Practical 2P12

Semiconductor Devices

Safety

All procedures and experiments in this practical do not involve any hazardous or unsafe activities.

All students must comply with the Laboratory rules, be familiar with the 'Department Safety in Laboratories' document, and endeavour to follow good laboratory practices.

Read the script carefully, listen to the SD and TA briefing, and follow instructions cautiously. If you do not understand parts of the script, consult the TA.

1 What you should learn from this practical

1.1 Science

This practical provides hand-on experience measuring physical quantities in semiconductor devices. The background concepts for the operation of such devices were studied in the lectures. Here you will be able to relate the theory to the real-life operation of diodes and transistors, using the help from LabVIEW data acquisition.

1.2 Practical Skills

You will gain experience in constructing very simple electronic circuits using breadboard, voltage power supplies, and electronic components. You will be able to use LabVIEW to generate and read voltage signals, and characterise circuits using data acquisition and a digital multimetre.
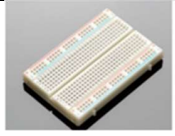
1.3 Overview of the practical

This practical has four parts:

(1) to investigate the electrical characteristics of a rectifier diode,
(2) to explore the working conditions and electrical behaviour of light emitting diodes and photodiodes,
(3) to build and characterise a switching light signal using a MOSFET,
(4) and to examine the electrical characteristic of a solar cell under operation.

2 List of equipment

Name	Maker Reference	RS Stock uk.rs-online.com	Example Image
Red LED Yellow LED Green LED	Kingbright L-7113ID Kingbright L-7113YD Kingbright L-1513GT	619-3158 619-4892 862-2819	
Visible Light Si Photodiode	Osram Opto, SFH 203	654-8154	
Rectifier diode	1N4001	628-9029	
Capacitor	1000 micro Farads	749-7123	
Resistors	Multiple values: 100 kΩ, 10 kΩ, 220 Ω, 1 Ω	-	
National Instruments data acquisition card	NI-USB6008 https://www.ni.com/pdf/manuals/375295c.pdf	-	
N Channel MOSFET	Infineon IRLZ34NPBF	541-1247	

Potentiometer (variable resistor)	3310Y-001-102L	522-0603	
Silicon solar cell	Seeed Studio 313070004	179-3740	
5V dc Power Supply DC	Power Supply 5V dc, 550mA, Level V Efficiency	737-8161	
Prototyping board	Various models		
Digital Multimetre	Various models		

3 Experimental

3.1 Electrical characteristics of a rectifier diode

Most semiconductor devices contain at least one junction between p-type and n-type semiconductor regions. The characteristics and operation of semiconductor devices are intimately connected to these *pn* junctions, so it is crucial to understand this basic device. The *pn* junction diode itself provides characteristics that are used in rectifiers and switching circuits. In this part of the practical you are provided with a 1N4001 rectifier diode and you are asked to examine its current-voltage (IV) characteristics when it operates in a signal rectifier circuit.

a)   Set up LabVIEW data generation and acquisition

Your first task is to use LabView software and the NI-USB6008 DAQ (Data acquisition) card to generate and acquire voltage waveforms. Open LabVIEW and build the circuit illustrated in Figure 1 to generate a sinusoidal 0-5 volts signal in the pin Analog Output 0 (AO0). A guidance video is provided to achieve this, with links at the end of the script. Once you can generate that signal you should be able to read it back into your LabVIEW software, using the pin Analog Input 0 (AI0).

Labview licence note: If you are using a laptop from the teaching labs, make sure you are connected to the internet and connected to Oxford University VPN network. You will need this to authenticate the Labview license.

Help: The DAQ Assistant path is illustrated in Figure 2. Once you place the DAQ Assistant box 1, select Generate, Analog Signal, Analog Output, under

