Temperature Dependence of Diodes

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I. ABSTRACT

In this report, we demonstrate the use of current measurements across a range of temperatures as a method of calculating both E_{gap} and the material makeup of a given p-n junction diode. We analyzed the current running through a diode, as a function of the voltage across it, at varying temperatures to find I_s at each temperature, which we then used to calculate E_{gap}. We calculated the band gap energy of a silicon diode to be E_{gap}=1.22 ± 0.01 eV , a value not within range of the accepted value [1]. This could have been due to ignoring the temperature dependence of the band gap energy [2] which, in future experiments, can be included by using a more sophisticated model in the analysis.

II. INTRODUCTION

P-n junction diodes are one of the most universally present electrical components. They appear throughout digital and analog electronics, with applications varying from logic gates to clipping circuits. The objective of this experiment was to identify the material of a p-n junction diode. We did this by analyzing the current running through the diode, as a function of the voltage across it, at varying temperatures. This allows for the calculation of the characteristic band gap energy of the material. In this experiment, we used a silicon (Si) p-n junction diode and the calculated band gap energy was compared to the accepted values for Silicon(Si), Germanium(Ge), and Gallium Arsenide(GaAs),to determine if this method could accurately determine a diode's material.

We calculated the band gap energy of the diode to be E_{gap}=1.22 ± 0.01 eV. Between Si, Ge, and GaAs, the calculated value was closest to $E_{gap,Si} = 1.14eV$ [1], confirming the method's ability to identify a semiconductor. The calculated value was closest to Si, but it was still significantly outside of the calculated range.

III. THEORY

For any given material, the valence band is the electron energy range that is directly below the material's Fermi level, and the conduction band is the electron energy range that is directly above the material's Fermi level [3]. The difference in energy between these two gaps determines a material's conductivity. In metals, these two bands overlap, giving them a high conductivity. In semiconductors and insulators, this band gap is present, with semiconductors having a smaller gap than the insulator, which is illustrated in Fig. 1. The difference between these two bands is referred to as the band gap energy of the material, and varies between different elements. Si, Ge, and GaAs, three commonly used semiconductors in electronics, have band gap energies 1.14 eV, 0.67 eV, and 1.43 eV, respectively, at T=302K [1].

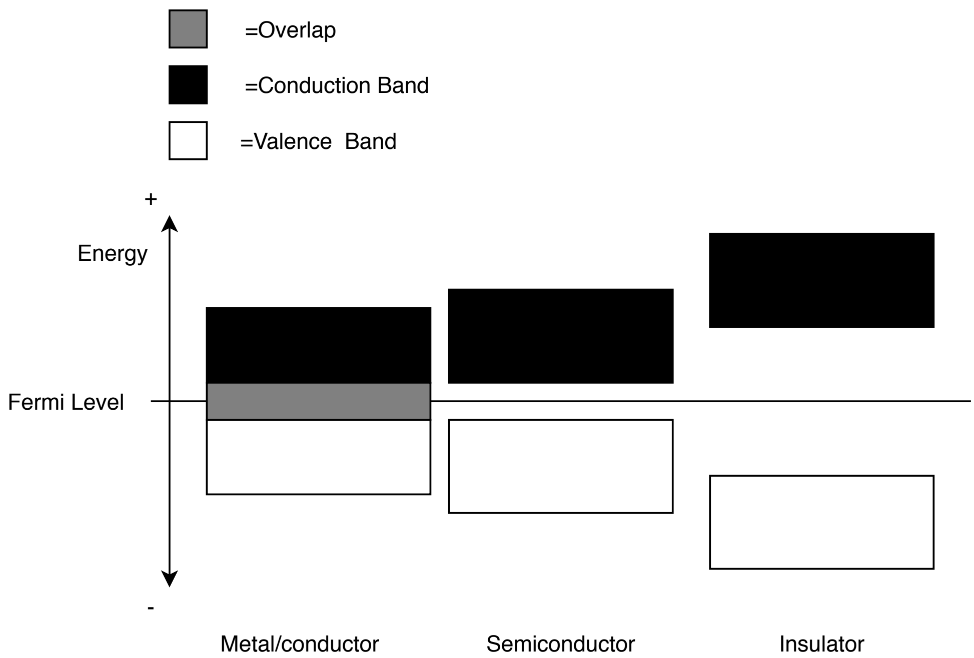

FIG. 1: Energy diagram showing band gaps for a typical conductor, semiconductor and insulator in relation to their Fermi level.

