Introduction

As we mentioned before, diodes have many applications which are based on the fact that diodes conduct in one direction and not the other. In general a diode consists of a junction between two dis-similar semiconducting materials, or the junction between a metal and a semiconductor. The junction acts like a barrier or a gate which allows electric current to go through only in one direction. What if we create devices made up of two or more junctions? That is how transistors are made! What if we connect many transistors on a chip in sophisticated patterns? That is how Integrated Circuits (ICs) are made. In order to understand the structure of transistors, one needs to understand the properties of semiconducting materials: Silicon (Si), Germanium (Ge), Gallium Arsenide (GaAs), etc. These topics are covered in more advanced electronic courses. For now, it is sufficient to note that semiconducting materials are generally divided into three categories:

(i) **Intrinsic**: the material is pure void of impurities. Intrinsic semiconductors are generally poor conductors.

(ii) **n-type**: impurities have been introduced into the material. The impurities have more electrons in their outer atomic shells compared to the host atoms. By adjusting the concentration of additional electrons, we can adjust their conductivity.

(iii) **p-type**: impurities have been introduced into the material. The impurities have fewer electrons in their outer atomic shells. By adjusting the concentration of lack of electrons (holes), we can adjust their conductivity.

A variety of sophisticated electronic devices have been designed and manufactured using various arrangements of layers of n-type, p-type, and intrinsic materials. A class of such devices are called transistors. Transistors are divided into two general categories: Bipolar Junction Transistors (BJT) and Field-Effect Transistors (FET). The latter is divided into several different sub categories (JFET, MOSFET, etc.). Each type is manufactured in a variety of forms and sizes and one chooses a transistor based on the required parameters, which include current and voltage amplification properties, switching speed, frequency response, power ratings, cost, etc.

In this laboratory we will primarily use BJT Transistors which in their simplest form consist of two junctions between n-type and p-type materials, p-n-p or n-p-n. Transistors are also commonly and abundantly used in many analog and digital integrated circuits. We will start with a single transistor today. In order to achieve higher amplification rates we can combine two or more transistors.

Specific transistors are designed for voltage amplification, current amplification, power amplification, or for switches. Depending on the type of applications, various physical sizes,
shapes and packaging are utilized. Some packaging types are described in the following diagram. From left: TO-92; TO-18; TO-220, and TO-3 (TO stands for Transfer Outline). In general, transistors have three pins. For BJT transistors they are identified as Collector, Base and Emitter. The TO-3 type only has two pins (Base and Emitter). In this packaging type the metal casing acts as a Collector. For Field-Effect transistors (FET), the pins are called Source, Gate and Drain. There is no universal agreement on the arrangement of the pins and in order to identify transistor pins one must view the manufacturers' pin diagrams, which are easily accessible on the web.

In general, an input signal is applied to a transistor with the goal of obtaining an output signal which is larger and more pronounced (amplified) than the input. The input and output signals must have a common ground. For example, if the emitter of a transistor is common between the input and the output signals, the arrangement is called a "common emitter" arrangement. Two other configurations are "common base" and "common collector". In this lab we will use a "common emitter" configuration. As we mentioned earlier, BJT transistors come in NPN or PNP configuration. Here we will use NPN transistors in which the collector and emitter are constructed of n-type semiconductors, and the base is made of a p-type semiconductor. The symbol for NPN and PNP transistors are shown below.

![Bipolar Transistor Circuit Symbols](image)

The principle of operation of a common emitter transistor amplifier is to apply a small current/voltage to its base and obtain an amplified current/voltage at its collector. When used as a switch, a small base current turns on a much larger collector-emitter current. When used as an
amplifier, a small AC or DC input voltage/current will be amplified at the output. For example, an audio amplifier has two stages of amplification. In the first step, the input voltage is amplified (preamplifier), and in the second stage the current is amplified. The current amplification is necessary for driving large speakers consisting of large magnets and coils.

Amplification concept: a small base current ($I_B$) results in a large collector current ($I_C$). The base current/voltage could be a small current/voltage generated by an electronic sensor. The transistor is connected to a source of power (battery or power supply). When a base current $I_B$ is detected, the transistor switches “on” and allows a larger current $I_C$ to flow from the power supply through the device/load into the ground. The magnitude of the large $I_C$ depends on the magnitude of the small $I_B$. For example, for a transistor with a current gain of 50, a 0.4 mA base current leads to a 20 mA collector current ($50 \times 0.4 = 20$) as shown in the diagram below. The figure below illustrates the graphical relationship between the base current and the collector current of a transistor. Transistors can amplify both DC and AC current. AC current in the base and collector are referred to as $i_b$ and $i_c$. A transistor is referred to as a “switch” when a small current $i_B$ switches on a larger current $i_C$. For transistor switches, $i_c$ is chosen in the plateau region (saturation) of the $i_C$ vs. $V_{CE}$ diagram. The switch is “off” when the base current is too small or zero, and the switch is “on” when the base current is sufficiently large. The diagram shows the plateau regions for a few different base current values. For voltage amplification, the base current is kept in its active range, where is the high slope region before reaching the plateau. The details of operation of transistors as switches and voltage/current amplifiers will be covered in more advanced electronic courses.

