Determination of the Band-gap of Semiconductors

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ABSTRACT

This paper provides a method to determine the band-gap of semiconductors based upon the relation between temperature and forward voltage of diode. Silicon diode, germanium diode, and Al-Ga-As diode (red LED) is used in this experiment.
Keywords: Band-gap, forward voltage, diode

1. INTRODUCTION

The spotlight is on the method of determining the band gap energy of certain semiconductor, starting with a function of current as a function of temperature and potential difference, namely $I = I_0\left(e^{\frac{eV}{kT}} - 1\right)$. Several steps of derivation leads to a relationship between energy gap and temperature. In order to study the relation between these two, a current source is used in the circuit to hold the current through semiconductors constant. To create a change in temperature of the semiconductor, a device named 'cold finger' with semiconductor inserted inside is half submerged in liquid nitrogen and taken out. Thermocouple is used to measure the temperature the whole time. This method can be applied with operational amplifier as a constant current source and Arduino interface as a data collector. The data is output into a text file from Arduino.

2. MATHMETICAL EQUATIONS

According to Shockley diode equation [1] or diode law, we can express current through diode as:

$$I = I_0\left(e^{\frac{eV}{kT}} - 1\right) \tag{2.1}$$

Where I_0 is the saturation current, e is the elementary charge, V is the voltage across the diode, k is Boltzmann constant, and T is the temperature in Kelvin. When temperature is low, the exponential part gets large, and we can approximate Equation (2.1) as:

$$I = I_0 e^{\frac{eV}{kT}} \tag{2.2}$$

Saturation current in the equation can be further expressed as:

$$I_0 = AT^{(3+\frac{\gamma}{2})} e^{\frac{Eg(T)}{kt}} \text{[2]} \tag{2.3}$$

A and γ are both constants, and Eg(T) is the minimum energy gap. Plug the equation of saturation current into Eq(2.2) and simplify, we get:

$$eV = kT(\ln\left(\frac{I}{A}\right) - (3 + \frac{\gamma}{2})ln(T)) \tag{2.4}$$

Energy gap as a function of temperature can be written as:

$$Ep(T) = E_0 - \frac{\alpha T^2}{T+\beta} \text{[3]} \tag{2.4}$$

Therefore, the band gap energy is:

$$eV = -E_0 + \frac{\alpha T^2}{T + \beta} + kT\ln\left(\frac{I}{A}\right) - (3 + \frac{\gamma}{2})ln(T)T \tag{2.5}$$

3. METHODOLOGY

3.1 Current Source

From Equation (2.5), the band gap is depend on current. Therefore, to obtain the relation between temperature and band gap energy, current through diode needs to be constant. Here is the current source used in this experiment:

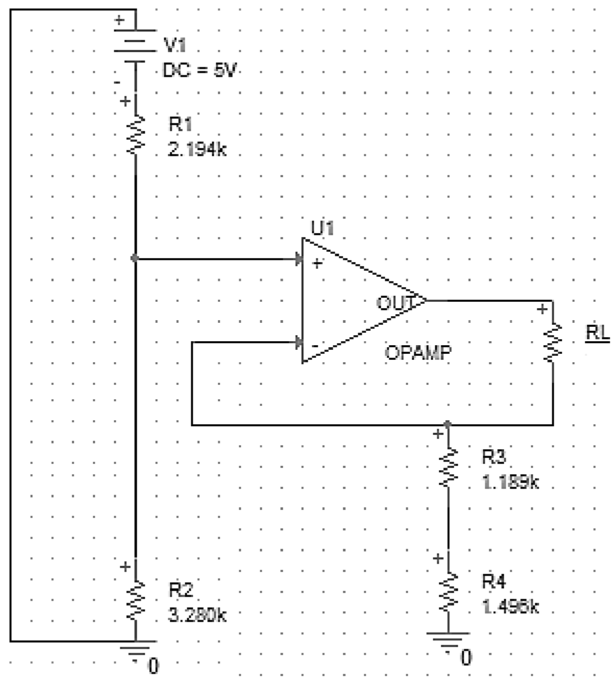

Figure 3.1 Current source.

