

Exercise 9: Transistors and rectifiers

Purpose: to investigate the basic characteristics of an *npn* transistor. Three different circuits will be observed: (1) digital switch, (2) current amplifier, and (3) voltage amplifier.

Introduction

In order to understand how transistors work, we must examine the basic chemical properties of silicon-based semiconductors. Silicon is in group IVA of the periodic table and has 4 valence electrons with which it forms covalent bonds. In a pure silicon crystal as shown in Fig. 1, every silicon atom is covalently bound to four other silicon atoms. Pure silicon has no free electrons, and is therefore a very poor conductor. In a process called doping, impurities are purposely added to pure silicon to alter its characteristics. Typically, these impurities are in low concentration (1 part in 10^6 or 10^7). There are two types of doping elements used. Arsenic, comes from group VA, and has five valence electrons as illustrated in Fig. 1. Four of the valence electrons form covalent bonds with silicon, and the extra electron is "free," somewhat like electrons in a metallic conductor. When the fifth electron leaves the arsenic atom, the atom becomes a fixed positive ion. One fixed positive ion exists for every free electron in the doped silicon crystal. This type of silicon crystal is called an *n*-type semiconductor because negative charges (electrons) carry the current.

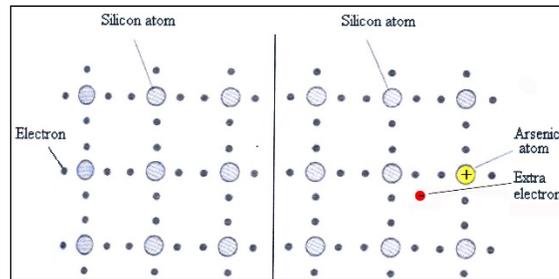


Fig. 1: covalent bonding in (left) pure silicon and in (right) arsenic doped silicon.

A second type of impurity comes from Group IIIA elements, such as gallium, which has only three valence electrons. Gallium forms three covalent bonds with silicon, and the fourth bond has only one electron rather than two. This missing electron can be obtained from a neighboring silicon atom, resulting in a negative gallium ion, and a positive neighboring silicon ion, which is called a positive hole. This positive hole can be filled by an electron from yet another silicon, etc. Although electrons are jumping from silicon to silicon, it appears as though the positive hole is the mobile charge carrier. This type of silicon crystal is called a *p*-type semiconductor because positive charges (holes) carry the current.

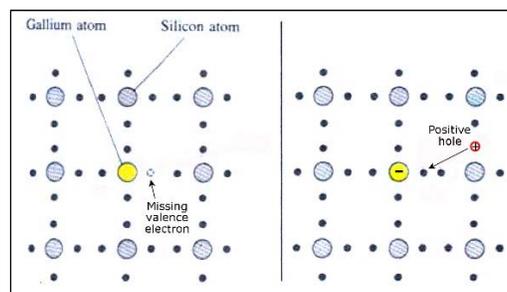


Fig. 2: (right) covalent bonding in gallium doped silicon and (left) the formation of positive holes.

In addition to the chemical nature of doped semiconductors, we must also understand how they behave when placed in physical contact, such as in a p-n junction diode. When an *n*-type semiconductor comes in contact with a *p*-type semiconductor, free electrons diffuse from the *n*-type material into the *p*-type side, and positive holes diffuse in the opposite direction as observed in Fig. 3.

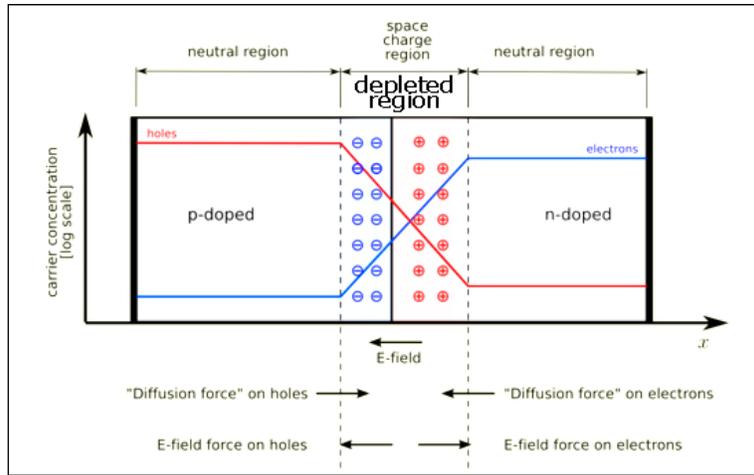


Fig. 3: *pn* junction with no external voltage applied

The electrons and holes neutralize each other, removing all charge carriers in a boundary layer called the depletion region. As the charge carriers diffuse across the layer, a fixed positive charge develops on the *n*-side and a fixed negative charge develops on the *p*-side. This creates an intrinsic electric field that opposes the diffusion.

