Simple measurement of the band gap in silicon and germanium

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A simple experiment which measures the forbidden energy gap in silicon and germanium is described. The procedure utilizes a *p-n* junction, and thus illustrates much of the physics connected with semiconductors and this basic electronic device. The results are accurate to within 2% and are consistent with more precise determinations of the band gap.

INTRODUCTION

The existence of bands in the distribution of energy of the electrons in a solid is an important concept in the undergraduate curriculum. Not only is a sound introduction into this band structure necessary for understanding semiconductor electronics, but the explanation of these energy bands is also an example of a quantum-mechanical phenomenon. In spite of this importance, undergraduate laboratories usually do not include an experiment which directly illustrates or measures these forbidden energy gaps.

This paper describes a simple undergraduate experiment which accurately measures the energy gap in silicon or germanium. Since the experiment utilizes a *p-n* junction, it has the additional benefit of illustrating the physics necessary for a thorough understanding of this important semiconductor device. The experiment can be designed for completion in a regular afternoon laboratory session, or can be made appropriate for an advanced laboratory by performing the measurements at many temperatures.

THEORY

The current I through a *p-n* junction is strongly dependent on the polarity of the applied potential difference V. In one direction, the current increases exponentially with voltage, while in the other direction the current approaches a very small value with increasing applied voltage. This dependence is given by the diode or rectifier equation, which is derived in solid-state[1] and electronics[2] textbooks,

$$I = I_0(e^{qV/(kT)} - 1). \quad (1)$$

I_0 is the maximum current for a large reverse bias voltage, q is the charge of the electron, k is Boltzmann's constant, and T is the temperature in K.

Equation (1) follows from the realization that there are two opposite currents through the junction. One current is due to majority carriers which must overcome the electric field of the thin depletion zone at the junction. Since the applied potential difference creates a field which either adds to or subtracts from this depletion-zone field, this current is highly voltage dependent and is large for forward bias and small for reverse bias. The other current is due to minority carriers which are accelerated across the junction by the electric field in the depletion zone. As long as V is not too large in the forward direction, this current depends only on the number of minority carriers in the conduction band and the rate at which they diffuse to the junction. Since the electric field simply accelerates them across the junction, this current does not depend on V. For large forward voltages, this current is reduced, but under these circumstances the current due to majority carriers is so large that the minority current is negligible anyway.

Since the energy gap E_g is 1.12 eV in silicon and about 0.68 eV in germanium, room-temperature thermal energy (kT about 0.025 eV) is not sufficient to excite many electrons from the valence band to the conduction band where they can act as charge carriers. The number of minority carriers (electrons in *p*-type material and holes in *n*-type material) is therefore small and is roughly proportional to the Boltzmann factor $e^{-Eg/(kT)}$. It is this fact, namely that the number of minority carriers strongly depends on E_g and T, which is the crucial element of this experiment.

In a slightly more advanced treatment involving Fermi-Dirac statistics and the concept of the density of states,[3] it can be shown that the number of minority carriers present is actually proportional to $T^{3/2}\, e^{-Eg/(kT)}$. Thus I_0 depends on this factor and also a temperature factor due to diffusion. For the range of temperatures used in this experiment (200–300 K), the $T^{3/2}$ dependence and the diffusion temperature dependence are completely negligible compared to the exponential dependence. I_0 should therefore be proportional to $e^{-Eg/(kT)}$ alone. If I_0 can be measured at several different temperatures, a graph of $\ln(I_0)$ vs $1/T$ should have a slope of $-E_g/k$. From the slope the energy gap can be determined.

PROCEDURE

The *p-n* junction used in the experiment was the base-emitter junction of either the silicon 2N3645 transistor or the germanium 2N407 transistor. A simple circuit which measured the current through the junction as a function of the potential difference across the junction was set up using a 1.5-V cell, a ten-turn 100-Ω potentiometer to divide this voltage, and a 1-Ω resistor in series with the junction. The potential difference across the junction was measured by a Fluke 845A high impedance voltmeter and the current was calculated from the voltage drop across the series resistor as measured by a Keithley 148 Nanovoltmeter. Instrumentation of this caliber is not essential to the experiment. Any high impedance voltmeter can be used to measure the potential difference across the junction, while a voltmeter with a lower input impedance is satisfactory for the current measurement. As shown in Fig. 1, the transistor with voltage and current leads was placed in a test tube containing thermal compound.[4] Also embedded in the thermal compound was a toluol thermometer[5] to measure the temperature of the junction. The test tube was then

