N_A, \)
and
\[ n_i(T) \ll |N_D - N_A|. \]
At high temperatures, the thermally generated intrinsic carriers outnumber the
dopants \( (n_i > |N_D - N_A|) \). In this intrinsic region, carrier concentration increases with temperature
as shown in Equation 3 because \( n_i \) has become the dominant term of Equation 4.
Figure 2. Carrier Concentration vs. reciprocal temperature for silicon doped with $10^{15}$ donors/cm$^3$.

3.4 Temperature Dependence of Conductivity for a Semiconductor

Remember that Equation (1) showed that conductivity depends on both carrier concentration and mobility, so there are a variety of possible temperature dependencies for conductivity. For instance, at fairly low temperature (less than 200 K), the dominant scattering mechanism might be impurity scattering ($\mu \propto T^{3/2}$) while the carrier concentration is determined by extrinsic doping ($n = N_D^+$), therefore, conductivity would be seen to increase with temperature ($\sigma \propto T^{3/2}$). Other possibilities, depending on the material, doping, and temperature will show different temperature dependence of conductivity. One particularly interesting case occurs at high temperatures (above 400k or higher) when carrier concentration is intrinsic (Equation 4) and mobility is dominated by lattice scattering ($\mu_{\text{lattice}} \propto T^{-3/2}$). In such cases, the conductivity can easily be shown to vary with temperature as:
\[ \sigma \propto \exp \left( \frac{-E_g}{2kT} \right) \]  

(5)

In this case, conductivity depends only on the semiconductor bandgap and the temperature. In this temperature range, measured conductivity data can be used to determine the semiconductor bandgap energy, \( E_g \).

4.0 Experimental Procedure

In this experiment we measure the resistivity of an unknown sample as a function of temperature, from about 80 K up to 540 K, using a cryostat with a heating stage. A cryostat is an enclosure, which can be cooled to very low temperature. The system is very easy to use and should work perfectly if you follow a few simple steps. Below is an outline to how the apparatus works, what you should expect to measure, and how to do it. The results will show the saturation region (extrinsic) and the intrinsic region of conductivity. The temperature will not be low enough to observer the ionization region.

4.1 The cryostat

The apparatus consists of a micro-miniature refrigerator (inside the small metal vacuum enclosure which contains a window through which you can see the semiconductor sample), a tank of high-pressure nitrogen for the refrigeration fluid, and a vacuum pump and manifold. The apparatus uses the Joule-Thompson expansion of a high-pressure gas to achieve enough cooling to liquefy the gas in a small reservoir underneath the sample mount. The refrigerator is made up of a laminated set of glass slides, each of which has micro-channels etched into it, providing a serpentine path for the gas to proceed through a heat exchanger.

The sample is mounted on a cold mount at the end of the refrigerator with the thermal grease, which make excellent thermal contact between the sample and the refrigerator. The sample can be cooled to 80 K from room temperature in about 10 minutes. The refrigerator also has a heater built in (thin wires) with which we can heat the sample or control the temperature stability.
4.2 Procedure

Please use the instruction manual located next to each station:

1. Close all valves on manifold. (See drawing located near instrument).

2. Switch on backing pump. (It may be on already.)

3. Connect vacuum meter to power.

4. Connect temperature controller to power.

5. Open valve to begin pumping on cryostat).

6. Watch the reading on vacuum meter, the pressure will begin to fall.

7. When the pressure drops to about 20 millitorr, pass pure N\textsubscript{2} at 500 psi to purge the system for about 10 minutes.

8. While purging, make the electrical connections. Connect the leads from the two ends of the sample to the ohm meter.

9. When the pressure in the system is close to 20 millitorr, increase the N\textsubscript{2} pressure to 1800 psi. This starts the sample cooling down to 80 K.

10. To control and read the sample pressure use the computer. It has the following commands.

    TS- Enter – will display the sensor used and temperature range covered.

    Press TE- Enter- will display the current temperature of the sample.

    Press Skxx- Enter – will bring the sample to the requested temperature (where xx is the temperature you entered)

    Press MO1-Enter- will display the sample temperature every second.
11. Set the temperature to 80K, record the sample resistance.