Eventually equilibrium is reached and diffusion is balanced by the electric field. Since the depleted region has no charge carriers, current cannot pass through it. There are two different ways in which a source of emf can be attached to a junction diode. If the positive terminal of a DC power supply is attached to the *n*-doped end and the negative terminal is attached to the *p*-doped end, the electric field generated by the source of emf will be in the same direction as the intrinsic field, and holes and electrons will move further away and widen the depleted region. This situation is called reversed biased, and no current will pass under these conditions. If the power supply terminals are reversed such that the positive terminal is attached to the *p*-doped side, the electric field due to the source of emf opposes the intrinsic field. As the power supply emf is increased, the depleted region gets thinner, and eventually, at what is called the bias potential, charge carriers reach the interface and a current passes through the diode. This situation is called forward biased.

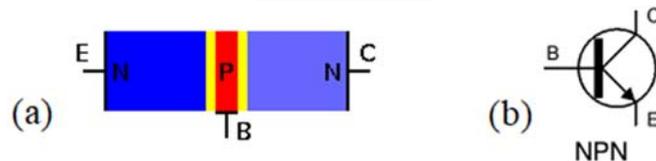


Fig. 4: (a) schematic and (b) circuit diagram symbol of a *npn*-type transistor.

A simple junction transistor is composed of a very thin ($\sim 10 \mu\text{m}$) layer of one type of doped semiconductor sandwiched between two crystals of the other type. Both *npn*-type and *pn*-type transistors are available. We will be using an *npn*-type for this laboratory. The three regions are designated the emitter (E), base (B), and collector (C), respectively as illustrated in Fig. 4(a). The circuit

diagram symbol for this type of transistor is shown in Fig. 4(b). In modern versions of this device, the emitter region is heavily doped with the appropriate impurity, while the base region is very lightly doped. The collector region has a moderate doping level so it will have a low internal resistance.

In normal operation, a large reverse bias is applied to the collector relative to the base, and a small positive bias is applied to the base relative to the emitter as illustrated in Fig. 5. The positive base-emitter bias attracts electrons from the emitter into the base. Most of these electrons, however, have enough momentum to pass through the base into the collector, where they are attracted by the high positive voltage on the collector. There is a small current through the base, but most of the current is through the collector. Controlling the small base current allows control of the much larger collector current. The base-emitter and base-collector circuits behave as diodes. As we are going to see, the transistor has a variety of uses in circuits, from a digital switch to a current or voltage amplifier.

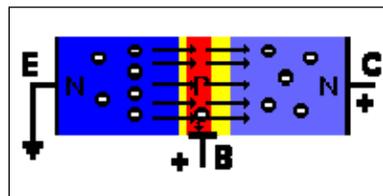


Fig. 5: Schematic of an operating *npn*-type transistor.

The first circuit you are going to investigate is a simple digital switch as seen in Fig. 6. In this circuit, a small AC potential applied to the base-emitter part of the circuit is going to be used to drive a current through a light emitting diode and load resistor in series in the emitter-collector part of the circuit. The LED will turn on and off, controlled by the characteristics of the base-emitter circuit.

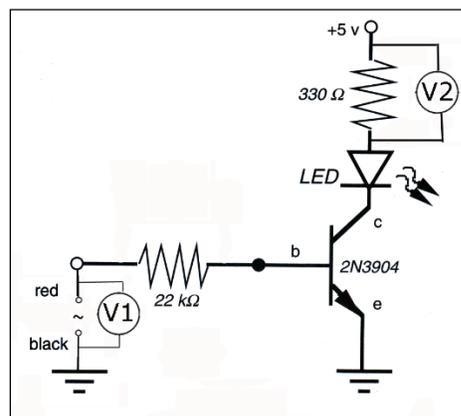


Fig. 6: a simple digital switch circuit.