Dev USB-6008 select Port 0 (AO0). This will generate a Signal on pin 14 with respect to GND (pin 16). To construct the rest of the circuit use the right click, and search functions like the Sine, product, or sum. Once the DAQ Assist 1 is done, place another DAQ assist, number 2, and instead of generating, select acquire signal, voltage, analog input 0, AI0. The connection diagram of AI0 is shown below. After this, connect the pin 14 (AO0) to pin 2 (AI0+), and pin 3 (AI0-) to pin 16 (GND).
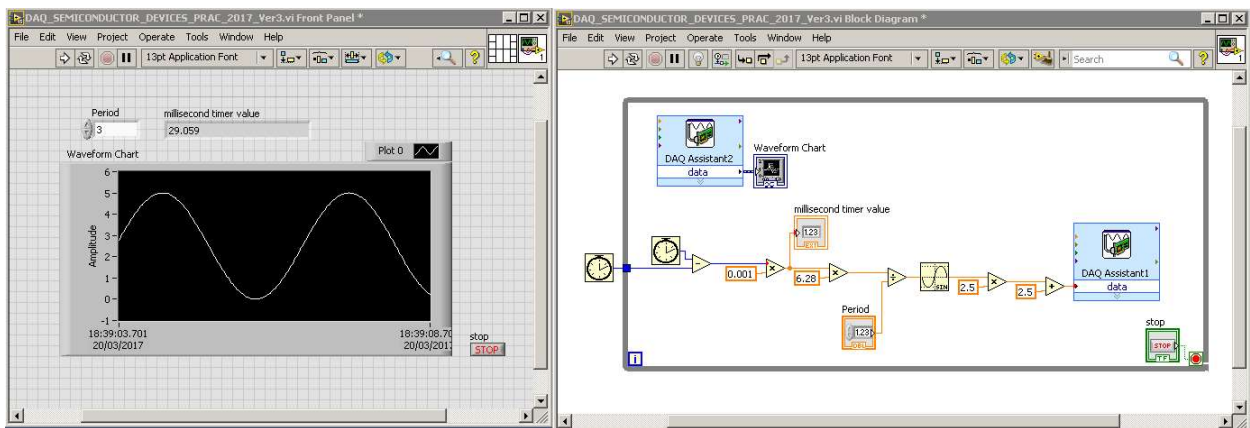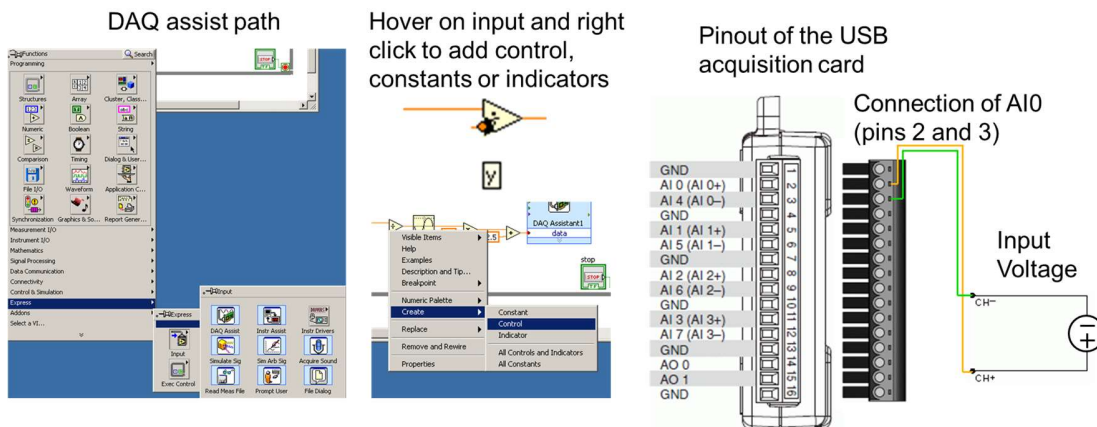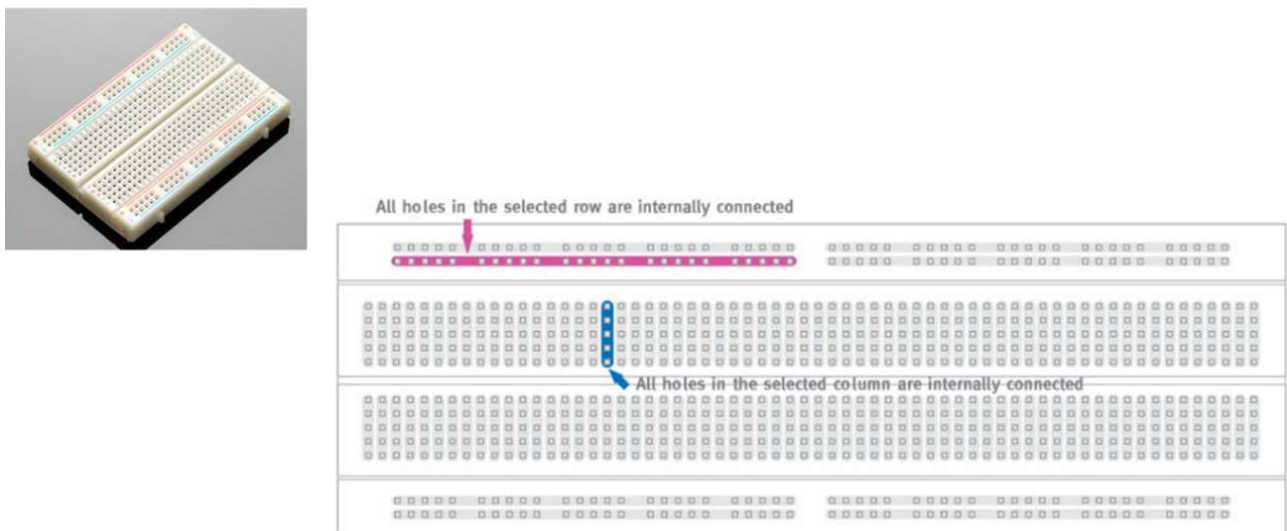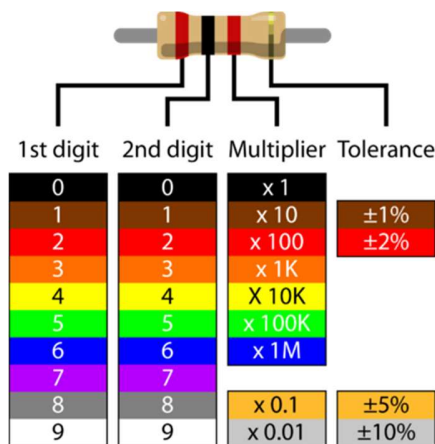
Figure 1

