Experiment #3
Semiconductor Diodes and Transistors
PHYS 219

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1 Pre lab exercise (due at 2 PM of the day of your lab)

a. Make a plot of the absolute value of the current, $\mid I \mid$, versus voltage across a diode at temperature T=300K assuming I_0 is 10 μA over the voltage range -0.4V to +0.4V. It is easiest to use cgs units where $k_B = 8.617 \times 10^{-5} eV K^{-1}$. Note the exponent of the exponential in Eq. 1 has no units. Modify the Python script Plotfunction.py to do this. Hint: Look at the script Curvefitvdiode.py to see how to make this function. Also plot $\log \mid I \mid$ versus V to see the behaviour more clearly (2 marks).

b. Consider the circuit in Fig. 1. If the voltage across the resistor (to ground) V_r is +1.8V and the input voltage V_{in} is +2.0V what is the current through the diode? What is the voltage drop across the diode V_d? (1 mark)

c. Suppose the amplitude of the oscillating input voltage from the function generator in Fig. 4 is 100 mV. Estimate the offset voltage you need on the function generator to keep the base emitter junction forward biased through the whole cycle.(1 mark)

2 Objective

The two most basic semiconductor devices will be studied in this lab: the junction diode and the junction transistor. After this experiment, you will be able to characterize the behaviour of these devices and build simple circuits which perform useful functions such as have rectification and amplification.

3 Introduction

Introductory material on the physics of semiconductor devices can be found on Connect under Essential Reading in a file called Semiconductor Notes. Please read these before proceeding since this experiment is designed to complement those notes and to give you the opportunity to explore the properties and uses of diodes and transistors. A junction diode is the simplest semiconductor device and is used for many purposes such as converting of electrical energy into light (LEDs), converting light into electrical energy (solar cells) , light sensors, particle detectors and rectification. Nevertheless the most important semiconductor device is the transistor which was invented in 1947 and is at the heart of modern electronics and all its applications e.g. your laptop, cell phone and just about every piece of electronics you own. A single integrated circuit, can contain up to several billion transistors. However, single transistors are still useful in some applications such as high power/voltage switching. In this lab you will characterize and use the properties of a single diode and a single transistor.

4 Semiconductor Diode

A semiconductor junction diode has a single junction separating an n-type semiconductor on one side and a p-type semiconductor on the other with electrical connections to each side (see semiconductor notes for details). The different electronic properties (doping) between the two semiconductors lead to a non-linear and asymmetric relationship between current and voltage across the diode. This is very different than a resistor where the $I-V$ relationship is highly linear (Ohm's law) and symmetric. Under ideal conditions and with certain restrictions the relationship between current and the applied voltage ($I-V$ curve) for a diode has a simple exponential form:

$$I = I_0[\exp(eV/k_BT) - 1] \tag{1}$$

where I is the current passing through the diode, I_0 is a constant depending on the properties of the diode, V is the voltage drop across the diode, T is the temperature in Kelvin, e is the charge of the electron, and k_B is Boltzman's constant. Note that the current is zero when $V = 0$ as it must be. Also when the diode is reverse-biased ($V < 0$) the current is exponentially suppressed as a function of the magnitude of V whereas when it is forward-biased ($V > 0$) the current increases exponentially with applied voltage.

4.1 Measurement of the I-V characteristics of a diode

The goal in this part of the experiment is to measure the $I-V$ characteristics of the diode and find out how well and under what conditions Eqn. 1 describes the data.

- Make a voltage divider using the +5V supply from the protoboard along with the variable resistor on the protoboard. The variable resistor has a thumb wheel and three connection points. Using one of the DMMs check that the resistance between the two end connection points and verify it is constant independent of the thumb wheel position. Then check how the

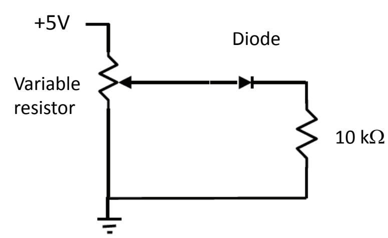

Figure 1: Circuit to measure the $I - V$ characteristics of a junction diode.

resistance between the middle connection point and one end. Make note of how the resistance varies as a function of the thumb wheel position.

