Experiment 281: Diodes and Transistors (ELVIS version)

Aim

To experimentally investigate the characteristic behaviours of diodes and NPN bipolar transistors, and to construct simple circuits based on these devices.

Introduction

Diodes and transistors are components based on the idea of a semiconductor junction, where the conductivity of the junction depends on the voltage applied across it. These devices have revolutionised modern electronics, and in particular have enabled the production of smaller, cheaper, and more powerful computers. In this experiment we will characterise a common diode and transistor, as well as construct circuits that display how their properties can be utilised.

Note: This experiment utilises the ELVIS II from National Instruments. If you are not familiar with this device, please refer to Appendix A. Be sure to include all oscilloscope and two-wire plots in your report. An image can be exported from both the oscilloscope and 2-wire devices by selecting the **Print** button and choosing to **Export to File**. If you wish to import data from the log files into python, the functions `importElvisOsc()` and `importElvis2wire()` are provided in `phylab.py`.

1 Rectifying Diode

Diodes are extremely prevalent in modern electronic circuits. Here we will characterise a common diode and construct some simple circuits based on its functionality.

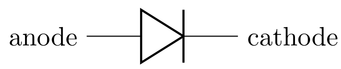

Figure 1: The circuit symbol for a diode, where current flows from the anode to the cathode. The black bar on the case of the 1N914 diode represents the cathode.

Current vs. Voltage

Theoretically, the current I through a diode obeys the equation

$$I = I_s \left[\exp\left(V/V_0\right) - 1\right], \tag{1}$$

where I_s is the leakage current (also called the reverse saturation current), V is the voltage applied across the diode, and $V_0 = Nk_BT/q$. Here k_B is the Boltzmann constant, T is the temperature in kelvin, q is the electronic charge in coulombs, and N is known as the *ideality factor*, having a value that generally lies between $1 - 3$. We wish to verify this prediction for a typical silicon diode.

To do this, we will use the two-wire current-voltage analyser built into the ELVIS II. This allows you to apply a range of voltages to the diode and measure the current response. We will perform multiple scans, as different gains must be used to accurately measure the resulting currents. Save logs of each scan so that you can import the data into python. Note that the currents measured are given in mA.

(1) Obtain a 1N914 diode, and place the diode into the DUT+ and DUT- terminals found on the left of the ELVIS II board. The cathode of the diode should be inserted into the negative terminal (DUT-).

(a) We will initially investigate the behaviour of the diode in the *forward biased* direction, where current is allowed to flow through the diode. Open the two-wire program from the instrument launcher, and using the low gain setting, obtain the current response for 0.5 V to 10 V using a 0.1 V step. Note that the two-wire program will cut out when the current gets too high, so you won't be able to measure the whole region.

(b) To investigate the non-linear region close to 0 V, perform a scan using high gain to obtain the current response of the diode from 0 – 0.5 V with a 0.01 V step.

(c) Lastly we will investigate the *reverse biased* direction, where the diode prevents current from flowing. Run the analyser using the high gain setting from −10 V to 0 V with a 0.5 V step and high gain.

We will now characterise our diode by determining the leakage current I_s and the ideality factor N from our data. The data can be imported into python using the function `data = importElvis2wire('logFile.txt')` found in `phylab.py`.

For the region where $V > 0.5V$ we find that $\exp(V/V_0) \gg 1$, and we can therefore reduce equation (1) to $I = I_s \exp(V/V_0)$.

(2) Import your data for the region $V > 0.5\ V$ into python and plot $\log(I)$ vs V. This should give a reasonably linear plot. Use the `polyfit` function to determine the values of both I_s and N, noting that the current data is given in mA.

(3) On the same figure, plot all three sets of experimental data and overlay this data with a theoretical curve using your experimentally determined values of I_s and N. Comment on how well the data agrees with the theory.

The full theoretical description given in equation (1) is usually not necessary to understand the behaviour of a diode placed in an electronic circuit. We can often approximate the current-voltage relation for a diode as a step function, where

$$I = \begin{cases} 0, & \text{if } V \leq V_D \\ \infty, & \text{if } V > V_D, \end{cases} \tag{2}$$

where V_D is a characteristic threshold voltage that must be exceeded before the diode will conduct freely. This shows that below V_D the diode allows no current to flow, and acts like an open circuit. Above V_D, the diode is said to be *forward biased*, and allows an unlimited amount of current to flow through it.