12. Set the temperature to 100K, and record resistance.

13. Repeat the measurement every 20 K until 360 K is reached. **Do not exceed 360 K!**

14. To stop the experiment

15. Press SKO-Enter

16. Stop the gas flow (close main valve of N\textsubscript{2} cylinder).

17. Leave the backing pump **ON**

18. Turn on vacuum meter and resistance meter.

19. To calculate the **resistivity** from the **resistance**, you need the sample dimensions from your instructor.

**5.0 Written Lab Report Guidelines**

The written lab report should be in the form of an Engineering Report. The report should be between 5 and 10 pages long, double-spaced and word-processed. Use a spell-checker and a dictionary to insure you spelling is correct. Your English grammar, spelling and syntax will be graded. In all parts of the report, *do not copy any material, not even a single sentence*, from the laboratory notes or from any textbook.

The purpose of an engineering report is to inform the reader about work, which was done. You are partly teaching the reader. Imagine that the person reading the report is your supervisor or a client. They want to know what you did, why you did it, and what you found out. They want to know enough about the procedure that they believe you did a careful job; but they don’t want so much detail that they fall asleep reading the report. The following sections should be included in the report. An explanation of each section is included below.

1. Executive Summary
2. Theoretical Background

3. Experimental Procedure

4. Results and Discussion

5. Conclusions.

**Executive Summary**

A person should be able to read the Executive Summary and know what the experiment was, what the results were, without reading the entire report. There will be some repetition between the Executive Summary and the rest of the report. This section should be between one-half and one page long.

**Theoretical Background**

The purpose of this section is to explain to the reader the physics behind the experiment, *in your own words*. If the reader wants more information, they can go read a book. Here you are demonstrating your own understanding of the physics relevant to the experiment.

**Experimental Procedure**

In your own words, explain how you did the experiment. Include your own sketches of the apparatus, but do not include too much detail. What did you measure, what range of conditions did you use, what was the sample made of, etc. *Absolutely do not copy* the procedure from the LabNotes.

**Results and Discussion**

This is the most important part of the report. Data should be presented in a tabular or graphical from (usually not both). In a plot of data, all axes should be labeled and include proper units. All figures should have captions. The text should refer to the Figures and explain what the figures
show. Assume that the reader needs some help in interpreting the graphs. In the text, describe what the results were that you derived from the measured data.

Note: data is what you measured; results are what you derive from the data. An example of a data set is a plot or table of resistance values as a function of temperature. An example of a result is the value of the bandgap calculated from the data. The results are the important part of the experiment. Be very clear in reporting your result. You may want to compare your results to values found in your textbook or other reference books. Is your result different from published values by a few percent? Try to explain why. If it is off by orders of magnitude, then chances are you are not doing your calculation correctly.

Include at least the following in your discussion of the results:

1. What behavior did you observe in terms of temperature dependence of mobility and carrier concentration in the different regions of temperature. Identify the intrinsic, extrinsic, and ionization regions, if they appear. Plot the conductivity on a log or natural log scale. (Why?)

2. From the temperature of the transition between extrinsic and intrinsic behavior, estimate the dopant concentration in the sample.

3. From the appropriate portion of your plot, calculate the band gap energy \(E_g\) for germanium and compare to the published values.

4. Discuss the results and how they relate to the underlying physics you have learned.

5. Comment upon the accuracy of the results, cite and estimate possible sources of error.

Conclusions

The section simply repeats the measured results and indicates whether the experiment was successful, what conclusion should be drawn and what was learned.
In this experiment you will measure the resistivity of a semiconductor as it is heated from 80K to about 360K. Your objective is to measure the bandgap of the sample from intrinsic region as well as to observe its behavior in the extrinsic region.

You may answer the following questions even before you have taken any data:

A. How will you convert you raw data (either V and I, or R) into conductivity?
B. What should you use for the axes of your scatter plot?
C. After you perform a linear regression on your data, what is the meaning of the slope and intercept?
D. Some sample data is below. Make a sketch (or use an Excel spreadsheet) and determine the bandgap of this semiconductor.
E. After doing a similar analysis on the real sample used here, how would you know whether your answer is correct?
F. Question about the refrigerator: Why very high purity nitrogen gas is used to operate the refrigerator? Would the refrigerator work with high purity Hydrogen gas (what are possible advantages or disadvantages)? How about high purity Helium gas?

Have your lab instructor check over your Lab questions to be sure you have done the work correctly.