Since a semiconductor's valence and conduction bands do not overlap, current will flow differently through the material than it would through a metal. A typical conductor's current carriers are its free electrons, but a semiconductor's current carriers are the electrically positive electron holes or the electrically negative free electrons found in the material's conduction band.

In an undoped semiconductor, the thermal equilibrium of these electron holes and free electrons are equal, as an electron hole would mean that the electron moved into the conduction band and is now a free electron. By doping the semiconductor with particles that have more or less electrons, the semiconductor can be made to have more free electrons or more electron holes, while maintaining no electrical charge. A doped semiconductor that has an excess of electron holes is called a p-type semiconductor, and one with an excess of free electrons is called an n-type semiconductor.

The contact between a p-type and n-type semiconductor is called a p-n junction. In a p-n junction, the difference in concentrations of holes and free electrons causes an attraction between the p-type's holes and the n-type's free electrons. Near the junction of the two materials, this attraction is strong enough to cause the movement of free electrons from the n-type into the p-type's electron holes. Since the two materials were originally neutral, this jump now causes the region near the junction to become charged negatively on the p-type's side and positively on the n-type's side. This creates an electric field moving from the n-type towards the p-type. A diagram of this charge and it's resulting electric field is shown in Fig. 2.

As a result of this electric field, there is a small flow of electrons back to the p-type's holes. This creates a current density denoted by J_{nr} and referred to as the majority current. This process is called electron hole recombination, and is balanced out with thermal generation in the p-type's conduction band, which results in electrons being swept back to the n-type [4]. This creates a current density denoted by J_{ng} and referred to as the minority current. There is a similar process occurring with the current-carrying electron holes, and these majority and minority currents are denoted by J_{pr} and J_{pg}, respectively. The electrical current through the diode is the sum of J_{nr}, J_{ng}, J_{pr}, and J_{pg}.

When a p-n junction is used in a circuit, where potentials are possibly applied to either end of the system, it is referred to as a p-n junction diode. In the case of no applied voltage, the majority and minority currents directly cancel one another, resulting in no current through the diode. When a potential difference is applied so that the p-type receives a positive

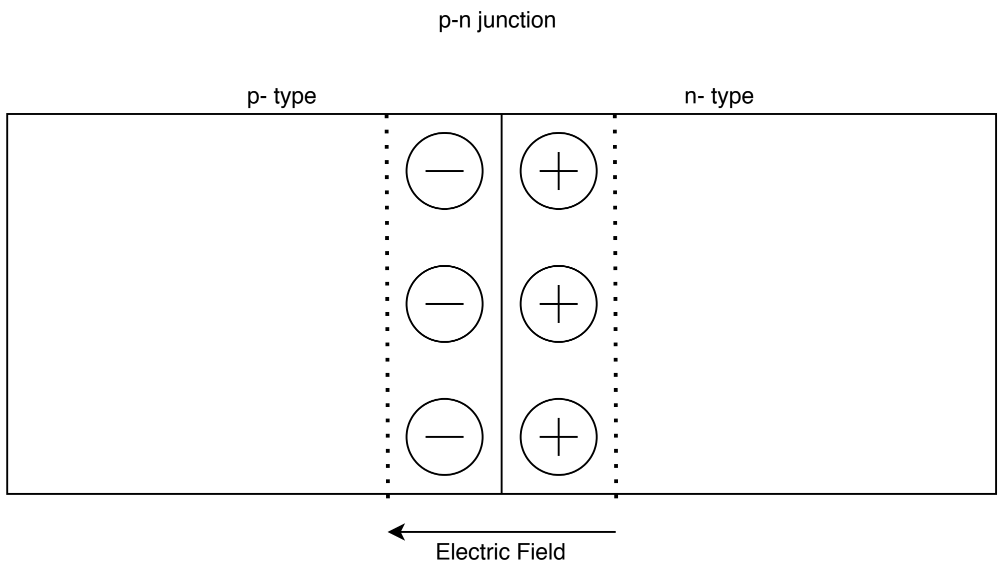

FIG. 2: Diagram of a p-n junction's charge. Near the junction, there is a negative charge on the p-type semiconductor, and a positive charge on the n-type semiconductor. This results in the electric field shown, pointing from the n-type to the p-type in the center region.

