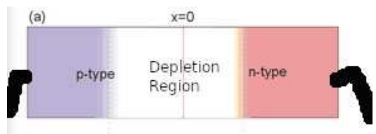
Boltzmann Thermal Probability

Physics 3705: Spring 2025

Objective: Use a simple Drude model of a reverse bias diode to test the exponential dependence of the leakage current with temperature.



Theory: Undoped semiconductor is an insulator at zero temperature since the valence band is filled and there is an energy gap (called the "band gap") to the empty conduction band. At finite temperature however some electrons are thermally excited into the conduction band, and so the semiconductor's resistivity goes down with temperature.

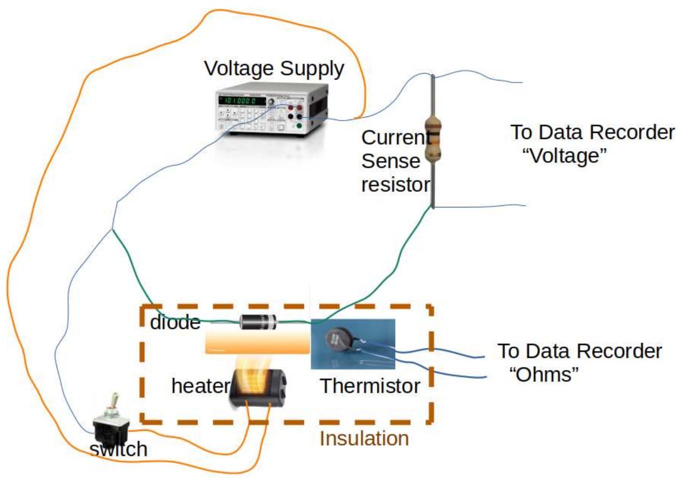
But at a given fixed temperature what is the chance that an electron could randomly have enough energy to make it into the conduction band? At modest temperatures we expect that electrons near the top of the valence band are most likely to get enough thermal energy to make it into the conduction band, and doing so, are most likely to populate the lowest energies in the conduction band. Thus we're really asking the question what is the likelyhood in equilibrium at temperatire T that an electron at the top of the valence band could have a thermal excursion of energy E_g, the energy difference between the valence and conduction band. This likelyhood was determined by Boltzmann to have a universal form, dependending only on the energy difference (that is E_g) between its intial state (valence band) and its final state.

$$P(E) \sim \frac{1}{Z} e^{-\frac{E}{k_B T}} \tag{1}$$

where Z is a temperature dependent normalization constant for the probabiblity.

Without going into too much detail about semiconductors and diodes[1], we note that semiconductors can be "doped" with small quantitites of impurities that either add electrons or add deficits of electrons ('holes') into the material, making it more conducting. When we put one with extra electrons right up against one with a deficit of electrons (an arrangment called a **diode**), some electrons from the excess side shimmy (OK, biased diffusion) over to the deficit side. This forces there to be a region in between where the material is basically in its pristine semiconductor state as if it had no doping at all. This region is called the **depletion region** because at zero temperature it would have no cariers (no electrons or holes) at all. The width of this region is basically controlled by the voltage. When an external voltage is placed on the depletion region by putting the excess electron side at a positive voltage relative to the deficit electron side, the depletion region gets wider. This is called a **reverse bias** condition.

Now recall the Drude model of Ohm's law, $R = \rho l/A$, where $\rho = \frac{m_e}{ne^2\tau}$ where n is the number density of electrons. At finite temperature, if we hold the reverse bias at a constant voltage, then the resistance of the depletion region should (by the Drude model) be inversely proportional to the number density of carriers. This means that the current $I = V/R$ should be proportional to the number density of the charge carriers. Then, according to the Boltzmann probability, we expect that the reverse bias current is proportional to $e^{\frac{-E_g}{k_B T}}$. In this laboratory we test (1) this expectation of the exponential dependence on the temperature and (2) measure the E_g.



Method:

1) Identify the wires and connect up the circuit as shown. The thermistor at room temperature should read around 11 KΩ. Make sure that the switch is in the off position. Verify that the data acquisition pipeline is working; you are recording the thermistor reading and the voltage over the current sense resistor (about 50 to 120 KΩ). Record the value of the current sense resistor.

2) Put the voltage at between 8 and 10 volts and record the value. Throw the switch and drive the temperature up (the thermistor resistance will decrease) until the thermistor reads about 1 KΩ, then SHUT THE SWITCH OFF.

3) Immediately start the sequential data acquisition, recording a (thermistor, voltage) pair each second.

4) Conclude the data acquisition when you are back near room temperature, say about 9 KΩ. You now have a bicolumnar list of thermistor readings and voltages over the current sense diode.

Analysis:

1) Use the formula T(R) = -29.15ln(R/26.9KΩ) to convert the thermistor readings to a Celcius temperature of the diode.

2) Plot the current flowing though the diode (the voltage you recorded divided by the sense resistance) as a function of the temperature.

3) Fit the data with an exponential of the form $Ae^{-B/T}$ were T is the absolute temperature. Report the values and fit errors for A and B. Is it a reasonable fit?

4) Finally, as described in the theory section, the B should be $\frac{E_g}{k_B}$. Use that to determine E_g, the band gap for this semiconductor. Here are bandgaps of several common semiconductors: Silicon 1.12 eV, Germanium 0.65 eV, InGaAs 0.75eV, BiTe 0.12 eV.

Can you determine which semiconductor your diode is made of?

References:

[1] "Britney Spears Guide to Semiconductor Physics," https://britneyspears.ac/physics/pn/pnjunct.htm