With 5V dc power supply and a voltage divider, V_+ is set to be about 3V. V_+ is approximately equal to V_-, so V_- is equal to 3V, so do the potential difference across R_3 and R_4. (R_3 + R_4) is approximately 3kΩ, therefore the current through R_3, R_4 and RL is 1mA. During the actual experiment, R_L is changed to different diode.

3.1.1 Theoretical Value of Current Calculation

$$V_+ = V_- = \frac{V_{DC}R_2}{R_1 + R_2} = 5V \times \frac{3.280k\Omega}{2.194\text{k}\Omega + 3.280\text{k}\Omega} = 2.996V \quad (3.1)$$

$$I = \frac{V_-}{R_3 + R_4} = \frac{2.996V}{1.189k\Omega + 1.496\text{k}\Omega} = 1.116mA \quad (3.2)$$

3.1.2 Measured Value of Current

Current source is tested with different R_L. The result is shown below:

RL/Ω	15	22	33	47	51	67	100	150
V/V	2.9478	2.9477	2.9477	2.9477	2.9477	2.9477	2.9476	2.9477
I/mA	1.098	1.098	1.098	1.098	1.098	1.098	1.098	1.098
RL/Ω	200	220	270	330	470	500	560	1000
V/V	2.9476	2.9476	2.9476	2.9475	2.9475	2.9474	2.9474	2.9474
I/mA	1.098	1.098	1.098	1.098	1.098	1.098	1.098	1.098

Table 3.1

3.2 "Cold Finger"

In the experiment, we used a cold finger, a piece of experiment equipment that holds the electric components (Diodes and LED), and cool down these components via thermal conduction of heat when it is placed in liquid nitrogen. The Cold finger is made of copper for good its thermal conductivity. Several holes was drilled on the top surface for the placement of electric components and thermal couples. When cooling the components and measuring temperature of the cold finger, thermal grease was added into these holes for better thermal conductivity. There was also a tunnel through the cold finger, which allows a steel bar to be inserted so that its position is fixed when it is placed upon the container with liquid nitrogen.

Figure 3.2

3.3 Integrated Setup with Arduino

To combine all the setup to one piece, Arduino Mega 2560 board is used to collect both voltage across diode and temperature. A thermal couple is used to test the temperature of cold finger. Adafruit_MAX31855 amplifier is used to amplify the signal from thermal couple, and at same time act as a temperature reference. Potential at two ends of diode are read by two analogy input of Arduino board.

Here is the Arduino code for acquire, processing, and print out results:

```
#include <SPI.h>
#include "Adafruit_MAX31855.h"
#define MAXDO   3
#define MAXCS   4
#define MAXCLK  5

// initialize the Thermocouple
Adafruit_MAX31855 thermocouple(MAXCLK, MAXCS, MAXDO);

//#define MAXCS   10
//Adafruit_MAX31855 thermocouple(MAXCS);

void setup() {
  while (!Serial); // wait for Serial on Leonardo/Zero, etc

  Serial.begin(9600);

//  Serial.println("MAX31855 test");
  // wait for MAX chip to stabilize
  Serial.print("IntT");
  Serial.print("\t");
  Serial.print("T");
  Serial.print("\t");
  Serial.print("V1");
  Serial.print("\t");
  Serial.print("V2");
  Serial.print("\t");
  Serial.println("V");
  delay(500);
}

void loop() {

  //print the current temp
   Serial.print(thermocouple.readInternal());

   double c = thermocouple.readCelsius();
   if (isnan(c)) {
     Serial.println("Something wrong with thermocouple!");
   } else {
     Serial.print("\t");
     Serial.print(c);
     Serial.print("\t");
   }
//   delay(1000);

  //print the current votage across diode
  int V1 = analogRead(A0);
  float V1F = V1*(5.0/1023.0);
  int V2 = analogRead(A1);
  float V2F = V2*(5.0/1023.0);
  float V = V1F - V2F;

  Serial.print(V1F);
  Serial.print("\t");
  Serial.print(V2F);
  Serial.print("\t");
  Serial.println(V);
  delay(5000);
}
```

With software ‘CoolTerm’, data printed on serial monitor can be captured to a text file at same time during the measuring.