potential, and n-type receives a negative potential, the applied voltage reduces the potential difference across the junction caused by the electric field. This allows more electrons to move from the n-type toward the p-type, meaning a positive current flowing from p-type to n-type. This current, as a function of voltage difference is described by Eq. III.1 and Eq. III.2, where q is the fundamental charge, k_B is the Boltzmann constant, and T is the temperature of the system in Kelvin:

$$J_{pr} = J_{pg} e^{q|V|/k_B T} \tag{III.1}$$

$$J_{nr} = J_{ng} e^{q|V|/k_B T} \tag{III.2}$$

The sum of thermally generated minority currents, referred to as the saturation current, is denoted by I_s. The total current across the diode can then be described as:

$$I = I_s(e^{q|V|/k_B T} - 1) \tag{III.3}$$

I_s is a function of both the temperature, and the band gap energy of the material. This relationship, where E_{gap} is the band gap energy of the material, is expressed as:

$$I_s \propto e^{-E_{gap}/k_B T} \tag{III.4}$$

Which can be modified, using A as a stand-in variable, to now show:

$$I_s = Ae^{-E_{gap}/k_B T} \tag{III.5}$$

IV. EXPERIMENTAL SETUP AND MEASUREMENT

We depressurized a chamber containing a diode circuit with a vacuum pump, and controlled its temperature by use of a cold cycle refrigerator(CCR), and a heating element. This setup was able to accurately maintain temperatures as low as T=7 K. The diode was in a vacuum to protect it from condensation throughout the experiment. We connected a multi meter in series to measure the current across the diode, and connected the circuit to a DC power supply. An interface, referred to as the diode interface board, was used to automate the DC source. The experimental setup is shown in Fig. 3.

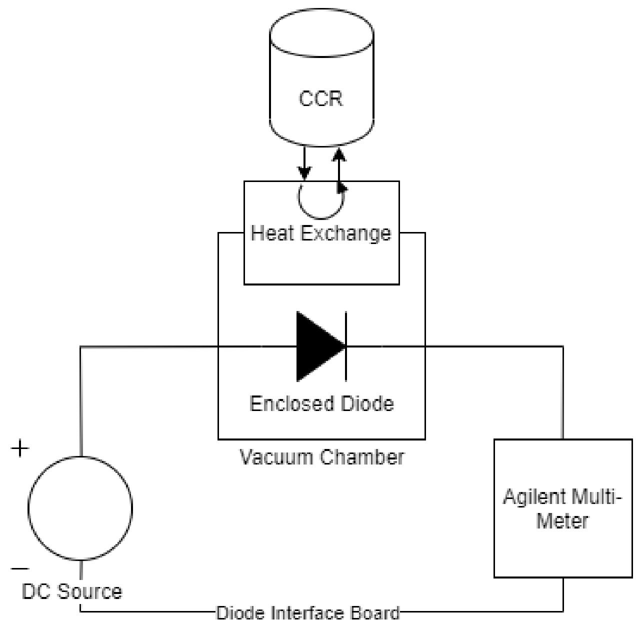

FIG. 3: Experimental setup with diode enclosed in vacuum chamber.

While maintaining T≈300 K, we measured the current as voltage increased from 0 V by 0.05 V steps, until current began to flow through the circuit. When current was detected, the steps were then decreased. We then repeated this as we decreased the temperature to 10 K by 10 K steps.

V. DATA AND ANALYSIS

Starting at T=300K, we recorded the current through the diode as we varied the applied voltage. Fig. 4 shows these measurements for T=300.01 K, 199.71 K, 100.04 K and 39.84 K. The data show exponential growth in the current as a function of applied voltage. Lower temperatures required a larger voltage to produce current but when compared to the diode at high temperatures, the current grew more abruptly.