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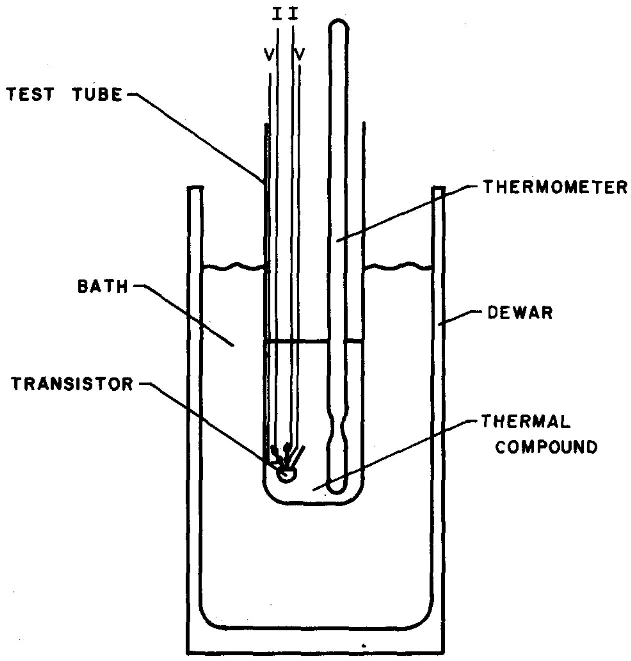

Fig. 1. Experimental arrangement. Current and voltage leads are connected to the base-emitter junction of the transistor. See Ref. 4 for a description of thermal compound.

placed in an open neck dewar containing the temperature bath.

Five temperature baths were used: (1) room temperature water; (2) a water-ice mixture; (3) a mixture of solid and liquid carbon tetrachloride; (4) a frozen 50-50 mixture of ethylene glycol and water; and (5) a mixture of dry ice and acetone. At each temperature the voltage-current relationship was recorded for currents ranging from 1 μA to 1 mA. This large range of current was not a necessary part of the experiment, but was used to see if Eq. (1) was valid over such a wide range.

RESULTS

The current-voltage measurements with the silicon *p-n* junction are shown in Fig. 2. Notice the exponential dependence, with the "turn-on" voltage being inversely proportional to the temperature. This is exactly what the diode equation predicts.

If voltages which make $e^{qV/(kT)}$ much greater than one are considered, then $I = I_0 e^{qV/(kT)}$. A graph of $\ln(I)$ vs V should be a straight line with slope $q/(kT)$ and $\ln(I)$ intercept equal to $\ln(I_0)$. These graphs are shown in Fig. 3, where the temperature dependence of the slope is evident along with the strong effect of temperature on I_0. This analysis is very similar to the procedure used by Kammer and Ludington in their measurements on silicon solar cells.[6]

As previously explained, a graph of $\ln(I_0)$ vs $1/T$ should have a slope of $-E_g/k$. The values for $\ln(I_0)$ were obtained from Fig. 3 using a least-squares fit to a straight line. The resulting intercept values are plotted against $1/T$ in Fig. 4. Notice how small the values for I_0 are in silicon. This is due to the small number of electrons which have enough energy to jump across the gap to the conduction band. The result obtained for the band gap in silicon from a least-squares linear fit to the data in Fig. 4 is 1.13 ± 0.02 eV. The actual value for the energy gap is slightly temperature dependent and for this temperature range varies from 1.11 to 1.13 eV.[7]

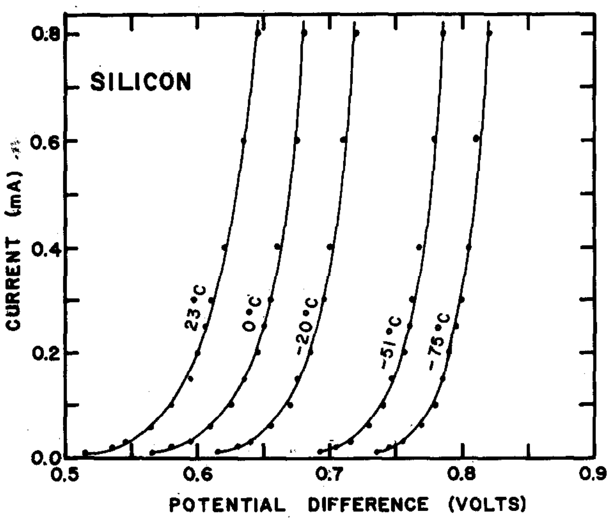

Fig. 2. Current vs voltage for a silicon *p-n* junction. Temperature baths are described in the text. The solid lines have been drawn to aid the eye.