4. ANALYSIS

Data recorded by Arduino board are attached on appendix. Here are plots of band gap energy versus temperature of different diode:

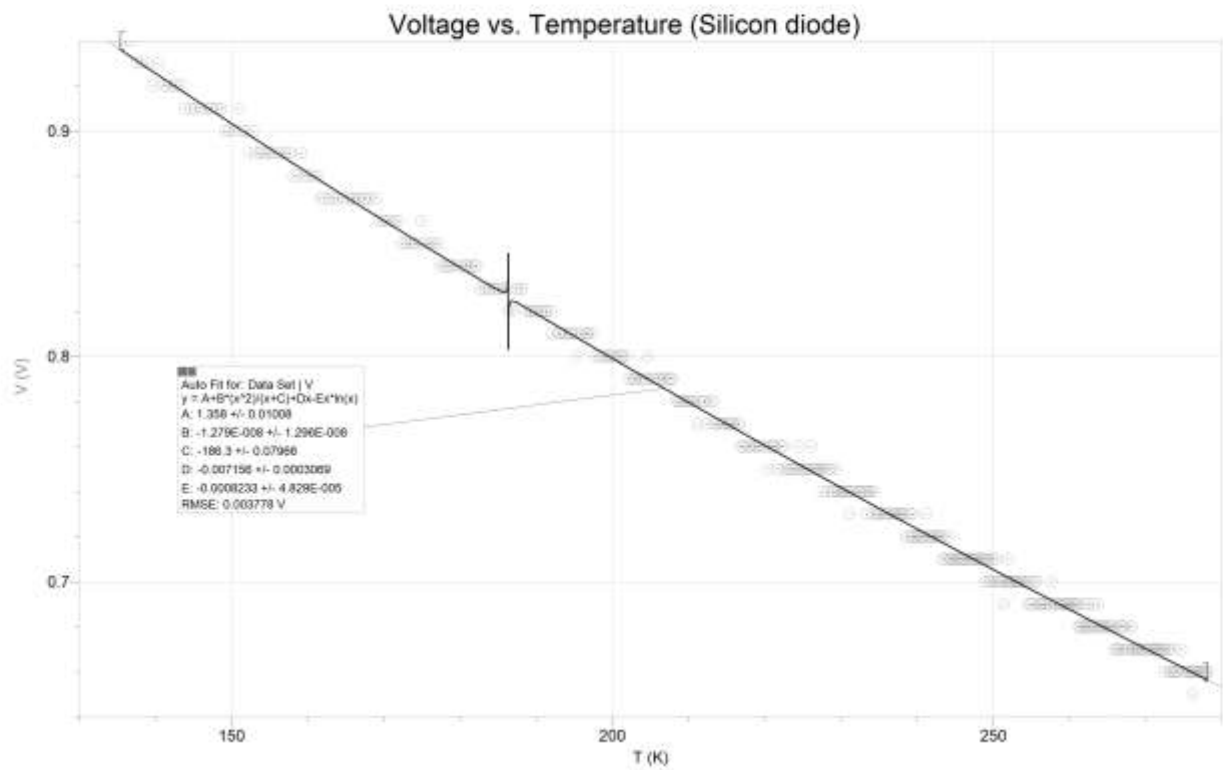

Figure 4.1

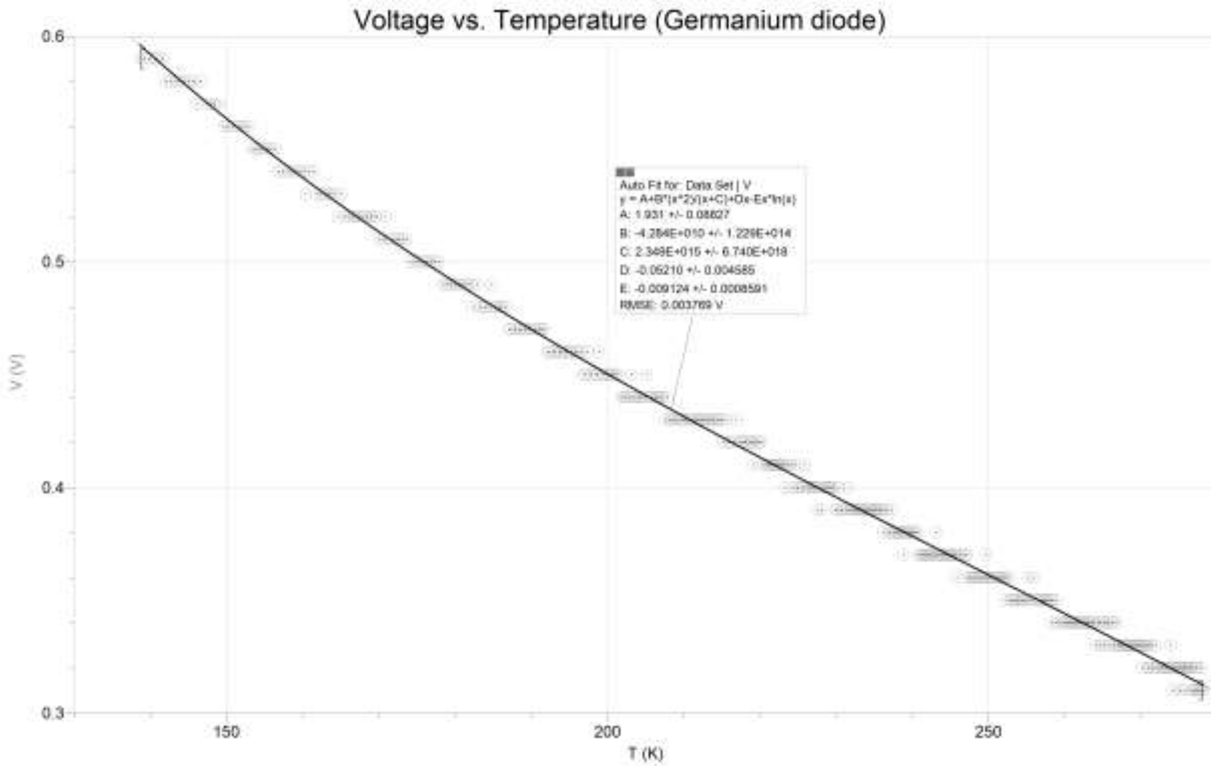

Figure 4.2

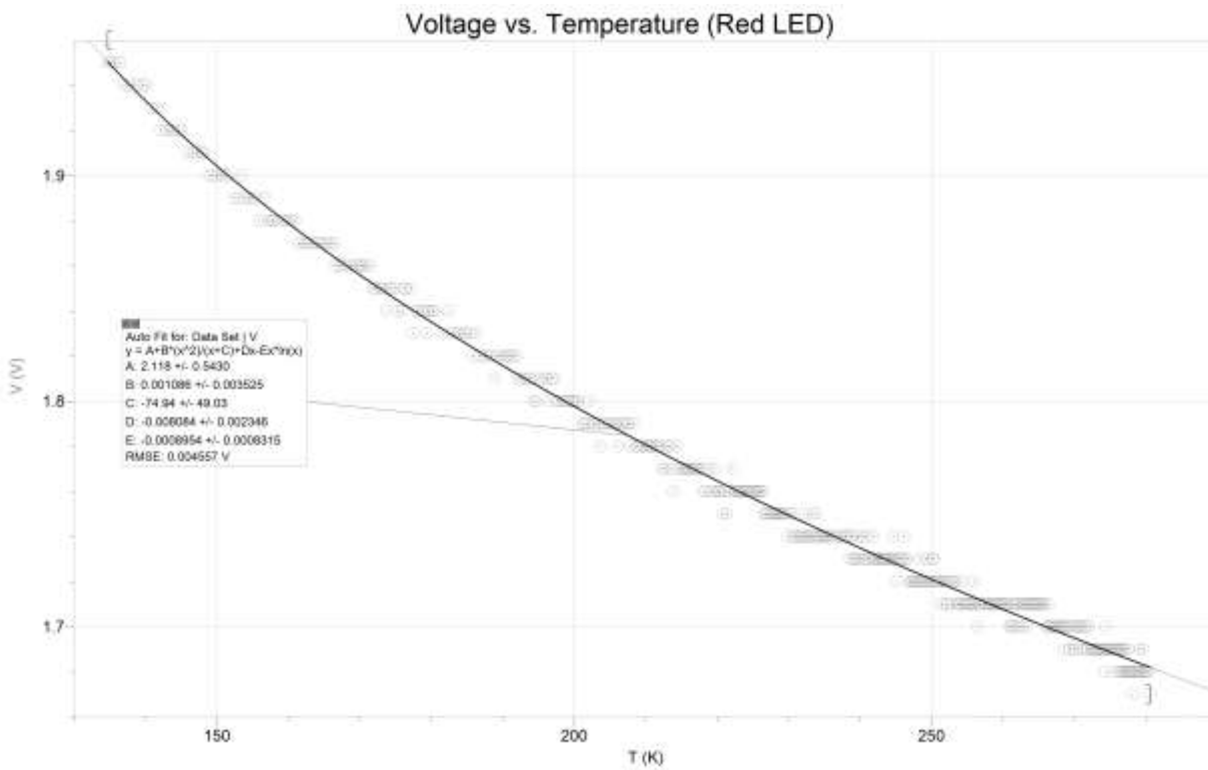

Figure 4.3

5. RESULTES

From plots, band gap energy and other constants in the equations for different diodes are listed below:

	E_0/eV	α/eVK^{-1}	β/K	γ	A/A
Si	1.358 ±0.010	-1.279E-8 ±1.3E-8	-186.3±0.08	-25.11	1.274E33
Ge	1.931±0.09	-4.284E10 ±1E14	2.349E15±7E18	-217.8	4.103E259
Red LED (Al-Ga-As)	2.118±0.5	1.086E10-3±3E10-3	-74.94±50	-26.78	6.056E37

Table 5.1

	Accepted value for energy gap at 0K/eV
Si	1.170±0.001