The same circuit used as a digital switch functions as a current amplifier, where a simple circuit is shown in Fig. 7. A small current passing through the base-emitter circuit controls a large current passing through the emitter-collector circuit. We are going to measure voltage across resistors in the two parts of the circuit, and calculate the ratio of current in the two parts.

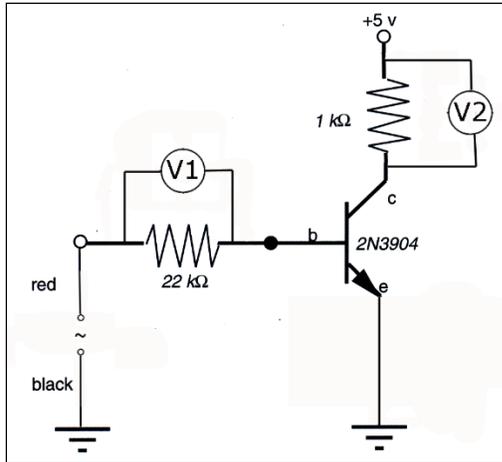


Fig. 7: current amplification circuit.

The *npn*-type transistor can also be used in a voltage amplification circuit as shown in Fig. 8. The circuit shown below is designed to take a low voltage AC signal in the base-emitter circuit and convert it to a higher voltage AC signal in the collector emitter circuit. Because the transistor also functions as a diode, the input signal must be “added” to a DC signal so the base-emitter remains forward biased at all times, and then the output signal must have the dc component “subtracted” from the final signal. In the following circuit, Section 1 is the input signal, isolated from the DC component by the capacitor (which only passes AC current). Section 2 adds a +5 volt forward bias to the base-emitter, so it will pass all of the signal coming in from the ac source. Section 3 represents the voltage amplification of the transistor. The final output voltage across the load resistor in Section 4 has had the dc component removed by the capacitor.

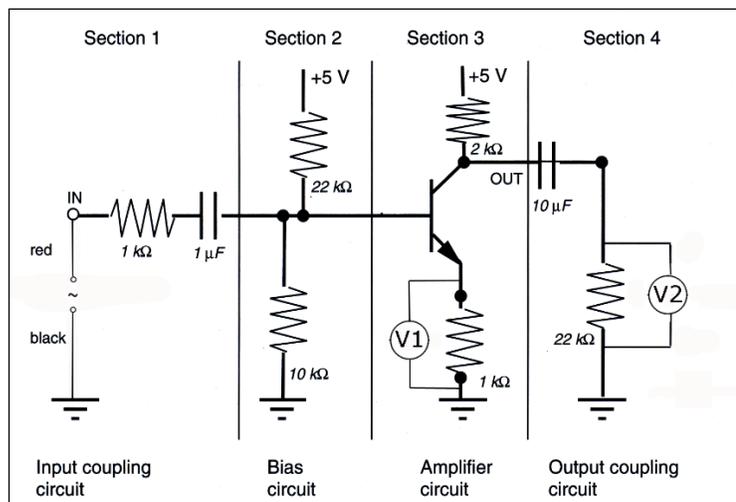


Fig. 8: voltage amplification circuit.

Laboratory assignment

I. Digital switch

1. Attach one voltage sensor directly to the frequency generator. Set the frequency to 1 Hz, and use the scope feature in data studio to adjust the voltage amplitude to 2 volt.
2. Now turn the frequency generator off, but do not change the amplitude or frequency settings. Also remove the voltage sensor.
3. Build the circuit shown in Fig. 9. Attach the voltage sensors last. Make sure to connect a patch cord from the negative terminal (black) of the DC power supply to the ground terminal (green) of the same unit.

