ENERGY GAP ESTIMATION OF SILICON SEMICONDUCTORS BY TEMPERATURE CONTROL USING PELTIER ELEMENTS

Kenji Yamada

National Institute of Technology, Ishikawa College, Tsubata, Ishikawa, Japan

Email: kenji@ishikawa-nct.ac.jp

The global semiconductor shortage has now extended to a shortage of skilled semiconductor engineers, placing increased pressure on higher education institutions to bridge this gap through specialized training programs. Simultaneously, abnormal weather patterns have intensified concerns related to heat and energy management. In this context, Peltier devices—which can either absorb or dissipate heat depending on the direction of current flow—offer promising applications.

This study investigates the unique thermal properties of Peltier devices through an experiment conducted by fourth-year students in the Department of Electronics and Information Engineering. Previously, a simple thermostatic chamber was constructed by wrapping nichrome wire around a test tube to study the voltage-current (V-I) characteristics of a Zener diode at elevated temperatures. These experiments yielded five V-I plots at temperatures above room temperature, including one at room temperature.

In the present study, a Peltier element was integrated to enable measurements at sub-room temperatures. Figure 1 shows the V-I characteristics of the Zener diode mounted on the surface of the Peltier element. As the temperature decreased, the current through the diode also diminished. From the processed data, the energy band gap of the silicon material was estimated to be approximately 1 eV.

The experiment demonstrated that diode temperature could be precisely controlled by adjusting the current supplied to the Peltier device. The underlying principle is explained in the section *Estimation of Energy Band Gap of Silicon Materials*, while *Temperature Characteristics of Peltier Element* discusses how the temperature depends on the current input. The *Temperature Characteristics of Diodes* section presents measured data and details the process of estimating the energy band gap using Peltier devices.

Finally, the *Conclusions* section reviews the experimental results and offers suggestions for further educational experiments involving Peltier elements. This study not only serves as an effective educational resource for students in semiconductor device engineering but also provides meaningful insights for those studying electrical, electronic, and information science. Moreover, the findings may be beneficial for mechanical systems courses, particularly in the field of thermoelectric conversion.

Keywords: *Constant temperature chamber, Peltier Elements, Silicon Energy Band Gap, Physics Experiment, Education Material*

Introduction

As the demand for semiconductors continues to rise, manufacturing plants are being constructed at a rapid pace, creating an urgent need for engineers to work on-site. However, the supply of qualified engineers is not keeping up with this growing demand. For this reason, educational institutions are expected to begin training students interested in the semiconductor field from an early stage.

As part of the student experiment curriculum in our Department of Electronics and Information Engineering, Yamada (2019) conducted experiments to estimate the energy band gap of silicon materials using the voltage-current (V-I) characteristics of diodes, with temperature as a variable. This is a physics-based experiment that provides valuable insight into semiconductor behavior in response to temperature changes. In previous experiments, the ambient temperature of the diode was increased using a thermostatic chamber constructed with a filament wound around the bottom of the test tube. The temperature was gradually raised from room temperature — approximately 25 ℃, which was the lowest temperature recorded in the data.

However, this approach posed two key limitations: the risk of overheating if the temperature was increased excessively, and the inability to collect measurements at temperatures below room temperature. To overcome these limitations, the current study focuses on obtaining data below room temperature by leveraging the Peltier effect—a unique thermoelectric phenomenon observed in semiconductors.

This experiment aims to stimulate student interest in semiconductors by introducing phenomena that are distinct to these materials. The Peltier structure consists of multiple p-type and n-type semiconductors bonded to metal and connected in series. The device features a heat-absorbing (cooling) side and a heat-generating (heating) side. Temperature control is relatively simple, as the amount of heat transferred is proportional to the current flowing through the element.

Peltier elements are widely used for electronic cooling in semiconductor components such as charge-coupled devices (CCDs), laser diodes used in optical communication, and CPUs that require localized cooling. They are also applied in the temperature regulation of small biological samples.

