I-V Measurements of a P-N Junction Diode

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The experiment performed in this report goes over how to find the electron charge in Columbus, which can be determined using the P-N junction diode using the forward bias and plotting the found values, giving us a line on a log scale. Which provides us with a slope that finds the electron charge, which was determined to be $1.759 * 10^{-19}$ C, which is within 9.8% accuracy of the true value. This errors come from insufficient data, in other words; a lack of data at low voltage. Next, we will determined the energy gap of our metalloid, we can determine this by using reverse bias and plotting it on a linear plot finding the y-intercept of our data, and then plotting our found y-intercepts in log vs the inverse temperature. The found value of the energy gap 0.3 eV, which tells us that it is within decent agreement of the true value, which is 1.1 eV. The error in this case comes from systematic error, This is out of our control, which includes the potential contact difference.

I. BACKGROUND INFORMATION AND INTRODUCTION

A PN junction diode is a semiconductor in which it has the properties between an insulator and conductor, it should be noted that semiconductors are made of a metalloid, this experiment uses Silicon as our metalloid [3]. Insulators and conductors are made of nonmetals and metals respectively, so a semiconductor can conduct electricity, however; its conductivity increases as temperature increase while conductors conductivity decreases as temperature increases. Semiconductors only allow the electricity to flow in one direction from an n-type diode to p-type diode, hence the name P-N junction. The differences between p and n type diodes are the valence electrons, a p-type diode has Silicon doped with a impurity that contains 1 less valence electrons, while n-type has the same element Silicon doped with a impurity that has 1 more excess valence electron. If we put the two types together we have a build up of negative charge on p-type and build up of positive charge on the n-type, which makes it difficult for electrons to travel from p to n, but not the other way around. it is still possible to travel from p to n, however; to do so would need a huge amount of voltage. Electrons flow from a battery or any electron inducing source, the input must be put in a with the correct side for the semiconductor to operate optimally, a example would be a battery. Reversing the input gives us a huge band for the electrons to cross, which can be crossed only if a huge amount of volts were to be applied to shoot the electrons. An illustration below demonstrates the bridge that the electrons must face to travel on either side.

But before that I want to mention that semiconductors are very important in technology, not having semiconductors would literally not allow modern technology to work as well as it does today. They are that important.

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A. Forward vs Reverse Bias

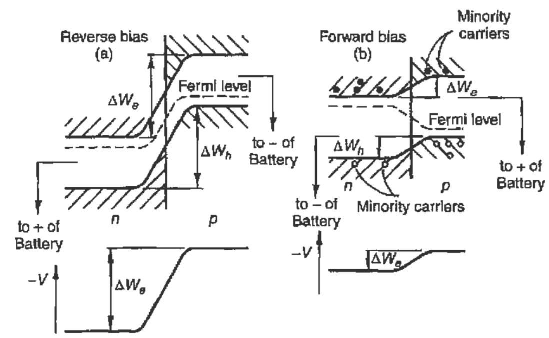


FIG A : The PN junction from [1] (a) demonstrates how difficult it is to move from p to n if oriented in reverse bias, while (b) demonstrates the little amount of voltage required to move electrons through the diode from n to p.

II. CALCULATIONS

The general formula for a ideal P-N Junction is

$$I = I_0(e^{eV_B/kT} - 1) \tag{1}$$

Where I is the current, I_0 is the saturation current, e is exponential, e inside the exponential is electron charge, V_B is the voltage induced, k is Boltzmann's constant, and T is temperature. however; the P-N junction does not obey the ideal P-N junction formula but does follow the following formula, the reason for this is because we can have a current in reverse bias:

$$I = I_0(e^{eV_B/2kT} - 1) \tag{2}$$

Further analysis tells us that when voltage is 0, then the current must be 0, hence the minus 1 in the formula, however; at higher voltage neglecting the minus 1 leads to a increased accuracy. which gives us:

$$I = I_0 e^{eV_B/2kT} \tag{3}$$

The first experiment covers finding the electron charge and the way to do this was to use the forward voltage in a log scale, which gives us a slope that is represented by:

$$e/2kT = log(I - I_0)/V_B \tag{4}$$

Where the y-axis must be in log to give us a proper slope. With the known values of k and T we can achieve e for all different temperatures.