Figure 2

b) Build rectifier circuit using prototyping board

The prototype board is used to construct simple electronic circuits quickly without the need for making soldered joints. Electrical connections are made by pushing wires into the holes in the surface of the board. The holes in the board are arranged in columns with all the holes in any given column electrically connected to each other whilst being electrically isolated from all other holes on the board. One of such columns is labelled in blue in Figure 3. All five pins in that column are electrically interconnected. Electrical contact between two wires is achieved simply by pushing them into holes which lie anywhere in the same column on the board. The next set of electrical contacts can then be made by using holes in another column of the board and so on until the circuit is completed. A scheme of a typical prototyping (bread) board is given in Figure 3, together with a colour code chart to select resistor correctly.

Figure 3

All holes in the selected row are internally connected

All holes in the selected column are internally connected

1st digit	2nd digit	Multiplier	Tolerance
0	0	x 1	
1	1	x 10	±1%
2	2	x 100	±2%
3	3	x 1K	
4	4	X 10K	
5	5	x 100K	
6	6	x 1M	
7	7		
8	8	x 0.1	±5%
9	9	x 0.01	±10%

For example: 2000 Ω.

Using a 1 kΩ resistor, and the 1N4001 rectifier diode build the circuit illustrated in Figure 4, with the help of a prototyping board. The Anode (+) of the diode is the end without the silver stripe, while the Cathode (-) is indicated by the silver stripe. You will need to add to your LabView program an additional voltage input in the data acquisition (DAQ) box. Double click the DAQ Assist 2 and add a voltage input on channel AI1 (Pins 5 and 6). This is illustrated in the second image in Figure 4.To save your data set, stop the software, right click on the waveform chart, and navigate to the Export Data to Clipboard function, as also shown in Figure 4.