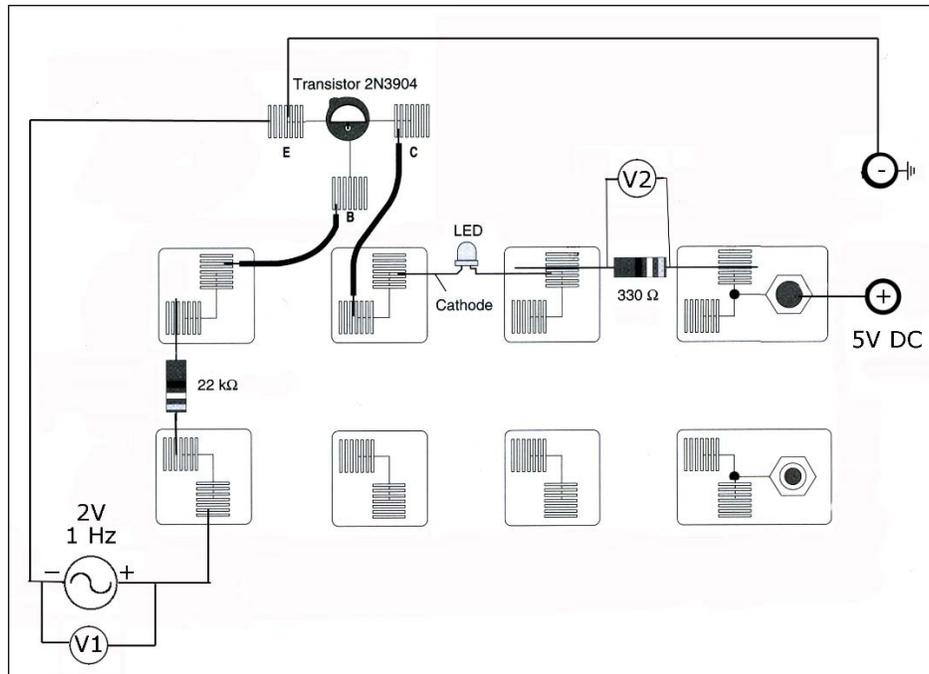


Fig. 9: circuit to build in step 3.

4. Turn on the frequency generator. Turn on the DC power supply and adjust to +5 volts.
5. Adjust the sampling rate in Data Studio to 200 Hz. Use a scope to verify that both voltage signals are being read correctly. The two signals, as seen in Fig. 10, show the voltage across the frequency generator (red, V_1) and the voltage across the 330 Ω load resistor (green, V_2).

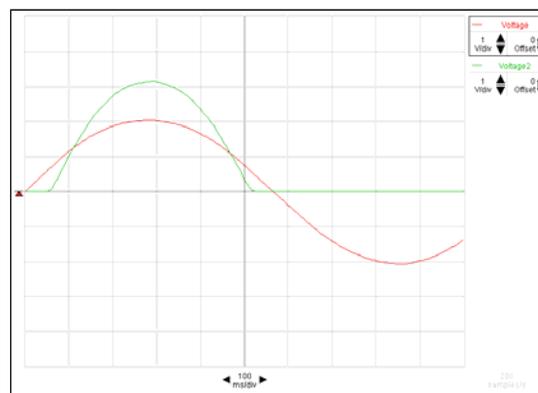


Fig. 10: example of oscilloscope image in step 5.

6. Use the smart tool to determine the bias voltage for the transistor. The bias voltage is the minimum positive voltage on the base that allows a current to pass from emitter to collector. Be sure to [save an image of the oscilloscope graph](#).
7. Display the voltage between the base and emitter on the transistor as V_1 . Do not move the voltage sensor leads from the $330\ \Omega$ resistor. [Save an image of the oscilloscope graph](#).
8. Display the voltage across the $22\ \text{k}\Omega$ resistor as V_1 . Do not move the voltage sensor leads from the $330\ \Omega$ resistor. [Save an image of the oscilloscope graph](#).
9. [Comment on the base-emitter voltage in step 7 and the voltage in step 8.](#)

II. Current amplifier

10. [Measure the precise resistance of the \$1\ \text{k}\Omega\$ and \$22\ \text{k}\Omega\$ resistors.](#)
11. Attach one voltage sensor directly to the frequency generator. Set the frequency to 1 Hz, and use the scope feature in data studio to adjust the voltage amplitude to 1 volt.
12. Turn the frequency generator off, but do not change the amplitude or frequency settings. Remove the voltage sensor.
13. Build the circuit shown in Fig. 11. Attach the voltage sensors last. Make sure to connect a patch cord from the negative terminal (black) of the DC power supply to the ground terminal (green) of the same unit.