Ge	1.931±0.001
Red Led (Al-Ga-As)	1.424(pure GaAs) to 2.628(pure AlAs)

Table 5.2[4][5]

6. CONCLUSIONS

The value for the energy gaps of silicon and germanium are out of range comparing to the accepted value. The value for the energy gap of red LED (Al-Ga-As diode) falls within the range of accepted values. Low resolution of the voltage measurement is likely to be the source of error. Arduino is 10 bits, while the range of voltage measurement is 0V ~ 5V. The resolution of the equipment is therefore about 0.0049V. The equipment is not able to detect value change that is smaller than its resolution. As a result, there are multiple points in the graph with same voltage difference while they are at different temperature. These points make fitting the curve more difficult and less reliable.

REFERENCE

[1] Shockley W., "The Theory of p-n Junctions in Semiconductors and p-n Junction Transistors". The Bell System Technical Journal. 28 (3): 435–489 (1949).

[2] Kirkup L. and Placido F., “Undergraduate Experiment: Determination of the Band Gap in Germanium and Silicon”, American Association of Physics Teachers, 54(10), Oct 1986, 918-920 (1986).

[3] Van Zeghbroeck B. J., ‘Temperature Dependence of the Energy Bandgap’, http://ecee.colorado.edu/~bart/book/eband5.htm (1996).

[4] Thurmond C. D., J Electrochem, Soc. 122, 1133 (1975).

[5] Palankovski V., “Bandgap Energy”, http://www.iue.tuwien.ac.at/phd/palankovski/node37.html (2001).