The Band Gap of Silicon

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Abstract

This experiment was designed to find the band gap of silicon as well as the charge of an electron. A transistor was heated to various temperatures using a hot plate. The resistance was measured over the resistor and transistor in the circuit. In performing this experiment, it was found that the band gap of silicon was (1.10 ± 0.08) eV. In performing this experiment, it was also found that the charge of an electron was (1.77 ± 0.20) × 10^{-19} C.

Introduction

When a substance is placed under the influence of an electric field, it can portray insulating, semi-conducting, semi-metallic, or metallic properties. Every crystalline structure has electrons that occupy energy bands. In a semiconductor, there is a gap in energy between valence band and the bottom of the conduction band. There are no allowed energy states for the electron within the energy gap. At absolute zero, all the electrons have energies within the valence band and the material it is insulating. As the temperature increases electrons gain enough energy to occupy the energy levels in the conduction band. The current through a transistor is given by the equation,

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

where I_0 is the maximum current for a large reverse bias voltage, q is the charge of the electron, k is the Boltzmann constant, and T is the temperature in Kelvin. As long as V is not too large, the current depends only on the number of minority carriers in the conduction band and the rate at which they diffuse. In this experiment, the band gap of silicon was measured and compared with the value measured by precision optical methods. At room temperature, the thermal energy, kT, is approximately 0.025 eV, which is minute compared to the band gap. The number of minority carriers is also small and is expressed as

$$N_m \propto e^{-E_g/2kT} \tag{2}$$

where E_g is the gap energy. A more precise value for the number of minority carriers is

$$N_m \propto T^{3/2} e^{-E_g/2kT} \tag{3}$$

However, for the range of temperatures used in this experiment, equation (2) is sufficient since the $T^{3/2}$ dependence is negligible. Therefore, I_0 should only be proportional to N_m, and the Boltzmann factor on the right hand side of equation (2). The accepted value for the band gap of silicon is 1.12 eV It is also possible to find the charge of the electron, the accepted value for the charge of the electron is 1.60×10^{-19} C.

Experimental Procedures

Initially some simple circuits were set up to see how diodes reacted in a circuit. A light emitting diode (LED) was connected to a 2.5 V power supply. When the circuit was completed, the LED turned on, however, when LED's leads was reversed, the LED did not turn on. Figure 1 shows what occurs when the LED is in the circuit correctly, and figure 2 shows what occurs when the LED is in the circuit backwards.

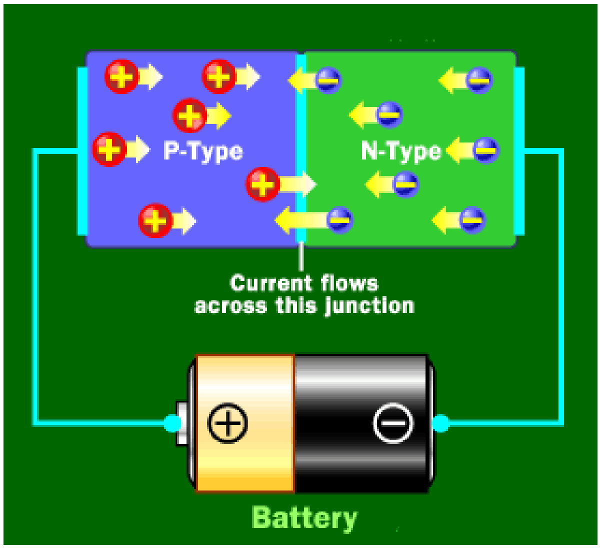

Fig. 1. When the diode is connected correctly in a circuit, the bad gap disappears, and charge moves across the diode.[1]

[1] taken from http://www.howstuffworks.com/led1.htm

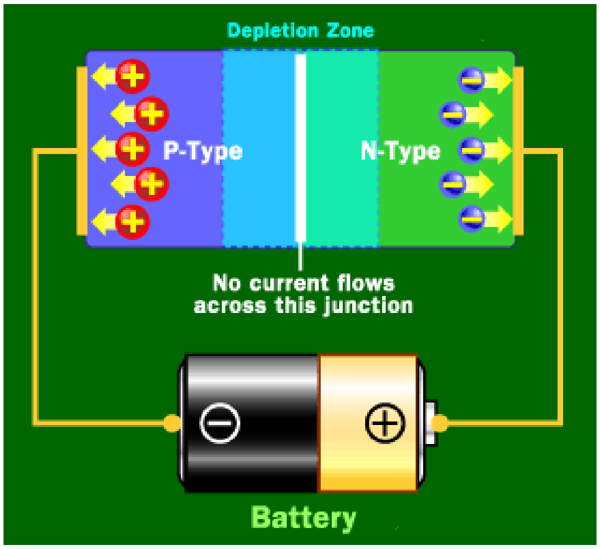

Fig. 2. When the diode is connected incorrectly in the circuit, the band gap increases.[2]

A circuit was set up with two light emitting diodes (LEDs) with a dual throw double pole switch. Figure 3 show the diagram of this circuit.

