Experiment 272: The Bandgap in Silicon

Aim

This experiment measures the forbidden energy gap in silicon.

Reference

1. Millman J. and Halkias C.C., "Integrated Electronics", McGraw-Hill

Theory

The current through a p-n junction arises from several effects. It is found that over relatively wide ranges of temperature and applied voltage the current is given by:

$$I = I_s \left[\exp\left(\frac{qV}{\eta kT} \right) - 1 \right] \tag{1}$$

where

I_s is the reverse saturation current,
q is the electronic charge,
V is the applied voltage,
k is Boltzmann's constant, and
T is the absolute temperature.

The factor η depends on the processes producing the current flow. For silicon diodes, the drift and diffusion currents are the main contributions, but other effects are also present. A value of η between 1.3 and 1.6 gives good agreement with experiment. The actual value of η depends on the device geometry and the amount of current. For silicon transistors, η for the base-emitter junction has a value closer to 1 because of the recombination of the collector and base currents in the emitter region. The reverse saturation current I_s is temperature dependent, and is related to the forbidden energy gap at absolute zero, E_{g0} (eV), by:

$$I_s \propto T^x \exp\left(\frac{-E_{g0}}{\eta kT} \right) \tag{2}$$

where x is also material dependent, being approximately equal to 1.5 for silicon. The reverse saturation current can be seen to be a sensitive function of temperature. In fact, at room temperature a 6 °C rise will approximately double I_s. The energy bandgap is of the order of an electron volt and it can be shown that over the temperature range 100 – 300 K, the dependence of I_s on T^x is completely overwhelmed by its dependence on $\exp(-qE_{g0}/\eta kT)$. To a good approximation, therefore:

$$I_s \propto \exp\left(\frac{-E_{g0}}{\eta kT} \right) \tag{3}$$

For voltages greater than about 0.1 V, equation (1) is well-approximated by:

$$I = I_s \exp\left(\frac{qV}{\eta kT} \right) \tag{4}$$

A graph of $\ln(I)$ -vs- V at constant temperature should therefore have a gradient of $q/(\eta kT)$ and a $\ln(I)$-intercept of $\ln(I_s)$. If the diode's current-voltage characteristic is measured for several temperatures, it should be possible to plot the resulting values of $\ln(I_s)$ against $q/(\eta kT)$. The gradient of the graph of $\ln(I_s)$ -vs- $q/\eta kT$ should be a straight line of gradient $-E_{g0}$.

Experimental Set-up

For silicon, the p-n junction used in the experiment is the base-emitter junction of an *npn* transistor. The experimental set-up is shown in Figure 1 and the circuit used to determine the current-voltage characteristic of the p-n junction is shown in Figure 2.

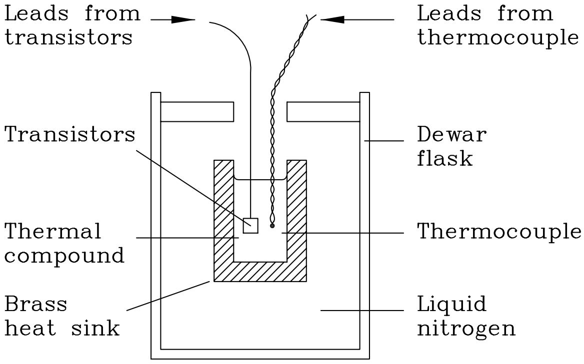

Figure 1: View of the cryostat

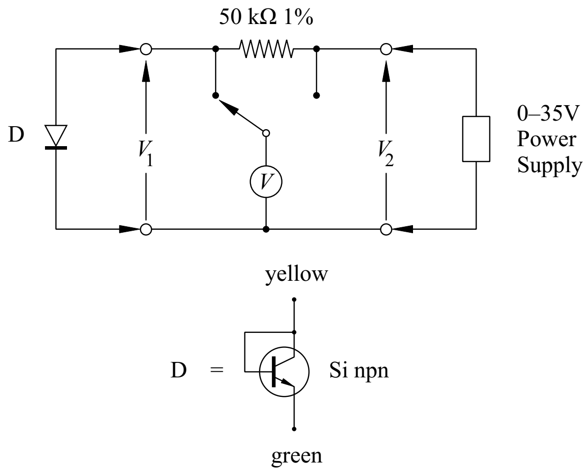

Figure 2: Circuit used to take measurements

Procedure

(1) Note the temperature before and after each set of measurements. Take measurements of I and V for the silicon transistor at room temperature. The current I is determined from the difference in voltage $V_2 - V_1$ across the 50 kΩ resistance. Adjust the voltage V_2 until the difference between V_2 and V_1 is about 0.5 V. This corresponds to a current of about 10 μA. Commence recording V_1 and V_2 for increases of 0.01 V in V_1. This ensures I is measured at regular intervals of V_1. As the maximum voltage of V_2 is about 35 V, the current I ranges from 10 to 680 μA.

(2) Pour sufficient liquid nitrogen into the dewar flask to cool the heat sink to about -100 °C and try no to exceed -100 °C. Pour the liquid nitrogen in the dewar back into the thermos flask. Place the heat sink in the now empty dewar and wait for the temperature to stabilise. Repeat the measurements in procedure (1). Do not forget to record the temperature before and after the set of measurements.

(3) Take the heat sink out of the dewar and let it warm up to about -70 °C. Place the heat sink back into the dewar, wait for the temperature to stabilise and repeat the measurements in procedure (1). Repeat for temperatures about -40 °C and -10 °C.

(4) Using Python, plot I -vs- V_1 at various temperatures in one diagram and $\ln(I)$ -vs- V_1 at various temperatures in another diagram. For I -vs- V_1 curves, plot the points with "+" or "x" and join them with lines. For $\ln(I)$ -vs- V_1 curves, plot the points with "+" or "x" and draw a line of best fit through them.

(5) From the `polyfit` function used to determine the coefficients for the best fit for $\ln(I)$ -vs- V_1, obtain $\ln(I_s)$ and $q/(\eta kT)$. Plot these points with "+" or "x" and plot the line of best fit through them. Determine the energy bandgap at absolute zero for silicon from the resulting $\ln(I_s)$ -vs- $q/(\eta kT)$ plots.

Questions

1. What is the error in your values for E_{g0}?
2. Show that the dependence of I_s on T^x contributes negligibly to the temperature dependence of the reverse saturation current.

List of Equipment

1. 2× Dewar flask
2. 1× Brass Heat Sink
3. 1× Thermocouple Thermometer
4. 1× 0 – 35 V Power Supply
5. 1× Digital Voltmeter
6. 1× Silicon npn Transistor (BC318B)

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Updated for silicon transistor only: January 19, 2015