(4) Use the diode function built into the digital multimeter (DMM) to measure the voltage drop across your diode, both in the forward and reverse directions. Give a value for V_D from these measurements. For instructions on using the digital multimeter, see Appendix A1.

Diode Clamp

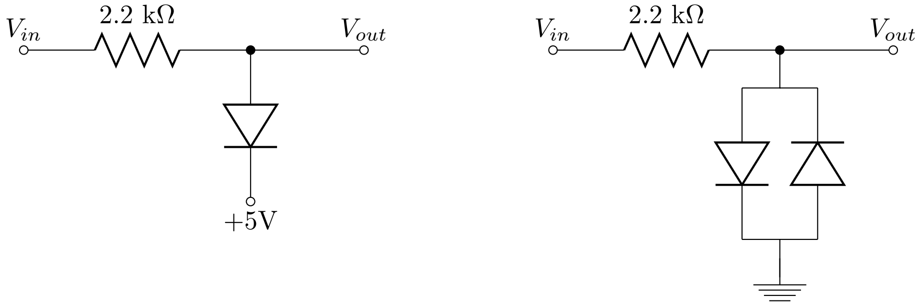

Figure 2: A simple voltage clamp (left) and a voltage limiter (right)

Diodes can be used to convert alternating current (AC) to direct current (DC), for isolating signals from a supply, or to extract the modulation from radio transmissions. Here we will study another use for diodes, limiting the output voltage to a certain level. Here we will make use of the function generator (FGEN) built into the Elvis II (see Appendix A3).

(5) Construct the circuit shown on the left of figure 2. Connect the FGEN input to V_{in}, and insert a 100 Hz 10Vp-p sine wave. Simultaneously observe the input and output on the oscilloscope of the ELVIS II. Vary the DC offset of the input signal from -5V to +5V and confirm the circuit performs as you would expect.

(6) Modify your circuit to the voltage limiter shown on the right of figure 2. Insert a 100 Hz 10Vp-p sine wave and observe both V_{in} and V_{out} on the oscilloscope. Explain why the circuit behaves as it does.

Question 1: Obtain a value for V_D from the behaviour of the voltage limiter. How does this value compare to the value found in (4)?

2 Binary Junction Transistor

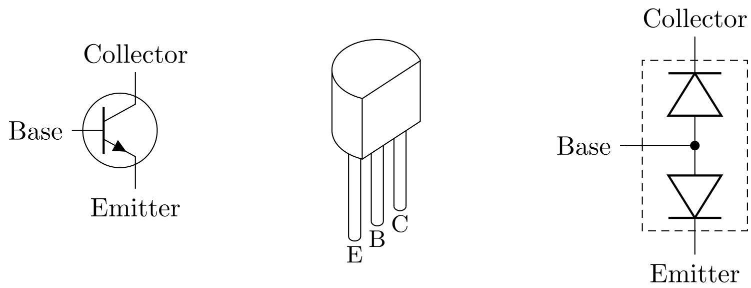

Figure 3: The symbol for an *NPN*-type transistor (left). The pin layout for the 2N3904 transistor (centre). The effective circuit diagram for testing a transistor (right).

A transistor is another semiconductor device that generally comes in two types, the Bipolar Junction Transistor (BJT) and the Field Effect Transistor (FET). In this experiment we will study the properties of a BJT, and build a few simple BJT circuits.

We will use the *NPN*-type 2N3904 transistor, which consists of a layer of *P*-doped semiconductor (the "base") sandwiched between two *N*-doped layers (the "collector" and "emitter"). To investigate the properties of this transistor, we will construct the circuit shown in figure 4.

(7) Obtain a 2N3904 transistor and determine whether it is working correctly using the diode function of the digital multimeter (DMM). The transistor should behave like the circuit shown on the right of figure 3. Record the voltages measured when the junctions are *forward biased*.

