Electrical Transport Measurements from First Principles: a Senior Undergraduate Experiment

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Abstract. A final year undergraduate experiment has been designed and constructed with the aim of illustrating numerous aspects of low temperature measurements, with the objective of determining the electrical transport properties of materials. The experiment is designed to ensure that the students cannot treat the experimental apparatus as a data-producing "black box", and the students are obliged to manually control the temperature, take much of the data by hand, and to calibrate the thermocouple used to measure the temperature. The use of a desktop computer and software packages during the experiment are encouraged. Much of the apparatus was assembled at relatively low cost.

1 Introduction

Experiments at temperatures below ambient are ubiquitous in research laboratories all over the world. Since the liquefaction and solidification of gases during the 19th century, temperature control was achieved using heat baths of these cryogens, and by developing experimental apparatus that allows for accurate temperature control, and precision measurements of the temperature (and the physical quantities of interest). While low temperature experimental arrangements for teaching laboratories may be obtained commercially, the trend is towards computer control. In these circumstances the student experience becomes one of starting a computer program, waiting several hours, and then obtaining a beautiful set of data that has to be analyzed, and the underlying physics obtained. This experience is incomplete, as the students do not learn actively much about what is required to ensure that the data obtained is reliable.

A hands-on experiment that gives the the students the responsibility of determining the temperature of their calibration points, calibrating their thermometer, and controlling the temperature is described. The experiment re-inforces concepts learned in thermodynamics, and provides a data set that is adequate, but to some degree flawed. The experiment encourages a continuous interaction between the teaching assistant (or demonstrator) and the students, in which the students are active participants.

2 Experimental Apparatus

Fig. 1 shows a collage of the experimental apparatus used in the experiment. The caption provides detail on each of the highlighted components. There are three samples in the cryostat: a standard resistor with an ambient temperature resistance of approximately 26 kΩ, a large band-gap semiconductor with an ambient temperature resistance of approximately 65 Ω, and a thin copper wire with an ambient temperature resistance of approximately 9 Ω. Liquid nitrogen is used as the cryogen for the experiment, and the thermocouple reference temperature is an ice-water bath prepared by the demonstrator. Ambient temperature and pressure are measured by the students. The experimental procedure, which involves determing the boiling point of nitrogen using the ambient pressure, calibration of a copper-constantan thermocouple, using a VARIAC and an urn element to achieve rapid cooling, and a resistive heater to control the warming of the cryostat will be discussed in the conference presentation.

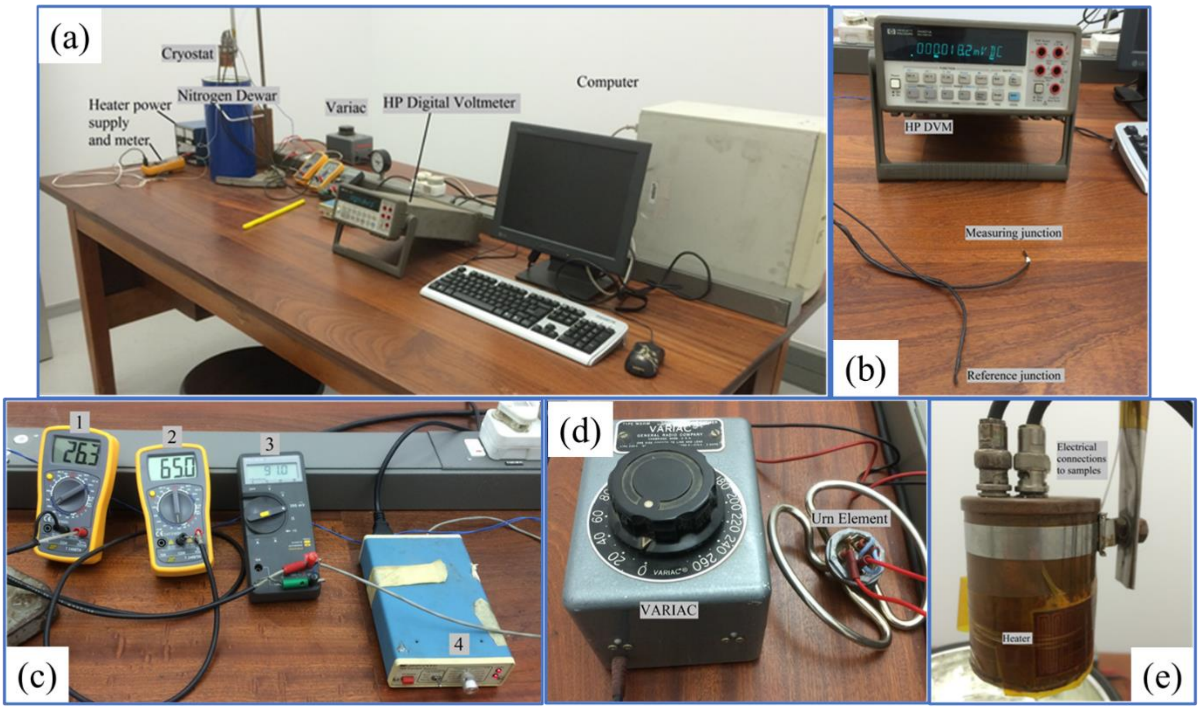

Fig. 1 An annotated collage of the experimental apparatus. Fig. 1 (a) is an overview of the experiment bench, showing most of the apparatus, including the mercury bulb thermometer, and the pressure gauge. The nitrogen dewar has a loose-fitting styrofoam lid that is used to provide thermal insulation of the measuring chamber during the experiment. Fig. 1 (b) shows the thermocouple, and the high precision digital voltmenter (DVM) used to measure the emf produced by the thermocouple. The reference junction of the thermocouple is placed in an ice-water bath throughout the experiment. Fig. 1 (c) shows the handheld DVMs used to determine the resistance of the three samples. The meters labelled 1 and 2 measure the resistance of the standard resistor and the semiconductor directly, while the resistance of the copper sample is determined using a constant current source (4) and the potential drop across the sample (and the co-axial wire connecting the sample to the cryostat) using a DVM (3) . Fig. 1 (d) shows the VARIAC and the urn element that are used to provide rapid cooling of the measuring chamber to approximately 100 K during the first phase of the experiment. Fig. 1 (e) is a close-up of the copper cryostat, showing the co-axial cable connecting the three samples to the the measurement DVM, and the non-inductive heater. The resistive heater has a separate power supply which has a maximum current output of 1 A, and the current may be monitored using a handheld DVM as shown in Fig. 1 (a).

3 Summary

A (relatively) cheap experiment that can be used to determine the electrical transport properties of materials in the range 100 K to 300 K has been described. The experiment allows for the demonstration of vital low temperature techniques, such as thermometer calibration. Students are taught how to avoid pitfalls in low temperature measurements, such as thermal lag. The data obtained from even a well-executed experiment are flawed, which allows for the discussion of improvements e.g. four-point resistance measurements. The experimental design encourages interaction between the instructor and the students.