Figure 4

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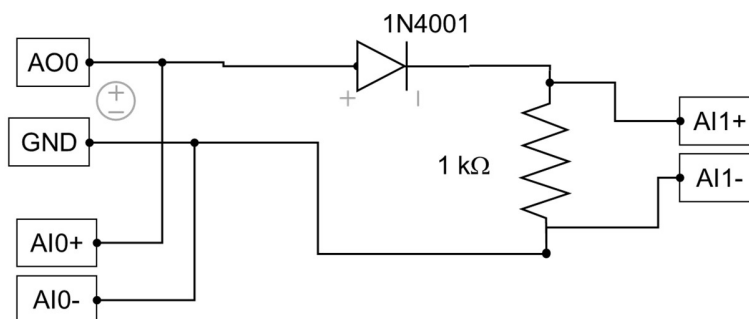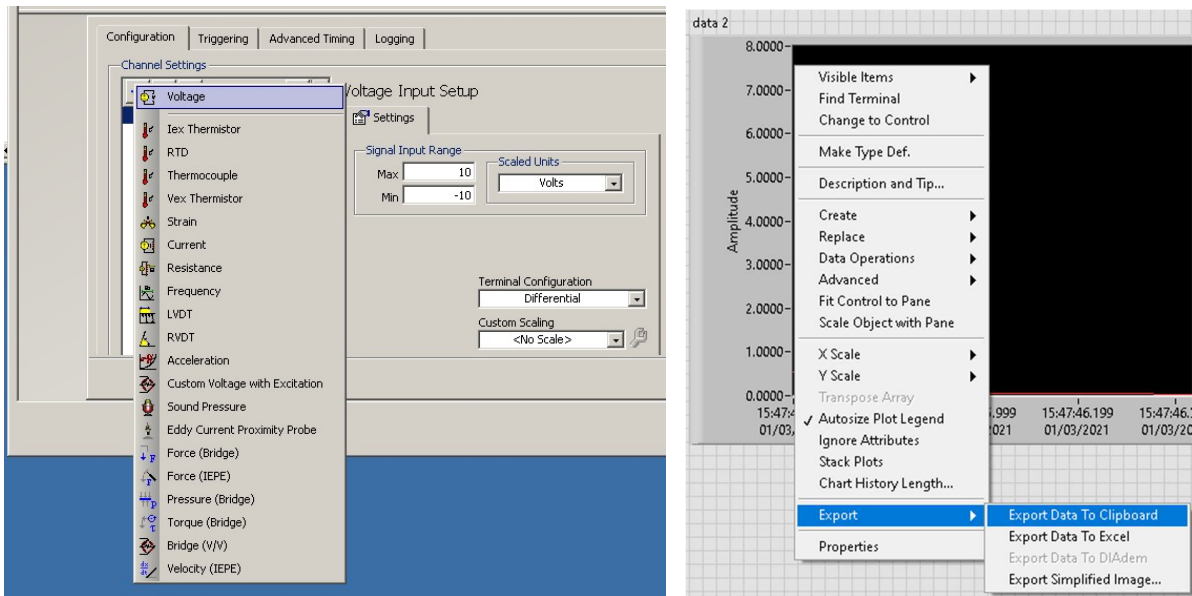
Run the LabVIEW software again, and observe the characteristics of the input sinusoidal signal in AI0, and the output signal in AI1. Note down the shape and voltage magnitude of the signals that you observe in your lab book. What characteristics do you notice in these signals? How can these be explained using the theory of a *pn* junction diode?

To build a complete IV curve for the diode we need to measure the exact value of the resistor, such that you can calculate the current flowing through the diode at any time using Ohm's law. To obtain the value of the resistor you will need a digital multimetre (DMM). A DMM is a tape measure for making electrical measurements. It may have any number of special features, but mainly a DMM measures volts, ohms, and amperes. Resolution refers to how fine a measurement a meter can make. By knowing the resolution of a meter, you can determine if it is possible to see a small change in the measured signal. For example, if the DMM has a resolution of 1 mV on the 4 V range, it is possible to see a change of 1 mV (1/1000 of a Volt) while reading 1 V.

You would need ruler marked in one-millimetre segments if you had to measure down to one millimetre. Accuracy is the largest allowable error that will occur under specific operating conditions. It is an indication of how close the DMM's displayed measurement is to the real value of the signal. Accuracy for a DMM is usually expressed as a percent of reading. An accuracy of one percent of reading means that for a displayed reading of 100 volts, the actual value of the voltage could be anywhere between 99 volts and 101 volts. What is the accuracy of the instrument you are using? And what is the exact resistance value of the resistor you are using? Note these down on your lab book.

The voltage in the diode is given by (AI0+) - (AI1+). To obtain the IV curve for the diode in the range 0 to -5V, you can swap connection of the cables that connect AO0 and GND to the diode and resistor. Capture data sets for both polarities of the AO0 – GND signal, and complete the IV curve of the diode for the entire range of -5 to +5 volts. Note these down on your lab book. After obtaining the IV curve, swap the AO0 – GND connections back to the ones illustrated in Figure 4 as you will need them for the next part.

After getting the IV, replace the 1 kΩ resistor for a 100 kΩ resistor, and insert a 1000 μF capacitor in parallel to the resistor as indicated in Figure 5. Make sure that the positive pin of the capacitor is connected to the positive branch of the power supply (AO0) -i.e. the diode's cathode. Run the LabVIEW software again and observe the characteristics of the different signals. Note these down on your lab book. What is this circuit doing to the sinusoidal signal? How can that be achieved by the *pn* junction diode?