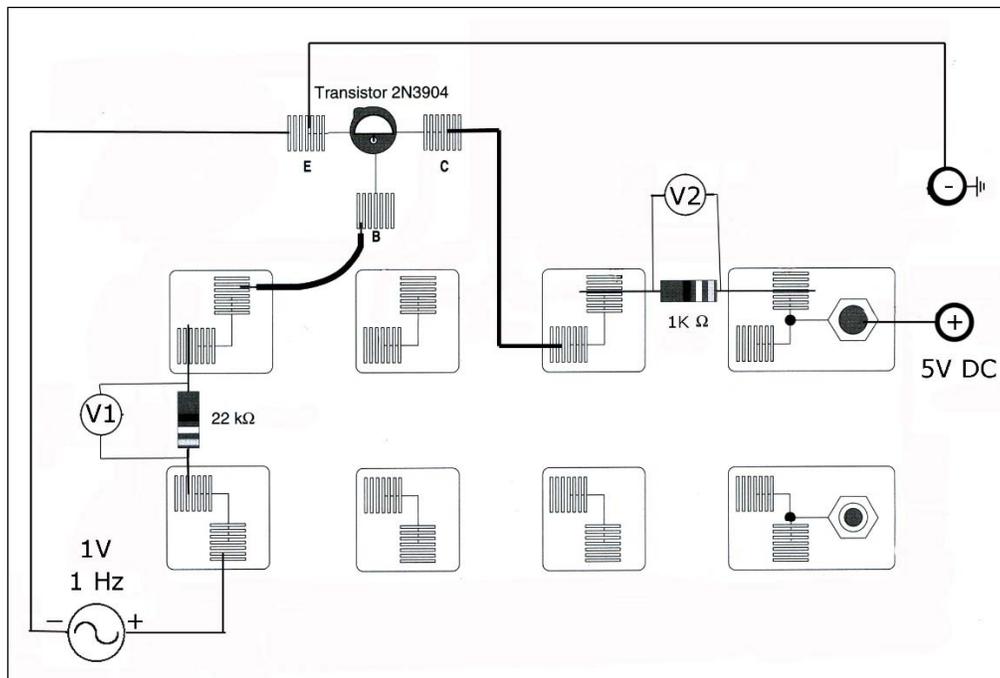


Fig. 11: circuit to build in step 13.

14. Turn on the frequency generator. Turn on the DC power supply and adjust to +5 volts.
15. Adjust the sampling rate in Data Studio to 200 Hz. Use a scope to verify that both voltage signals are being read correctly. The two signals, as seen in Fig. 12, show the voltage across the $22\ \text{k}\Omega$ resistor (red, V_1) and the voltage across the $1\ \text{k}\Omega$ load resistor (green, V_2). The red voltage signal essentially represents the current, $I = V/R$, flowing through the base-emitter part of the transistor functioning as a diode, although not a perfect diode because the base is so thin. The

green voltage signal shows the voltage across the resistor as current flows through the transistor when the base voltage exceeds the minimum necessary to allow a current. [Save an image of the oscilloscope graph.](#)

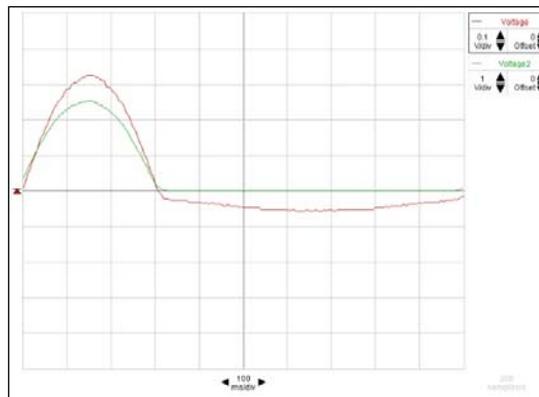


Fig. 12: example of oscilloscope image in step 15.

16. Stop data collection, close the scope window, and open a graph window that plots the $1\text{ k}\Omega$ resistor voltage vs. the $22\text{ k}\Omega$ resistor voltage.
17. Set the graph to plot only data points, not connecting lines between data points. Collect data for one minute. Select only the data points for which both voltages are positive. Do a linear curve fit on the selected data. Make sure you have enough significant figures in your equation's parameters. [Save an image of the oscilloscope graph.](#)
18. Using the measured resistances and the slope of the line, [calculate the amplifier gain](#) (ratio of current through the $1\text{ k}\Omega$ resistor to the current through the $22\text{ k}\Omega$ resistor).