- Now connect the +5V supply to one end of the variable resistor and the other end to ground. Check how the voltage at the central connection point varies as function the thumb wheel position. Note in your logbook the range of voltages that can be obtained in this way.
- Set up the circuit in Fig. 1 using your voltage divider. Make sure to include the 10 kOhm resistor in series with the diode since this limits the current through the diode so it will not be damaged.
- Set up one DMM to measure the voltage across the resistor V_r (to ground) and the other DMM to measure the input voltage applied to the circuit V_{in} i.e. the voltage drop across the diode and resistor in series to ground.
- Determine how to calculate current through the diode and the voltage drop across the diode from the measured values of V_r and V_{in}. Record your reasoning and the equations in your logbook.
- Determine which orientation of the diode corresponds to forward biasing. When the diode is forward biased the voltage drop across the 10 kOhm resistor saturates a value close to $V_{in} - 0.6V$ whereas the voltage drop across the diode is saturates at some small value close to 0.6V. In this case the effective resistance of the diode is much less than 10 kOhm and the current is limited by the 10 kOhm resistor. Conversely when the diode is reverse biased the voltage drop across the 10 kOhm resistor is very small and the voltage drop across the diode saturates close to V_{in}. In this case the effective resistance of the diode will be much larger than 10 kOhms and the current is very small and close to I_0 in Eqn. 1.
- Investigate the $I - V$ characteristics of the diode when it is forward biased. i.e. when the current increases exponentially as a function of the voltage

drop across the diode. You'll need about 50 points on the curve. Create a .csv file where the first column is the voltage drop across the diode V_d , the second column is the absolute value of the current passing through the diode I and the third column is σI (the uncertainty in I).

- Using the same +5V supply think about how to obtain $I - V$ data for reverse biasing. You won't need as many points to characterize the behaviour in the reverse biasing direction. Explain why that makes sense. Add the reverse bias points to the .csv file but with a minus sign in front of the V_d. Record the absolute value of the current versus $-V_d$ in the csv file so all the data can be plotted on a log scale. (Log of negative numbers are undefined).

- Determine how well your data is described by Eqn. 1 . Use the Python script Curvefitvdiode.py to fit the data where the free parameters are Boltzman's constant k_B/e and I_0. Determine the range of voltages where the data agrees reasonably well with Eqn. 1. Describe how and where it deviates from the theory. Compare your fitted value of k_B with the literature value. Is there agreement? What is your conclusion?

4.2 Diode as a Rectifier

It is sometimes necessary to convert an AC voltage into a DC voltage, a process called rectification. To demonstrate this set up the circuit in Fig. 2 .

- Apply a 60 Hz sinusoidal voltage with an amplitude of 1V using the function generator. Look at the input voltage signal on Channel 1 of the scope and output signal voltage $V_r(t)$ across the 1 kOhm resistor on Channel 2 of the scope.Note the scope inputs should be DC coupled. Make plots of both signals in your lab book.

- Explain the observed $V_r(t)$ based on the $I-V$ characteristics of the diode.

- Now place some capacitor (e.g.1μF) in parallel with the 1 kOhm resistor. Explain what you observe.

- Make plots of $V_r(t)$ with and without the capacitor and record them in your lab book.

- Now find a resistor with reduces the oscillating part of the signal on $V_r(t)$ to less than 5% of constant or time independent part of the signal. The idea is to make the RC time constant longer than the period of the 60Hz signal. Make plots of both signals in your lab book.

- Think of some application(s) for such as device and record it in your logbook.

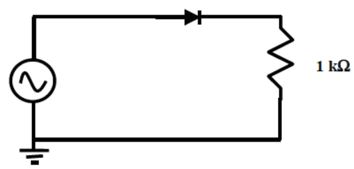

Figure 2: Circuit to measure rectification properties of a diode.

5 Bipolar Junction Transistors (BJT)

5.1 Background

There are two distinct kinds a BJT, a *npn* and a *pnp* where the n and p refer to the kind of doping in each layer of the semiconductor (see notes for more details). They have similar properties and in the this lab we will only study the former. The circuit symbol for a *npn* BJT is shown in Fig. 3. Unlike all other electrical elements we have looked at, the transistor has 3 electrical connection points (or ports) which are labeled as Collector (C), Emitter (E), and Base (B).

