Bandgap in a Semiconductor Diode

Dr. Eric Ayars
California State University, Chico
ayars@mailaps.org
(530) 898-6967

AAPT Summer meeting, Edmonton Alberta
Advanced and Intermediate Instructional Labs Workshop

July 20, 2008

Band Gap in a Semiconductor Diode

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]

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

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

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

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

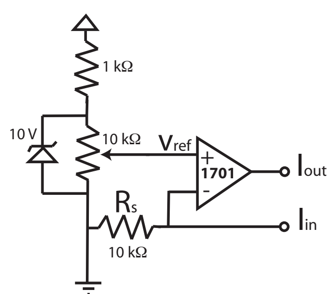

Figure 1: Constant-current source

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.

Instructor's notes

This lab is extremely well-suited for computer control with LabVIEW, and I usually make my students write a LabVIEW program to collect their data. Taking data by hand works well also, though.

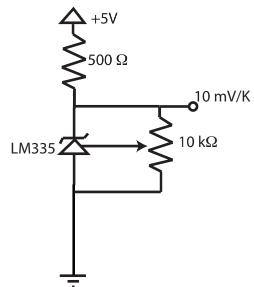

Figure 2: LM335 thermometer circuit

For temperature measurement, I use an LM335-based thermometer. Other thermometers work also, of course: I just have some familiarity with this particular chip so that's what I use. The LM335 is based on a temperature-dependent zener diode, and generates a voltage equal to the temperature in Kelvin divided by 100. It's linear from -55°C to 150°C. The simple circuit I use is shown in figure 2. Once assembled, calibrate by adjusting the trimpot so that the output is 2.7315 V at a temperature of 0°C.

The constant-current supply is fairly easy to build also. Just about any op-amp will work for this: I use a 1701 op-amp because it has the advantage of being able to send the output all the way to the supply voltage levels, and it works well with a single-sided supply. With the circuit shown in figure 1, using the values given, a 10-turn pot on V_{ref} will adjust the current from 0–1 mA, with current noise/drift at the level of 100 pA or less. Depending on your needs, it might be worthwhile to have the students build this circuit themselves on a small breadboard as part of the activity.

The diode should be attached using a 4-wire connection: two wires to supply the current from the constant-current supply, and two for measurement of the voltage. It's quite possible to collect data from multiple diodes simultaneously. Attach the diodes in series with the constant-current supply, and measure the voltage across each one separately. For best results, the current should flow in the "forward" direction on each diode.

The approximations used in the experiment are somewhat dramatic, as you've probably noticed. ($T^3 \approx$ constant, for example!) It's important to cover this well with your students, and explain that a "mere" cubic function *is* approximately constant when compared to an exponential term. It's also important to note that the approximations break down eventually. This is most readily apparent when using a Ge signal diode at higher temperatures: see sample data below.

Equipment sources

All electronic components are available from the usual sources:

- Digikey: `www.digikey.com`
- Allied Electronics: `www.alliedelec.com`
- Mouser: `www.mouser.com`
- Newark: `www.newark.com`

Of these, Mouser usually has the best price.

Sample Data

Silicon diodes work very well for this experiment, as shown in figure 3. The bandgap calculated with this data set works out to 1.24 eV, which is