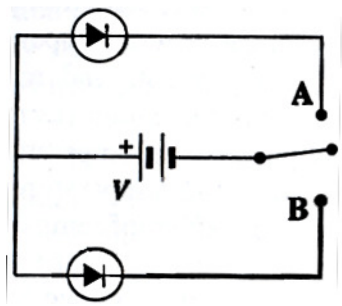

Fig. 3. Circuit with 2 LEDs and a dual throw double pole switch

When the switch is turned to A, the top LED is lit and when the switch is turned to B, the bottom LED is lit. A circuit in this configuration might be used to in early traffic lights where there were only red and green lights. This circuit could also be used in a light source that has two brightness settings or multiple light bulbs. This circuit was then changed to have a diode in series with a

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[2] taken from http://www.howstuffworks.com/led1.htm

150 Ω resistor and in parallel with a 1500 Ω resistor. Figure 4 shows the graph of the input voltage versus the voltage measured parallel to the diode.

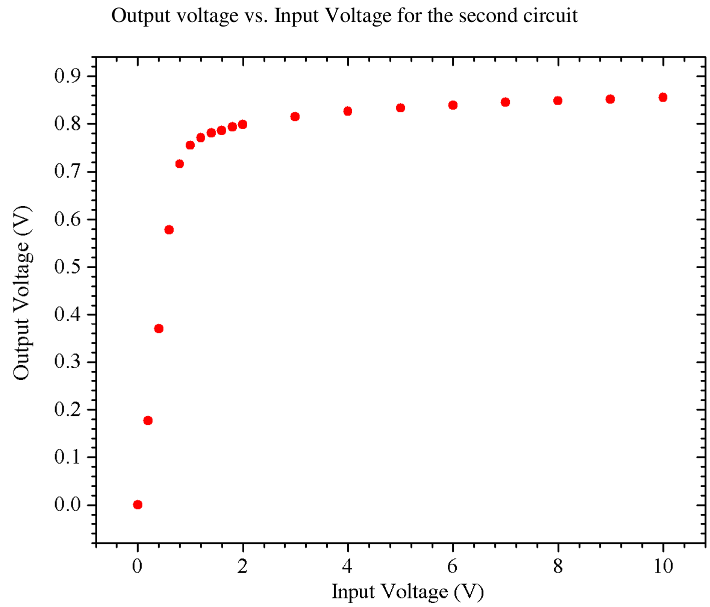

Fig. 4. Output voltage vs. input voltage for the second circuit

Notice that it appears that the graph rises quickly and then levels off after it reaches 0.8 V. This type of circuit could be used as a voltage limiter that would cut off the voltage after a certain voltage is reached. This would be useful in making toys and games last longer on batteries if they do not need the full 1.5 or 3.0 V. Figure 5 sows this circuit.

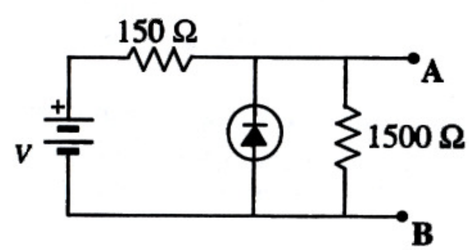

Fig. 5. Circuit with 150 Ω and 1500 Ω and a diode

A prepared circuit was used that contained an n-p-n transistor (Motorola MPS2222A). The transistor is connected in series with a 1 Ω resistor and a DC power supply that outputted 3.0 volts. The voltage across the transistor and the resistor was measured with two voltmeters. The transistor was placed on a hotplate and a glass enclose was placed over the transit. A thermocouple was placed in close proximity to the transistor to measure its temperature. Figure 6 shows the diagram of the circuit.

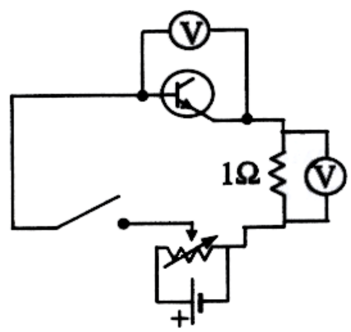

Fig. 6. Circuit used o find the band gap of silicon

In order to analyze the data, one must consider that the diode does not follow equation (1) precisely; it can be approximated by,

$$I = I_0\left(e^{qV/2kT} - 1\right) \approx I_0 e^{qV/2kT} \tag{4}$$

this approximation is possible because the term *qV/2kT* is much greater than 1. The data followed a curve defined by $y = A\,x^n$, where *A* and *n* are real numbers. Figure 1 shows the graph of current versus the voltage with a power law curve fit.

