Nonlinear Circuits

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I. Introduction

Nonlinear circuits are circuits whose components' properties, such as resistance, change with respect to voltage or current. When plotting current vs. voltage for the output of the circuit, there will be some nonlinear relationship between the two as we will show in experiment 1. The two nonlinear circuit components we will analyze in the following experiments will be diodes and transistors.

Diodes work as one-way valves blocking the flow of current in one direction. Diodes also have a characteristic voltage drop based on the material which can be thought of as a kickstart for the component to become active. Diodes we will analyze in our experiments include silicon, germanium, and LEDs.

Transistors is essentially a pair of diodes that work as both switches and amplifiers for a supplied input at the base. The input current creates a current flow from the emitter to the collector which becomes the observed amplified output current.

II. Diode I-V Curves

In this experiment, we will record plots of current vs. voltage for silicon diodes, germanium diodes, and light emitting diodes (LED) and compare with the theoretical Shockley model shown in Figure 1. To do this we will setup a simple circuit as shown in Figure 2 where Input B records the current through the circuit and Input A records the voltage across the diode.

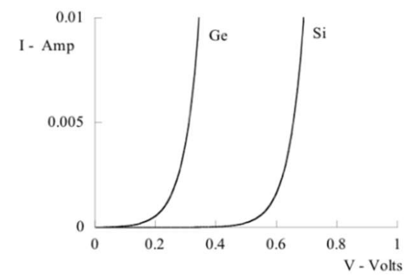

Figure 1: Shockley model for diode I-V relation

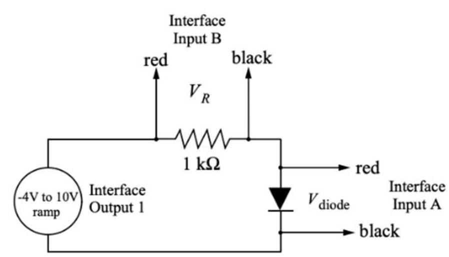

Figure 2: Circuit setup for diode current and voltage measurements

The Shockley model expects an exponential curve of the form:

$$I(V) = I_0(e^{V/V_{th}} - 1)$$

Where I_0 represents the saturation current, and V_{th} represents the threshold voltage.

The capstone interface was initialized to apply a "Ramp up Wave" sweeping from -4V to 10V in order to record the full picture of the curve. The resistor was recorded to be $R = 990 \pm 1\Omega$ by the handheld multimeter. Voltage and current across the silicon diode were recorded and its graph can be seen in Figure 3. The silicon diode was later replaced by a germanium diode and LED for qualitative analysis which can be seen in Figures 4 and 5 respectively.