Next it is time to find the energy gap E_g, As stated in the introduction as we increase the temperature, the conductivity increases, so we should see a general increase y-intercept for all the slopes in both forward and reverse bias. Finding the E_g is necessary to determine since it directly determines the conductivity of the metalloid. To determine the E_g we need to look at the reverse bias because the band gap is at its maximum and breaking that band is essentially the energy gap of the metalloid. A P-N Junction has a voltage limit before it essentially fried, in this experiment our initial P-N junction actually fried when reaching the higher voltage. Since the conductivity increases as temperature increases then the limit voltage also increases as we increase the temperature, and reaching the later voltages gives us a exponential influx of electrons since the band has been overtaken. We care only about when it is plateaued at the bottom since the y-intercept is the what we are looking for, we can get I_0 which is the y-intercept we do this 5 times for the 5 different temperatures we have. E_g is represented by formula (3) re-written for I_0 initially then with some clever algebra we can rewrite it into

$$log(I_0) = log(I) - E_g/(2 * 2.303 * kT) \tag{5}$$

We can re write this to give us

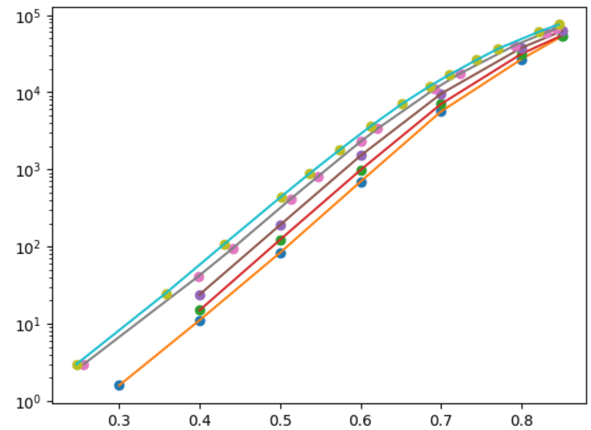
$$E_g = 2 * 2.303 * k * (log(I_0)/T) \tag{6}$$

where the log(I - I_0)/T is a slope that can be determined with all the experimental values

III. DATA OBSERVATION

First we setup the P-N junction in forward bias where a slight increase in voltage resulted in a massive influx of electrons, initially it was an exponential graph on a linear plot, however; if we set the y-axis to a log scale we will see a linear slope, as shown by formula (4). We took data at 5 different temperatures where the increase in temperature resulted in an increase of the y-intercept. The result of this is shown in the following data:

A. Data 1: Forward bias in Log scale



Data 1 : x-axis is voltage in V and y-axis is current in Amps. the furthest bottom line is lowest temperature and highest line is highest temperature.

Notice how as we increase the voltage we get a mini plateau of data, this is due to the minus 1 in the equation from equation(2). As stated earlier; as we increase voltage neglecting that minus 1 would result an increased linear slope. So if we just go from where voltage is .4 and voltage is .6, we can get a very linear slope that is well represented by the data. this slope gives us the e/2k slope from formula (4) we multiply by our known constant of temperature and Boltzmann's constant and we get:

B. Table 1: Determined e of Data 1

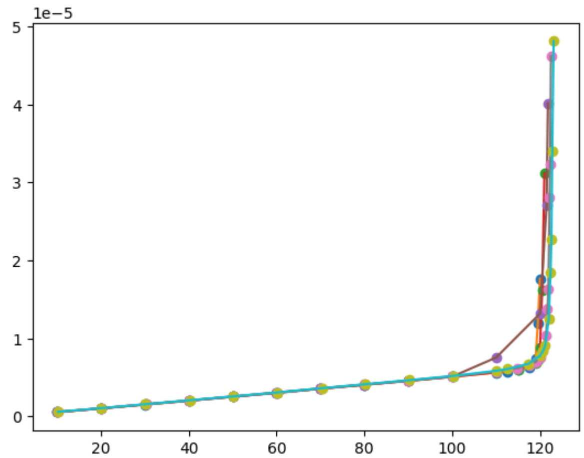
T	e
291.25 K	2.40 $*10^{-19}$ C
301.45 K	1.34 $*10^{-19}$ C
312.25 K	2.05 $*10^{-19}$ C
322.15 K	1.51 $*10^{-19}$ C
332.35 K	1.50 $*10^{-19}$ C

TABLE 1 : where T is temperature in Kelvin, and e is electron charge in Columbus

We can then average out all the found electron charge and obtain a value of $1.759 * 10^{-19}$ C comparing it to the true value of $1.602 * 10^{-19}$ C we have a percent difference of 9.8% which is a fairly accurate reproduction. An error here could be the lack of lower voltage data since missing data can be seen between 0.3 V and 0.4 V for two of our temperatures.

Next we want to determine the energy gap of our unknown metalloid. To do so would give us the type of metalloid we are using here. First of all we look at the reverse bias of P-N junction, as explained earlier the band gap in reverse bias is much higher so an increase of voltage would result a very small current, that initial amount of current allowed to flow is the diode where we have no voltage is the energy gap of our metalloid. Let's plot our data first and see what happens as we increase the voltage.

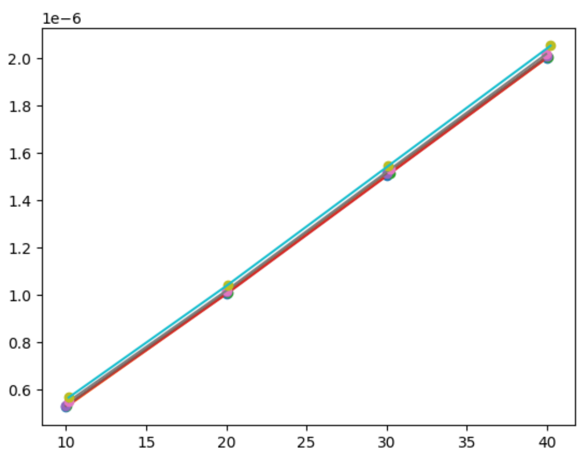
C. Data 2: Reverse bias



Data 2 : x-axis is voltage in V and y-axis is current in Amps

Notice the slope at the bottom, we can look at that slope and determine the y-intercept which gives us our I_0 if we only look at the part of the graph we will have 5 similar slopes that have different intercepts but are extremely close to one another, with my limited knowledge on computer software it is hard to show the intercept, but I can give a value for it with some math for now here is the graph:

D. Data 3: Reverse bias with only the slope



Data 3 : x-axis is voltage in V and y-axis is current in Amps

E. Table 2: Y-intercept and slope of Data 3

T	m	b
291.25 K	$4.93 * 10^{-7}$	$2.65 * 10^{-7}$ A
301.45 K	$4.92 * 10^{-7}$	$2.79 * 10^{-7}$ A
312.25 K	$4.94 * 10^{-7}$	$3.35 * 10^{-7}$ A
322.15 K	$4.94 * 10^{-7}$	$4.01 * 10^{-7}$ A
332.35 K	$4.96 * 10^{-7}$	$5.53 * 10^{-7}$ A

TABLE2 : where T is temperature in Kelvin, m is the slope of the given graph, and b is the y-intercept, or in other words our value of I_0 in amps

Notice how as temperature increases so dose our y-intercept, that is because as temperature increases the conductivity increases, in other words the band gap increases. Now that we have our values of I_0 we can follow formula (5) and graph it in terms of log vs inverse temperature, and that slope gives us our value of E_g since the graph will have a very odd slope increase, I will just list the data and the determined value with the given data sets