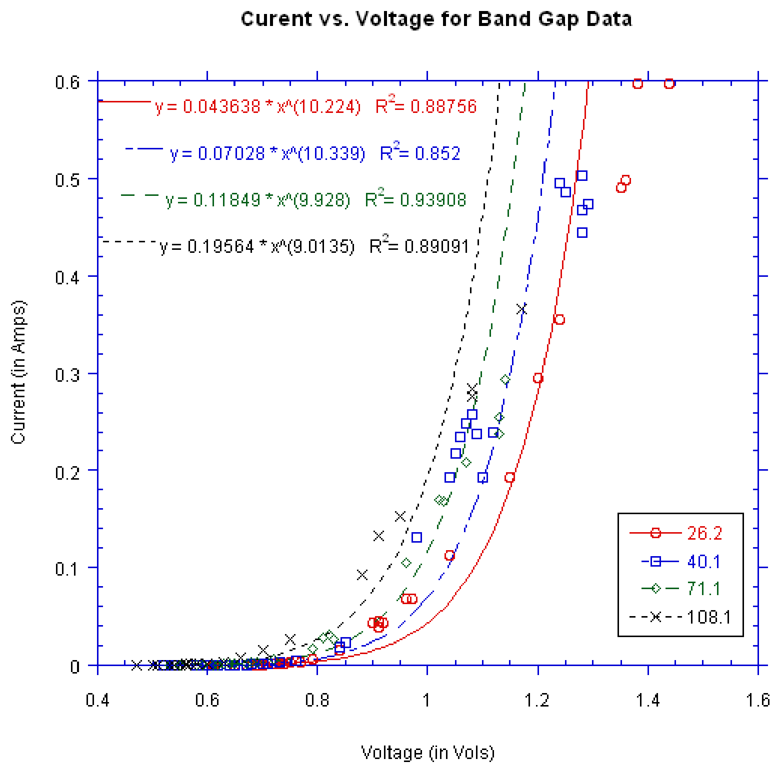

Fig. 7. Current vs. Voltage for band gap data

Using the data gathered during the experiment, a graph of the natural log of the current versus the voltage shows the value of *q/2kT*. From this, the value for the charge of the electron can be found. Figure 5 shows the graph of this with a linear curve fit.

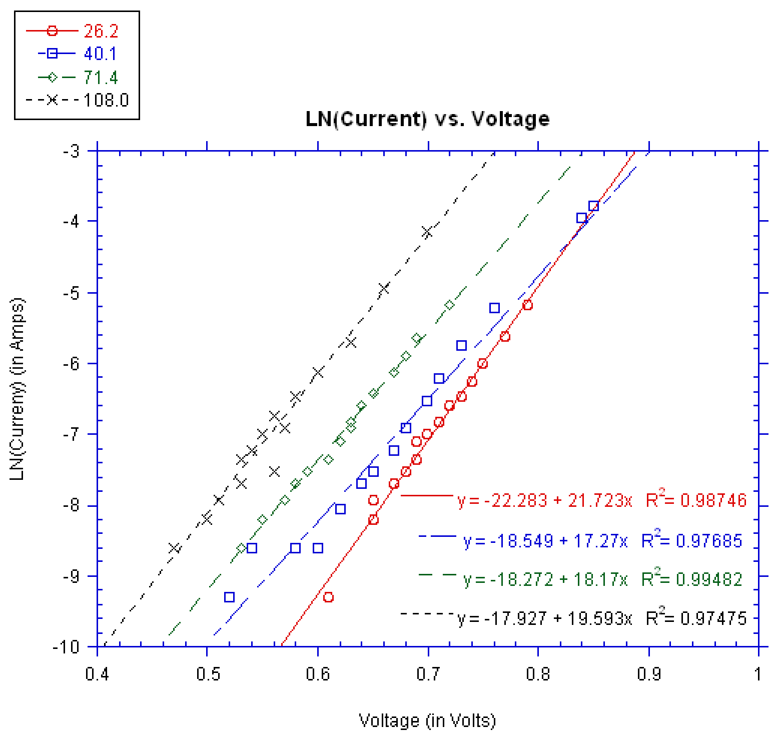

Fig. 8. Natural log of current versus voltage for the four temperatures

Table 1 shows calculation steps in finding the charge the electron. First, the temperature was converted to the Kelvin scale. Then the slope from figure 5 was multiplied by the temperature in Kelvin. This result was multiplied by twice the Boltzmann constant,

$$2k_B = 2\times1.38\times10^{-23}\ \mathrm{m^2\,kg\,s^{-2}\,K^{-1}} \tag{5}$$

thus resulting in the charge of the electron. The mean value for the charge of an electron was 1.77×10^{-19} C. This value has a percent error of 10.6%. The standard deviation of the values for the charge of the electron is 2.03×10^{-20} C. Therefore, the value for the charge of the electron can be most accurately stated as $(1.77 \pm 0.20) \times 10^{-19}$ C.

