Laboratory Exercise 4 – DIGITAL THERMOMETRY

There are two parts to this exercise, which takes two 3-hour laboratory sessions. In part A you make and calibrate a direct-reading digital thermometer usable over the range 0–100 °C. In part B you use this thermometer to investigate the rate at which various liquids cool. There are few instructions provided for part B — instead you are given a copy of a published study of this topic, and asked to repeat the procedures and check the conclusions for yourself.

You must write a **short formal report** on this exercise, using the published paper as a model. S**ubmit** only the **report**. There is more on what must be included in the report on page 4–4.

Because the calibration of the thermometer is very sensitive to any changes in its electrical circuit, *you should do parts A and B on successive days*, Monday/Tuesday or Thursday/Friday. Your circuit will be left undisturbed on the bench between the two sessions.

Making the thermometer requires you to use and understand some of the electrical circuits covered in experiment 1, which you must have completed before starting this exercise.

Part A: Making the digital thermometer

Introduction

The temperature sensor is a semiconductor diode whose resistance varies with temperature. The diode is used as one arm of a Wheatstone bridge circuit, which will therefore only balance at one temperature. The off-balance voltage is measured with a digital multimeter (DMM) and adjusted with a potential divider to give a direct digital reading, in mV, of the temperature in degrees Celsius. There are three separate tasks: (i) measure the properties of the diode related to its temperature dependence; (ii) set up and adjust the Wheatstone bridge circuit; (iii) use a potential divider to adjust, calibrate and check the performance of your thermometer. You should allocate at most an hour to each of these tasks (including tabulating and plotting data), so as to complete part A in the first afternoon.

Characteristics of the diode

Diodes are electrical devices which allow current to pass in only one direction, the **forward** direction. In the **reverse** direction they have a high resistance, and so can act as one-way switches. The symbol for a diode is -▷|- with the arrowhead indicating the forward direction, so a voltage applied thus +-▷|-− causes current to flow; the diode is then said to be **forward biased**. To make a diode, a semiconducting material (silicon in this case) is **doped** with an impurity in order to give a deficit of electrons, hence excess **p**ositive charge, in one region, and another impurity to give an excess of electrons, hence excess **n**egative charge, in an adjacent region. The boundary between the regions is the **junction**. So the diodes you use here are called **silicon p–n junction diodes**. The diodes themselves are small, the size of a match head; the one you use has been encased in insulating mastic with only its two electrical leads left exposed.

The diode does not obey Ohm's law since the current I is *not* proportional to the voltage V. The relation between I and V is called the **characteristic**, and has the theoretical form:

$$I = I_{\mathrm{S}}\left(\mathrm{e}^{eV/kT} - 1\right)$$

shown in figure 1. Here e is the electronic charge, k is Boltzmann's constant, T is the temperature in degrees Kelvin (i.e. absolute) and I_{S} is the very small current which flows when the diode is reverse biased. The characteristic is not only strikingly non-linear, much more so than the very mild non-linearity studied in exercise 2, but it also has an explicit dependence on temperature. If the current is kept constant then a change in temperature will be accompanied by a compensating change in voltage. Thus as T changes the resistance of the diode, that is the ratio $R = V/I$, also changes. You are to measure the characteristic of the diode and find its resistance at a suitable operating current.

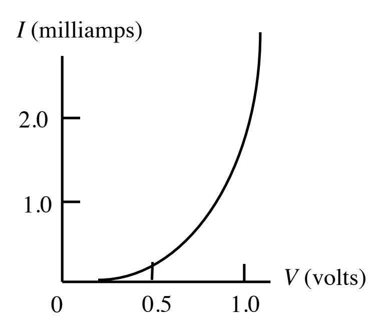

Figure 1 Diode characteristic

- Construct the circuit of figure 2 on the breadboard. The 10 kΩ variable resistor forms a potential divider, allowing you to vary the voltage across the diode.

- Measure and tabulate V and I (up to a **few** mA) and plot the forward characteristic of the diode.

- When used *later* as a temperature sensor the current should not exceed about 1 mA, in order to avoid excessive heating of the diode. **What voltage, approximately, does this correspond to?**

- What is the resistance of the diode at this current and voltage?

