Band Gap in Semiconductors

The band gap is one of the most important characteristics in a semiconductor. It is the width of this energy gap that makes a semiconductor a *semi*conductor. In this experiment you will use the temperature-voltage curve of a diode under constant current to determine the band gap for the diode material.[1]

Safety note

In this lab you will be working with a high-temperature mineral-oil bath. This oil boils at over 250° C, and can cause *severe* burns if used incautiously.

- *Do not* exceed a temperature of 150° C.
- *Do not* spill hot oil on yourself or your lab partners.
- *Do not* touch the oil, or items that have been in the oil, until you are certain that they are at or near room temperature.
- *Be careful.*

Mathematical Background

The current through an ideal diode is given by [3, 482]

$$I = I_0 \left(e^{eV/kT} - 1 \right) \tag{1}$$

with I_0 the reverse bias current (at $V_b = -\infty$), V the applied voltage, T the temperature in Kelvin and k Boltzmann's constant. We will limit ourselves to regions where $e^{eV/kT} \gg 1$ (i.e. $eV/kT > 4$ or so) so

$$I \approx I_0 e^{eV/kT} \ . \tag{2}$$

The reverse bias current I_0 is dependent on temperature also, and the dependence is somewhat more complicated:[2]

$$I_0 = A T^{3+\gamma/2} e^{-E_g/kT} \tag{3}$$

where E_g is the band gap energy. For the relatively small temperatures and temperature differences used in this experiment, the power dependence term $T^{3+\gamma/2}$ changes relatively little compared to the exponential term $e^{E_g/kT}$. This allows us to approximate the temperature dependence of I_0 as

$$I_0 \approx B e^{-E_g/kT} \ . \tag{4}$$

If we combine equations 2 and 4, we obtain

$$I \approx Be^{-E_g/kT + eV/kT} \ , \tag{5}$$

which can be rearranged to the form

$$T = \frac{eV}{kC} - \frac{E_g}{kC} \ . \tag{6}$$

where $C \equiv \ln\left(\frac{I}{B}\right)$.

Equation 6 is a linear equation in V, if the current is held constant so that C is approximately constant. The slope is $a = e/kC$, and the intercept is $b = E_g/kC$. The kC term can be eliminated by dividing the intercept by the slope, leaving us with the band gap in electron volts:

$$E_g = -\frac{b}{a} \ . \tag{7}$$

So if we plot the temperature versus voltage for a diode with constant current, we can obtain the band gap energy from the slope and intercept of the plot.

Equipment

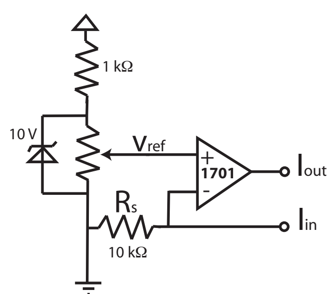

Figure 1: Constant-current source

The impedance of the diode depends on temperature, so the first requirement for this lab is a constant-current supply. The current requirements are not large — a few tens of micro-amps is sufficient — so a simple op-amp circuit as shown in figure 1 is adequate for the job. The variable resistor provides a voltage $V_{ref} = V_+$ at the positive input of the op-amp. The current through the resistor R_s creates a feedback voltage V_- at the negative input, and the op-amp output voltage increases so that $V_- = V_+$. Since the current through the inputs of the op-amp are approximately zero, the current through I_{out} and I_{in} is equal to the current through R_s, and

$$I = \frac{V_{ref}}{R_s} \ . \tag{8}$$

The remainder of the equipment consists of a hot plate with a beaker of non-conductive mineral oil, a digital thermometer, a power supply, and one or more high-sensitivity voltmeters.

Procedure

1. Connect a 12-V supply to the constant-current supply.
2. Connect the diode(s) you wish to test to the constant-current supply. We have two good voltmeters available, so if you wish to perform the experiment on two diodes simultaneously, connect them in series. (The constant-current source will drive two in series without problem.) Make sure the diodes are connected with the right polarity. Connect the sense wires to the voltmeter(s) so that you can measure the voltage across the diode(s).
3. Immerse the diodes in the mineral oil, and gradually increase the temperature of the oil bath. Record temperature and voltage up to a maximum temperature of 150° C.
4. Plot T versus V. Are there regions where the graph deviates from the linear prediction? If so, why?
5. Calculate the band gap for your sample(s), using slope and intercept data from appropriate regions of your graph.

Controlling this experiment via computer

Most high-quality measurement instruments (including the Keithley 2000 and 2700 meters we are using for this experiment) can be computer-controlled through a GPIB[1] connection. The thermometer we are using for this experiment just generates a voltage, so its output can be read by a computer interface also. This means that this experiment is ideal for LabView control.

There are three sample files in the shared documents/LabView folder on the computer: 2000-read.vi, 2700-read.vi, and DAS08-voltage-read.vi. These three should be sufficient to get you started on a LabView program to automatically take your data.

1. Set up a 'while' loop in Labview that takes data readings every 10 seconds or so. Remember to include a 'stop' button in the loop.

[1] General-Purpose Interface Bus

2. Use code similar to these examples to read the two resistance measurements and the temperature, once per loop. Note that the initialization and measurement-selection portions of 2000-read.vi and 2700-read.vi only have to be done once, so you will probably want these bits of code to be outside of the loop.

3. Have the program exit the loop and save the data to a spreadsheet-readable file when the 'stop' button is pressed.

4. It's relatively easy to do other fancy stuff in LabView, which may or may not be useful. Examples might include graphing the data as it's collected, setting off flashing lights and sirens when the temperature exceeds 150°C, etc. While impressive, these are not actually *physics*. They are optional.

References

[1] Jürgen W. Precker and Marcílio A. da Silva. Experimental estimation of the band gap in silicon and germanium from the temperature-voltage curve of diode thermometers. *American Journal of Physics*, 70(11):1150–1153, 2002.

[2] S. M. Sze. *The Physics of Semiconductor Devices*. Wiley, 1969.

[3] Paul Allan Tipler and Ralph A. Llewellyn. *Modern Physics*. W. H. Freeman, 4^{th} edition, 2004.