In this study, we measured the V-I characteristics of a Zener diode using the temperature-controlling properties of a Peltier element and estimated the energy band gap of the silicon material. In addition, we discuss the potential application of Peltier devices as effective teaching tools for semiconductor device education.

Estimation of Energy Band Gap of Silicon Materials

Zener diodes were fabricated using a p-n junction structure with silicon as the base material. Figure 1 illustrates the general V-I characteristics of the diode under forward bias. This figure is adapted from a graph presented in the book by E.S. Yang (1981). Notably, in some cases, the slope of the curve differs between the low- and high-voltage regions.

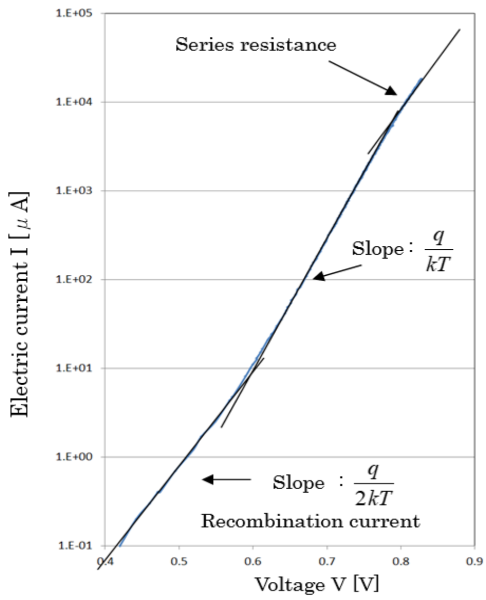

Figure 1 Voltage-current characteristics of p-n junction diodes under forward bias condition

Based on the result obtained, the diode current can be expressed using the ideal factor *n*, as shown in Eq. (1). In the relatively high-voltage region, the constant term "1" within the parentheses in Eq. (1) becomes negligible, allowing the expression to be approximated as Eq. (2), where I_0 denotes the reverse saturation current. As shown in Eq. (3), I_0 is proportional to the square of n_i, which is proportional to the product of temperature T^3 and exp(-E_g/k_BT) (Eq. (4)). As the change in exp(-E_g/k_BT) is larger than that in T^3, I_0 can be considered proportional to exp(-E_g/k_BT). With a proportionality factor of 1, Eg can be expressed as Eq. (5). In other words, if I_0 at each temperature is known with the temperature as a parameter, Eg can be calculated from the slope of the graph of I_0 against the reciprocal of the temperature.

$$I = I_0\left\{\exp\left(\frac{qV}{nk_BT}\right) - 1\right\} \quad (1)$$

$$I \approx I_0 \exp\left(\frac{qV}{nk_BT}\right) \quad (2)$$

$$I_0 = qA\left(\frac{D_n}{L_n}n_{po} + \frac{D_p}{L_p}p_{no}\right) = qAn_i^2\left(\frac{D_n}{L_nN_a} + \frac{D_p}{L_pN_d}\right) \quad (3)$$

$$I_o \propto n_i^2 \propto T^3 \exp\left(-\frac{E_g}{k_BT}\right) \quad (4)$$

$$E_g = -k_B\frac{d(\ln I_0)}{d\left(\frac{1}{T}\right)} \quad (5)$$

Temperature Characteristics of Peltier Element

The temperature characteristics of a Peltier element (TES1-12739, 4.6A, 16V), 30 mm in length and width on low- and high-temperature surfaces are shown in Figure 2. The current values ranged from 0.5 A to 2.0 A. The temperature changed as soon as the current started to flow and became almost constant after 120 s.