F. Data 3: $Log(I_0)$ vs 1/T in K^{-1}

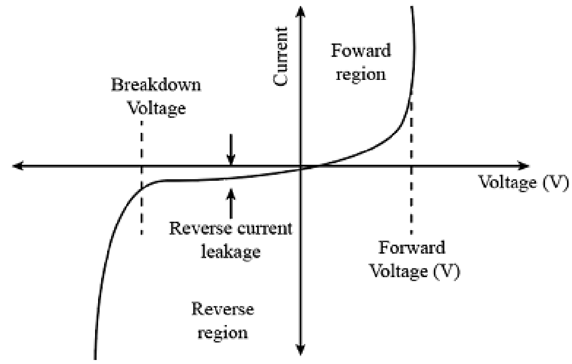
$1/T$	$log(I_0 * 10^{-6})$
$3.43 * 10^{-3}\ K^{-1}$	-12.58
$3.32 * 10^{-3}\ K^{-1}$	-12.55
$3.20 * 10^{-3}\ K^{-1}$	-12.47
$3.10 * 10^{-3}\ K^{-1}$	-12.40
$3.01 * 10^{-3}\ K^{-1}$	-12.26

DATA3: The reason why we multiplied the Saturation current by 10^{-6} is because we want it in micro Amps before using the log function

Now that we have our data, we find that the slope of this is -740, we plug this value into formula (6) and we get $E_g = .29$ eV which is a decent value compared to 1.1eV There are many error contributes here, 1 the slope determination could have been better determined if I had taken more values at the lower voltage for reverse bias, error number two comes from a systematic error, meaning I can't actually alter it. In this case that systematic error happens to be contact potential difference.

IV. CONCLUSION

The P-N Junction diode is used to allow current to come from one direction to the other, it does not allow the two-way transfer of electricity. The reason for this is due to the P-type and N-type diode stuck on to one another, where electrons flow from n to p fairly easily, while the opposite is not true. Conductors allow the transfer of energy in any direction and are all made of metals such as copper, zinc, etc. Semiconductors are mainly made of Silicon and Germanium and each metalloid have their own unique energy gap. Insulators are nonmetals that do not conduct electricity. There are many uses to each one, transfer of electricity for conductors, insulators for separating conductors, and semiconductors for the transfer of energy in a single direction. As determined by this experiment conductivity increases of a semiconductor, as temperature increases. Also we determined that we can transfer energy in the not intended direction of a semiconductor by overloading the voltage, as we saw we do have conductivity at lower voltage for reverse bias, but this is very minuscule and is in micro amps. But if we increase the voltage to 120 we see a sudden increase in conductivity, which means that our band has been broken and electrons are moving through the big bridge. Which means that semiconductors are not ideal. We found the energy gap of our system by manipulating our equation for E_g, we then found a slope that determined the energy gap using temperature and saturated current, which gave us a energy gap of the metalloid. We can actually put the two graphs together and achieve the I-V curve of the P-N junction which looks like:



from [6]

Where the forward region is our forward bias and reverse region is our reverse bias. The breakdown voltage is that exponential we see on the far right of our graph, and the forward voltage is the exponential we see if the graph was not in logarithmic

This experiment generally is Extremely important in society, a semiconductors is in everything we use today, from the computer in front of us, to the smartphone in our pocket, its is very important to understand where everything around us comes from.

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[1] N. D. Birell and P. C. W. Davies, *Quantum Fields in Curved Space* (Cambridge University Press, 1982).
[2] V. Lashkaryov, Investigation of a barrier layer of the thermoprobe method (2008).
[3] T. Jenksin, A brief history of semiconductors (2005).
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[5] T. Mori, Perspectives of high-temperature thermoelectric applications and p-type and n-type aluminoborides, (2016).
[6] Vi characteristic of pn junction diode (2020).