(8) Accurately determine the resistance of the 100 Ω and 10 kΩ resistors that you will use to build the circuit shown in figure 4, as well as the voltage of the +5V power supply.

(9) Build the circuit shown in figure 4, using the positive terminal of the variable power supply as the input V_{in}. The variable power supply (VPS) control can be found in the instrument launcher. For values of V_{in} ranging from 0V to 12V, measure and record V_{in}, V_{be}, and V_{ce}. You will need to take more data points near $V_{in} = 1$V than near $V_{in} = 0$V or $V_{in} = 12$V to ensure your plots show sufficient detail.

(10) Use this data to prepare plots of (a) I_b vs V_{be}, (b) I_c vs I_b, and (c) V_{ce} vs I_b. Ensure you have enough points to observe critical features in all of your plots.

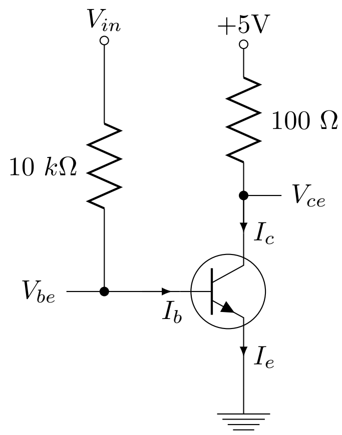

Figure 4: The test circuit that we will use to characterise the 2N3904 transistor. V_{be} and V_{ce} represent voltages to be measured relative to ground.

Plot (a) should show that the base-emitter junction essentially behaves like a forward biased diode, and that in conduction, the voltage V_{be} is the same as the voltage drop V_D of a diode.

Plot (b) should show that the transistor allows for current gain. You should see that for small I_b, the collector current and base current are related by $I_c \simeq \beta I_b$. For higher I_b you should also see that the transistor saturates, and this relation no longer holds.

Question 2: Determine β from your measurements. For what range of I_b does the relation $I_c \simeq \beta I_b$ hold?

Plot (c) should show that as the collector current I_c increases, the collector-emitter voltage V_{ce} decreases, due to the necessary voltage drop across the 100 Ω resistor. This means that for large I_b, there is not enough voltage at the collector to maintain the $I_c \simeq \beta I_b$ relation, and hence the transistor gain saturates. When almost all of the voltage is across the resistor ($V_{ce} \simeq 0$) we can say that the transistor is fully saturated.

Question 3: What is the collector-emitter saturation voltage V_{ces} for your transistor?

3 Emitter Follower

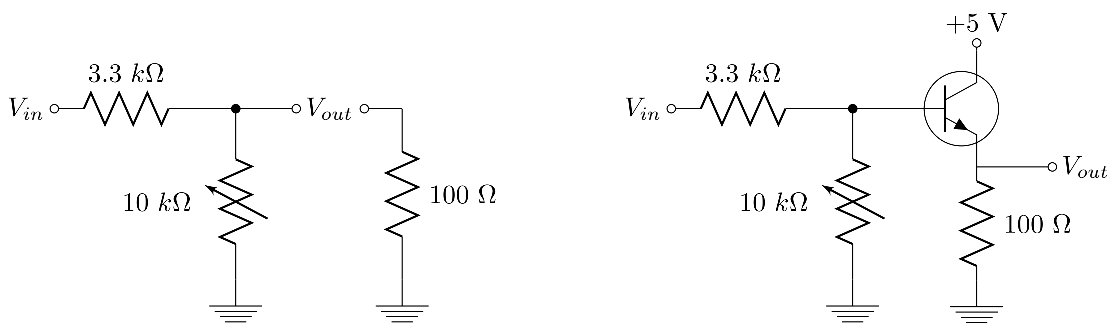

Figure 5: A voltage divider with a 100 Ω load resistance (left), showing the necessity of impedance matching. The same circuit using an emitter follower (right), allowing the circuit to function as desired.

We have seen that one useful feature of a transistor is its ability to provide *current gain*. A small current entering the base of the transistor can control a larger current flowing into the collector. In this section we will investigate one implementation of a current amplifier, the emitter follower. In general, a follower is a device capable of boosting the current of a signal without significantly changing the voltage. We say that the output 'follows' the input.