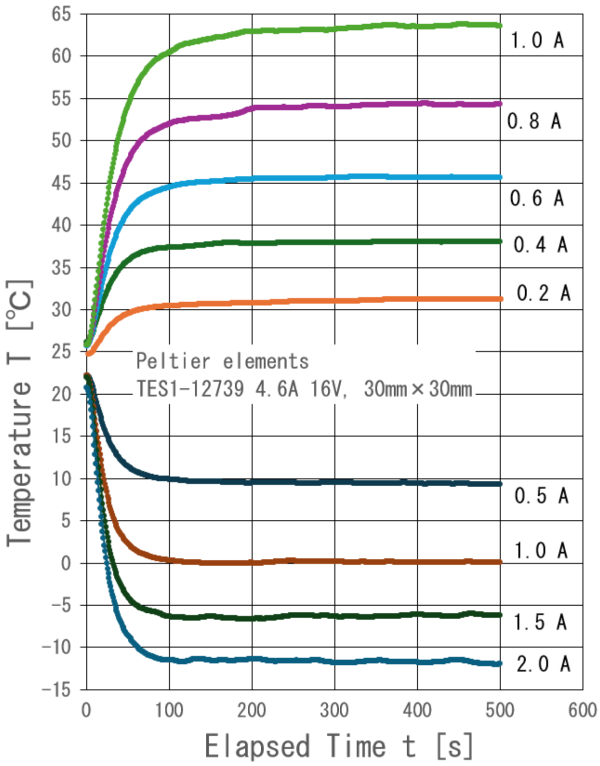

Figure 2 Temperature characteristics of Peltier elements

The average constant temperatures maintained during the experiment are listed in Table 1. These temperatures were measured using a commercially available IC temperature sensor (–40 to 85 °C) and recorded on a PC. The results from Table 1 are plotted in Figure 3, along with the corresponding approximate equations. The slope on the high-temperature side was 40.65, while the slope on the low-temperature side was 14.04—a significantly smaller value. This reduced rate of temperature decrease is likely due to heat inflow from the surrounding environment, as the Peltier element was installed only on the heat sink. The data presented in Figure 3 can be conveniently used to set arbitrary target temperatures with ease.

Table1 Saturation temperature versus current value

Current value [A]	Temperature [℃]
1.0	63.7
0.8	54.3
0.6	45.6
0.4	38.0
0.2	31.2
-0.5	9.3
-1.0	0.1
-1.5	-6.2
-2.0	-12.0

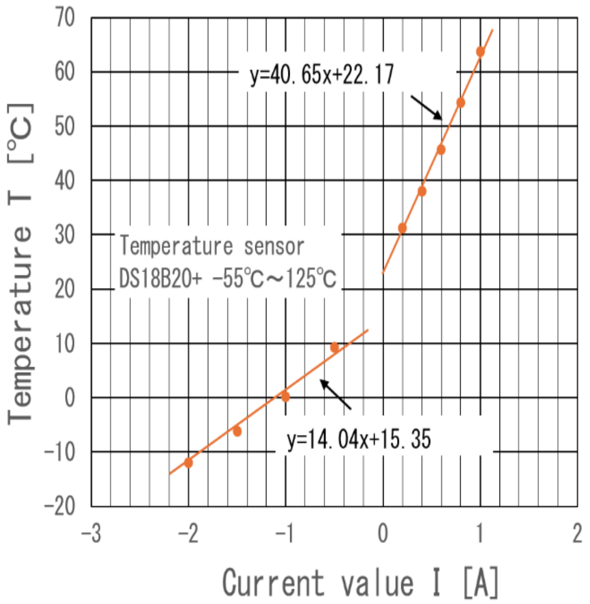

Figure 3 Saturation temperature variation with respect to the current value applied to the Peltier element and its approximate formula

For the low-temperature side of Figure 2, the 2.0 A graph shows a larger fluctuation than the 0.5 A graph. Figure 4 shows an enlarged graph used to estimate the extent of fluctuation, with the maximum variation observed being 0.55 eV. When measuring the voltage-current (V-I) characteristics with temperature as a parameter, it is essential to conduct measurements promptly once the temperature stabilizes. Any increase or decrease in temperature during measurement can affect the resulting graph. If the temperature remains constant at each measurement point, the resulting V-I curves will appear as straight, parallel lines, as shown in Figure 1. However, if the measurements are taken at fluctuating temperatures, these straight lines may intersect. To minimize such errors, it is recommended to maintain temperature fluctuations within Δ 1.0 °C. When this condition is met, the graph shown in section 2.0A remains reliable and does not significantly impact the measurement data.