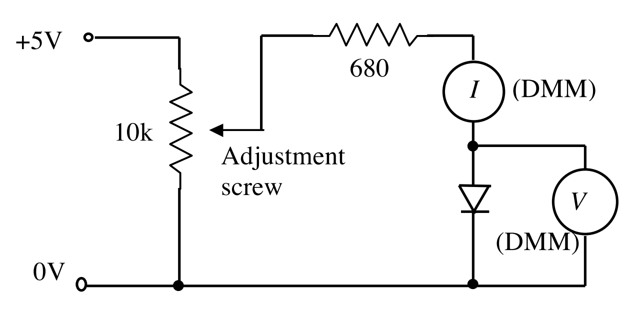

Figure 2 Circuit for measuring diode characteristic

- Use the characteristic equation given to **calculate** what voltage change will compensate for a temperature change of 1 °C at room temperature.

The Wheatstone bridge circuit

You may like to review the Wheatstone bridge circuit by referring to the lab script for Experiment 2 before continuing.

- Construct the bridge circuit of figure 3. First check that the 5V supply is stable using the DMM. The balance point of the Wheatstone Bridge will be affected if the power supply drifts. The leads on the small blue multi-turn variable resistor (helipot) are easily broken — do not stretch them!

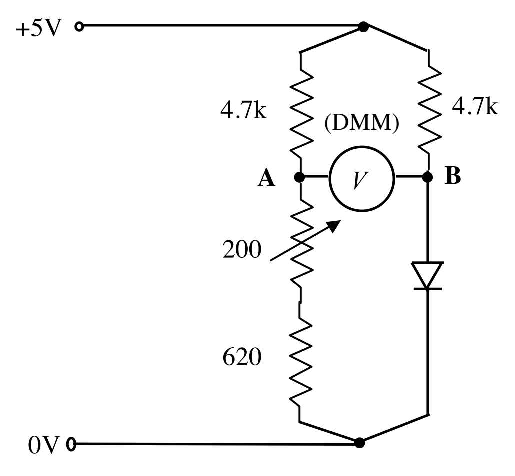

Figure 3 Wheatstone bridge circuit

We can easily place an upper bound on the current that will flow through the two arms of the bridge circuit by assuming that this circuit can be approximated by the two 4.7kΩ resistors. In other words by assuming that the other resistors and diode have zero resistance. The two 4.7 kΩ resistors in parallel present a combined resistance of 2.35 kΩ, allowing a current of no more than 5 V/2350 Ω. This corresponds to a current of about 2 mA to flow through the two arms of the bridge. At balance this will be divided equally between the arms, giving the desired 1 mA current through the diode. You should have calculated a diode resistance of several hundred ohms at this current; the 200 Ω helipot is adjusted to this value to balance the bridge.

- We wish to balance the bridge at 0 °C (so as to get a reading of zero at this temperature), so place the diode in a beaker of melting ice. Set the DMM to the 200 mV range, connect it across the outputs **AB** of the bridge, and adjust the 200 Ω helipot until the DMM reads zero. This is a tricky adjustment, very sensitive to small movements of the helipot. At balance the DMM may still be fluctuating a few tenths of a mV on either side of zero.

- Take the diode out of the ice bath and see whether the DMM voltage increases or decreases as the diode warms up. If it decreases, reverse the meter connections to **A** and **B** so that the digital reading will be positive for temperatures above 0 °C.

Calibration of the thermometer

Your calculation of the voltage change accompanying a 1 °C temperature rise should suggest that at 100 °C the DMM will register well over 100 mV. To get a direct reading of temperature we need to reduce this using a potential divider, preferably one with a high input resistance so that it does not overly disturb the currents flowing in the bridge circuit. A resistance of 10,000 Ω should be sufficient.

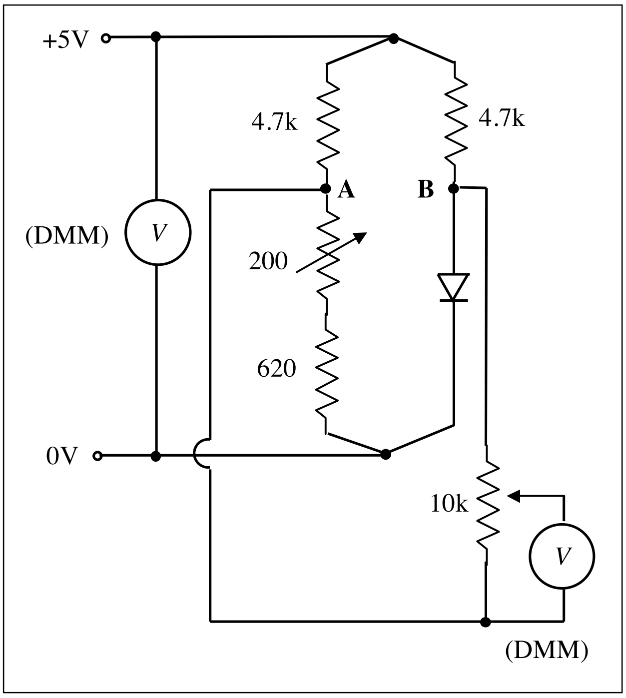

Figure 4 Final circuit for digital thermometer

- Replace the DMM across the output **AB** by the 10 kΩ helipot, and connect the DMM itself across the centre and an outside terminal of the helipot — this is shown in figure 4.