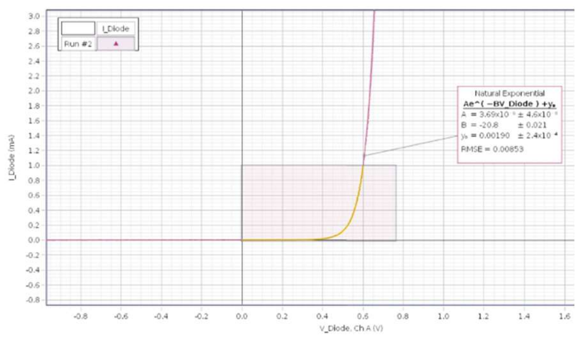

Figure 3: Current vs. voltage for silicon diode

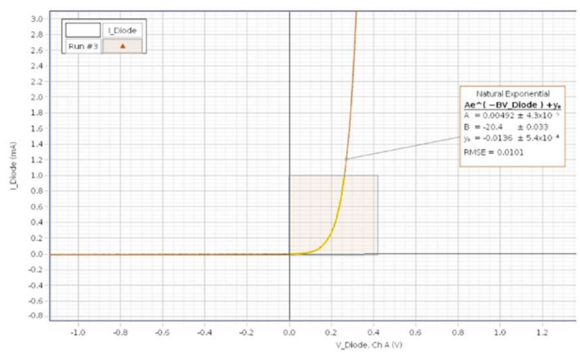

Figure 4: Current vs. voltage for germanium diode

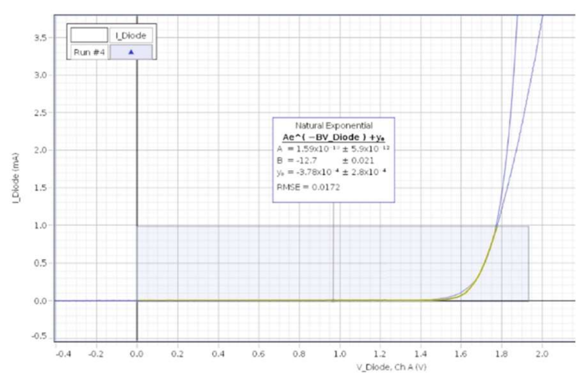

Figure 5: Current vs. voltage for LED

Natural exponential fits were established for the recorded values for currents less than 1mA as the curve diverges from an exponential. We will analyze the parameters for the silicon diode compared to the theoretical values. Values obtained from the fit come from the natural exponential model of $Ae^{-BV_{diode}} + y_0$:

$$I_0 = A = 3.688 \pm 0.046\ \mu\text{A}$$

$$V_{th} = -\frac{1}{B} = 47.98 \pm 0.11\ \text{mV}$$

$$n = -\frac{e}{Bk_bT} = 1.8456 \pm 0.0042$$

The value for I_0 was significantly higher than the expected value of 20nA, however, both V_{th} and n came within acceptable range of the expected values at V_{th} = 52mV and n = 2.

III. P-N Junctions and Light

In this experiment we will observe the behavior of photodetectors using and LED diode circuit. The setup for this experiment is shown in Figure 6.

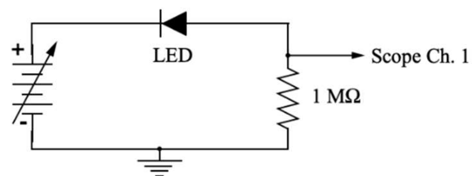

Figure 6: Circuit setup for LED photodetector

The circuit is supplied with a 5V voltage with current limit at 100mA as not to damage equipment. The circuit works as a photodetector because the LED functions as a break in the circuit until light incident on the junction creates a photo-current and the supplied voltage is able to flow.

Using a variable halogen desk lamp, we can shine light on the diode which jumpstarts the circuit and voltage across the resistor rises which appears as a static sinusoidal wave with a period twice that of the AC line (60 Hz).

IV. Half-Wave Rectifier

Rectifiers are components that convert AC to DC. Diodes can be used as rectifiers and using the setup shown in Figure 7, we can create a half-wave rectifier which allows current to flow at the positive half cycles of the AC voltage and blocks the negative cycle entirely.

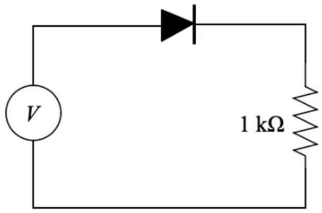

Figure 7: Circuit setup for half-wave rectifier

The same resistor was used as experiment 1 (R = 990 ± 1Ω) along with a silicon diode and function generator connected to an external amplifier to produce an output 1 kHz sine wave.

The oscilloscope was connected to portions of the circuit to measure desired values. Varying the amplitude of the output wave shows that the voltage across the resistor is directly proportional to the driving voltage. Switching the function generator between sine, square, and triangle waveforms showed similar changes in the voltage across the resistor as the diode appeared to be working properly.

With the since wave set to 8 V_{PP}, we can find the voltage threshold of the diode V_{th} by the difference between the input voltage V_{in} and voltage across the resistor V_R.

$$V_{th} = V_{in} - V_R = 0.68\ V$$

This value is very close to the nominal value for a silicon diode of 0.6V.

V. Transistor Characteristics

Similar to our exploration of diodes in experiment 1, we will measure characteristics of transistors and compare them to the expected results. The transistor has three connections which we will refer to as the: base, emitter, and collector. We will use a setup as shown in Figure 8 where the transistor has emitter resistance R_E = 99.4 ± 0.1 Ω and collector resistance R_C = 990 ± 1 Ω.

