Experiment 11: Hall Effect & Energy Gap in Germanium

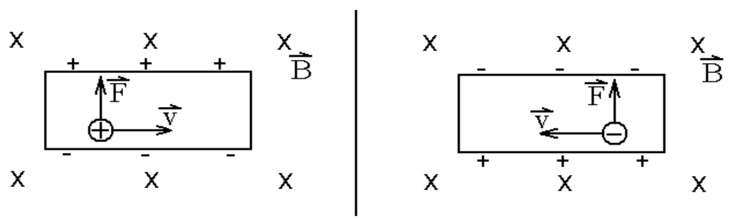
We will see if the charge carrying particles are negative in n-doped germanium, and if they are positive in p-doped germanium. We will also measure the energy gap between the conduction and valence bands in germanium.

We will observe the sign of the charge carriers from the sign of the Hall voltage. The Hall effect is a voltage across a current carrying conductor in a magnetic field, as opposed to the voltage along the conductor described by Ohm's law. The magnetic force pushes the moving charges in the same direction whether they are positive or negative, so the side of the conductor they are pushed toward will be positively charged if they are positive particles or negatively charged if they are negative particles.

To measure the energy gap, we will heat a germanium diode. At 0 kelvins, semiconductors are insulators. As the temperature goes up, more and more electrons have enough thermal energy to cross the gap into the conduction band, making the electrical resistance go down. If you heat two different materials, more electrons will cross the gap in the material where the gap is narrower than in the material with the wider, harder to cross gap. So, the resistance and the rate it changes with temperature are related to the energy gap, E_g, and therefore E_g can be deduced from them.

Part 1. The Hall Effect.

The pictures below both show a current toward the right. In one case, it consists of positive particles going right; in the other, negative particles going left. $\vec{F} = q\,\vec{v} \times \vec{B}$ says that either kind of particle is pushed toward the top of the sample by the magnetic force. So, if positive particles are flowing through it, the top gets charged positive, but if the particles are negative, the top is negative.

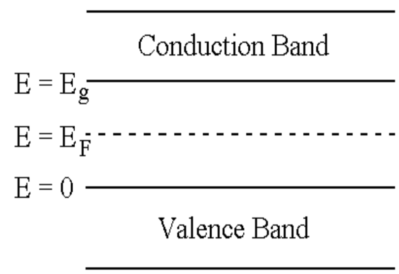


There is only one setup, which each group needs for just a minute or two. A sample of n-germanium and a sample of p-germanium are connected in series with 25 or 30 mA flowing through them from left to right, as in the diagram. Each has a voltmeter reading the potential difference between the top and bottom. Notice that the positive lead from each voltmeter goes to the top of the crystal, so the sign of the Hall voltage will be the same as the sign of the charge carriers. Bring the north end of a bar magnet near one then the other. What is the result?

Part 2. Energy Gap.

Theory. As a diode's temperature increases, more electrons have enough thermal energy to cross into the conduction band, so the number of free electrons per unit volume, n, increases. It was stated in class that

$$n = \int_0^\infty \frac{CE^{1/2}dE}{e^{(E-E_F)/kT}+1}$$



where C is a collection of constants. This was for a metal, where the valence and conduction bands are the same thing, and E = 0 is at the bottom of that band. For a semiconductor, the situation is as shown and the expression changes to

$$n = \int_{E_g}^\infty \frac{C(E-E_g)^{1/2}dE}{e^{(E-E_F)/kT}+1}$$

Saying $u = (E-E_g)/kT$ makes this into $n = \frac{C(kT)^{3/2}}{e^{(E_g-E_F)/kT}} \int_{u=0}^\infty \frac{u^{1/2}du}{e^u}$. The integral equals some constant. The $T^{3/2}$ is almost a constant compared to the exponential below it, if we stay in a fairly small range of temperatures. In a semiconductor, E_F is about ½E_g so $E_g - E_F$ = ½E_g. So,

$$n = (\text{a constant})\ e^{-Eg/2kT}$$

The current, I, is proportional to n; the charge per unit time flowing past some point is proportional to the number of charges that are free to flow.