Figure 5
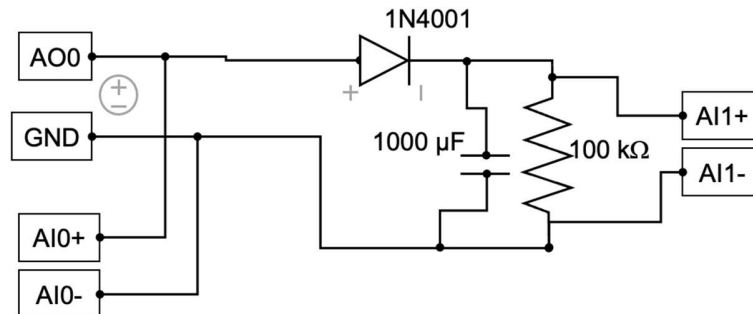
3.2 Light emitting diodes and photodiodes

In *pn* junction diodes we can also observe light emission, generally referred as luminescence. When excess electrons and holes are created by an electric field applied to the diode, we can generate photon emission. This process is termed electroluminescence. Conversely, we can use external light to generate excess electrons and holes inside of a *pn* junction giving rise to a photocurrent, and this is term photoluminescence. In this part of the practical we explore how light emitting diodes can generate photon emission, and how such photons can in turn produce a current on a photodiode. In this devices electric energy, in the form of a current, is converted directly into photon energy and vice versa.

### c) *Build circuit to power an LED*

In this part you are provided with a DC power supply which you will use to power your light emitting diode (LED). In this power supply the red wire indicates +5V while the black/brown wire indicates 0V. Once you have plugged the 5V supply to the mains plug, you can use the prototyping board to build the circuit indicated in Figure 6, and monitor the voltage signals using

the Analog Input 0 and Analog Input 1 ports of the DAQ card. Use the red LED for this first circuit. **Note:** do not forget to remove the Analog Output wires from the DAQ card, since you no longer need the sinusoidal signal for this part of the practical.

Visualise and plot two signals in your LabVIEW program. Note these down on your lab book including their magnitudes, in time and voltage. Compare these two signals. What do they indicate? **Note**: remember to connect both the (+) and the (-) wires between your breadboard and the acquisition card.

What do you observe in the LED? Can you deduce the operating conditions of the LED (voltage and current)? Accurately measuring the current requires to know the exact value of the 220 Ω resistor, when one uses Ohm's law. Use a DMM to measure the resistor and convert the voltage in the resistor to current. Note this down on your lab book.

Figure 6
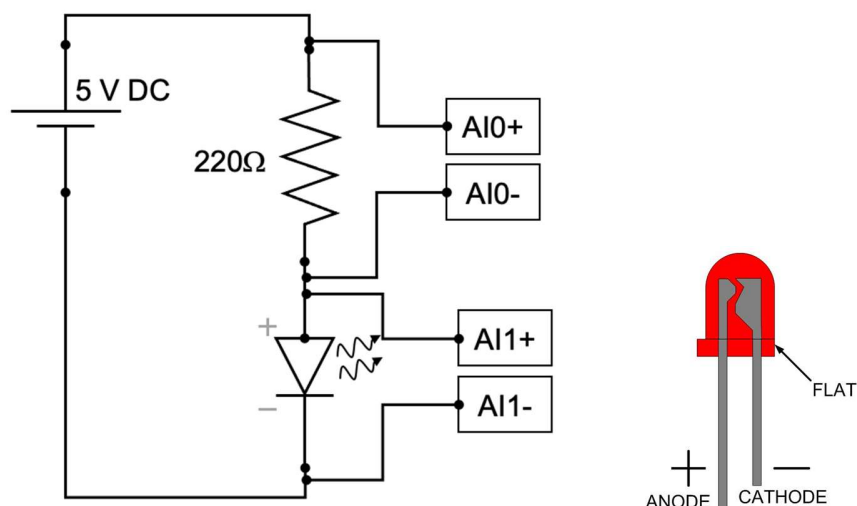
d)   Add a photodiode to the circuit

After observing light emission in the LED, we also want to detect that light using a photodiode. Connect the photodiode to the Analog Input 2 of the DAQ card, and place it in front of the LED, facing each other, as indicated in Figure 7. Double click in your DAQ assistant 2 this time add acquisition of a Current signal, from the Analog Input 2 port (AI2). In the DAQ assistant you must set the value of the external resistor to 10 kΩ, and the current range between -10 and 10 µA. This is illustrated in the second graph in Figure 7. In the Front Panel of your LabVIEW program create a new Waveform Chart visualizer, and connect it to the new output signal of your DAQ Assist. To obtain the current signal output from the DAQ assistant you will need to split the signals, since 2 of them are voltage, and 1 is current. To do this hover the mouse over the signal line coming out of the DAQ assistant, navigate to insert, and find a 'split signal' box, as the one pictured in Figure 7. Make the signal splitter into a 3 out-signals, and connect each one to a Waveform Chart in order to visualise them. You can connect the voltage signals in one chart, and the current signals to a different one as shown in .