deg. C	deg. K	q/2kT	q/2k	q	% Error
26.2	299.4	21.7	6.50×10^{3}	1.80×10^{-19}	12.2%
40.1	313.2	17.3	5.41×10^{3}	1.49×10^{-19}	6.6%
71.1	344.3	18.	6.26×10^{3}	1.73×10^{-19}	8.0%
108.1	381.3	19.6	7.47×10^{3}	2.06×10^{-19}	28.9%
			mean	1.77×10^{-19}	10.6%

Table 1. Calculating the charge of the electron

A similar method can be used to find the band gap of silicon. The graph from figure 5 is used again, only this tine the y-intercepts are used. The y-intercepts of this graph are equal to I_0 in equation (4). As long as the voltage is small, the current depends only on the number of minority carriers in the conduction band and the rate at which they diffuse. The number of minority carriers is proportional to the band gap according to equation (2). Table 2 shows calculation steps in finding the band gap of silicon. First, the temperature was converted to the Kelvin scale. Then the absolute value of the y-intercept from figure 5 is multiplied by the temperature in Kelvin. This result was multiplied by twice the Boltzmann constant,

$$2k_B = 2\times8.617\times10^{-5}\ \mathrm{eV\ K^{-1}} \tag{6}$$

thus resulting in the band gap of silicon. The mean value for the band gap of silicon was 1.10 eV. This value has a percent error of 1.5%.

deg. C	deg. K	E/2kT	E/2k	Band Gap	% Error
26.2	299.4	–22.3	6.67×10^3	1.15	2.6%
40.1	313.2	–18.5	5.81×10^3	1.00	10.6%
71.1	344.3	–18.3	6.29×10^3	1.08	3.2%
108.1	381.3	–17.9	6.84×10^3	1.18	5.2%
			mean	1.10	1.5%

Table 2. Calculating the band gap of silicon

The standard deviation of the values for the charge of the electron is 0.08 eV. Therefore, the value for the charge of the electron can be most accurately stated as (1.10 ± 0.08) eV.

There were several sources of error in this experiment. One source of error was the environmental factors. The temperature of the room fluctuated from day to day while performing this experiment. There was also the problem of the voltmeters and the thermocouple fluctuating rapidly when the transistor was heated for too long. The hotplate used in this experiment would give off a different temperature than was measured by the thermocouple. Moreover, the hotplate did not keep the transistor at a constant temperature. There was also hysteresis. It took the transistor several minutes to reach the desired temperature. It was difficult to determine if the apparatus had reached its equilibrium point, since even when it appeared to reach be at equilibrium, it would still fluctuated.

Conclusion

This experiment was designed to discover the band gap of by measuring the voltage and current through a circuit that had a transistor heated to various temperatures. In addition, the charge of the electron also can be determined from this experiment. The mean value for the charge of the electron was 1.77×10^{-19} C with a standard deviation of 2.0×10^{-20} C. This has a percent error of 10.6%. The band gap of silicon was calculated to be 1.110 eV with a standard deviation of 0.08 eV. This has a percent error of 1.5%. This experiment could be improved by making sure that the circuit worked properly or by replacing the components of the circuits. The transistor would be the most logical part to be replaced. Moreover, the thermocouple had a tendency to move away from the transistor and thus produce inaccurate results.

In the Millikan oil drop experiment, the charge of the electron was found to be 1.6×10^{-19} C. The percent difference between this value and the one found in performing the band gap experiment is 10.1%. In addition, in the electron charge to mass ratio lab, it was wound that the charge to mass ratio was 1.74×10^{11} C/kg. Using this ratio and charge of the electron found in the band gap lab, the mass of the electron is

$$\frac{1.77\times10^{-19}\text{C}}{m} = 1.74\times10^{11}\,{}^{\text{C}}\!/_{\text{kg}} \Rightarrow m = \frac{1.77\times10^{-19}\,\text{C}}{1.74\times10^{11}\,{}^{\text{C}}\!/_{\text{kg}}} = 1.02\times10^{-30}\,\text{kg}$$

This has a percent error of 12.0% with the accepted value of $9.10938188 \times 10^{-31}$ kg.