A Simple Transistor Switch

The main idea in this section is to use a transistor as a switch: Apply a small current to the base of the transistor and observe that it allows a larger current from the 5-V power supply to go through the LED to the ground. Note that the base current itself is too small to drive an LED. The size and type of the transistor is chosen depending on the voltage and the current (recall that power = $I V$). We will use a low-power 2N3904 (or 2N2222) NPN transistor. When viewing the flat side of the transistor, the pins from the left are E, B, and C.
We supply a small current to the base in µA-range, and observe a current in the mA range turns on the LED. The current gain of the transistor is defined to be $\beta = \frac{I_C}{I_B}$ which is typically around 100. Note that the transistor gain for inexpensive transistors could vary significantly from one transistor to the other. For this transistor, the power dissipated in the transistor must be less than 500 mW: $I_C V_{CE} < 500$ mW.

**Measurement 1:** Build the circuit below and use DC power supply to supply the shown DC voltages. Please note that it is very important to have a common ground. That means all ground wires connect to each other and to the ground of the power supply. As usual, you can choose slightly different resistor values if you do not have the exact resistors in your tool box.

Now increase $V_1$ with a step of 0.2 V until the LED ON and bright. Using a multimeter measure the following voltages (record the results in your notebook): (i) $V_{R1}$, the voltage across $R_1$ and (ii) $V_{R2}$, the voltage across $R_2$

Proceed to the next page.
Analysis

1. Using Ohm's law, calculate the current through resistors $R_1$ ($= I_B$) and $R_2$ ($= I_C$). 2. Calculate the current gain of this transistor, $\beta = I_C / I_B$. Record the results in your notebook.

Note that small current at the base ($I_B$) results in much larger current through the diode ($I_C$). This property of the transistor is utilized to design transistor based amplifier as well as use them as a switch or as a driver. For example, in situations where we need a higher current to run a device like motor but the circuit (or source) cannot provide enough current (think about $V_1$ in the circuit above), we can use an external power source to drive the motor (think about $V_2$ in the circuit above) but control the motor using the original circuit (or source) ($V_1$ in our example). In this example we would call our circuit a driver. You may come across such situation when you want to control a motor using a microcontroller output. The microcontroller output may not be able to provide enough current to run the motor. You would use a driver circuit to in such situations.

Darlington Pair

Next disconnect $V_1$ and touch the left end of the base resistor $R_1$ and observe that the LED shines dimly (we can call it a touch sensor!). Your touch could supply about 5 µA to the base, which in turn can amplify to a collector current of 0.5 mA with a current gain of 100. We can increase the sensitivity of this “touch sensor” device by connecting two or more transistors so that the amplified output of one transistor is fed into the input of a second transistor. This process can result into a huge amplification of the minute current provided to the base of the first transistor simply by touching it. In this method two or more transistors are connected in a formation called Darlington pair connections.

Ideally, the current gain of a Darlington transistor pair is equal to the product of the gains of each device. However, the actual gain may be less than the product of two gains. Connecting the third and the fourth transistors in Darlington configuration will further increase the sensitivity of the circuit, which means the LED will turn on (perhaps dimly) in response to the extremely low base current. In a Darlington combination, we simply connect the emitter of the first transistor to the base of the second transistor. This combination will act as a single transistor as shown below. Darlington pair transistors are available commercially. You can test the idea in an optional Touch Sensor experiment on the last page.
Light Detector

Before building the circuit, use your multimeter to measure the resistance of the photo resistor under “dark” and “light conditions. Shine a flashlight on it and observe the dramatic change in the resistance of the element when you shine strong light on it. Record the readings in your lab book.

The circuit below uses a single transistor. Photoresistor is used as photodetectors for controlling the base current. A photoresistor is included in your toolbox. The LED turns on when there is light. Build the circuit and observe what happens to the LED when you cover the photoresistor. Write your observation on in your lab notebook. You will need to provide the discussion in your report. Can you explain your observation?
Touch Sensor (Optional)

In this part of the experiment we wish to construct a sensor that will turn the LED on simply by touching a wire. We can increase the sensitivity of this “touch sensor” device by connecting two or more transistors so that the amplified output of one transistor is fed into the input of a second transistor called Darlington pair connections. Here we test the idea!

Measurement: Combine two or more transistors in the following Darlington configuration. We can treat this combination as a single transistor and connect the LED and resistors similar to part 1. Bring your finger close to the sensor tip and observe the LED light dimly. Touch the sensor tip and observe the increased light intensity. Place the sensor tip on a piece of paper and touch the other side of the paper and observe the LED light. You can create your own sensor applications using this configuration! We have connected four transistors for high sensitivity.

Caution: Each transistor in this cascading configuration draws more current than the previous transistor. Q4 carries the maximum current. Therefore, it is important not to allow too much current to go through the lower transistors. Exceeding the power rating of these transistors will destroy them. You must use transistors with high power ratings if you wish to turn motors on or draw large amounts of current.