Cover the photodiode and LED with your hand, such that the light from the room lamps does not contribute to the photocurrent in the photodiode. Run the software and note down the values of voltage and current you are observing on your lab book. Under those conditions, how much current flows through the photodiode? What happens when you block the path of light between the LED and the photodiode? Note down on your lab book what happens and the magnitude of current with and without line of sight between the LED and the photodiode. Now replace the red LED for the green LED

and repeat. Shine the light from the green LED into the photodetector. Monitor again the current signal from the photodiode and note your observations in the lab book. Repeat for the yellow LED.

Figure 7
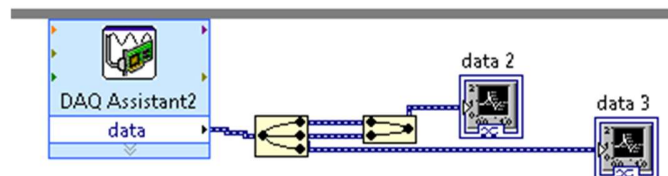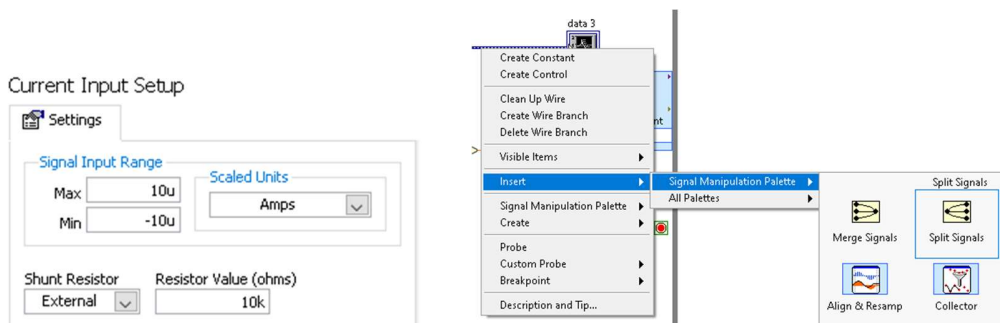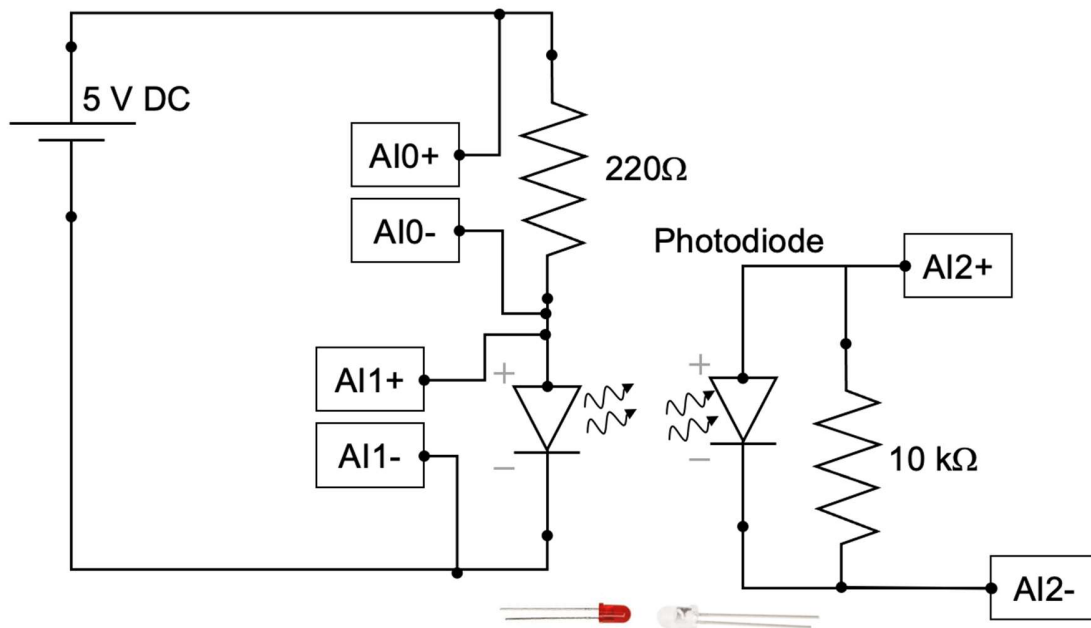
What differences do you observe between the different LED colours? How do those differences relate to the semiconductor used to manufacture each LED? Can you find the specifications datasheet for the LED that you are using and find out what semiconductor materials are used to manufacture it? Using the materials from the lecture, can you estimate the bandgap energy of each of LED you used? What conclusions can you make about the optical power coming out of each LED?