To see where such a device would be useful, we will consider the circuits shown in figure 5.

(11) Construct the voltage divider shown on the left of figure 5 *without* the 100 Ω resistor. Use the function generator (FGEN) of the ELVIS to input a 100 Hz 1Vp-p sine wave to V_{in}. Verify that the potentiometer can be used to vary the voltage V_{out}. Over what range of voltage amplitudes are you able to scan?

Question 4: Derive an equation for V_{out} in terms of the input voltage V_{in} and the variable resistance R_v.

This circuit could form a volume control for an audio source. Now consider adding a low impedance load to the output, such as a speaker. We will model this by connecting the 100 Ω resistor as a load.

(12) Add the 100 Ω resistor to your circuit as shown. What effect does this have on your output voltage?

Question 5: Derive a new equation for the output voltage V_{out} in terms of V_{in} and the variable resistance R_v for the circuit containing the 100 Ω load. What is the range of voltages that can be output from this circuit? How does this compare to the circuit without the 100 Ω load?

This is due to having a mismatched output impedance, and accounting for this issue is a common concern when designing electronic circuits. The emitter follower circuit on the right of figure 5 shows one way that this problem can be overcome.

(13) Adjust the potentiometer to give the maximum amplitude output and modify your circuit to the emitter follower circuit shown in figure 5. Input a 100 Hz 0.1Vp-p sine wave to V_{in}, and simultaneously observe both V_{in} and V_{out} on the oscilloscope. What do you observe initially? Adjust the DC offset of the function generator to make the input signal more positive. At which DC offset voltage does the output signal begin to appear? When is the input cleanly mapped to the output?

When designing transistor amplifier circuits, some care is generally needed to ensure that the voltage input to the base is within a suitable range. Like a diode, the transistor needs to be correctly biased in order to conduct, and achieving this usually involves additional circuitry.

4 Digital Logic Gates

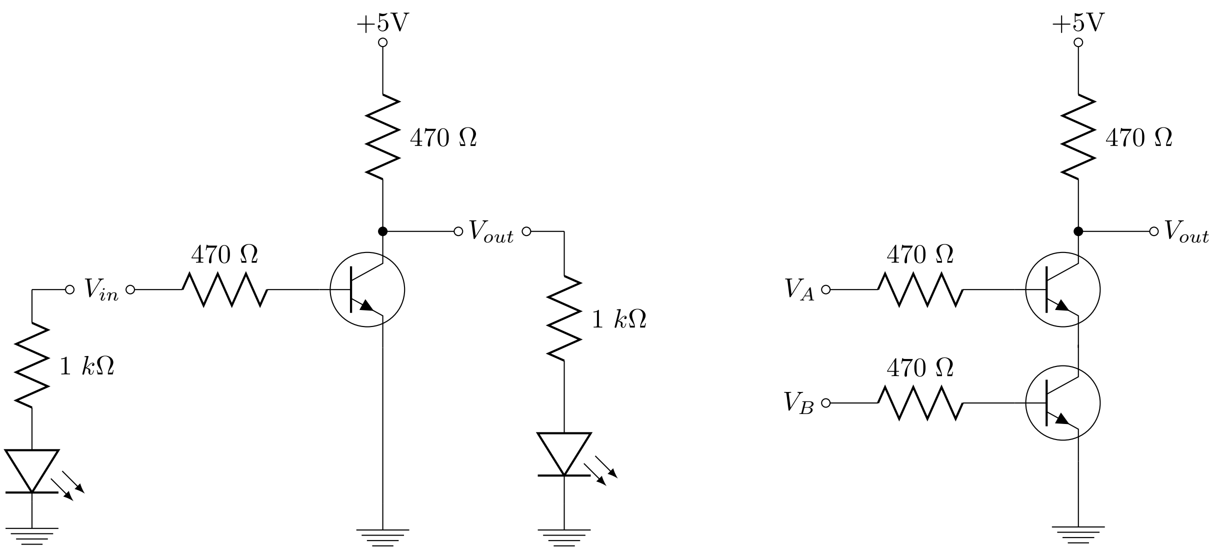

Figure 6: Two digital logic gates based on the switch operation of transistors. If you wish, you can use LED's to display the logical state of both the input V_{in} and output V_{out} as shown on the left, although this is not necessary.

