Non-linear circuit elements: thermistors and silicon diodes

This exercise studies the relationship between voltage and current in two non-linear (non-Ohmic) circuit elements: thermistor and silicon diode.

1. **Thermistors**
   Thermistors are temperature sensitive resistors, that usually exibit a negative temperature coefficient of resistance (NTC). The electrical resistance of a thermistor will be reduced when it is placed in a medium of higher temperature.
   A thermistor does not "read" anything, but with an appropriate calibration thermistors can be used to measure temperature.
   Steinhart-Hart Equation is the standard calibration equation for an NTC thermistor:

$$T = \frac{1}{c_1 + c_2(lnR) + c_3(lnR)^3} \tag{1}$$

   where: R is the thermistor resistance and T is temperature, in K.
   Procedure. The apparatus for measuring and calibrating the thermistor consists of: one multimeter (setup on Ohm function (Ω)), a thermos flask and a thermometer. You'll also have access to a kettle to boil water and to an ice machine.
   Use the ohmmeter connected directly across the thermistor to determine R at a variety of temperatures between 0^oC and the highest temperature you can get, close to 100^oC.
   Fitting the Steinhart-Hart Equation.
   Take the inverse of Equation (1): you'll obtain almost a polynomial of the form $1/T = f(ln(R))$. Adding the missing quadratic term gives:

$$\frac{1}{T} = a_1 + a_2 lnR + a_3(lnR)^2 + a_4(lnR)^3 \tag{2}$$

   With $y = \frac{1}{T}$ and $x = ln(R)$ you can do a least-squares fit on the polinomial:

$$y = a_1 + a_2 x + a_3 x^2 + a_4 x^3 \tag{3}$$

   Write a Python program to fit (3) to your experimental data. The output of your program is the set of coefficients a_1, a_2, a_3 and a_4. The calibration curve of the thermistor can be constructed as:

$$T(^oC) = \frac{1}{a_1 + a_2 lnR + a_3(lnR)^2 + a_4(lnR)^3} - 273.15 \tag{4}$$

   Write a Python program, using user input and the calibration function from (4) with calculated a_1, a_2, a_3 and a_4 to determine the temperature corresponding to a given measured resistance. Test it with a couple of measured values.

2. **The silicon diode**
   Diodes are basic unidirectional semiconductor devices that will allow current to flow through them in one direction only (forward biased condition). Diodes are made from a single piece of semiconductor material which has a positive P-region at one end and a negative N-region at the other.
   Semiconductor materials such as silicon (Si), germanium (Ge) and gallium arsenide (GaAs), have electrical properties somewhere in the middle, between those of a conductor and an insulator. They are not good conductors nor good insulators (hence their name semi-conductors). They have very few free electrons because their atoms are closely grouped together in a crystalline pattern called a crystal lattice.

On their own, Si and Ge are called intrinsic semiconductors (are chemically pure). But by controlling the amount of impurities added to an intrinsic semiconductor, it is possible to control its conductivity. Various impurities called donors or acceptors can be added to the material to produce free electrons or holes respectively. The process of adding donor or acceptor atoms in the order of 1 impurity atom per 10 million (or more) atoms of the semiconductor is called doping.

The most commonly used semiconductor basic material is silicon. Si has four valence electrons in its outermost shell which it shares with its neighbouring Si atoms to form full orbitals of eight electrons. The structure of the bond between the two Si atoms is such that each atom shares one electron with its neighbour making the bond very stable.

But simply connecting a Si crystal to a battery supply is not enough to extract an electric current from it. To do that, we need to create a positive and a negative pole within the Si allowing electrons and therefore electric current to flow out of the material. These poles are created by doping the silicon with certain impurities. Antimony (Sb) or Phosphorus (P) added to semiconductor basics material create an excess of current-carrying electrons and the resulting material is therefore referred to as an N-type material with the electrons called majority carriers.
Boron (B) doping results into an excess of holes (P-type material).
The silicon diode with P and N poles is a two-terminal device that minimizes current flow in one direction (reverse bias) while easily carrying current in the other direction (forward bias).
The Shockley diode equation relates the current I measured in a DC series circuit with a silicon diode and the applied voltage V:

$$I = I_o(e^{\frac{qV}{kT}} - 1) \tag{5}$$

where I_o is called saturation current, q is the electronic charge $q = 1.6 \times 10^{-19}C$, T is temperature and k is Boltzmann's constant.

Procedure The apparatus consists of two multimeters, a switch, a power supply and a silicon diode. Connect the diode, ammeter and power supply in series, add the voltmeter across the diode. Take data of voltage and current and plot the I-V curve in both forward (easy conduction, current in miliAmps range) and reverse directions (current in microAmps) of the diode. Measure the current as you gradually increase the voltage from zero. Generally, the switch has to be open only when you take a measurement.
Fit the Shockley equation (5) to your data and determine constants I_o and Boltzmann's constant k.

3. **What to submit**:
- Two programs for the Thermistor part: 1) to determine coefficients a_1, a_2, a_3 and a_4 and 2) a calibration program, using user input and the calibration equation. Provide the complete output for the first program: plot, parameters, χ^2 and uncertainties in calculated parameters. The second program can be used to output the temperature when a measured resistance value is given by the user.
- One program for the Silicon Diode part: data fitting with Shockley equation. Provide output: constants I_o and k, the I-V plot, χ^2, uncertainties in parameters.

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