The BJT may act as a current amplifier such that $I_E = G_I \times I_B$ where the current gain G_I depends on the details of the transistor. However, several conditions need to be satisfied: (i) the collector voltage must be *positive* relative to the emitter voltage ($V_C - V_E > 0$): (ii) the base-emitter must be forward biased ($V_B - V_E \gtrsim 0.7V$; and (iii) base-collector is reverse-biased ($V_B - V_C \lesssim 0.7V$. The relation between I_E and I_B holds within some range dependent on the particular model of BJT. As you will shown the relation between I_B and I_E enables one to switch /control a large current ($I_C \approx I_E$) with a smaller one (I_B).

5.2 Current Amplification using a BJT

The transistor circuit shown in Fig. 4 functions as a current amplifier.

- Setup the circuit in Fig. 4 on your protoboard. Measure the resistance of each resistor with a DMM and record them in your labbook. Do not power up the board until you have carefully checked the circuit and you have completed the next step. A picture of the 2N3904 transistor can be found near the front of the green binder along along with descriptions of several other devices. The first page of that section describes the LM741 operational amplifier. The transistor is on the last page of the section. Note there are 3 pins on the transistor and you have to get the orientation

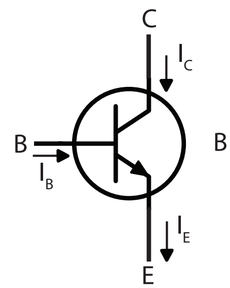

Figure 3: a) Block diagram of BJT.

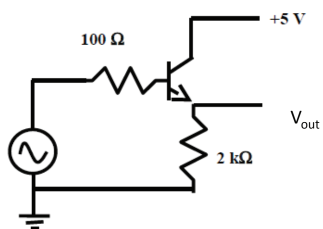

Figure 4: Circuit to amplify current with a transistor

correct. In particular the collector (pin 3) must be connected to +5V supply, the emitter (pin 1) is connected to the 2kOhm resistor with the other end of 2 kOhm resistor connected to ground. Also the base (pin 2) is connected to the 100 Ohm resistor and the other end the 100 Ohm resistor goes to the function generator. Think carefully how to insert the transistor on the protoboard so you can make multiple electrical connections to each pin, making sure the three pins are isolated and not connected each other.

- Select a sinusoidal waveform from the function generator (FG) with a frequency 100Hz, a peak to peak amplitude to 2V and a voltage offset equal to zero. Split the signal from the function generator with one side going to Channel 1 on the scope and the other side going to the emitter through the 100 Ohm resistor. Adjust the trigger on the scope to get a stable signal. Select AC coupling on the scope so you can adjust the voltage offset on the function generator without having to adjust the trigger level. Use Channel 2 on the scope to monitor the output voltage signal across the 2kOhm resistor to ground. As mentioned above it is best to use AC coupling for this part of the experiment.

- Find the range of offset voltages from function generator such that the transistor is functioning 'properly'. Note 3 conditions must be satisfied for the transistor to work properly. Condition (i) will naturally be satisfied since there is +5V at the collector, provided the voltage at the base is not too big. This means the input voltage should never go above +5V. Condition (ii) is that the base-emitter junction is forward biased $V_B - V_E \gtrsim 0.7V$. Condition (iii) is that the collector-base is reverse biased ($V_B - V_C \lesssim 0.7V$). The easiest way to see when conditions (ii) and (iii) are satisfied is to gradually increase the offset voltage from 0V to +5V and monitor the output voltage signal on the scope (Channel 2). As you increase the voltage offset on the input signal to the circuit you should see an output voltage signal across the 2 kOhm resistor which is similar to the input voltage signal. Do not apply more than +5V offset since you could damage the transistor. Make note of the range of offset voltages such that the output voltage signal looks similar to the input voltage signal and is undistorted. Record the input and output voltage signals when there is no distortion. It is best to put the scope back into DC coupling for this part of the experiment so you can see both the input and output signals with their offsets. Describe the main difference(s) and try to explain it. Describe the distortion when the offset voltage goes outside the range where there is no distortion (on both the high and low end). Taking into account the peak to peak amplitude of the input signal, what is your conclusion about the range of voltages applied to the base where the transistor is functioning properly?