- Place the diode in boiling water and adjust this helipot until the DMM registers 100 mV. Then check that the reading is still zero when the diode is in melting ice, making small adjustments to the 200 Ω helipot if necessary. Repeat the sequence until readings of zero and 100 mV are obtained at 0 °C and 100 °C. The hot water cools quickly so you may only reach a temperature of 80-95°C. In this case you should adjust the helipot such that the DMM registers in mV the temperature of the water in degrees Centigrade. You now have a direct reading digital thermometer!

- Finally, check and correct the calibration against the alcohol-in-glass thermometer. Adjust your digital thermometer when the two thermometers are placed side by side in melting ice and boiling water. Then record the readings when they are both placed in water at some intermediate temperatures, say about 70 °C, 50 °C and 20 °C, using water from the cold tap for the latter. Try to estimate the glass thermometer reading to one-fifth of a degree, and comment in your report on the agreement between the two temperature scales.

Part B: The cooling of coffee

A paper by Rees and Viney on this subject is attached. **Read it before you start this part of the exercise**. Rees and Viney found that black and white coffee cooled at different rates, and sought to explain this. We are not asking you to attempt an explanation, but to repeat some of Rees and Viney's measurements and comment on whether your results agree with theirs and if not, what differences you find. You should be able to make the measurements and draw the graphs in one laboratory period — you may also have time to make some of the additional checks mentioned by Rees and Viney. We suggest that, after checking that your thermometer still records the ice and boiling points correctly, you measure the cooling curves of:

- 200 ml of plain water, brought to the boil and poured into the china mug.
- Black coffee made by adding 200 ml of water to a level teaspoon of granules in the mug.
- White coffee made by adding 20 ml of cold milk to a freshly-made mug of black coffee (200 ml again), stirring, and pouring out 20 ml to leave 200 ml. Do not re-boil the coffee.
- Black coffee made by adding 20 ml of cold water to a freshly-made mug of black coffee (200 ml again), stirring, and pouring out 20 ml to leave 200 ml. Do not re-boil the coffee.

- Can you say **why** the fourth procedure might be informative?

- Use the digital thermometer to record the ambient room temperature.

Your **report** should describe what you did and the conclusions you draw, but it should not be as long as Rees and Viney's — about half the length is sufficient. It **must** be written using a **word processor**, a handwritten version is **not acceptable**. **The report *must* include:**

- A title.
- Author's name and affiliation.
- An abstract, which is a brief summary of a few lines *including results* but not too detailed.
- A short introduction — what are you describing, and why did you do it?
- A **brief** summary of the theory (you can refer to other publications for this, e.g. 'It is shown by Rees and Viney(1) that …').[1]
- A brief description of your digital thermometer.
- A brief description of what you did and measured.
- A summary of the results, together with calculated quantities. Show raw data as graphs (much more informative than tables), while derived quantities (such as time constants) can conveniently be tabulated. Use *log* rather than linear plots where appropriate.
- A discussion of the significance of the results, including any uncertainties due to measurement precision (errors) and whether or not differences found are meaningful.
- A short conclusion.
- A list of references with name(s) of author(s), journal name and volume number or book title and publisher, page number(s), and date.

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[1] Note that it is unacceptable to copy verbatim from the attached paper. You should present your results in your own words. When you refer to the paper by Rees and Viney you should cite that reference appropriately. If you are unsure about this, please ask a demonstrator.

Marks will be deducted for poor spelling (use a spell checker), lack of clarity (proof read and be scientifically objective), and poor presentation. We will go over these points and answer questions about the reports in the lectures.

Remember to *proof read* and *spell check* your report. Look at it with print preview to check that it looks o.k. before you print it. Remember to save your work frequently, and keep a separate (*backup*) copy on your own USB stick. If you need help with word processing ask a demonstrator or laboratory technician. Print your final copy ***well before*** the hand-in deadline, since the printers may be very busy (or down!) just before the deadline!