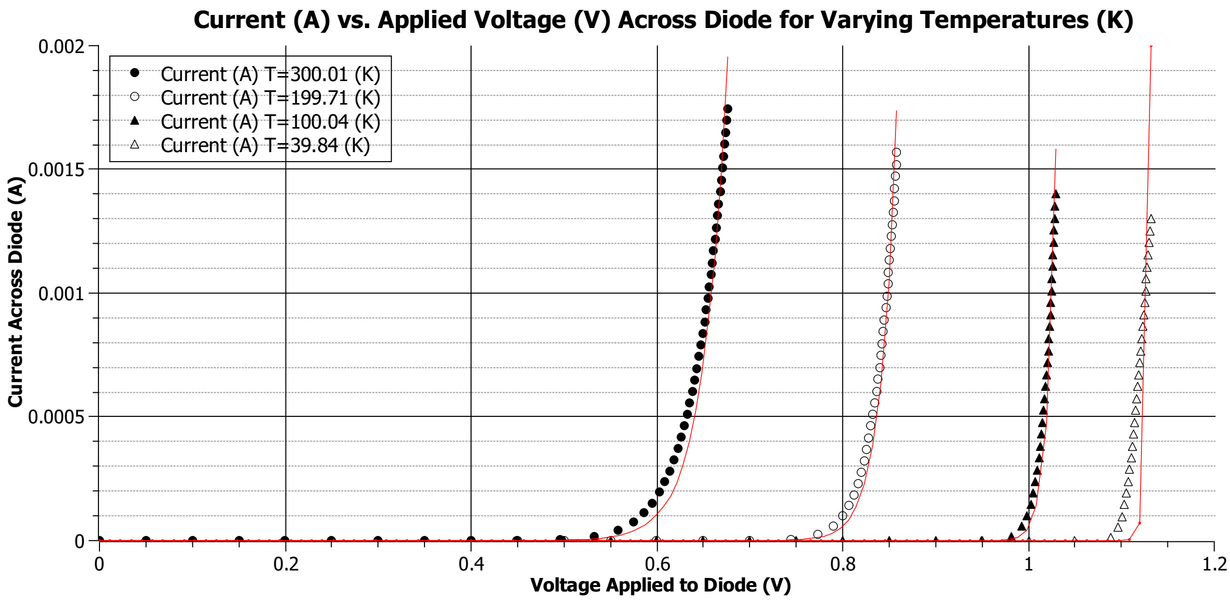

FIG. 4: Experimental data of Current (A) vs. Applied Voltage (V) for T= 300.01 (filled circle), 199.71K (empty circle), 100.04K (filled triangle), and 39.84K (empty triangle). Corresponding fits to Eq. III.3, shown in red, found that $I_{s,T=300.01} = 8.59\times10^{-15}\pm1.4\times10^{-16}$ A, $I_{s,T=199.71} = 3.78\times10^{-25}\pm5\times10^{-27}$ A, $I_{s,T=100.04} = 2.23\times10^{-55}\pm4\times10^{-57}$ A, $I_{s,T=39.84} = 1.47\times10^{-146}\pm1.7\times10^{-147}$ A.

We then calculated I_s at each temperature by fitting this data to Eq. III.3, using their corresponding values for T. For all temperatures, this was done using the Scaled Levenberg-Marquardt Algorithm with a tolerance 0.0001. Examples of these fits are shown overlaid on their corresponding data set in Fig. 4 .

As the the temperature decreased, one of the key trends that occurred was that the current rose more suddenly. This presented a limitation of Eq. III.3, as this models a more gradual growth than that found at lower temperatures. This limitation was apparent in our analysis for temperatures lower than 39.84 K. Data were taken at T= 29.90 K, 19.93 K, and 10.00 K, but the algorithm used for fitting was insufficient as the rate of growth became larger. At T=39.84 K, the algorithm was able to fit the data, but had a larger error than the data taken at other temperatures.