- Measure the current gain. This is most easily done by measuring the DC voltage drop across the 2kOhm resistor versus the DC voltage drop across the 100 Ohm resistor. Set the amplitude of the FG to a very small value (i.e. 10 mV) so the function generator is acting like a DC input voltage to the circuit. Use the Hewlett Packard DMM to measure the DC voltage drop across the 100 Ohm resistor using a cable with banana plugs on one end (connected to the DMM) and clips on the other end connected on both sides of the 100 Ohm resistor. You will be measuring a very small voltage (10-900 microvolt) since the current is very small. Be sure not to ground either end of the 100 Ohm resistor. Similarly, use the Keithly DMM to measure the DC voltage drop across the 2kOhm resistor. In this case one end is at ground. Make sure you keep the voltage offset from the FG in the range where the transistor is functioning normally, taking into account the amplitude of the oscillating signal is now almost zero. (This means your offset voltage range will be about 2V wider than in the previous section).

- Make a spread sheet or table with the data and create columns for the current going into the base through the 100 Ohm resistor and also the current leaving the emitter going through the 2 kOhm resistor to ground. Make a plot of the current into the base versus current leaving the emitter and report a measurement of the current gain $G_I = I_E/I_B$. You can use

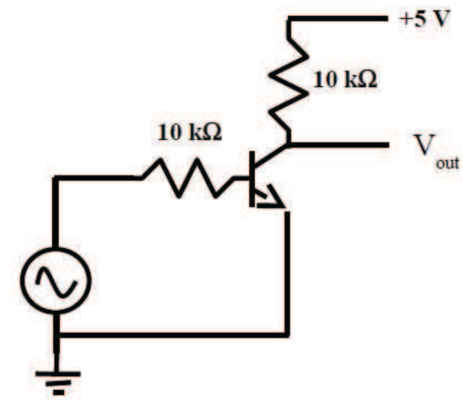

Figure 5: Circuit to amplify voltage with a transistor

Curvefitlinear.py to fit the data and obtain a measure of the gain and its uncertainty.

5.3 Voltage Amplification using a BJT

The circuit shown in Fig. 5 functions as a voltage amplifier.

- Set up the circuit in Fig. 5. Measure the resistors to make sure they are both 10 kOhms and record the values in your lab book. Do not power up the board until you have carefully checked the circuit and you have completed the next step.
- Adjust the function generator to have a sinusoidal signal with a frequency 100Hz, a peak to peak amplitude 100 mV and an offset voltage equal to zero. Split the signal from the function generator so one side goes to

Channel 1 of the scope and the other side goes the emitter through a 10 kOhm resistors. Adjust the trigger to get a stable signal. If you use an AC coupling to the scope you can adjust the offset voltage on the function generator without having to adjust the trigger level. Monitor the output voltage signal at the collector on Channel 2 of the scope.

- Turn on the power to the protoboard. Slowly increase the voltage offset on the function generator until to see a large amplitude undistorted signal at the output. Make note of the offset voltage range where the output signal is large and undistorted. It is a narrow range between 0.5 and 1.5 volts.
- Measure the AC amplitude of the output signal versus the AC amplitude of the input voltage signal. You may have to adjust the offset voltage when you do this.
- Determine the voltage amplification gain by making a plot of the output voltage amplitude versus the input voltage amplitude. Use the Pytho script Curvefitlinear.py to fit the data, determine the degree of linearity and to determine the voltage gain $G_V = V_{out}/V_{in}$. Check the limitations on the linear response of the amplifier (the range over which the output is proportional to the input).

6 Conclusion

Summarize your results on the diode and transistor? How well does Eq. 1 describe the I-V characteristics of a diode? What did you learn about using a diode for rectification?. What is your conclusion about the current gain and the voltage gain from the two transistor circuits studied? Under what conditions do the current and voltage amplifiers remain linear and undistorted?