## 3.3 Switching light signals using a MOSFET

The Metal–Oxide–Semiconductor Field-Effect Transistor (MOSFET) is one of two major types of transistors. The MOSFET is used extensively in digital circuit applications where, because of its small size, millions of devices can be fabricated in a single integrated circuit. Two complementary configurations of MOS transistors, the n-channel MOSFET and the p-channel MOSFET, can be fabricated in the same silicon substrate, and they can be interconnected together. Electronic circuit design becomes very versatile when the two types of MOSFET are used in the same circuit. These circuits are referred to as complementary MOS (CMOS) circuits and they are the building block of the large majority of microprocessors made today.

e) Include a nMOSFET into the LED circuit to switch it

In this part of the practical we will explore the switching properties of an N-channel MOSFET: the IRLZ34NPBF device fabricated by Infineon. Using the prototyping board, and the circuit that you already have constructed, disconnect the cathode of the LED, and insert the nMOSFET in series as indicated in Figure 8. Connect the 0V to 5V sinusoidal signal (Pin 14 AO0

and Pin 15 GND in the DAQ card) to the Gate (1) and Source (3) of the nMOSFET. Run your LabVIEW software and monitor the voltage and current signals that you observe in the different components of your circuit. Note these down on your lab book. Describe your observations and explain how those observations relate to the electrical characteristics of the semiconductor devices you are using. Can you deduce the threshold voltage for the MOSFET you are using. If you block the light from the LED such that it cannot reach the photodiode, what do you observe? Note your observations on the lab book.

Figure 8
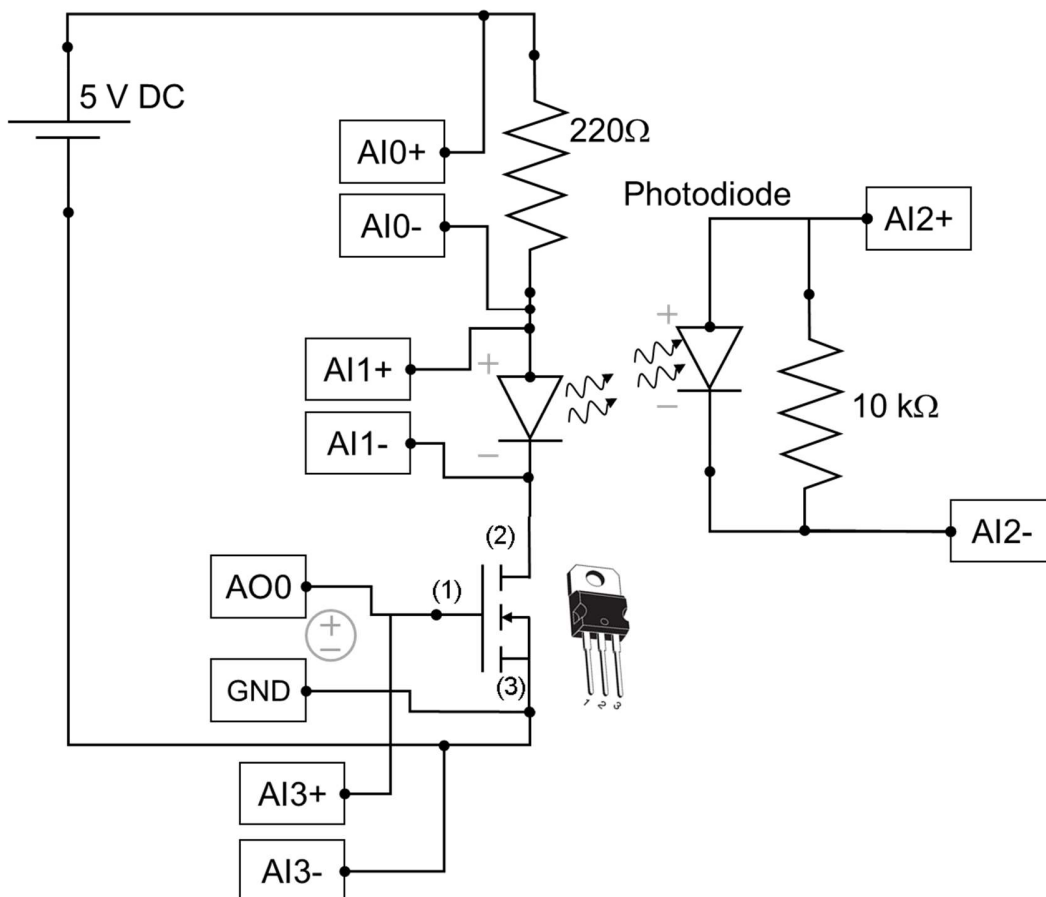
## 3.4 Electrical characteristic of a solar cell under operation