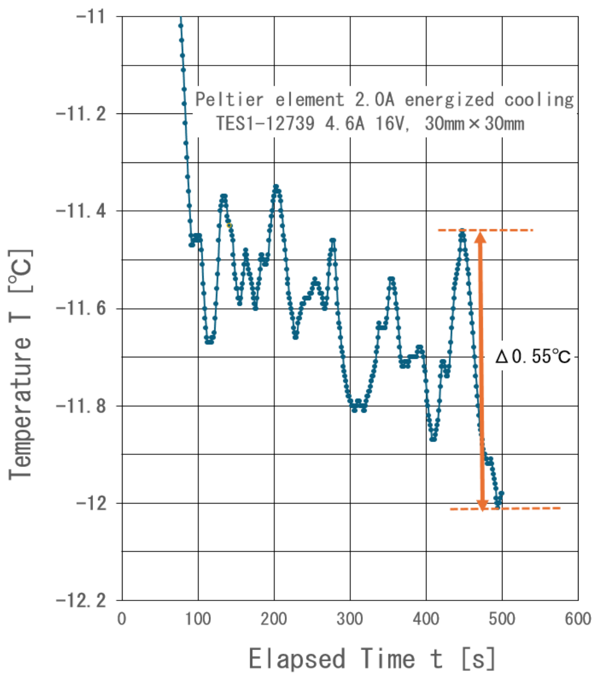

Figure 4 Fluctuations in the saturation temperature region of the Peltier element

Yamada (2024) previously used a thermostatic chamber with a filament to vary the ambient temperature of the diode. However, the use of a Peltier element has proven to be more effective, as it allows for more precise temperature control and enables measurements in the sub-room-temperature range. Moreover, since this course includes the study of low-temperature phenomena, exploring the functionality of the Peltier element itself can enhance student engagement and foster greater interest in semiconductor devices.

Additionally, by replacing diodes with transistors, temperature dependence can be explored in the context of transistor V-I characteristics. Because transistors, like diodes, are made of semiconductor materials and are highly sensitive to ambient temperature, amplifier circuits are typically designed to minimize the impact of thermal fluctuations. Using Peltier elements, students can easily conduct verification experiments that incorporate temperature variation into the analysis of transistor-based amplifier circuits. This provides a hands-on opportunity to understand and evaluate how temperature influences semiconductor device behavior in practical applications.

Experimental equipment

The experiments required three digital multimeters and two DC power supplies. Zener diodes, Peltier elements, and temperature sensors were also required electronic parts and devices. The DC power supply requirement for the Peltier element was 18 V at 2 A. The student laboratory was equipped with a DC power supply (with a maximum rating of several Amperes) so that it could also be used for motor experiments. Figure 5 shows a schematic of the circuit used for measuring the voltage-current characteristics of the diode with temperature as a parameter.

The electronic devices used in the experiment are readily available and inexpensive. Twenty-three sets will be prepared for groups, comprising two students each. These experiments will be conducted as a theme for fourth-year students in the Department of Electronics and Information Engineering. In two 90-min experiments, students will measure voltage-current characteristics and capacitance-voltage characteristics. In another two 90-min experiments, students will learn how to process data using a PC and analyze data using Excel. These experiments will be conducted during the winter season, close to December; by that time, students will have already learned about p-n junctions and energy gaps in the "Electronic Devices" course.