Voltage amplifier

19. Attach one voltage sensor directly to the frequency generator. Set the frequency to 60 Hz, and use the scope feature in data studio to adjust the voltage amplitude to 1 volt.
20. Turn the frequency generator off, but do not change the amplitude or frequency settings. Remove the voltage sensor.
21. [Measure the precise resistance values of \$R_E\$ and \$R_C\$](#) as illustrated in Fig. 13 and build the circuit. Attach the voltage sensors last. Connect a patch cord from the negative terminal (black) of the DC power supply to the ground terminal (green) of the same unit.

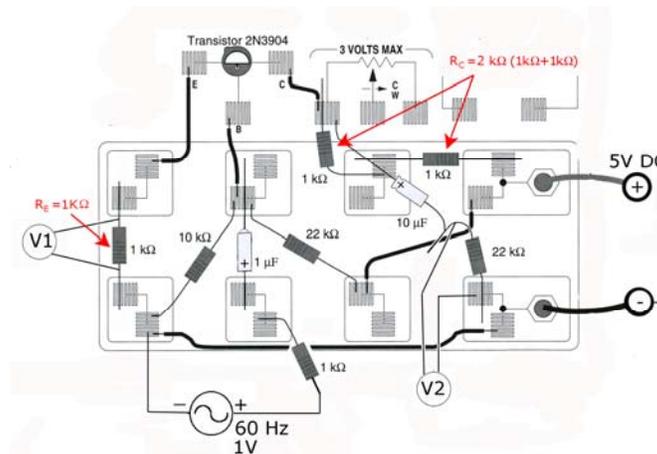


Fig. 13: circuit to build in step 21.

22. Turn on the frequency generator. Turn on the DC power supply and adjust to +5 volts.
23. Adjust the sampling rate in Data Studio to 200 Hz. Use a scope to verify that both voltage signals are being read correctly. The scope display should be similar to that shown in Fig. 14.

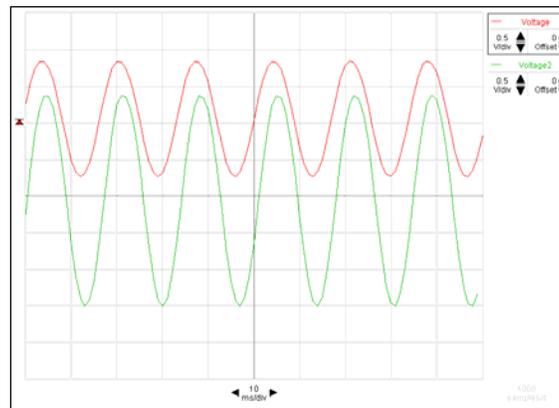


Fig. 14: example of oscilloscope image in step 23.

24. Measure and record the voltage amplitude V_{0-P} of both signals (one-half the peak-to-peak voltage V_{P-P}). Save an image of the oscilloscope graph.
25. Calculate the theoretical voltage gain using the ratio of R_C/R_E .
26. Calculate the observed voltage gain, V_2/V_1 .
27. Compare the measured voltage gain to the theoretical value by calculating a percent difference.
28. Move the V_2 voltage sensor leads so they are across R_C (two 1 k Ω resistors in series). Save an image of the oscilloscope graph.
29. What is different about the V_2 signal? What is the same? Explain.

Equipment list: Laptop computer with Data Studio, Pasco PasPort Powerlink, Pasco PasPort voltage/current sensor (2), red banana/banana patch cord (3), red banana/alligator adaptors (3), black banana/banana patch cord (3), black banana/alligator adaptors (3), Pasco Frequency Generator, Pasco DC Power Supply, Pasco EM8656 electronics laboratory board, Pasco wire kit, transistor [2N3904], 22 k Ω resistor (2), 10 k Ω resistor, 1 k Ω resistor (4), 560 Ω resistor, 330 Ω resistor, red light emitting diode, 1 μ F capacitor (polarized), 10 μ F capacitor (polarized), LRC meter.