A solar cell is a *pn* junction device which is able to generate a voltage and current when it absorbs light from the sun. The solar cell converts photon power into electrical power and delivers this energy to a load. These devices have long been used for the power supply of satellites and space vehicles, and also as the power supply to some calculators. In this section of the practical you will be characterising the electrical parameters that describe a solar cell.

f) Build circuit to characterise a solar cell

Using the prototyping board assemble the circuit illustrated in Figure 9. You will be capturing the voltage of the solar cell in Analog Input 1, while you also capture the voltage across a 1 Ω resistor. Make sure to measure the exact resistance of the 1 Ω resistor using the DMM. This way you can calculate the current that the solar cell is producing. Connect the variable resistor, known as potentiometer, in series with the cell, and the 1 Ω resistor. Notice that you will only need to use two out of the three pins of the potentiometer. Once you have built your circuit, place the solar cell under the halogen flood light with the assistance of the TA, and ask the TA to turn the light on. If you are doing this practical at home, place the solar cell under the highest intensity desk lamp you can find at home. Using the potentiometer capture at least 10 data points that allow you to from the minimum voltage at the solar cell (~0 V), to the maximum that you can read under such illumination conditions (~5-8 V). Monitor the current that the solar cell produces simultaneously using the voltage across the 1 Ω resistor. After acquiring at least 10 values for I and V

on the solar cell for different loads, obtain the average and standard deviation of each data set, so that you know how much variance there is in the measurements you took. Using this data draw an IV curve for your cell, and estimate V_{os} and J_{sc} under these illumination condition. Note the IV curve and estimated values on your lab book. What is the point of maximum power output in the I-V? How much power is the cell producing for that resistance? You are told that the solar cell has an efficiency of 17%, what is the optical power of the lamp that you are using?. **Note:** you will need the area of the solar cell to be able to compare the lamp power to the η of the cell.

Figure 9
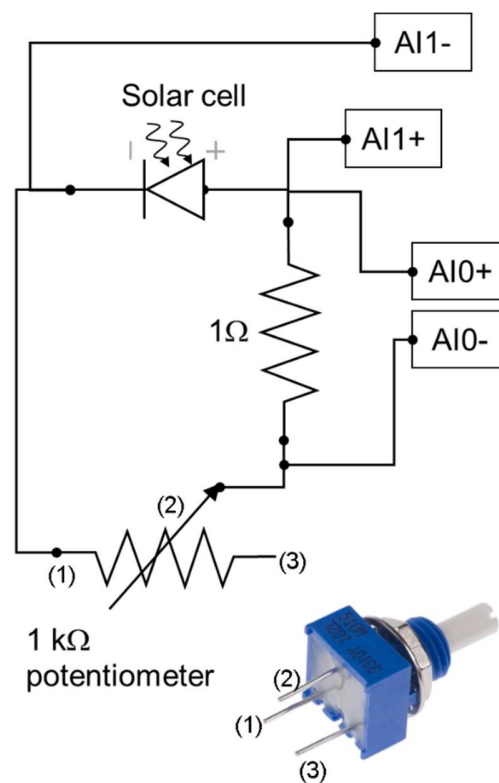
4 The report

Introduction: State clearly what you aim to achieve doing this practical. (2 marks)

Methods: Explain in what you did, the signals you measured. Include a description of methods used, including data processing, and a good account of the analysis of errors and uncertainties in the instruments you used. (3 marks)

Results: Display and describe what you observed with an appropriate level of presentation, accuracy, and detail, and having in mind the accuracy of your measurements. (4 marks)

Discussion: Explain your results putting them in the context of semiconductors theory in the lectures. Make sure you have answered all questions posed in this script. (3 marks)

Conclusions: Summarise the findings and conclusions drawn from data observation and analysis. (1 mark)

All reports must be a maximum of **3000 words**, and **10 figures**.

You are encouraged to plot your data and analyse it in Excel or any software of your preference, embed the figures into the allowed document, and properly comment on all the data you are displaying.

5 References

- Donald A. Neamen (2011) Semiconductor physics and devices
- Streetman, B., & Banerjee, S. (2016). Solid State Electronic Devices
- B. Van Zeghbroeck, 2011 http://ecee.colorado.edu/~bart/book.

Video guidance and reports on setting up the acquisition card, using the prototyping board, and report can be found on Canvas.