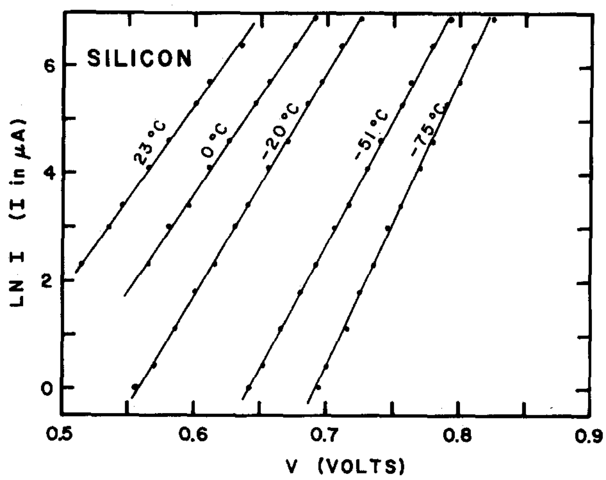

Fig. 3. Semilogarithmic plot of current vs voltage for a silicon *p-n* junction. The solid lines represent linear least-squares fits.

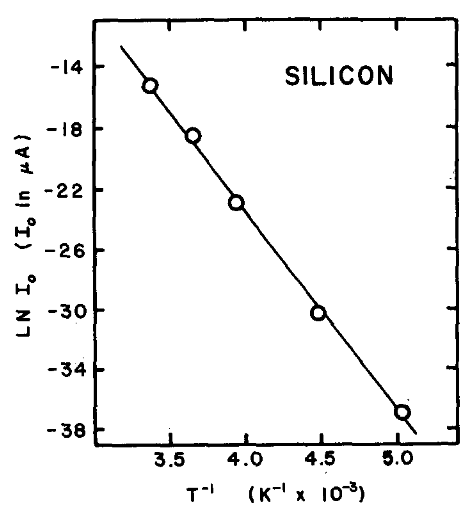

Fig. 4. Semilogarithmic plot of the minority carrier current vs inverse temperature for a silicon *p-n* junction. The solid line is the least-squares fit to a straight line.

A similar experiment was performed for germanium. The only difference was that the approximation $e^{qV/(kT)} \gg 1$ was not always valid. Therefore sometimes $\ln(I)$ was plotted against $\ln(e^{qV/(kT)} - 1)$. The I_0 values in germanium turn out to be much larger than the silicon values, due to the larger fraction of electrons which can be thermally excited across the smaller energy gap. The same analysis applies and gives a value for the band gap in germanium of 0.648 $\pm$ 0.013 eV, as compared to an accepted range of 0.660–0.698 eV.[7]

DISCUSSION

The results show that an accurate measurement of the energy gap in silicon and germanium is a very feasible undergraduate experiment. The additional benefit is that the physics of *p-n* junctions and semiconductor band structure is nicely illustrated. The experiment reported here took a few days to perform due to the preparation of the various temperature baths. An afternoon experiment could easily be developed using two or three of the most readily available temperature baths.

It is possible to determine the energy gap of silicon and germanium by measuring the resistivity of the pure semiconductor as a function of temperature.[8] The experiment described here has two features which make it more appropriate to the undergraduate curriculum than the resistivity measurement. First, the materials used here are more readily available and second, the necessity for the undergraduate to understand the *p-n* junction is pedagogically important.

ACKNOWLEDGMENT

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[1]C. Kittel, *Introduction to Solid State Physics*, 4th ed. (Wiley, New York, 1971), p. 388.

[2]R. E. Simpson, *Introductory Electronics for Scientists and Engineers* (Allyn and Bacon, Boston, 1974), p. 139.

[3]For example, see Ref. 2, p. 120.

[4]Thermal compound is an electrically insulating but highly thermal conducting silicone based paste. It is used to heat sink power transistors and is available at electronic supply outlets.

[5]Available from Sargent-Welch, 7300 North Lindner Avenue, Skokie, IL 60076. Catalog number S-80125.

[6]D. W. Kammer and M. A. Ludington, Am. J. Phys. **45**, 602 (1977).

[7]J. S. Blakemore, *Solid State Physics*, 2nd ed. (Saunders, Philadelphia, 1974), p. 306.

[8]P. Liebenauer, *Laboratory Manual for College Physics* (Collegiate, Columbus, 1978), p. 107.