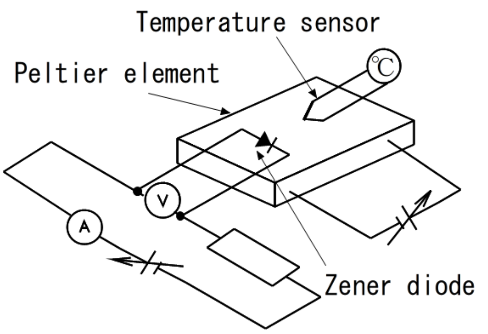

Figure 5 Schematic of Voltage-current characteristics measurement circuit

Temperature Characteristics of Diodes

The voltage-current (V-I) characteristics of the Zener diode were measured using temperature as a parameter (Figure 6). As the forward voltage applied to the diode increased, the current rose exponentially. When the vertical axis of the graph is plotted on a logarithmic scale, the curve transforms into a straight line—an effect that often captures students' interest. The graph is centered at 0.0 A and shifts upward to the left on the heat-generating side and downward to the right on the heat-absorbing side as the current increases. The linear portion of this graph was extracted and is shown in logarithmic form in Figure 7. The data exhibit a consistent shift to the upper left, from -12.0 °C to 63.7 °C. An approximate equation for the linear fit can be obtained using the "Add Trendline" function in Excel, highlighting the important of spreadsheet software in data processing.

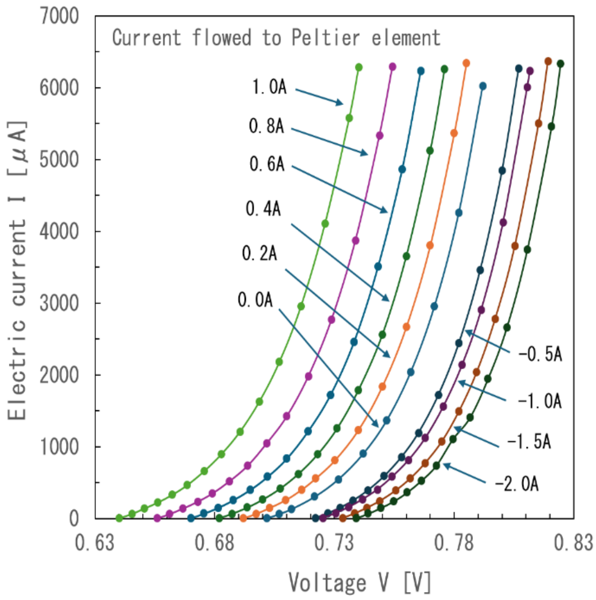

Figure 6 Voltage-current characteristics of Zener diodes with temperature as a parameter

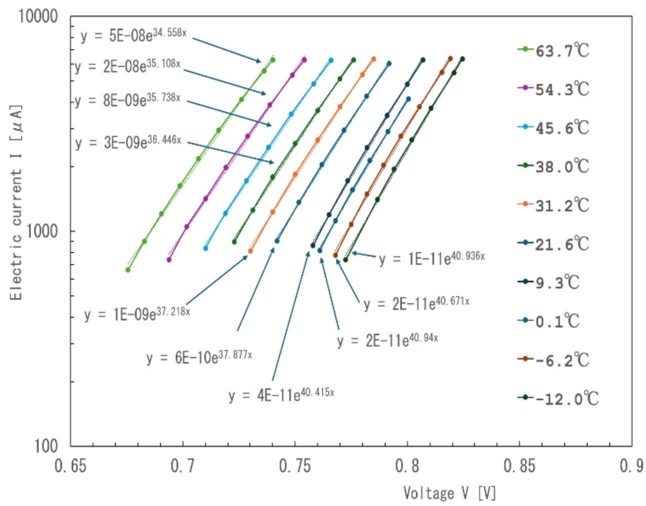

Figure 7 Logarithmic display of voltage-current characteristics

This exercise also reinforces students' understanding of how physical quantities can be derived from the slopes of linear graphs using mathematical techniques. As Yamada (2019) noted, this type of material serves as a valuable component of STEM education—integrating concepts from science, technology, engineering, and mathematics. For the graph at 21.6 °C, the inverse saturation current value is 6×10^{-16} A. The reciprocal values of the absolute temperatures used are listed in Table 2, and the corresponding results are plotted in Figure 8. The value of I_0 decreases in the lower-temperature range. The slope of the linear approximation in Figure 8 is approximately $1.025\text{x}10^4$. When this value is multiplied by the Boltzmann constant k_B and converted into electron volts, the result is approximately 0.88 eV. Rounded to one significant digit, this yields about 1 eV ― closely matching the known energy band gap of silicon.