If we ignore the region where the transistor behaves in a linear fashion, we can consider the transistor to behave like a switch. The transistor can have either no current flowing into the collector and be completely

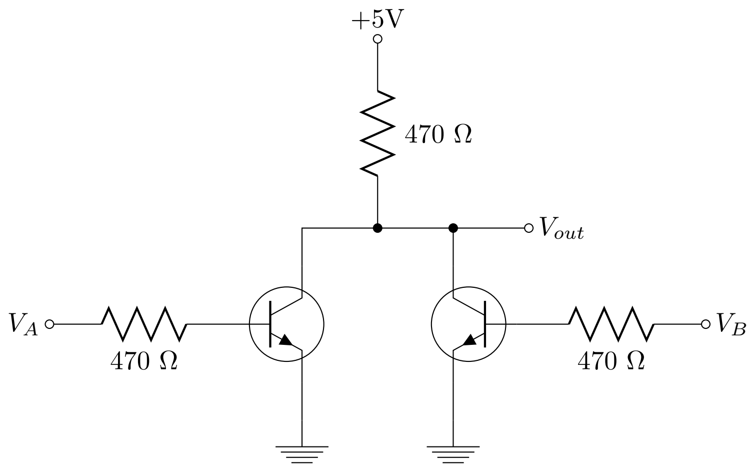

Figure 7: A two-input digital logic gate.

off, or be completely saturated with the maximum current flowing into the collector ($V_{ce} \simeq 0$). This method of operation is the basis for transistor-transistor logic (TTL) and many digital devices.

(14) Construct the logic circuit shown on the left of figure 6, and use the SYNC input to supply a logical 5Vp-p square wave square wave to V_{in}. The frequency of this signal can be controlled using the function generator (FGEN). Simultaneously monitor both the input and output with the oscilliscope. What logic operation is being performed here? Explain why the circuit works in this way.

Note: Light emitting diodes (LEDs) can be used to observe the logical state of your inputs and outputs, as shown on the left of figure 6. If you wish to make use these in your circuit, the flat face of the LED casing represents the cathode.

Many logical operations combine two inputs to give a single logical output. For example, the `AND` operation only outputs a `HIGH` voltage if both inputs are `HIGH`, and outputs a `LOW` voltage otherwise.

(15) A transistor circuit with two inputs, *A* and *B*, is shown on the right of figure 6. This circuit performs the `NAND` logic operation (`NOT AND`). Construct this circuit and apply digital logic voltages to the inputs (+5V and Ground) to show that the circuit behaves as you would expect.

Question 6: Figure 7 shows another digital logic circuit with two inputs. What logic operation does this circuit perform? Explain why it works this way. (You do not need to build this circuit).

A National Instruments ELVIS II

This experiment makes use of the ELVIS II from National Instruments. The layout of the ELVIS II allows circuits to be built without having to use solder to connect components, and also contains devices such as an oscilloscope and a function generator, all accessible via a USB connection to a PC with the appropriate software installed.

To access these components, ensure that the USB plug is connected to a PC and the ELVIS II is powered on using the switch on the side of the device. The LED indicator for the USB should display 'READY'. You can now launch the 'NI ELVISmx Instrument Launcher'. It is important to understand the layout of the