This assumes an undoped semiconductor. Doping moves the Fermi level so $E_F \neq$ ½E_g. That changes the 2 in the exponent to a number we will represent by the Greek letter eta: $e^{-Eg/\eta kT}$. Otherwise, a diode acts a lot like an undoped semiconductor if you apply a voltage in the direction which removes the electrons and holes that come from the impurity atoms ("reverse bias"). But with a reverse bias, the current is too small for us to measure. With a forward bias, current increases with voltage as follows. (Search for "Shockley diode equation" if interested.)

$$I = I_0\left(e^{\frac{qV}{\eta kT}} - 1\right)$$

I_0 is the reverse bias current, which was just said to be proportional to $e^{-Eg/\eta kT}$. The 1 is small compared to the exponential. Let's just drop it.

$$I = A\left(e^{-\frac{E_g}{\eta kT}}\right)\left(e^{\frac{qV}{\eta kT}}\right)$$ where A and η depend on the particular diode.

Take the log of both sides: $\ln I = \ln A - \frac{E_g}{\eta kT} + \frac{qV}{\eta kT}$. If we work in electron-volts, q, the charge of an electron, is 1. Filling this in and rearranging:

$$\underbrace{(\ln I - \ln A)(\eta k}_{\text{call this a}}T) = -E_g + (1)V$$

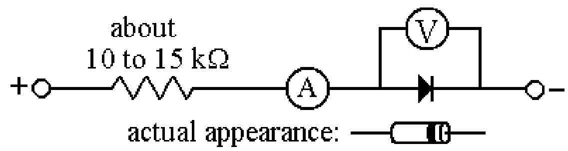
Divide by a: $\underbrace{T}_{y} = \underbrace{\left(\frac{1}{a}\right)}_{m}\underbrace{V}_{x} - \underbrace{\frac{E_g}{a}}_{b}$

So, if you keep a constant current through a diode and graph its temperature versus the voltage across it, the negative of its y intercept divided by its slope (which is also negative) equals E_g for the material it is made of.

To summarize: If the temperature of a diode increases, its resistance decreases, because more electrons jump into the conduction band when there is more thermal energy to kick them across the gap. A narrower, easier to cross gap means a smaller, faster changing resistance. The resistance and its rate of change determine the intercept and slope of the T vs. V graph, so these things are related to E_g. (From V = IR and the fact I is constant, V behaves like R.) Other factors affect the resistance too. Calculating the ratio of the intercept and slope cancels out the other factors and gives us E_g.

<u>Procedure.</u>

1. Connect the diode (1N34A), two meters and a resistor to a power supply as shown. One meter should be set to a scale appropriate for a few hundred microamps, the other for a few tenths of a volt. The diode will go in a beaker on a hotplate, so the wires need to be long enough to reach.



2. Put about an inch of water in the beaker. Put the beaker on the hotplate and submerge the diode. (Demineralized water would be better because of its lower conductivity, but tap water seems to work well enough.) Put a thermometer in the water.

3. Turn on the power supply and set it for 800 μA. You will need to make small adjustments during the experiment to keep this constant. Record the voltage and temperature.

4. Turn on the hotplate. The temperature will rise slowly at first, but then faster. We want the contents of the beaker at a fairly uniform temperature, so don't let it rise too fast. After the first couple of data points, turn the hotplate down to midrange or a little higher. Record the temperature and voltage at 5° intervals through 60°C. Remember to maintain 800 μA.

5. Plot the data with <u>absolute</u> temperature on the vertical axis and voltage on the horizontal axis. If you do it by hand, take the T axis to at least 600K so the intercept will show. To do it on Excel, refer back to lab 6B (Photoelectric Effect) for instructions.

6. Divide the negative of the intercept by the slope to obtain E_g.

7. The accepted value of E_g for Ge is 0.67 eV. In addition to the usual measurement uncertainties, the approximations mentioned earlier and conduction through the water affect your results. You should expect to be off by 10 or 15%. Comment on how close you came.

In your discussion, include a brief explanation of

- Why the sign of the Hall voltage tells you the sign of the charge carriers.
- Why the resistance and the rate it changes, corresponding to the y intercept and slope of the graph, are related to E_g.

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Part 1.

n - type: Were charge carriers positive or negative?

p - type: Were charge carriers positive or negative?

Part 2.

T (°C)	V (mV)	T (K)

Find Eg. (Attach graph or show it to instructor on computer screen.)