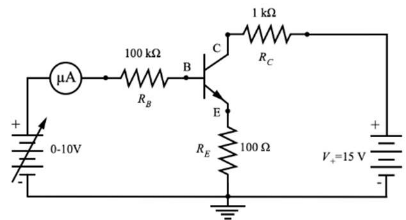

Figure 8: Circuit setup for testing transistor characteristics

Using our power supply, we vary the supply voltage between 0-10V to record base currents of I_B = 80, 60, 40, 20, 10, 5, and 1 μA while recording the voltages across the collector V_C and emitter V_E. These measurements allow us to calculate the current across the collector I_C which we will plot as a function of base current as shown in Figure 9.

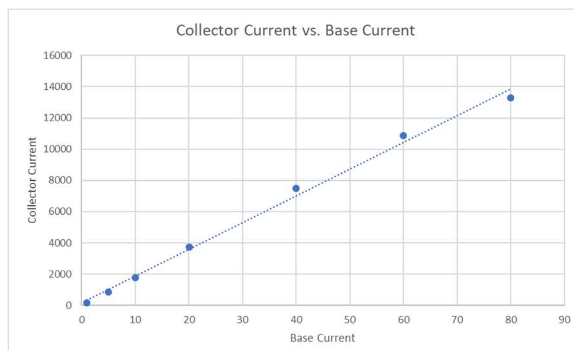

Figure 9: Collector current vs. Base current for transistor circuit

This plot has a distinctive slope which using a least-squares regression fit yields a slope of β = 170.9 ± 5.6. This β is the current gain of the transistor, the ratio of collector current to the supplied base current, which is expected to be between 100 and 200.

As we stated previously, a transistor is essentially two diodes. To test this, we can qualitatively analyze the I-V curve for the emitter side of the resistor. Plotting base current against voltage at the base-emitter junction yields the plot shown in Figure 10.

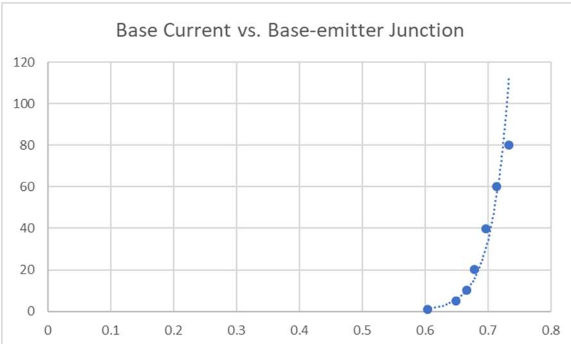

Figure 10: I-V curve at the base-emitter junction of the transistor circuit

This behaves as an exponential curve which is exactly as we'd expect from a diode as shown by the dashed natural exponent fit.

VI. Transistor Amplifier

Similar to the previous experiment we will be dealing with a transistor circuit as shown in Figure 11.

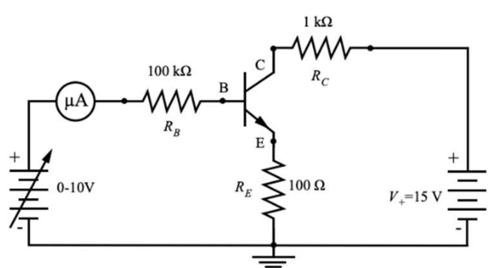

Figure 11: Transistor circuit for amplification

Using a function generator, we supply the circuit with a 1 V_{PP} sinusoid at 1 kHz and a 1.4 V DC offset. This offset is set in order to keep the circuit closed as no current can flow when the transistor is below its voltage threshold.

V_C was an inverted version of V_B with a higher amplitude, an example of inverted amplification. V_E however, was in phase with V_B but had an almost identical amplitude, known as the follower.

Using the function generator to vary the input amplitude we can observe that for too high AC amplitude, the transistor fails, and the peaks are cut off on the oscilloscope reading as too many charge carriers block the current flow in the transistor.

VII. Conclusion

In these experiments we have displayed the qualitative behavior of diodes and transistors through I-V curves and proved the theoretical models in calculating parameters such as the saturation current of diodes and voltage threshold for diodes and transistors.

We observed the photon-junction relationship in LEDs and the current bias of diodes which create one-way flow in circuits. We've shown that this can be used to create an AC rectifier and coupled with the voltage threshold allow us to manipulate currents within a circuit.

Nonlinear circuits exhibit behaviors crucial to our mastery of electronics. Most of the devices we use on a daily basis contain diodes and transistors, from computer chips to dorm room LED strips, and we should be able to understand their function.