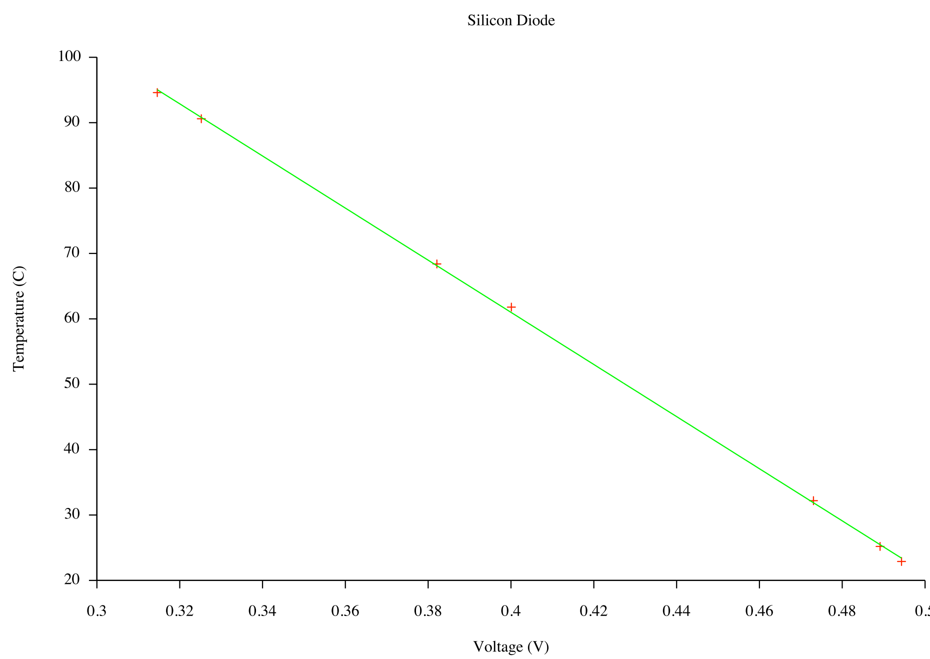

Figure 3: Actual data taken with a silicon diode.

reasonably close to the accepted value of 1.12 eV at 300 K.

Germanium diodes also work, with some interesting caveats. As seen in figure 4, there is a strong deviation from the linear graph predicted in the model, although it appears to be linear in the low-temperature region. This is consistent with what we'd expect from the approximations we made. The

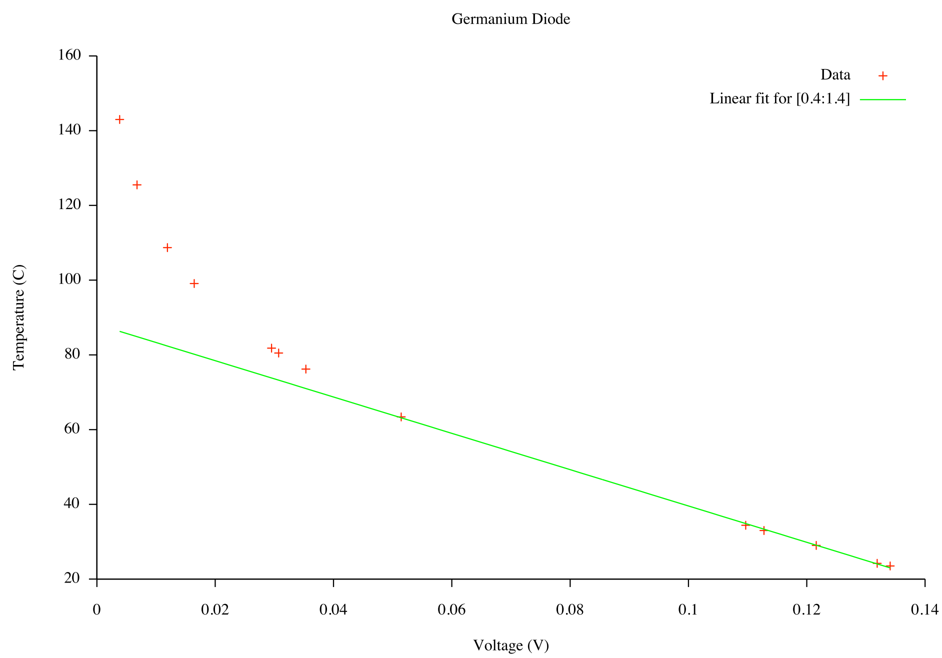

Figure 4: Actual data from a germanium diode

bandgap calculated with this data set, using the slope of the linear region at low temperatures, is 0.74 eV. This value is consistent with accepted values for Ge.

Acknowledgments

I did not invent this experimental method. Credit for that goes to Jürgen Precker and Marcílio da Silva, who wrote the AJP article [1] from which I got the idea.

Bibliography

[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.