Table2 Reverse saturation current value for the reciprocal of absolute temperature

T [℃]	1/T [1/K]	I_0 [A]	LN I_0 [A]
63. 7	0. 00297	5.00×10^{-14}	−30. 63
54. 3	0. 0030553	2.00×10^{-14}	−31. 54
45. 6	0. 0031387	8.00×10^{-15}	−32. 46
38. 0	0. 0032154	3.00×10^{-15}	−33. 44
31. 2	0. 0032873	1.00×10^{-15}	−34. 54
21. 6	0. 0033944	6.00×10^{-16}	−35. 05
9. 3	0. 0035423	4.00×10^{-17}	−37. 76
0. 1	0. 0036617	2.00×10^{-17}	−38. 45
−6. 2	0. 0037481	2.00×10^{-17}	−38. 45
12. 0	0. 0038314	1.00×10^{-17}	−39. 14

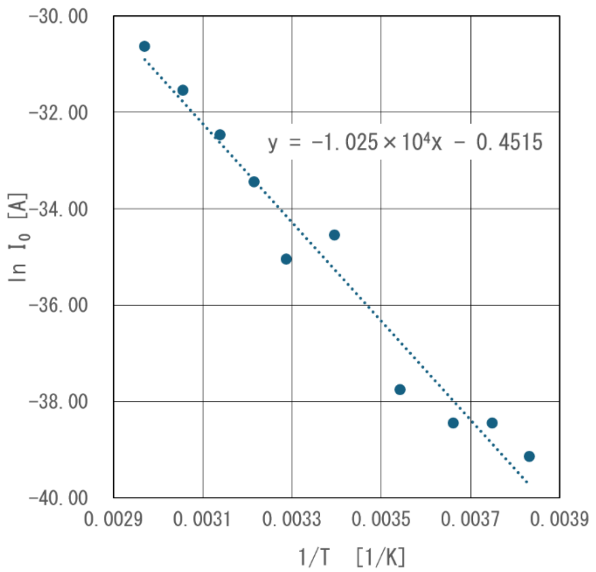

Figure 8 Reverse saturation current characteristic as a function of the reciprocal of absolute temperature

In semiconductor education, the energy band gap is a key material property that influences device performance, typically expressed in electron volts. However, estimating this value experimentally usually requires specialized equipment. This experiment is particularly meaningful because it enables students to directly apply concepts learned in lectures—such as energy expressed in electron volts—to real measurements using accessible tools.

Conclusions

As part of developing semiconductor experiments, we investigated the voltage-current characteristics of diodes using temperature as a variable. Until now, these experiments were conducted in thermostatic chambers with filaments wound around test tubes. In this study, we introduced a new approach by creating a temperature-controlled environment ranging from low to high temperatures using a Peltier element. This allowed us to estimate the energy band gap of silicon to be approximately 1 eV based on measured characteristics. Importantly, these experiments go beyond simple data collection—they aim to equip students with the skills to derive new physical quantities through data processing. The experiment integrates concepts from semiconductor physics, mathematics, and information processing, making it a valuable tool for comprehensive STEM education. Because Peltier elements are inexpensive and commercially available, this setup can be readily adopted by institutions of higher education.

The experiment is particularly significant as an applied physics exercise, utilizing temperature as a key parameter. Furthermore, it holds promise as effective teaching material for training future semiconductor engineers ― an area of growing importance amid the global demand for skilled professionals in the semiconductor industry.

Acknowledgements

This work was supported by the Shibuya Science Culture and Sports Foundation, Toyohashi University of Technology Collaborative Education and Research Project for KOSEN and the Japan Society for the Promotion of Science (JSPS) KAKENHI under Grant Number 22K02955.

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