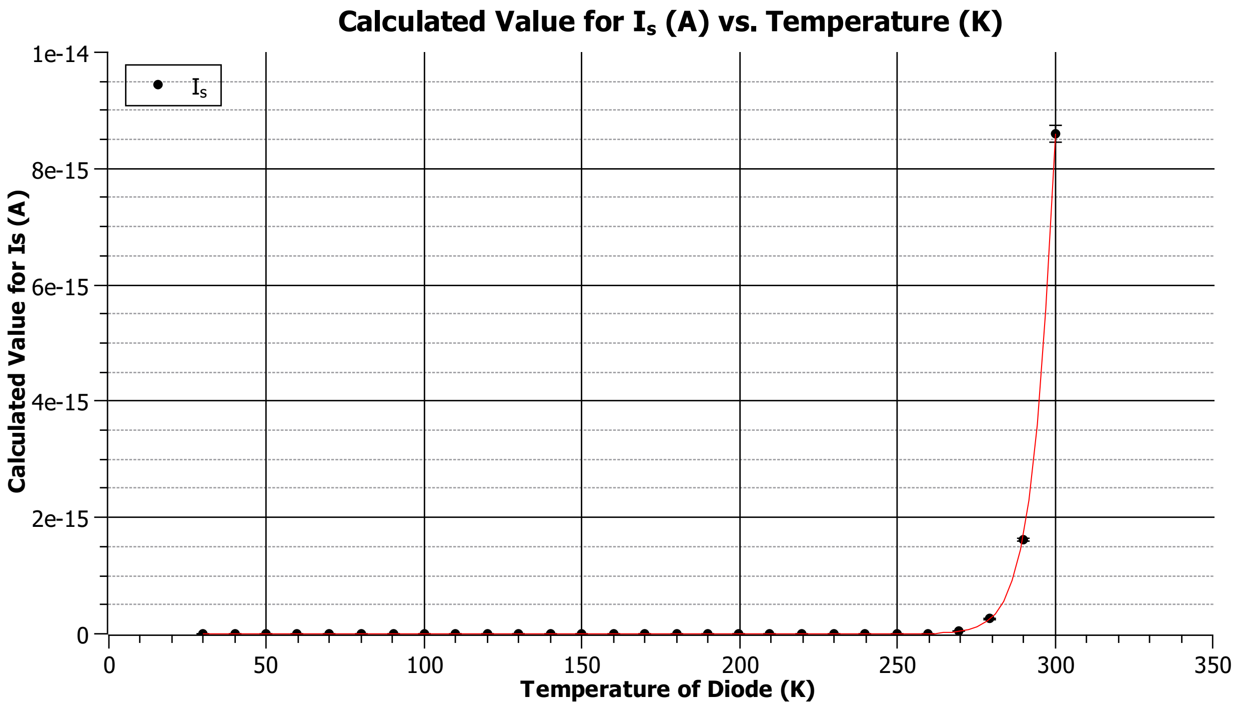

FIG. 5: Experimental data of I_s (A) vs T (K). Corresponding fit to Eq. III.5, shown in red, found $A = 2408734.95 \pm 127850.95$ A, and $E_{gap} = 1.22 \pm 0.01$ eV.

Using the same fitting algorithm as with the previous analysis, a plot of I_s vs. Temperature (K) was then fit to Eq. III.5, using A and E_{gap} as a fit parameter. This plot, as well as the fit, is shown in Fig. 5. We disregarded the value of A and calculated E_{gap} to be 1.22 $\pm$ 0.01 eV.

Our calculated band gap energy, E_{gap}=1.22 $\pm$ 0.01 eV differed from the accepted band gap energy of Si by .08 eV, Ge by 0.55 eV, and GaAs by 0.21 eV. This strongly suggests that the observed diode was made of Si, which was true.

While the closest accepted value to the calculated E_{gap} was Silicon's, the data were not within our range of error. The values for I_s could not be obtained for $T < 39.84$ K because of our model's limitations. Since the final calculation of E_{gap} is based on calculations of I_s, it is likely that our error is larger than we expected for E_{gap}.

While measuring the current across the diode, the temperature inside the vacuum chamber was subject to fluctuations. This could have led to slight changes of temperature throughout the measurement, so the value of temperature could have been inconsistent. This would increase our error for the calculation of I_s, and ultimately E_{gap} as well.

In addition, while E_{gap} was treated as a constant in Eq. III.4 and Eq. III.5, it is actually temperature-dependent, with at least 2 correction terms depending on temperature [2]. This temperature-dependence had a small effect when compared to the magnitude of our error, but it would change the relationship shown in Eq. III.4 and Eq. III.5, which could potentially impact our resulting value in a significant way.

VI. CONCLUSION

In conclusion, we demonstrated the use of current measurements across a range of temperatures as a method of calculating both E_{gap} and the material makeup of a given p-n junction diode. We applied varying voltages across a diode in a temperature controlled vacuum chamber, while sweeping the chamber's temperature from 300K to 10K, and measured the current through the diode at each voltage. With this, we then found I_s for each temperature and calculated E_{gap} for the diode as E_{gap}=1.22 $\pm$ 0.01 eV. Between Si, Ge, and GaAs, our calculated value was closest to the accepted value of $E_{gap,Si} = 1.14eV$ [1], which was the correct material.

The accepted value for Si was still out of the calculated range for E_{gap}. The source of the error is unknown, but one possibility was the neglect of E_{gap}'s temperature dependence [2]. This experiment should be repeated, taking this temperature dependence into account, to ensure the method's accuracy.

Diodes are a ubiquitous device throughout all electronics, and this method is well suited for deduction. The method presented could be applied to material science fields in order to manufacture and identify diodes of a specific specification.

VII. REFERENCES

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