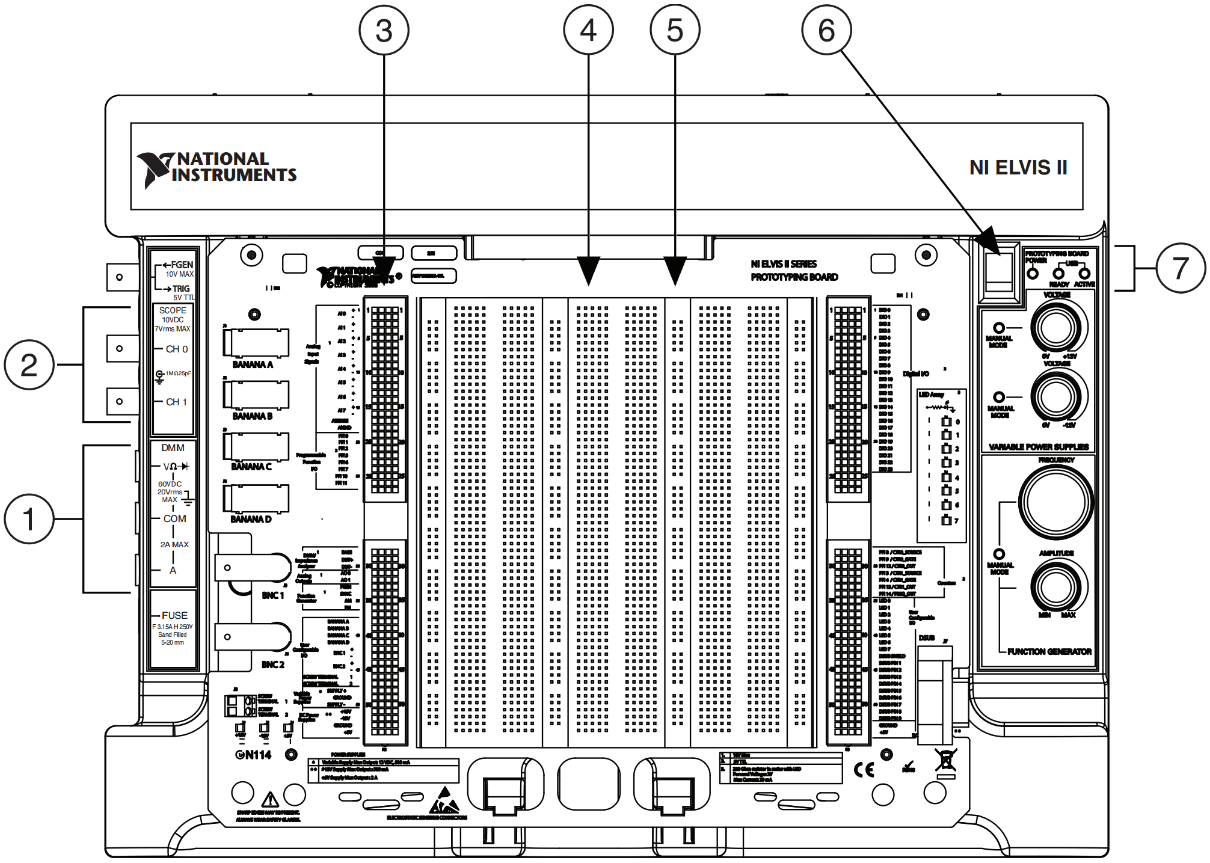

Figure 8: The ELVIS II from National Instruments.

NI ELVIS to ensure that the circuits that you build are wired correctly. An overview is shown in Figure 8, and some important features are numbered as follows:

1. Connections for the digital multimeter (DMM) leads. To use this instrument, select DMM from the instrument launcher, select the appropriate function and set it to 'Run'.

2. Connections for two oscilloscope (Scope) channels, labeled CH 0 and CH 1. The oscilloscope can be accessed from the instrument launcher.

3. Various connections that can be wired to circuits on the prototyping board. The DC power supplies (pins 51-54) and the function generator (FGEN, pin 33) are particularly useful.

4. The prototyping board, where circuits can be constructed. Ensure you understand how the pinholes are connected before you begin to wire up your circuits. An IC chip can be inserted so that its legs occupy columns E and F of the prototyping board, and wires can be taken from the four neighbouring pinholes to connect to other parts of your circuit.

5. Two columns of pinholes denoted by a red + and a blue −. It is good practice to take a wire from a power supply and connect it to the appropriate rail. Subsequent wires can then be used to power the components of your circuit.

6. Power switch for the prototyping board. This must be active for the power supplies and function generator to operate.

7. LED status indicators to show USB activity, as well as the prototyping board's power status.

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